DECISION SUPPORT PROJECT BP-2

Spatial & Economic Analysis for Policy and Decision Support in Agriculture and Environment

Annual Report 2006

Centro Internacional de Agricultura Tropical
International Center for Tropical Agriculture

TABLE OF CONTENTS
Decision Support Project Annual Report

THEME 4: ESTIMATING THE MAGNITUDE AND DISTRIBUTION OF SOCIO-ECONOMIC AND ENVIRONMENTAL IMPACTS OF AGRICULTURAL R&D ON POVERTY AND VULNERABILITY IN RURAL COMMUNITIES

Papers

THEME 5: OBTAINING, DEVELOPING, AND MANAGING DATA AND INFORMATION

Papers

ANNUAL REPORT SUMMARY

Project BP-2: DECISION SUPPORT

1. Project Logframe

Our goal is to improve the targeting of investments in agricultural and NRM research and development through economic and geographic analysis.

Our objective is to develop and provide analysis, information and tools to improve decisions about where, when and how innovations can be implemented to enhance rural livelihoods in a sustainable and equitable manner.

Project Logframe (MTP 2006 – 2008)

	Outputs	Intended User	Outcome	Impact
OUTPUT 1	Implications of alternative R&D decisions analyzed	Scientists and research managers; development planners and practitioners; policymakers; donors and others who make decision about how R&D resources are invested.	***Decision-makers informed regarding potential tradeoffs resulting from the allocation of research or development funds, either directly or indirectly via changes in policy***	Impacts to R&D investments are more efficient, equitable, sustainable
Targets	Valuation of productivity benefits and environmental services generated by land use systems in Colombia	Research managers in CIAT; Policymakers and planners in Colombia and other countries with similar ecosystems	Depending on the results, research priorities for R&D are confirmed or revised.	R&D investments generate beneficial impacts, minimizing tradeoffs between environmental and productivity benefits.
	Assessment of early adoption and impact of improved forages in Asia	CIAT forages project and national partners; CIAT research management	Researchers, research managers and extensionists better understand what did and didn't work, and use the knowledge to institutionalize results of current project and to improve design of future projects.	Benefits of improved forages on farmer welfare are larger and more widespread
	Analysis of the potential impact of water research projects under implementation by the CPWF in prioritized basins.	CPWF and research partners including NGO's, Universities and environmental authorities.	An estimation of the likely impact on poverty and improvements in water management as a resultant of CPWF implementation	R&D investments on water related project better targeted.
OUTPUT 2	Frameworks and tools for evaluating and targeting technology and/or management alternatives in agriculture and NRM R&D	Researchers and analysts in CIAT and partner organizations	Researchers use their better conceptual and empirical understanding of how impact occurs and is measured to design more impact-oriented projects.	R&D efforts more effective, equitable and sustainable.
Targets	User friendly empirical tool for quantifying and valuing environmental services developed	Researchers and planners working on economics of environmental services	Projects and policies about payment for environmental services schemes are better designed and targeted	Economic and environmental impacts of payment for environmental services schemes are more effective, equitable, wide-spread and sustainable.
	Homologue concept demonstrated, verified and published.	Decision makers in producer associations, NGOs, and GOs.	***Tools are used for identification of genetic resources that are deployed to support agricultural development.***	***More effective locating and targeting of germplasm leads to higher welfare and environmental benefits***
	Concepts and principles and potential for site sensitive natural hazard insurance.	Policy makers and planners in agriculture and finance ministries, Organizations that work for and with producers.	Identification of sites that can most benefit from natural hazard insurance. Enhanced effectiveness of scheme implementation	Widespread implementation of insurance for smallholder farmers. Enhanced income, equity and land management.
OUTPUT 3	Spatial, economic and other information and data developed, maintained and made available to internal and external users.	Researchers internal and external to CIAT, agricultural decision makers.	Researchers and decision makers have readily-accessible accurate and appropriate information from which to conduct analysis and base actions.	Better analysis and decisions are made thereby enhancing impacts
Target	Global derivates of high-resolution digital elevation models for tropical areas.	Researchers internal and external to CIAT. National agricultural and environmental NGOs and GOs.	***Accurate topographic information incorporated in analyses of agrobiodiversity and in research on soil and water management.***	

2. Output Targets

OUTPUT 1: Implications of alternative R&D decisions analyzed		
Output targets 2006 and Achievement		**Evidence**
Valuation of productivity benefits and environmental services generated by land use systems in Colombia	100%	Rubiano, J., Quintero, M., Estrada. R. & Moreno, A. (2006). Multiscale Analysis for Promoting Integrated Watershed Management. Water International Vol 31, No.3. Forthcoming
Analysis of the potential impact of water research projects under implementation by the CPWF in prioritized basins.	50%	Impact pathways constructed for 6 out of 9 CPWF basins http://impactpathways.pbwiki.com Draft impact pathway narratives constructed for 3 basins and posted on the web. Extrapolation domain analysis completed for 3 basins. Impact pathways methodology developed and published (see IPRA 2006 Output)
OUTPUT 2: Frameworks, tools for evaluating and targeting technology and/or management alternatives		
User friendly empirical tool for quantifying and valuing environmental services developed	100%	Quintero, M., Estrada, R.D. y García, J. 2006. A Manual for ECOSAUT: A Model for the Economic, Social and Environmental Evaluation of Land Use. CIAT-CIP-GTZ-CONDESAN-WFCP. Centro Internacional de la Papa. Lima, Perú. 86 p.(CD-ROM)
Homologue concept demonstrated, verified and published	95%	Homologue™ Version Beta a.0. A computer system for identifying similar environments throughout the tropical world. Jones, Diaz, Cock. CD with software and users manual. (CD-ROM)
Concepts and principles and potential for site sensitive natural hazard insurance	100%	Final Report: A system of drought insurance for poverty alleviation in rural areas. A feasibility study of a practical method of drought insurance that is self-sustaining and ready for use by poor farmers, NGOs or other development organizations. Diaz Nieto et al. 95 pages.
OUTPUT 3: Spatial, economic and other information and data		
Global derivates of high-resolution digital elevation models for tropical areas	100%	Download webpage @ http://srtm.csi.cgiar.org/; Reuter H.I, A. Nelson, A. Jarvis, accepted, An evaluation of void filling interpolation methods ods for SRTM data, International Journal of Geographic Information Science. Jarvis, A., Rubiano, J., Nelson, A., Farrow, A., & Mulligan, M. Practical use of SRBM data in the tropics – Comparisons with digital elevation models generated from cartographics data. Working Document no. 198, 32 pp. CIAT, Cali, Colombia.

3. Research Highlights

- ### Increased User Utility for the Topographic Data Base

The Digital Elevation Model that has been derived from the February 2000 Shuttle Radar Topography Mission (SRTM) has been one of the most important publicly available new spatial datasets in recent years. However, the 'finished' grade version of the data still contains data voids (some 836,000 km^2) – and other anomalies – that prevent immediate use for a wide range of applications. These voids can be filled using a range of interpolation algorithms in conjunction with other sources of elevation data, but there is little guidance on the most appropriate void filling method. Project scientists of BP2 and their partners developed (i) a method to fill voids using a variety of interpolators, (ii) a method to determine the most appropriate void filling algorithms using a classification of the voids based on their size and a typology of their surrounding terrain; and (iii) the classification of the most appropriate algorithm for each of the 3,339,913 voids in the SRTM data. Based on a sample of 1,304 artificial but realistic voids across six terrain types and eight void size classes, it was found that the choice of void filling algorithm is dependent on both the size and terrain type of the void. The best methods can be generalised as: Kriging or Inverse Distance Weighting interpolation for small and medium size voids in relatively flat low-lying areas; Spline interpolation for small and medium sized voids in high altitude and dissected terrain; Triangular Irregular Network or Inverse Distance Weighting interpolation for large voids in very flat areas, and an advanced Spline Method for large voids in other terrains.

- **Application of BP2 developed targeting tools by National Grower's Association for the development of Denomination of Origin for higher value crops**

The BP2 project and the directorate for Intellectual Property of the National Federation of Colombian Coffee Growers (FNC) led a pilot study to understand the feasibility of supporting the implementation of denomination of origin for coffee and to derive the principles for implementing denominations of origin for higher value crops. The rationale behind the study was to understand the relationship between environmental data and quality data of product samples collected from farms during the 2006 harvest. To this end, a field survey was designed on the basis of prior knowledge from similar studies. Technical staff of the regional FNC offices identified the participating farms with the aim of including farms that were accessible and covered the range of conditions that represent the coffee-growing environments in selected departments. A large number of farms were sampled. Each farm was geo-referenced to facilitate analysis of spatial correlation. To reduce variability within the data, product samples were processed in a mobile unit that standardizes harvest and post-harvest processes. Product quality characterization was conducted at the FNC headquarters and at the FNC research center CENICAFE in Chinchina. Soil samples were also obtained in each farm. We were able to show that spatial structures in the quality data are related to those found in the environmental data and documented clear relationships between growing environment and product quality characteristics.

- **Watershed management and poverty alleviation in the Colombian Andes**

The relationship between water and poverty was assessed in two watersheds in the Colombian Andes. The methodology includes both a participatory assessment of current poverty and an analysis of how household poverty status has changed over the last 25 years. Taken together, the two results capture both direct and indirect linkages between water and poverty. They identify situations where win-win solutions may be possible, and also where it is likely that trade offs will be required, not only between environmental, economic growth and equity objectives at the watershed scale, but also between households' welfare objectives and the strategies that they use to achieve them. The results of this research suggest that in the two investigated watersheds, the indirect relationships between poverty and water via employment and income linkages may be more important than direct linkages via domestic supply. This is consistent with the diversification of rural livelihoods and the importance of off-farm income in poverty reduction. Interventions to enhance domestic supply may have big impacts in a few specific communities, but would not generally contribute much to poverty alleviation. Interventions that would reduce employment in industries like dairying or mining in Fuquene or profitability in small scale agriculture in Coello, could have significant impacts on poverty, since these have been important pathways out of poverty over the past 25 years.

- **International prize**

  Zayed International Prize. 2006. *Scientific Achievements in the Environment* (www.zayedprize.org) awarded to the authors of the Millennium Assessment.

4. Important Project Outcome

Large research and development programs working on agricultural development for the rural poor throughout the developing world were able to systematically direct their interventions to regions and peoples where impacts were the most needed and interventions the most appropriate. This was possible based on using previously developed concepts of poverty mapping, systems analyses and livelihood system analysis. Concrete outputs include development of spatial poverty characterization approaches. These were published in the journal Food Policy and on the project Web site (http://www.povertymap.net/). The integration of these methods and high resolution spatial data such as childhood malnutrition, major crop distributions, irrigated areas and environmental data such topography and climate, enabled the systematic targeting of development interventions. The 2003 – 2005 CIAT MTP identifies these outputs as "Output 3 of the PE4-Project Logframe at page 29: Analyses and prediction of socio-economic factors influencing land use development performed. Measurable indicators: Distribution of poverty and its causes identified more accurately using spatial information."

A broad group of individuals and organizations utilized the outputs of our poverty mapping initiative. In 2006, our clients and partners downloaded 397 high-resolution poverty maps in formats suitable for analysis using geographic information system software (see http://gisweb.ciat.cgiar.org/povertymapping/). Users included officials of the government, non-governmental organizations, advanced research institutes, as well as university academics and students. Geographic targeting work based on spatial analysis methods that integrate poverty, demographic, agricultural and environmental information was also used for a major priority-setting exercise of the Generation Challenge Program (GCP), a long term program that invests substantially in research to improve the main crops produced by the poor in high risk drought-prone and marginal areas.

Poverty mapping work specifically focused on influencing government and non-government agencies, as well as universities in Ecuador, Honduras, Mexico, Nigeria, Kenya, Malawi, Sri Lanka, Bangladesh and Vietnam. Areas identified for targeting research and development resources of the GCP include parts of South and Southeast Asia, sub-Saharan Africa, and Mexico and Central America. Maps and related analytical approaches were used by research and development targeting exercises and academic research. For example, Ecuador uses poverty and food security maps from the project in targeting food security resources. CIMMYT used their Mexico analysis to re-orient their breeding and variety testing programs to poor and marginal environments. International agencies used Bangladesh poverty maps to respond to flooding by identifying the coincidence of damage and the vulnerability of the population. In Kenya, the poverty maps were integrated into local information systems, and were used to target development assistance. Mapping work for the Generation Challenge Program was used to prioritize and focus the work on a reasonable number of crops and environments where impacts on reducing poverty was the most needed. Use of poverty maps was partly documented when our partners and clients downloaded high-resolution poverty maps from our Web site. The Generation Challenge Program adopted the poverty-drought analysis and database as a key element of their overall strategic planning and prioritization. The use of some of the studies was documented in the publication, "Where the poor are: an atlas of poverty", published by Columbia University.

5. Project Publications

Articles in refereed journals

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Gonzalez, C.E., Jarvis, A. and Palacio, J.D. (2006). Biogeografía del roble común (Quercus humboldtii Bonpl.): distribución geográfica y su adaptación climática. Simposio Internacional sobre Robles y Ecosistemas Asociados. Santafé de Bogotá, Colombia, 11-12 May, 2006.

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Cook, S.E., Gichuki, F., Turral, H. and Fisher, M.J. (2006). *Analyzing Water Poverty: Water, Agriculture and Poverty in Basins*. Basin Focal Project Working Paper. no. 3. 1-18 pp.

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Yamamoto, Y., Oberthür, T. and Lefroy, R. (2006). *Rainfed Agriculture in Northern Laos -Identification of Land Use Cycles in Slash-and-Burn Agriculture by Satellite Imagery*. JIRCAS Working Report no. 47: 1-6.

6. Funded Project Proposals

Project	Donor	Total US$ in 2006	CIAT
Challenge Program on Water and Food (CPWF) Theme 2	IWMI	303,423	303,423
New opportunities for hillside farmers: Matching product quality, environment and market demand for high-value agricultural products	GTZ	485,541	329,296
Spatial Trade-Off Analyses for Site-Sensitive Development Interventions in Upland Systems of Southeast Asia	Austria	141,060	94,060
Overcoming Land Degradation to Mitigate Deforestation in the Humid Tropic Ecoregions	UNEP/GEF	100,000	31,900
Development of Measures for Impact on Poverty and Hunger in fair-traded and Organic Coffee Producing Communities	SFL	41,727	41,727
Agreement between CIAT and CPWF for Provision of Leader of Basin Focal Projects	CP	84,489	84,489
Análisis Espacial para la Identificación de Amenazas para la Conservación en América del Sur	TNC	44,750	44,750
Analyses of Coffee Quality and Production System Characteristics in the Nariño and Cauca Departments of Colombia	FNC	30,875	30,875
Sustaining Inclusive Collective Action that Links Across Economic and Ecological Scales in Upper Watersheds (SCALES)	CPWF	219,356	47,919
		1,451,221	**1,008,439**

7. **Project Staff** (* Left during 2006; ✓ Arrived during 2006)

Thomas Oberthür (100%)	PhD, Geography	Project Manager
Nancy Johnson (100%)	PhD, Economist	Senior Scientist
Simon E. Cook (50%)	PhD, Crop Biology	Senior Scientist
Glenn G. Hyman (100%)	PhD, Geography	Senior Scientist
Douglas White (75%)	PhD, Agr. & Environ. Econ.	Senior Research Fellow
Andrew Jarvis (100%)	PhD., Geography	Senior Scientist
Roberto Porro (50%)	PhD., Anthropology	Senior Scientist
Arjan J. Gijsman	PhD, Soil Science/Crop Modeling	Assoc. Senior Scientist
Jorge Rubiano* (100%)	PhD, Geography	Postdoctoral Fellow
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Norbert Niederhauser (100%)	DI(FH), Inf. & Com. Engineering	Research Fellow
Carolina González (100%)	Lawyer and Economist	Research Associate
William Díaz* (100%)	MSc, Admin./System Engineer.	Systems Analyst 1
Liliana Rojas (100%)	MSc, Natural Resources	Research Assistant 1
Viviana Gonzalías (100%)	MSc, Sustainable Forestry	Research Assistant 2
Andrés J. Peña* (100%)	MSc, Meteorology	Research Assistant 2
James García (100%)	MSc, Statistician	Data Base Specialist
Lilian Busingye (100%)	MSc, GIS	Spatial Analysis Intern
Germán Lema (100%)	BSc, Industrial Engineering	Statistical Consultant 2
Lilian P. Torres (100%)	BSc, Business Administration	Administrative Assistant 1
Luz A. Clavijo (100%)	BSc, Geography	Research Assistant 1
Germán Escobar (100%)	BSc, Biology	Research Assistant 1
Sandra Bolaños (100%)	BSc, Industrial Engineering	Research Assistant 1
Magda L. Perez* (100%)	BSc, Catastral & Geodesta Engineer	Research Assistant 1
Jenny L. Correa (100%)	BA, Social Communication	Research Assistant 1
María A. Peralta (100%)	BSc, Economist	Research Assistant 2
Marcela Estrada (100%)	Agronomy Engineering	Research Assistant 3
Mike H. Salazar (100%)	Ecology	Research Assistant 3
Elizabeth Barona (100%)	BSc, Systems Engineer	GIS Analyst 3
Silvia E. Castaño (100%)	BSc, Systems Engineer	GIS Coordinator
Claudia J. Perea (100%)	BSc, Systems Engineer	Systems Analyst 3
Jorge A. Cardona (100%)	BSc, Systems Engineer	Systems Analyst 3
Hermann Usma (100%)	Agricultural Technology	Expert Research 1
Edward Guevara (100%)	Environmental Engineering	Technician 1
Marisol Calderón (100%)	Architectural Drawing	Office Clerk 1
Juan C. Barona* (100%)	Topographic Engineer	Office Clerk 4
Ovidio Rivera (100%)	Systems Technology	Office Clerk 4
Víctor M. Soto (100%)	BSc, Business Administration	GIS Expert
Alexander Cuero (100%)	Systems Technology	GIS Expert
Carlos Nagles (100%)	Agricultural Technology	GIS Expert
Yuviza Barona* (100%)	Bilingual Secretary	Bilingual Secretary
Ana M. Guerrero (100%)	Bilingual Secretary	Bilingual Secretary
Peter Läderach (100%)	MSc, Geography	Visiting Researcher
Natasha Pauli* (50%)	MSc, Biology & Geography	Visiting Researcher
Juergen Piechaczek (100%)	MSc, Agriculture	Visiting Researcher
Reinhild Bode (100%)	MSc, Rural Development	Visiting Researcher
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Walter Ritter✓* (50%)	DI(FH), Inf. & Com. Engineering	Visiting Researcher
Martin Wiesinger✓ (100%)	DI(FH), Inf. & Com. Engineering	Visiting Researcher
Michael Gau✓ (100%)	DI(FH), Inf. & Com. Engineering	Visiting Researcher
Carlos González (100%)	BSc, Biologist	Visiting Researcher
Karl Atzmanstorfer* (100%)	BSc, Geography	Visiting Researcher
Scott Gebhardt✓ (100%)	BSc, Geography	Visiting Researcher

Daniel Jiménez (100%)	Agronomic Engineering	Visiting Researcher
Julien Henique✓* (100%)	Agronomic Engineering	Visiting Researcher
Diana Tangarife* (100%)	Environmental Engineering	Visiting Researcher
Ginger Roberts✓ (100%)	Environmental Development	Visiting Researcher
Aske Bosselman✓ (100%)	Forestry Engineering	Visiting Researcher
Klaus Dons✓ (100%)	Forestry Engineering	Visiting Researcher
Abson Sae-Tang✓* (100%)	Electronic Engineering	Visiting Researcher
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Marlene Stroj✓ (100%)	Engineering	Visiting Researcher
Sibylle Katinig✓* (100%)	Computer Science	Visiting Researcher
Natalia Uribe* (100%)	Topographic Engineering	Undergraduate Student
Luz A. Suárez* (100%)	Topographic Engineering	Undergraduate Student
Liliana Ramírez* (100%)	Environmental Engineering	Undergraduate Student
María J. Paternina✓ (100%)	Agronomic Engineering	Undergraduate Student
Diego Sánchez* (100%)	Economist	Undergraduate Student
Gettsy Quiñones * (100%)	Statistics	Undergraduate Student
Peter G. Jones	PhD, Crop Physiology	Consultant
Myles James Fisher	PhD, Crop Physiology	Consultant
Samuel Fujisaka	PhD, Anthropology	Consultant
Meike Andersson*	PhD, Animal Science/Agronomy	Consultant
James H. Cock	PhD, Plant Physiology	Consultant
Laure D. Collet	MSc, Environmental Sciences	Consultant

8. Project Budget Summary Project (including Amazon Initiative, and also the Communities and Watersheds Project that is in Phase Out)

Decision Support BP-2

SOURCE	AMOUNT US$	PROPORTION (%)
Unrestricted Core	933,328	39%
Restricted Core		0%
		0%
Sub-total	**933,328**	**39%**
Special Projects	785,199	33%
Water and Food CP	645,205	27%
Total Project	**2,363,732**	**100%**

Amazon Initiative

SOURCE	AMOUNT US$	PROPORTION (%)
Unrestricted Core	38,433	14%
Restricted Core		0%
		0%
Sub-total	**38,433**	**14%**
Special Projects	230,660	86%
Total Project	**269,092**	**100%**

Communities and Watersheds PE-3

SOURCE	AMOUNT US$	PROPORTION (%)
Unrestricted Core	110,502	30%
Restricted Core		0%
		0%
Sub-total	**110,502**	**30%**
Special Projects	252,631	70%
		0%
Total Project	**363,133**	**100%**

Communities and Watersheds in Asia PE-3

SOURCE	AMOUNT US$	PROPORTION (%)
Unrestricted Core		0%
Restricted Core		0%
		0%
Sub-total	**0**	**0%**
Special Projects	308,880	100%
Total Project	**308,880**	**100%**

Communities and Watersheds in Central America PE-3

SOURCE	AMOUNT US$	PROPORTION (%)
Unrestricted Core	0	0%
Restricted Core	0	0%
	0	0%
Sub-total	**0**	**0%**
Special Projects	14,453	100%
Total Project	**14,453**	**100%**

THEME 1:

UNDERSTANDING SPATIAL AND TEMPORAL VARIABILITY OF PLANT-ENVIRONMENTAL INTERACTIONS WITHIN AN ACROSS LANDSCAPES

Phenotypic variation in important economic species of medicinal plants and its implications for product quality management in high value chains

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Introduction

Markets are highly dynamic and especially so in plants used for medicinal or aromatic purposes. For these species, the markets are characterized by being very specific in terms of their commercial niche, with strict requirements for the characteristics of the agricultural product (for example, percentage content of active ingredients to the level of individual compounds). Yet many of the species used in the natural medicines market are poorly understood, often lacking basic agronomic guidelines for production and post-harvest practices, unknown environmental preferences and almost always have no information about variability of the active ingredients. Furthermore, the genotypes used are often selected locally, and so production systems are built on large varietal diversity with little consideration of the implications of using different lines on product quality.

This paper aims to develop a rapid means of evaluating the performance of species across large environmental gradients in order to define rapidly and cheaply the production niche for species with an emerging market, and to examine the important role of phenotypic variation in both biomass production and in the concentration of active ingredients. It is hoped that better understanding of phenotypic variation, and the processes that generate this variability, will permit producers to engage more rapidly in emerging markets, and improve the quality of the produce depending on dynamic market preferences.

Specifically, the objectives of the study are to:

- Quantify the phenotypic variability in biomass and chemical composition and quality) of three important medicinal plant species brought about by different edapho-climatic conditions;
- Identify the principle causal factors that generate the phenotypic variability;
- Analyze the implications of phenotypic variability for high-value market chains of niche medicinal plant species; and
- Suggest a suitable experimental design to permit the rapid evaluation of phenotypic variability in species with emerging economic importance or undefined but significant phenotypic variability in product quantity or quality

The work presented here is ongoing, and represents only a preliminary analysis of findings from the first round of field experiments. Laboratory reports of phenotypic variability in the extracted essential oil have only just been received, and so statistical analyses are not presented.

Methodology

In order to address the objectives, we took an approach of combining participatory field-based experimentation with laboratory analyses, statistical data analysis and qualitative market studies.

Species selection and planting material

Through expert consultation, three species were selected based on their market potential and relative lack of agronomic knowledge. Furthermore, sub-specific genotypes with different chemical compositions were identified in two of the species and included in the study to examine within-species phenotypic variability between genotypes. Six genotypes were therefore studied:

- *Justicia pectoralis* Jacq.
- *Lippia alba* Mill. *cítrica*
- *Lipia alba* Mill. *tipica*
- *Lippia origanoides* H.B.K. *cítrica*
- *Lipppia origanoides* H.B.K. *tipica*
- *Lippia origanoides* H.B.K. *patia*

***Justicia pectoralis* Jacq.:** Commonly known as "amansa toros" in Colombia, this is a herb of the family Acanthaceae that can grow up to 1m tall (Estrella 1995). It is used for diverse purposes ranging from insect repellent, insecticide, expectorant, skin-healing treatment, and has been demonstrated to exhibit anti-oxidant activity against lipid peroxidation in brain tissue of rats (Pérez *et al.* 2002). The essential oil extracted from *J. pectoralis* contains saponines, napthalides, cumarine, betaine, umbelliferone and lignans amongst other components (Estrella 1995).

Lippia: This genus of the family Verbenaceae, includes approximately 200 species of herbs, small bushes and small trees. The majority of species are found in Latin America and tropical Africa. *Lippia* species are used typically to treat respiratory disorders, and provide a wide range of essential oils with pleasant fragrances. The chemical composition of the oils typically consists of limonene, β-cariofilene, *p*-cymene, camphor, linalol, α-pinene and thymol (Pascual *et al.* 2001).

Lippia alba (Mill): Of all *Lippia* spp., *L. alba* is among the most studied. Known locally in Colombia as "pronto alivio" (literally, "rapid relief"), the species is used very widely as an analgesic, anti-inflamatory, antipyretic (Klueger *et al.* 1997), as a sedative, a remedy for dysentery, a treatment for disorders of the skin, liver and bladder and gastrointestinal and respiratory disorders, as an anti-malarial and for the treatment of syphilis and gonorrhea (Pascual *et al.* 2001). The principal components of the essential oil are borneol, camphor, 1,8-cineol, citronellol, geranial, linalool, myrcene, neral, piperitone, sabinene, 2-undecanone, α- muurol, β-cariofilene, β-cubebene, β-elemene, γ-cadinene (Pascual *et al.* 2001).

Lippia origanoides: Found to demonstrate anti-microbial activity, especially against *Escherichia coli, Staphlococcus aureus* MRSA, *Candida albicans* and *Candida tropicalis* (dos Santos *et al.* 2004). The essential oil contains greatest volume of *p*-cymene, γ-terpinene, thymol, carvacrol, butyl hydroxy anisole, α-terpinene, 1,8-cineole, *p*-thymyl acetate, β-caryophyllene (Pascual *et al,* 2001).

Planting material was obtained from the field genebank of the National University of Colombia, run and coordinated by the local NGO Fundación Colombiano de Farmacia Natural (FUNDACOFAN). Planting material was generated from vegetative propagation of single mother plants for all genotypes, and kept 2 months in greenhouses in oasis foam to ensure root development.

Field experiments

The field experiments were located on 24 farms in the Cauca department in southern Colombia. Small experimental plots were designed to capture phenotypic variability in biomass production and quality of plant derivatives (essential oils in the case of the two *Lippia* species, and ethanol extract in the case of *J. pectoralis*).

The experimental design was developed on the basis of the following criteria:

- Small-scale to enable replicability for resource-poor organizations and associations
- Efficient in capturing G x E interactions across the broadest gradient possible
- Capable of providing data useful for identifying the edaphic and climatic factors driving phenotypic variability

These criteria lead to an experimental design distinct to classical agronomic trial sizes, where the number of replications is high and the number of different trial sites often limited (<5). The low number of sites causes significant problems in ascertaining the factors driving variability in biomass production as the number of dependent variables (edapho-climatic) often supersedes the number of different sites (*n*), leading to problems in statistical analysis.

Twenty-three farms, widely distributed throughout the Cauca department (Figure 1), were selected as evaluation sites. They lie broadly in four regions: Santander de Quilichao, Totoro, Popayan and Timbio/Tambo. The farms cover an altitudinal range from 1000m to 3200m, have soils from highly acid to neutral, and annual rainfall varies from 1500mm to 2300mm.

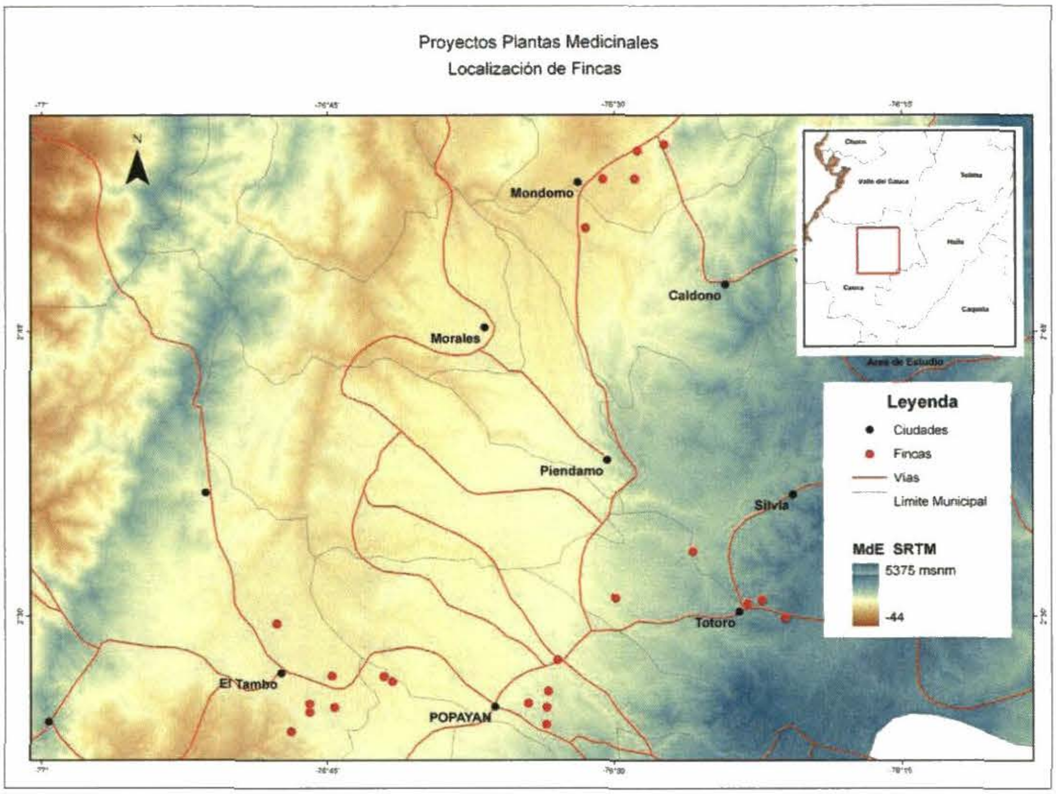

Figure 1. Distribution of experimental sites in Cauca department, Colombia.

Soil samples were taken at each site, and analyzed for 20 different physical and chemical characteristics (Table 1). Manual rain gauges and maximum/minimum thermometers were also installed in each site, and farmers trained in their use. Measurements were taken on a daily basis at 7am and registered on a specially designed form. These data were then used to provide 8 climatic indices for each site, some of which were based on a simple water balance model Spatial datasets were also mined to provide a range of climatic variables using the WorldClim climate database (Hijmans *et al.* 2005) and 19 associated bioclimatic variables (Busby 1991) (Table 2).

Table1. Soil characteristics for each of the 22 experimental sites

Farm #	Farm name	Municip.	Lat.	Long	Elev.	pH	OM	P	K	Ca	Mg	Al	Na	$N\text{-}NH_4$	$N\text{-}NO_3$	B	Fe	Cu	Mn	Zn	CICE	Sand	Silt	Clay	Text
			°	°	masl		g/kg	Bray II mg/kg	cmol/kg	cmol/kg	cmol/kg	cmol/kg	cmol/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg		%	%	%	
1	San Diego	S.Quilichao	2.914	-76.457	1955	4.74	83.74	1.39	0.27	5.25	1.43	2.23	0.00	19.97	34.33	0.50	5.83	1.54	192.02	3.75	9.19	48.81	12.66	38.53	5
2	La Angelita	S.Quilichao	2.908	-76.480	1564	5.64	163.46	4.21	0.58	6.76	2.22	0.00	0.09	15.08	30.46	–	–	–	–	–	9.66	60.59	14.49	24.92	11
3	El Parnaso	S.Quilichao	2.884	-76.482	1543	5.66	57.07	1.15	1.26	4.06	3.11	0.00	0.05	10.35	12.31	0.55	30.11	1.28	53.44	4.54	8.47	23.57	17.67	58.76	1
4	Penjamo	S.Quilichao	2.883	-76.510	1470	6.01	78.51	7.33	1.64	7.22	3.46	0.00	0.08	17.56	10.79	1.29	65.34	0.95	135.83	5.89	12.40	37.35	18.73	43.92	1
6	Las Acacias	Popayan	2.461	-76.550	1925	4.91	68.33	3.68	1.35	4.52	1.36	0.85	0.00	17.33	73.85	0.85	5.06	0.75	154.38	4.97	8.09	–	–	–	–
8	El Matadero	Popayan	2.420	-76.559	2060	5.56	75.56	0.95	0.32	3.35	0.55	0.00	0.03	11.51	13.46	0.64	2.58	0.10	8.43	1.22	4.24	48.76	32.13	19.11	2
9	La Fortaleza	Popayan	2.405	-76.559	2162	5.51	258.14	9.18	0.73	10.23	2.35	0.00	0.09	14.54	39.72	1.16	1.71	0.17	29.36	3.97	13.39	50.21	29.38	20.41	2
11	La Laguna	Popayan	2.434	-76.558	2087	5.58	200.98	1.50	0.81	6.49	2.14	0.00	0.05	15.74	31.85	0.79	1.39	0.19	26.44	1.74	9.49	50.11	29.43	20.46	2
12	El Provenir	El Tambo	2.493	-76.795	1680	5.48	158.63	0.28	0.42	0.78	0.36	0.00	0.04	15.72	10.09	0.35	7.74	0.20	3.82	1.32	1.60	50.38	30.09	19.53	2
13	La Muyunga	El Tambo	2.423	-76.766	1730	5.82	134.35	0.69	0.39	6.50	1.27	0.00	0.04	17.35	23.97	0.67	2.17	0.08	17.45	10.66	8.19	44.37	32.33	23.30	2
14	Loma Larga	El Tambo	2.415	-76.766	1776	5.70	222.96	5.18	1.15	5.77	1.70	0.00	0.03	19.60	34.29	1.36	6.36	0.14	10.10	4.62	8.66	53.64	25.68	20.68	11
15	El Porvenir	El Tambo	2.420	-76.744	1738	5.59	211.16	6.90	0.83	4.79	1.05	0.00	0.06	18.68	23.39	0.96	3.24	0.18	19.12	2.61	6.74	50.92	27.04	22.04	2
16	Villa Stella	El Tambo	2.447	-76.746	1703	6.03	122.72	1.36	2.41	5.11	1.79	0.00	0.10	14.65	28.03	0.73	2.22	0.23	20.79	4.16	9.41	53.34	27.21	19.45	8
17	Asomuripik	Totoro	2.511	-76.384	2678	5.99	146.31	80.50	1.93	11.55	4.18	0.00	0.06	14.57	34.01	2.24	2.52	0.09	71.19	6.49	17.72	49.95	22.19	27.86	11
18	Vista Hermosa	Totoro	2.514	-76.371	2801	6.02	187.58	7.20	1.26	9.55	2.94	0.00	0.09	17.86	23.59	1.61	3.08	0.13	28.02	2.32	13.84	49.47	24.86	25.67	11
20	San Jose	Totoro	2.557	-76.432	2363	5.84	157.03	25.34	1.31	10.49	4.15	0.00	0.08	19.31	32.54	2.05	7.95	0.19	98.73	6.31	16.03	46.04	24.60	29.36	11
21	El Agrado	Totoro	2.516	-76.499	2140	5.73	197.76	0.69	0.41	3.54	1.06	0.00	0.04	17.19	24.89	0.81	4.31	0.10	10.30	1.39	5.05	47.11	33.53	19.36	2
22	Villa Nueva	Timbio	2.447	-76.701	1756	5.52	229.39	1.51	0.59	3.40	1.07	0.00	0.04	19.46	17.92	0.71	4.95	0.19	16.15	1.52	5.10	47.90	29.00	23.10	2
23	La Coronita	Timbio	2.442	-76.694	1800	6.77	147.91	7.51	1.79	16.78	4.36	0.00	0.04	14.15	29.32	1.70	0.89	0.10	13.77	3.44	22.97	56.42	26.04	17.54	8
24	MiraValle	Tambo	2.398	-76.782	1785	7.21	145.23	3.43	1.11	21.86	3.75	0.00	0.07	17.19	14.82	1.20	0.42	0.06	5.98	7.13	26.79	53.47	28.88	17.65	8

Table 2. Climatic conditions at each experimental trial site based on data extracted from the WorldClim climate database.

Farm #	Farm name	Municip.	Lat.	Long.	Elev.	P1 Mean annual temp.	P2 Mean diurnal range	P3 Iso-thermality	P4 Temp season-ality	P5 Max temp of warmest period	P6 Min temp of coldest period	P7 Temp annual range	P8 Mean temp of wettest quarter	P9 Mean temp of driest quarter	P10 Mean temp of warmest quarter	P11 Mean temp of coldest quarter	P12 Annual Precip.	P13 Precip of wettest period	P14 Precip of driest period	P15 Precip Season-ality (Coef Var)	P16 Precip of wettest quarter	P17 Precip of driest quarter	P18 Precip of warmest quarter	P19 Precip of coldes quarte
			°	°	masl	°C	°C			°C	°C	°C	°C	°C	°C	°C	mm	mm	mm		mm	mm	mm	mm
1	San Diego	S.Quilichao	2.914	-76.457	1955	17.6	11.7	86	24.5	24.6	11.1	13.5	17.2	17.6	17.8	17.2	2144	291	64	42	786	223	566	786
2	La Angelita	S.Quilichao	2.908	-76.480	1564	20.4	11.4	87	25.4	27.2	14.1	13.1	20.1	20.4	20.7	20.1	2039	263	56	38	682	225	624	682
3	El Parnaso	S.Quilichao	2.884	-76.482	1543	20.6	11.4	87	27.2	27.2	14.2	13	20.2	20.5	20.8	20.2	2028	261	58	37	676	227	573	676
4	Penjamo	S.Quilichao	2.883	-76.510	1470	21.0	11.3	86	25.9.	27.8	14.7	13.1	20.7	20.9	21.2	20.7	2142	273	72	36	721	260	563	721
6	Las Acacias	Popayan	2.461	-76.550	1925	17.3	11.6	86	25.5	24.4	11.0	13.4	17.0	17.3	17.5	17.0	2001	285	52	45	808	203	212	808
8	El Matadero	Popayan	2.420	-76.559	2060	16.7	11.4	87	22.3	23.6	10.5	13.1	16.4	16.8	16.9	16.4	2210	307	68	43	875	246	253	875
9	La Fortaleza	Popayan	2.405	-76.559	2162	16.1	11.2	86	22	22.8	9.9	12.9	15.7	16.1	16.2	15.7	2373	318	83	40	908	285	295	908
11	La Laguna	Popayan	2.434	-76.558	2087	16.4	11.3	86	22.1	23.3	10.2	13.1	16.1	16.5	16.6	16.1	2277	309	75	41	880	263	272	880
12	El Provenir	El Tambo	2.493	-76.795	1680	18.5	11.1	84	24.1	25.4	12.3	13.1	18.2	18.5	18.7	18.2	2267	335	67	44	897	244	302	897
13	La Muyunga	El Tambo	2.423	-76.766	1730	18.2	11.1	84	23.3	25.1	11.9	13.2	17.8	18.2	18.3	17.8	2119	332	58	48	896	210	252	896
14	Loma Larga	El Tambo	2.415	-76.766	1776	17.9	11.1	85	23.2	24.7	11.7	13	17.5	17.9	18.1	17.5	2113	335	55	50	915	204	240	915
15	El Porvenir	El Tambo	2.420	-76.744	1738	18.2	11.1	84	23.3	25.0	11.9	13.1	17.8	18.2	18.3	17.8	2127	331	58	48	894	210	251	894
16	Villa Stella	El Tambo	2.447	-76.746	1703	18.4	11.1	84	23.3	25.3	12.1	13.2	18.1	18.4	18.6	18.1	2185	331	62	45	888	224	272	888
17	Asomuripik	Totoro	2.511	-76.384	2678	12.4	10.3	91	18.0	18.0	6.8	11.2	12.2	12.2	12.5	12.2	1652	226	77	35	613	255	381	255
18	Vista Hermosa	Totoro	2.514	-76.371	2801	11.8	10.0	90	19.9	17.5	6.5	11.0	11.6	11.5	12.0	11.5	1550	204	82	30	552	274	346	274
20	San Jose	Totoro	2.557	-76.432	2363	15.1	11.3	86	21.1	21.8	8.8	13.0	14.8	15.1	15.3	14.8	1946	258	70	39	717	236	561	717
21	El Agrado	Totoro	2.516	-76.499	2140	16.3	11.4	85	22.0	23.3	10.0	13.3	16.0	16.4	16.5	16.0	2185	284	78	38	802	267	278	802
22	Villa Nueva	Timbio	2.447	-76.701	1756	18.1	11.1	84	21.8	25.0	11.8	13.2	17.8	18.1	18.3	17.8	2184	326	61	45	883	222	260	883
23	La Coronita	Timbio	2.442	-76.694	1800	18.0	11.2	84	22.9	24.9	11.6	13.3	17.7	17.9	18.1	17.7	2179	325	61	45	884	221	254	884
24	MiraValle	Tambo	2.398	-76.782	1785	18.4	11.1	85	24.2	25.2	12.2	13.0	18.1	18.4	18.6	18.1	2130	341	56	49	910	205	252	910

At each site, 13 plantlets of each genotype were planted in small plots in native soil, and two plantlets were planted in a mollisol control soil (taken from CIAT-Palmira) in 3kg plastic bags (Figure 2). Additionally, 2 plantlets were planted in a greenhouse at CIAT in 3kg potted native soil from each of the sites as a counter control. This methodology is designed to aid in separating the complex interactions between plant performance, climate and soil. Additional experiments using 13 plantlets for *L. alba* "tipica" and *J. pectoralis* were set up in CIAT-Palmira under three different shade treatments; full sun, 25% shade and 50% shade.

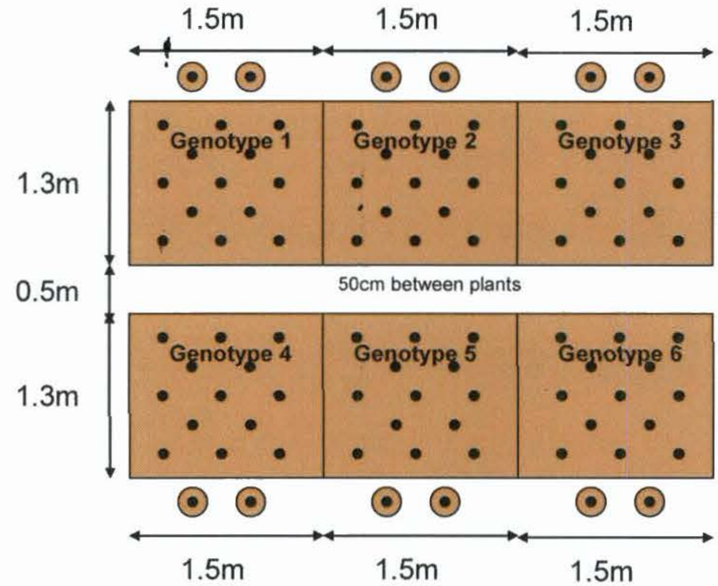

Figure 2. Field experiment plan for rapid evaluation trials.

The relatively low number of replications is designed to maintain the cost of performing this kind of multi-site trial to a minimum, ensure that the experiments can be made in small plots of land with local farmers, and to permit a greater number of different sites without requiring large volumes of planting material.

The trials were planted in February 2006 over a 5-day period. Farmers were instructed not to apply any fertilizers, and only to irrigate under extreme dry conditions, carefully noting the dates when water was applied. They were also provided with forms to make observations about plant pests and mortality.

Two monitoring visits were made during the experiment to ensure farmers were correctly managing the experiment, and harvest took place in August 2006, precisely 6 months after planting. Total weight of green biomass was taken for the 13 plantlets in native soil, and for the 2 plantlets in control soil separately.

Green biomass was placed in paper bags, and left in shaded conditions for 3 days to dry. This material was then sent to the University of Cauca for extraction of essential oils and vegetative extract.

Laboratory analysis of chemical composition

Shade dried leaves were used in the University of Cauca to extract essential oils (*Lippia spp.*) and vegetative extract diluted in ethanol (in the case of *J. pectoralis*). Standard practice was used in all cases to provide these extracts. Oil production per unit biomass was measured for all samples.

A subset of extracts from *Lippia spp.* were then selected for further chemical analysis based on the following criteria: 1) matching the required volume of oil (>1g), 2) representing a broad range of environmental conditions (elevation, temperature and rainfall). *L. alba* essential oils were sent for gas chromatography analysis in the Industrial University of Santander, to identify volume for 120 principal components. All *J. pectoralis* samples were sent to the University of Tolima for qualitative analysis of chemical composition for 12 components.

Statistical analysis of phenotypic variability

A range of statistical techniques were applied to explain variability in biomass. For each genotype, the average biomass per plant was used as the independent variable, with the 47 edapho-climatic variables used as dependent variables. Linear correlation and regression, cluster analysis, principal components analysis and multiple stepwise linear regression were all applied in the search for a high regression coefficient between the independent and dependent variables.

Results and discussion

Analysis of results is still ongoing, and so only preliminary results can be shown here. Performance of genotypes in terms of biomass production varied greatly between farms, with complete mortality occurring in some trial sites, whilst other trial sites produced almost 1 kilo per plant of green biomass during the experiments (Table 3). None of the genotypes survived at the maximum elevation (Farm 19, 3,400m), though two did survive at Farm 18 at 2800m elevation. Two farms stood out in biomass production: El Parnaso and El Porvenir, both being at mid elevations (1500 – 1700m). However, there was no correlation between biomass production and elevation (Figure 3), signifying that other factors are more important in generating variability in production.

Table 3. Biomass production for each genotype in each experimental trial site.

Farm #	Farm name	Municip	Lat	Long	Elev	Biomass					
						J. pectorales	*L. alba* "citrica"	*L. alba* "tipica"	*L. origanoides* "citrica"	*L. origanoides* "tipica"	*L. origanoides* "patia"
1	San Diego	S.Quilichao	2.914	-76.457	1955	12.7	21.1	26.5	16.2	19.5	0.0
2	La Angelita	S.Quilichao	2.908	-76.480	1564	1.8	0.0	0.0	0.0	0.0	9.7
3	El Parnaso	S.Quilichao	2.884	-76.482	1543	42.1	102.4	109.5	827.7	215.2	77.5
4	Penjamo	S.Quilichao	2.883	-76.510	1470	14.6	0.0	84.0	4.4	42.4	101.1
6	Las Acacias	Popayan	2.461	-76.550	1925	12.2	117.2	75.6	45.2	45.1	98.3
8	El Matadero	Popayan	2.420	-76.559	2060	4.0	19.1	12.4	10.9	0.0	105.4
9	La Fortaleza	Popayan	2.405	-76.559	2162	5.8	87.9	67.4	1.7	2.5	12.6
11	La Laguna	Popayan	2.434	-76.558	2087	24.2	174.1	107.4	66.9	120.1	196.1
12	El Provenir	El Tambo	2.493	-76.795	1680	0.4	2.3	17.5	76.6	48.7	32.4
13	La Muyunga	El Tambo	2.423	-76.766	1730	1.1	7.5	0.5	41.3	16.0	67.0
14	Loma Larga	El Tambo	2.415	-76.766	1776	10.5	44.7	11.4	82.5	64.7	0.0
15	El Porvenir	El Tambo	2.420	-76.744	1738	30.6	547.3	564.1	509.6	555.8	0.0
16	Villa Stella	El Tambo	2.447	-76.746	1703	14.5	119.8	189.5	54.4	0.0	0.0
17	Asomuripik	Totoro	2.511	-76.384	2678	2.3	0.0	35.2	0.0	0.0	0.0
18	Vista Hermosa	Totoro	2.514	-76.371	2801	0.7	0.0	35.8	22.4	0.0	0.0
20	San Jose	Totoro	2.557	-76.432	2363	27.5	113.5	210.4	0.0	15.6	0.0
21	El Agrado	Totoro	2.516	-76.499	2140	1.3	172.3	97.5	0.0	0.0	0.0
22	Villa Nueva	Timbio	2.447	-76.701	1756	1.9	7.3	37.5	131.3	0.0	0.0
23	La Coronita	Timbio	2.442	-76.694	1800	5.8	156.0	132.4	118.7	0.0	0.0
24	MiraValle	Tambo	2.398	-76.782	1785	37.1	244.2	98.6	104.3	0.0	0.0

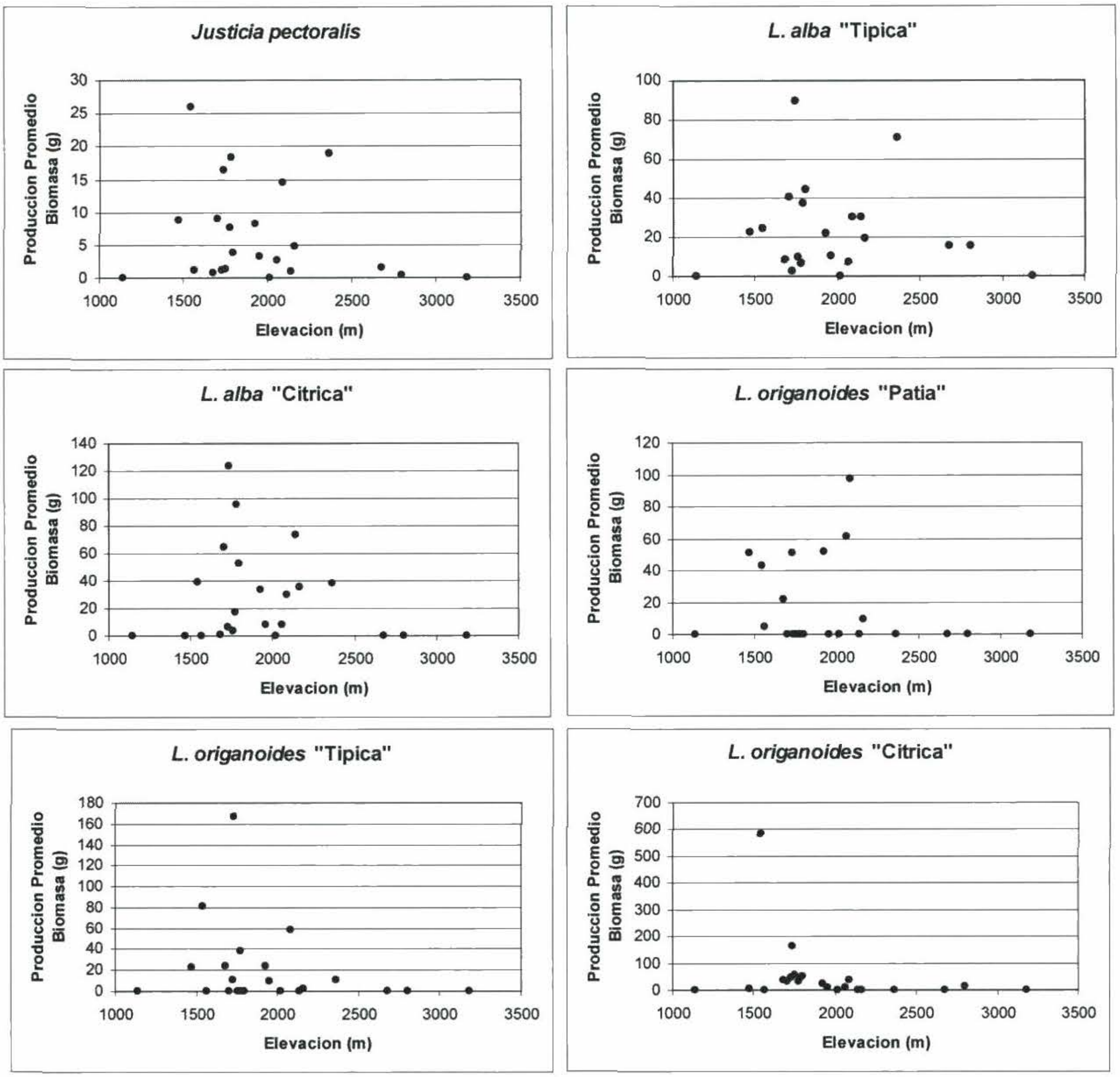

Figure 3. Biomass production for each genotype across the environmental gradient

Correlation analysis of biomass production against each of the 47 edapho-climatic independent variables yields no significant relations (p always > 0.05). However, separating the farms into distinct groups does yield statistically significant results. Through cluster analysis of the biomass production data, Farm 12 (El Porvenir) is highlighted as a clear outlier (Figure 4). When this farm is excluded, multiple stepwise linear regression successfully explains 90% of variability in biomass production for *L. alba* "citrica" through the following equation:

$$\text{Biomass} = -2406 + 89.5\,k + 128.2\,P7 + 0.3\,\text{Elevation} - 1.7\,\text{“}NNo_3\text{”}$$

Where k = Potassium content of soil;

P7 = Annual range in temperature; and

NNO_3 =Nitrate-N

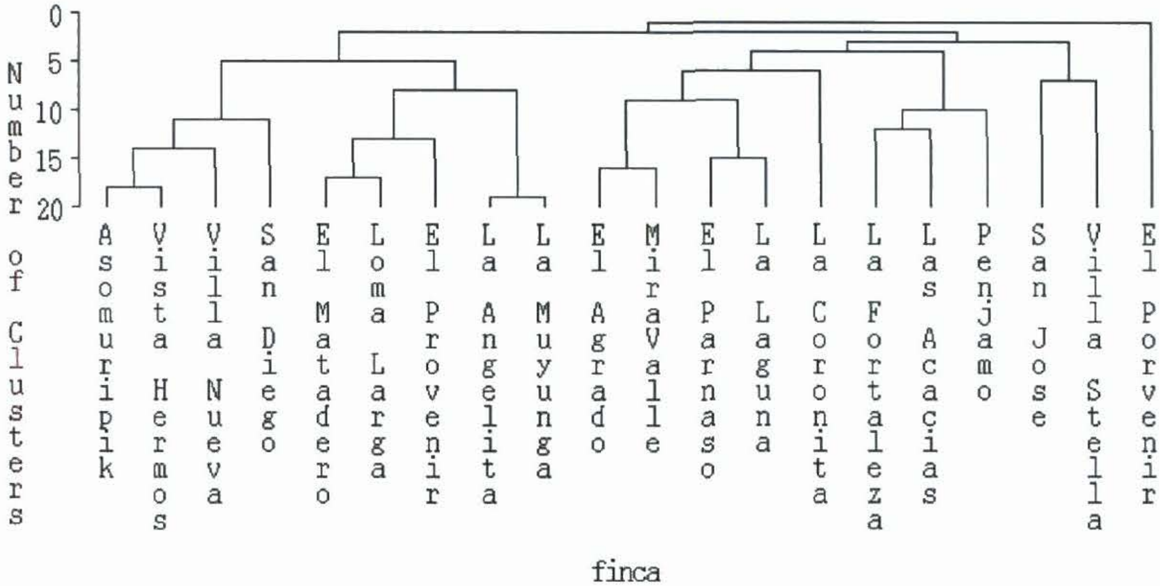

Figure 4. Cluster analysis of biomass production *L. alba* "tipica".

These preliminary results highlight the importance of soil factors in determining biomass production. The control experiments of soil *in situ* permit the examination of how characteristics of the native soil might constrain growth through a comparison of biomass produced in control soil (but same climate) as opposed to the native soil (Figure 5).

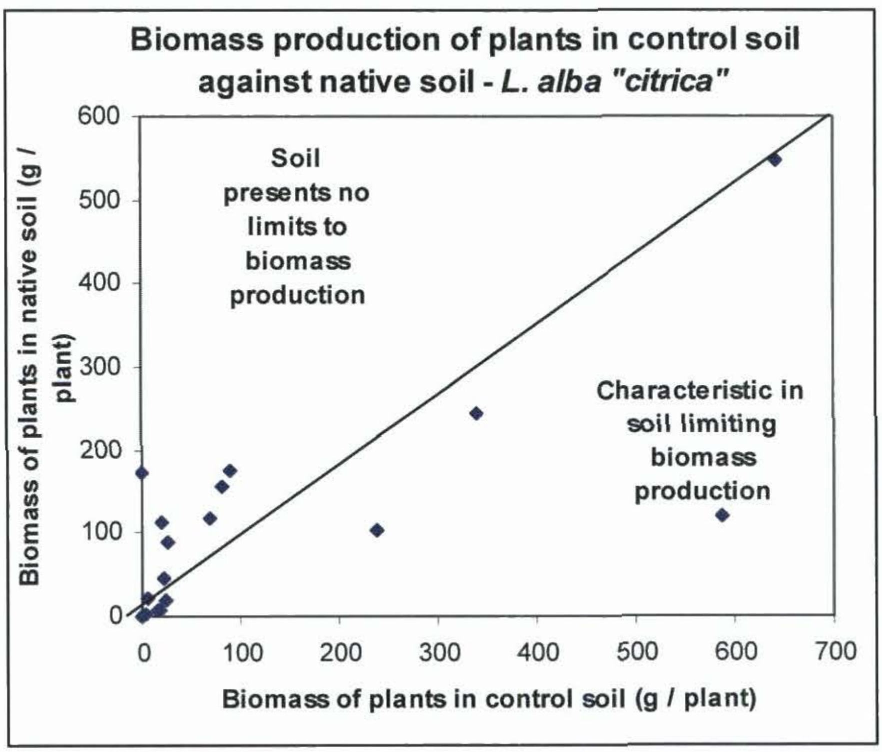

Figure 5. Analysis of soil constraints to biomass production for *L. alba* "citrica"

In the majority of farms the native soil appears to contain no constraints to biomass production, although three farms do exhibit some constraints, especially Farm 16 (Asomuripik) where the control soil produced over five times more biomass than the native soil. Preliminary analysis indicates the possibility of phosphorus being the major constraint, with Farm 16 having the lowest levels of all. Further statistical analyses should confirm this, and identify similar constraining factors for the other genotypes.

Preliminary laboratory results of chemical composition of the derivatives from the plants show extremely high variability between farms for each genotype, indicating that environment has a major role in determining the volume of active ingredients of the plant derivatives. Analysis of these results is ongoing, but will focus on explaining the variability, especially in chemical components, which are particularly sought after in terms of their use in the market.

Conclusions

The results presented are still preliminary and more rigorous statistical analysis is pending. However, some conclusions are already becoming clear:

1. Biomass production is highly variable, and not correlated with elevation despite this typically being the variable used to describe plant adaptation
2. Variability in biomass production can be explained using more rigorous statistical methods, including multi-variate analyses, and edapho-climatic variables can explain up to 90% of this variability
3. Preliminary results from laboratory analyses also indicate very high phenotypic variability in terms of chemical composition, indicating very complex G x E interactions

The implications of these findings are many. Firstly, a new means of defining plant suitability is needed, that moves away from the over-simplification of thermal zones (elevation) as the principle factor. The plants studied here exhibited considerable variability in production both at the species and sub-species level, indicating that producers must choose carefully the crops that they grow, especially when little is known about their adaptation. Farmer experimentation in such cases is recommended, and the protocol developed in this paper could serve as a rapid means of defining plant adaptation.

In the case of species where product quality is just as or more important than quantity (medicinal and aromatic plants for example), the phenotypic variability in chemical composition of the extractions indicates that a further level of complexity exists in choosing the most suitable species for a given location, and the market itself should also consider more carefully the sourcing of plant material.

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The effect of climate change on crop wild relatives

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Abstract

Crop wild relatives are an important source of genetic diversity for crop improvement. However, the survival of some of these wild plant species could be threatened because of climate change. We used current and projected future climate data for ~2055, and a climate-envelope species-distribution model to predict the impact of climate change on the wild relatives of peanut (*Arachis*), potato (*Solanum*) and cowpea (*Vigna*). We considered three migrational scenarios for modeling the range shifts (unlimited, limited, and no migration). Climate change strongly affected all taxa, with an estimated 16-22% of these species predicted to go extinct and most species losing over 50% of their range size. Moreover, for many species, the suitable areas become highly fragmented. Wild peanuts were the most affected group, with 24 to 31 (depending on the migration scenario) of 51 species projected to become extinct and their distribution area reduced by 85 to 94% over the next 50 years. The number of suitable areas changed by -19% to +4% and patch size decreased by 55 to 60%. For potato, 7 to 13 of 108 species were predicted to go extinct, and their range sizes were reduced by approximately 38 to 69%. The number of patches changed by -34% to 7% and patch size decreased by 20 to 37%. In terms of species extinction, *Vigna* was the least affected of the three groups, losing 0-2 of 48 species. The mean range size changed by -65% to 8%, with 8-41 of the 48 species losing more than 50% of their current geographic range. The number of *Vigna* patches increased by 12-115%, but the size of those patches shrank by 51-59%. Our results suggest that there is an urgent need to identify and conserve effectively crop wild relatives that are at risk from climate change. While increased habitat conservation will be important to conserve most species, those that are predicted to undergo strong range-size reductions should be a priority for collection and inclusion in genebanks.

Key words: crop wild relatives, climate change, conservation, cowpea, distribution model, peanut, potato.

Introduction

Crop wild relatives (CWR) include crop ancestors as well as other more or less closely related species. In the process of domestication, a crop goes through a genetic bottleneck, ending up with much less genetic variation than is available in the wild species from which it was derived. This genetic uniformity can make crops more vulnerable to biotic and abiotic stresses. CWR have been used in formal crop improvement programs for over 100 years (e.g. Mujeeb-Kazi and Kimber 1985, Large 1940), especially for increasing resistance to insect pests and diseases. For example, they have been used to enhance resistance against wheat curl mite (Malik *et al.* 2003), late blight in potato (Pavek and Corsini 2001), and grassy stunt disease in rice (Brar and Khush 1997). Crop wild relatives are being used to improve tolerance of stressful abiotic conditions such as tolerance to drought in wheat (Faroq and Azam 2001) and have been tested for heat tolerance in rice (Sheehy *et al.* 2005). They have also been used to raise the nutritional value of some crops, such as protein content in durum wheat (Kovacs *et al.* 1998), calcium content in potatoes (Bamberg and Hannema, 2003), and provitamin A in tomato (Pan *et al.* 2000). It is expected that the use of CWR in breeding will increase due to recent advances in molecular technologies that increase efficiency and accuracy in transferring desired traits from CWR to crops (Hajjar and Hodgkin in press).

Seeds of many CWR have been collected and conserved in genebanks (*ex situ* conservation). This has greatly facilitated their use, but the world's genebanks are conserving only a fraction of the total genetic variability that exists in CWR and only a small proportion of conserved accessions have been characterized. Moreover, genebank collections are not exposed to natural selection processes that affect natural populations. Conservation of species *in situ* allows new variation to arise and species to adapt to gradual changes in environmental conditions such as temperature and rainfall patterns. This has been referred to as the conservation of the evolutionary "process" in addition to the current "pattern" of biodiversity (Pressey *et al.* 2003). Therefore, an *in situ* conservation approach is needed that complements the *ex situ* collections to maintain a much larger reservoir of genetic diversity, and to ensure that habitats where CWR occur are protected and wild species continue to evolve in the wild.

Setting *in situ* conservation priorities for habitats and taxa is not a trivial task, especially for CWR species, which are large in number, have a range of different biological, ecological and use characteristics and occur in multiple ecosystems. The conversion of natural vegetation to agriculture is a major threat to the survival of many species in the wild, but climate change is identified as an increasingly strong additional threat (van Vuuren *et al.* 2006). Climate is one of the major factors governing the distribution of wild plant species, acting directly through physiological constraints on growth and reproduction or indirectly through ecological factors such as competition for resources (Shao and Halpin 1995). The relatively modest climatic changes over the past century have had significant impacts on the distribution, abundance, phenology and physiology of a wide range of species. Many instances have been recorded of species range shifts towards the poles or upward in altitude, and progressively earlier seasonal migrations and breeding (e.g. Walther *et al.* 2002, Parmesan and Yohe 2003, Root *et al.* 2003, Parmesan 2006). Global warming has accelerated over the past 30 years (Osborn and Briffa 2005), and is predicted to be in the range of 1.1-6.4°C by 2100 (IPCC 2007). Modeling studies (e.g. Thomas *et al.* 2004) indicate that climate change may lead to large scale extinctions.

Given the potential impact of climatic change on global food production (Rosenzweig and Parry 1994, Hijmans 2003, Jones and Thornton 2003), and the demonstrated importance of crop wild relatives in breeding of novel varieties with improved adaptations to biotic and abiotic stresses, it is of paramount importance that crop wild relatives are adequately conserved. Safeguarding and using CWR to broaden the genetic base of modern crops is vital for adapting agricultural systems to the impacts and consequences of climate change. Yet due to climate change, these very genetic resources may themselves be under threat of extinction in the wild. Therefore, assessing the potential impact of climate change on CWRs and developing adequate conservation responses is a key activity to sustain agricultural production.

The objective of this study was to estimate the impact of climate change on the distribution of wild relatives of selected crops and to assess implications for their conservation. We selected the CWR of peanut (*Arachis hypogea* L.), potato (*Solanum tuberosum* L.) and on African wild *Vigna* spp., which are related to cowpea (*Vigna unguiculata* (L). Walp.) and Bambara groundnut (*Vigna subterranea* (L.) Verdc.). There are 68 species of wild peanut (Krapovickas and Gregory 1994), which occur in South America (Bolivia, Brazil, Paraguay, Argentina and Uruguay). The 187 species of wild potatoes occur from the southwestern United States through the highlands of Central and South America into Argentina, Chile, and Uruguay (Hijmans and Spooner 2001; Spooner *et al.* 2004). Only *Vigna* species occurring in sub-Saharan Africa are included in this analysis. The African taxa comprise 61 species and 63 subspecific taxa (Maxted *et al.* 2004). These species occur in a wide range of habitats but especially in grasslands, savannas, open woodlands and shrublands and generally at low to mid-low altitudes (Maxted *et al.* 2004).

We used a climate-envelope model to quantify the impact of climatic change on the geographic distribution of these three groups, and we assessed the impact of likely range shifts on conservation status. Climate-envelope models use environmental data for the locations where a species has been found (or not found) to infer its climatic requirements. These inferred requirements can then be used to classify the suitability of any other location (Guisan and Thuiller 2005).

A number of studies have applied climate-envelope-based species-distribution models to the problem of understanding the impacts of climatic change through the use of climatic data for the present and the future (Thomas *et al.* 2004) and the past (Ruegg *et al.* 2006). These methods essentially transfer a species adaptation temporally, assuming on the one hand no more plasticity than currently observed and on the other hand zero evolution, and many overlook the possible consequence of changes in biotic interactions such as competition (Lawler *et al.* 2006). There is a growing body of research evaluating the suitability of applying species-distribution models to predicting range shifts and assessing extinction risk in the face of climate change (Thuiller *et al.* 2004, Araújo *et al.* 2005*a*, *b*, Araújo and Rahbek 2006, Hijmans and Graham 2006, Lawler *et al.* 2006).

A central question in the application of species-distribution models to understanding the impacts of climate change relates to the migrational (dispersal) capacities of species (Pearson 2006). Species capable of migrating at high rates are more likely to survive, and indeed in some cases may gain geographic range thanks to greater land mass in higher latitudes, and species-energy relationships (Menendez *et al.* 2006). Most modeling studies account for migration by assuming it to be either unlimited or non-existent, yet the reality is likely to be somewhere in-between (Pearson 2006). Thomas *et al.* (2004) estimate extinction rates of 1103 species in diverse parts of the world under these two migrational scenarios, reporting extinction rates of 21-23% with unlimited migration, and 38-52% with no migration. When the migrational rate is known for a particular species, it is relatively easy to account for this in modeling (Midgley *et al.* 2006).

Despite the uncertainties associated with species-distribution modeling applied to understanding the likely impact of climate change in species survival, the results are important because they can help select and prioritize actions to mitigate negative impacts. In this paper we use climate-envelope models to assess the potential geographic shifts in distribution of these species. Using three migrational scenarios, we evaluate changes in potential range size, and in fragmentation of these climatically suitable areas.

Materials and Methods

CWR occurrence data

Only species for which we had at least 10 distinct localities of occurrence were included in the analysis, resulting in a study of 210 individual species in the three groups analyzed.

The wild peanut data (Jarvis et al. 2003) consisted of 2175 unique point localities for the 68 species but only 51 species had 10 or more unique point localities. The wild Vigna data consisted of 7733 unique point localities for 65 species (Maxted et al. 2004). Just 51 species had 10 or more point localities, and were included in the species distribution analysis. The wild potato data (Solanum sect. Petota) consisted of 9822 unique point localities for 187 species (Hijmans and Spooner 2001, Spooner et al. 2004). Of these, 108 species have 10 or more point localities and were used in the modeling.

Species distribution modeling

Many different statistical techniques have been used in species-distribution modeling (Segurado and Araújo 2004, Elith *et al.* 2006). We used the Bioclim model (Busby, 1991) as implemented in DIVA-GIS (www.diva-gis.org). While this model performed relatively poorly in the comparative study of Elith *et al.* (2006), we use it because it represents a stable modelling approach for application to climate change research (Hijmans and Graham 2006). While it is somewhat biased towards underestimating future species ranges, it does not have occasional erratic behaviour that some other models display and it is easy and fast to run, both important considerations when dealing with as many species as we did. The semi-continuous output from the Bioclim model was transformed into presence/absence by assigning presence to the areas where the Bioclim scores were within the 2.5 - 97.5 percentile range.

We ran this model to predict the current and future geographic distribution of each wild relative species in the genepools under study. The environmental data consisted of climate surfaces for present and projected future conditions. For data on present climate, this study uses WorldClim climate surfaces (Hijmans *et al.* 2005) for their high spatial resolution (~1 km) and global extent. Future climate data are available from a number of global climate models (GCMs) with differing greenhouse gas emission scenarios, model characteristics and spatial resolutions. There continues to be heated debate on the uncertainty in GCM predictions and the emission scenarios that drive them and the approach taken in many studies is to use several GCMs and emission scenarios (Stainforth *et al.* 2005). We did not consider variation between GCM projections. We used data from Govindasamy *et al.* (2003) because it had the highest spatial resolution available. They used the CCM3 model at a 50 km spatial resolution and for a concentration of CO_2 in the atmosphere of 600 ppm (twice that of pre-industrial conditions). This CO_2 concentration (including other greenhouse gasses expressed as CO_2 equivalents in terms of their warming potential) might occur around 2055. In order to match the 1 km resolution of the current climate conditions, a downscaling procedure was applied to the CCM3 data by calculating the predicted change in monthly means from the CCM3 model. These change data were then downscaled to 1km resolution using smoothing (spatial interpolation), and added to the current WorldClim climate surfaces.

For both present and future monthly climate data, the following 'bioclimatic' variables were derived: annual mean temperature, mean diurnal range, isothermality, temperature seasonality, maximum temperature of warmest month, minimum temperature of coldest month, temperature annual range, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of warmest quarter, mean temperature of coldest quarter, annual precipitation, precipitation of wettest month, precipitation of driest month, precipitation seasonality, precipitation of wettest quarter, precipitation of driest quarter, precipitation of warmest quarter, precipitation of coldest quarter.

Range metrics for quantifying threat

We used the estimated current and future species ranges to calculate a number of range metrics that describe the extent and configuration of a species' range, that were subsequently used to calculate extinction risk. The range metrics were designed to capture three scenarios of migrational capacity, ranging from "unlimited" (populations can move to any site where the climate is suitable), to "limited" (populations can move only a defined distance), to "no migration" (populations cannot move). We used 300km as the migrational limit under the limited migration scenario, based on previous studies (Jarvis *et al.* 2003).

All range area metrics were analysed using Arc/Info and using Arc Macro Language (AML) scripts for automating the analysis. In addition to range area metrics, we calculated two metrics associated with the configuration of species distributions, with emphasis on fragmentation. For this, we used the Patch Analyst V extension to Arcview 3.2. The metrics calculated are total number of patches and average area of each patch for each of the three migrational scenarios.

Species richness

We mapped species richness under current and future conditions for each of the three genepools under the unlimited migration scenario and the no-migration scenario to identify the broad spatial patterns of the impact of climate change. We analyzed broad patterns to examine shifts in species richness across latitudinal and elevational gradients.

Results

Climatically suitable area

For all migration scenarios we considered, the wild peanut species were most affected, followed by wild potatoes, with *Vigna* projected to be least affected (Table 1). Climate change reduced the size of the climatically-suitable area of 80-100% of species, affecting 98-100% of the *Arachis* species, 80-100% of *Solanum* species, and 63-100% of *Vigna* species. We predicted 16-22% of all species modeled to go extinct due to complete loss of climatically suitable areas. *Arachis* was most affected with 24-31 species (47-61% of species) facing extinction; *Solanum* was projected to lose 7-13 species (7-12% of species) and *Vigna* 0-2 species (0-8% of species).

Table 1. Average effect of climate change on potential distribution (climatically suitable area) of species from three crop wild relative genera. Data were averaged for each genus and computed for three migratory scenarios: unlimited, limited, and no migration (see Methods).

	Arachis - 51 species			Potato - 108 species			Vigna - 51 species		
	Unlimited migration	Limited migration	No migration	Unlimited migration	Limited migration	No migration	Unlimited migration	Limited migration	No migration
Average area Loss (%)	85	89	94	38	52	69	-8	51	65
No. species with area gains	1	0	0	21	9	0	19	1	0
No. species with area losses	26	51	51	79	92	95	31	50	48
No. species with area loss = 100%	24	27	31	7	7	13	1	0	3
No. species with area loss > 50%	46	48	51	41	52	80	8	23	41
No. species with area loss > 75%	41	42	47	23	37	48	3	6	13

Under the limited migration scenario, for *Arachis* species the average size of the suitable areas was reduced by 89%, with 48 species losing more than 50%. The amount of area lost varied significantly with the current potential area of distribution, with the highest losses occurring where currently suitable area was smallest (r^2=0.73, P<0.001). For *Solanum* species, loss of climatically suitable area averaged 52% with 52 species losing more than 50%. The relationship between size of the currently suitable area and area lost was not significant (r^2=0.07, P>0.05). *Vigna* species lost an average 51% of climatically suitable area and 23 species suffered losses of over 50%. As we found for *Solanum*, the relationship between size of current area and size of loss was not significant (r^2 = 0.19, P>0.05) for *Vigna*.

The effects of climate change were much larger under the no migration scenario. Obviously no species saw gains in distributional area as species could not move into new areas. Complete loss of suitable areas (i.e. extinction) was projected for 31 *Arachis* species, 13 *Solanum* species and three *Vigna* species.

The area projected to be suitable-in the future for *Arachis* species was 36,486 - 74, 867 km^2 but 1-3 species on top of the 24-31 predicted to lose all area will have suitable areas of less than 500 km^2 (including *A. batizocoi*, *A. gracilis* and *A. kempff-mercadoi*). For *Solanum*, the projected average size of the suitable area was about 38,672 - 60,000 km^2 but 7-8 species that retained an area of less than 500 km^2. *Vigna* species had a relatively large future distribution area of about 1.26 - 2.40 million km^2 and apart from the 0-2 species projected to go extinct (*V. longifolia* and *V. keraudrenii*), no species had less than 500 km^2 of suitable area in the future. Species with a relatively small suitable area are more vulnerable to loss of genetic diversity and possibly extinction and could be priority species for conservation. For peanuts, species with less than 1000 km^2 projected to be suitable in the future included: *A. batizocoi*, *A. burkartii*, *A. decora*, *A glandulifera*, *A. gracilis*, *A. kempff-mercadoi*, *A. kretchmeri*, *A. matiensis*, *A. oteroi*, *A. paraguariensis*, *A. pseudovillosa*, *A. retusa*, and *A. subcoriacea*. For *Vigna* the suitable area for most species remains high, although specific habitat constraints may mean the actual distributional area is considerably less than reported with the climate-suitability models. Only one species faced intermediate threat: *V. angivensis* with 26,000-61,000 km^2 of predicted future area (a loss of 71-82% of current distributional area). For *Solanum*, species with less than 1,000 km^2 of predicted future area were *S. arnezii*, *S. acroscopicum*, *S. clarum*, *S. lignicaule*, *S. limbaniense*, *S. piurae* and *S. raquialatum* and *S. ×sambucinum*.

It is important to note that not all species had a reduction in their climatically-suitable area under climate change. No *Arachis* species gained area, but some 19 *Vigna* species gained area under the unlimited migration scenario with *V. praecox* gaining as much as 4.1 times its current suitable area, and four other species (*V. longifolia, V. nyangensis, V. radiata, V. richardsiea*) more than doubling their potential range. Under limited migration only *V. schlechteri* gained area (0.4 times current area), and under no migration there were no gains. For *Solanum*, 21 species gained area assuming unlimited migration, and nine species under the limited migration scenario. However, only three species gained more than 10% of current area (*S. hastiforme, S. maglia* and *S. ×setulosistylum*) and none more than 30%.

To aid in the prioritization of species suitable for conservation, a list of priority species based on extinction probability, percentage loss of suitable area and projected future range size is presented in Table 2.

Table 2. List of priority species for conservation based on likelihood of extinction, percentage loss of range size and predicted remaining range area, assuming unlimited dispersal.

	Predicted extinction (no future range area)	10 species with <10,000 km^2 future range area (km^2)	10 species with greatest % loss of range area (% loss)
Peanut	*A. appressipila, A. archeri, A. benensis, A. cryptopotamica, A. douradensis, A. guaranitica, A. hatschbachii, A. helodes, A. hermannii, A. lignosa, A. marginata, A. palustris, A. setinervosa, A. simpsonii, A. stenophylla, A. magna, A. tuberosa, A. hoehneii, A. burkartii, A. retusa, A. glandulifera, A. paraguariensis, A. pseudovillosa, A. decora*	*A. benthamii* (9465), *A. cardenasii* (5163), *A. correntina* (3264), *A. triseminata* (1308), *A. matiensis* (802), *A. batizocoi* (717), *A. oteroi* (609), *A. subcoriacea* (301), *A. gracilis* (232)	*A. gracilis* (99%), *A. kretschmeri* (99%), *A. oteroi* (99%), *A. matiensis* (99%), *A. subcoriaceae* (98%), *A. triseminata* (97%), *A. kempff-mercadoi* (96%), *A. major* (96%), *A. batizocoi* (96%), *A. correntina* (95%)
Potato	*S. velardei, S. tarnii, S. xmichoacanum, S. xrechei, S. ugentii, S. chancayense, S. incamayoense*	*S. irosinum* (5), *S. paucissectum* (5), *S. hoopesii* (41), *S. piurae* (87), *S. raquialatum* (146), *S. longiconicum* (179), *S. arnezii* (193), *S. lignicaule* (250), *S. acroscopicum* (422), *S. xsambucinum* (475)	*S. irosinum* (99%), *S. hoopesii* (97%), *S. piurae* (96%), *S. xsambucinum* (96%), *S. paucissectum* (95%), *S. acroscopicum* (95%), *S. raquialatum* (93%), *S. jamesii* (91%), *S. arnezii* (88%), *S. trifidum* (85%)
Vigna	No species	*V. monantha* (16), *V. virescens* (38), *V. keraudrenii* (110), *V. phoenix* (363), *V. mungo* (1066), *V. richardsiae* (2866), *V. bosseri* (3686), *V. hosei* (4387), *V. mudenia* (9590)	*V. keraudrenii* (98%), *V. decipiens* (85%), *V. phoenix* (78%), *V. procera* (64%), *V. mungo* (63%), *V. angivensis* (59%), *V. antunesii* (56%), *V. gazensis* (55%), *V. platyloba* (51%), *V. juncea* (50%)

A number of wild relatives of peanut that have been used in breeding are projected to lose a considerable amount of suitable area: *A. diogoi* Hoehne (77-97% loss) and *A. batizocoi* Krapov. (96-98% loss) has provided resistance to root-knot nematode; *A. cardenasii* Krapov. (93-99% loss) for resistance to corn earworm and southern corn rootworm (Stalker and Lynch 2002); and *A. paraguariensis* (100% loss) and *A. appressipila* (100% loss), have been used as a source of resistance to early leaf spot (ICRISAT 1995).

Amongst *Solanum* species, *S. demissum*, which has resistance to late blight (Ross 1986), kept 33-90% of the size of its currently suitable area; *S. chacoense* and *S. berthaultii* with resistance to Colorado potato beetle (Plaisted *et al.* 1992) will lose 40-53% and 2-65% of distribution areas respectively; and *S. microdontum*, which can be used to breed for varieties with increased calcium content (Bamberg and Hanneman 2003) stands to have a change of -28% to 9% in its suitable area.

A number of wild *Vigna* species that contribute to food security are under threat from climate change. For example, the tubers of *V. adenantha*, (50-68% loss), are eaten (Padulosi and Ng 1990); fruit and seeds of *V. junceum* are eaten by humans but will lose 50-80% area, and the tubers of *V. stenophylla*, a species that stands to gain 67% or lose 93% of area depending on the migrational scenario, are eaten by humans (Padulosi and Ng 1990).

Species richness

The change in the patterns of species richness under the unlimited migration scenario (Figure 1a) and no migration scenario (Figure 1b) was variable in space and between the three CWR groups. There is a general pattern of *Arachis* species moving south-eastwards towards some of the cooler climates of the higher elevations of south-east Brazil under the unlimited migration scenario. Species richness at lower latitudes was least affected, and the general trend of species richness across the elevational gradient shifts some 200m upwards (Figure 2). Indeed, species richness increased at 800-1100m assuming unlimited migration. For *Solanum*, species richness diminished most in lower elevations as areas suitable for species moved to higher altitudes. Greatest losses in species richness were found in mid-northern latitudes (20-25°N) and far southern latitudes (20-40°S). Under the unlimited migration scenario, *Vigna* species moved southwards into South Africa and northwards particularly into Ethiopia. Greatest losses occurred in northern latitudes (0-15°N), and at low elevations. Under unlimited migration species richness increased at elevations above 1500 m.

Figure 1. Modeled potential species richness under current and future climate scenarios and the difference between the two for each of three groups of crop wild relative species. Peanuts (*Arachis*), Potatoes (*Solanum*), and *Vigna* (related to cowpea and bambara groundnut) species. Data shown are for (A) an unlimited migration scenario and (B) a no migration scenario.

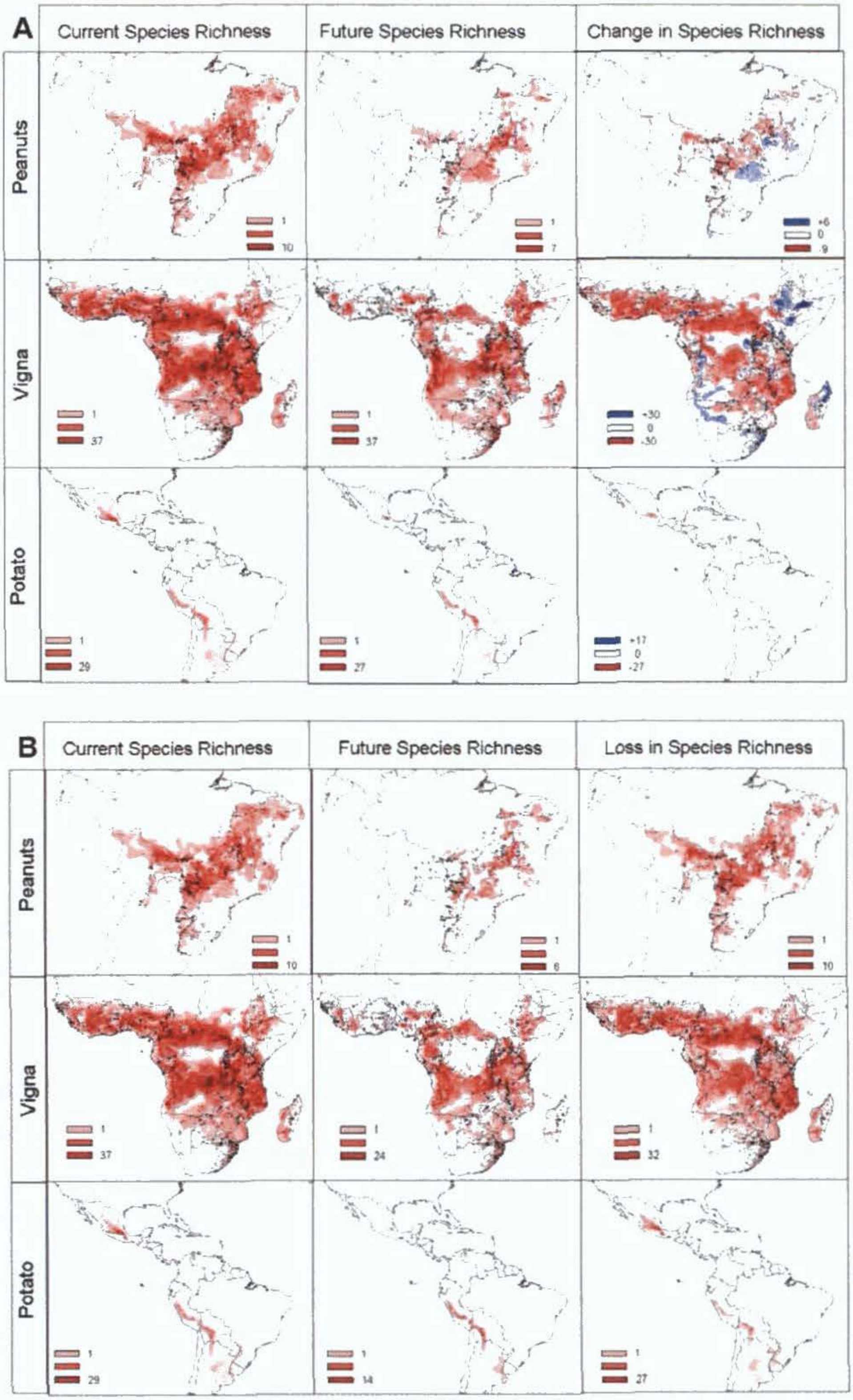
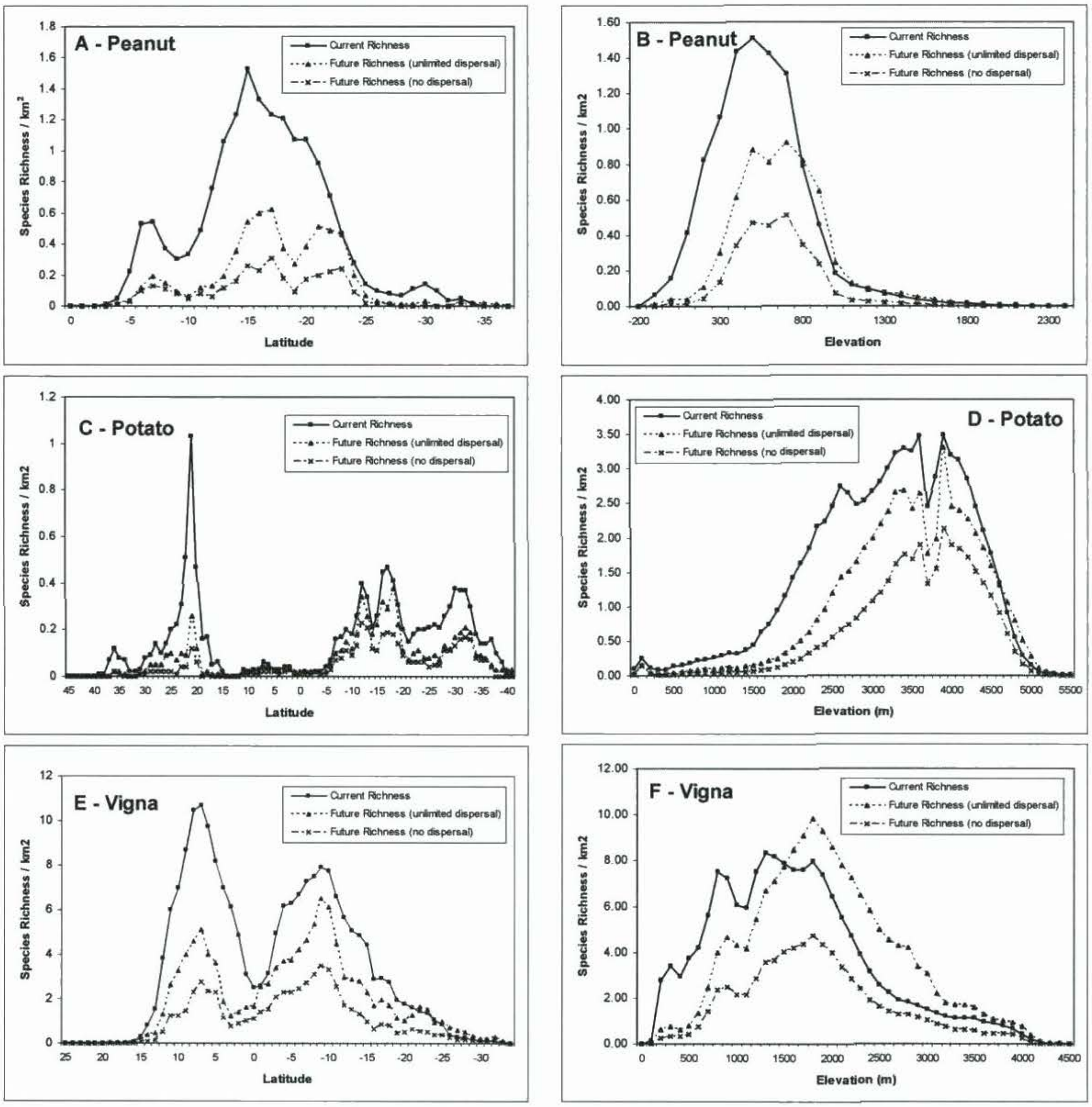


Figure 2. Shifts in species richness across latitudinal and elevational gradients for each of three groups of crop wild relative species. A, B: *Arachis*; C, D: *Solanum*; and E, F: *Vigna* species.



Fragmentation of suitable area

Current habitat patches of *Arachis*, *Solanum* and *Vigna* became smaller as a result of climate change (Table 3). Again, *Arachis* species were most affected, with the average patch size decreasing by 55-60%. The total number of patches, however, remained relatively stable, with a 4% gain assuming unlimited migration, and a 19% loss under the no migration scenario. The smaller the habitat patch for these species the greater the loss of area ($r^2 = 0.42$) and the more vulnerable it was to the impacts of climate change. For *Solanum*, there was a 20-37% decrease in average patch size, accompanied by a +7 to -35% change in total number of patches. There was no relationship between patch size and potential loss of patch area ($r^2 < 0.001$). *Vigna* species gained 12-115% in the number of patches, but had decreases in average patch size of 51-59%.

Table 3. Predicted effect of climate change on patch size and area for the potential distribution (climatically suitable areas) of species from three crop wild relative genera. Data are averaged by genus and computed for three migratory scenarios: unlimited, limited, and no migration (see Methods). The number of patches and average patch size in the future is calculated based only on species predicted to survive.

	Arachis - 51 species			Potato - 108 species			Vigna - 51 species		
	Unlimited migration	Limited migration	No migration	Unlimited migration	Limited migration	No migration	Unlimited migration	Limited migration	No migration
Current average patch area (km^2)		65			39			199	
Future average patch area (km^2)	26	29	27	28	32	25	84	98	81
Current number of patches		1538			1309			9461	
Future number of patches	1600	1246	1314	1397	858	891	20403	11143	10568

Potentially most at risk from fragmentation were *Solanum* species as the patch sizes are in general low, both at present (39 km^2) and in the future (25-32km^2). The number of patches for many *Vigna* species increased and for 1-4 species, which had some of the smallest mean patch sizes, patches actually increased in size under some or all migrational scenarios. These species were *V. schlechteri* (+1% to 43%), *V. juncea* (+ 13% to -28%), *V. davyi* (+5 to -40%) and *V. procera* (+7% to -14%), the latter despite losing 64-72% of distribution area. This species is restricted to southern-central-west Africa where it is uncommon (Maxted et al. 2004).

Discussion

Uncertainties in predictions

There are a number of sources of uncertainty about the projections presented here. One of the principal problems with the use of species distribution modeling is that when they are used to project future conditions, the results cannot be validated (Araújo and Rahbek 2006). Some authors have used "hindcasting" to validate modeling approaches, whereby the past is used as a key to the future (Martínez-Meyer *et al*, 2004; Araújo *et al.* 2005a). Uncertainty due to differences between modeling algorithms and climate projections can be addressed through multi-model inference (Thuiller *et al.* 2004) and sensitivity analysis. However we considered these to be beyond the scope of this study given the large amount of species and large geographic areas that we covered. Rather we opted for a preliminary analysis to investigate whether we would find large responses and variation between species and groups of CWR. Future work could focus on some of the species identified as being under threat, and do more elaborate modeling for these species. In addition, we believe that more emphasis should be given to experimental work, for example by assessing species adaptation to different climatic conditions, including conditions outside of the species' current range (Zavaleta, 2006).

Our results might overstate the threat from climate change to some species because Bioclim has been shown to underestimate distributional area with climate change (Hijmans and Graham 2006). However, the analysis presented here also fails to account for other impacts on species distribution, like past, present and future habitat alteration and harvesting of species from the wild. This may lead to overestimation of future suitable area as species are already severely limited in distributional area and migrational capacity due to fragmentation of habitats. Climate models should ideally be coupled with land-use projection models to understand the current pattern of habitat fragmentation and predicted future patterns based on projection of parameters that drive land use change such as population and consumption (Hannah *et al.* 2002).

Another major source of uncertainty stems from assumptions made about plants' capacity to migrate, though it is known that many plant species have a low capacity to migrate (Pearson 2006). We found considerable variability in the results depending on the migrational scenario used, especially for fragmentation measures. Another source of uncertainty is the likelihood of new climates, where climate change brings about climatic conditions not currently experienced. This occurs especially in hot lowland regions, where future temperature increases create climatic conditions with temperatures do not occur. This is the case in some regions where wild peanuts are currently found. Finally it is important to note that climate-envelope models do not take into account competition, habitat or other biotic interactions, and the extent to which plasticity is accounted for is aslo debatable (Parmesan 2006). The true range of a species is likely to be reduced by these factors. The model we used here does not take into account these complex interactions, which will also be affected by climate change.

The significant differences in extinction rates between the groups studied are of interest. Essentially, for a species to maintain its range size in the face of climatic change the species must migrate at a rate equal or greater to the speed of horizontal displacement of climates, or be able to adapt to keep pace with a changing climate. The horizontal displacement of climate depends partly on the magnitude of the climate change in that particular region, and landscape characteristics such as topographic heterogeneity. Relatively flat areas are likely to have much faster horizontal displacements in climate than mountainous regions, where a climate could be tracked over short distances by moving uphill. Many *Arachis* spp. are predicted to suffer higher extinction rates due to their distribution in predominantly flat regions where the horizontal displacement of climate is fastest. Furthermore, the fate of wild *Arachis* may be further compounded by a migrational capacity that has been reported to be as low as 1m per year (Gregory *et al.* 1973) due to its geocarpic habit (burying its seed), but no empirical data are available, and this rate seems very low given the large distribution areas of some species. On the other hand, *Arachis* species are currently found in some of the hottest and driest parts of Latin America. Climate change is expected to created "new" climates not currently found on the continent. The degree to which these species are adaptated to these "new" very high temperatures is not known and could be examined through experimental work.

Implications for conservation

Habitat fragmentation creates spatial barriers to species migration and diminishes colonisation of suitable habitats. Prevention and reduction of habitat fragmentation therefore is critical to mitigating impacts of climate change (Lavendel 2003). Migration corridors to connect landscape fragments could facilitate range shifts of mobile species. Linking corridors between habitat patches expand the potential range of species and, as indicated by this study for some groups, larger areas have greater buffering potential against climate change than smaller areas. Species like *Arachis* are highly vulnerable to climate change impacts and have a limited capacity to migrate. Moreover, with little time to adapt their conservation may require human intervention such as translocations and collection for *ex situ* conservation.

Strategically placed protected areas may be key in preserving genetic diversity (Lavendel 2003). Areas selected should be evaluated for their potential as climate change refugues for vulnerable species. Such reserves should contain target populations large enough to ensure persistence as the larger the number of individuals of a species in a given area, the greater the probability that the species will survive (Araújo *et al.* 2004).

Some crop wild relatives, including some wild potato and *Vigna* species are weedy or early colonizers and prefer disturbed environments. Thus, these species do not require pristine habitat and persist along roadsides provided that disturbances are not too frequent or intense. Road networks and other tracts of disturbed areas could become corridors for the migration of these species (Peters *et al.* 2005).

These analyses can help in prioritizing species for conservation in the wild (*in situ*). However, in some cases *ex situ* conservation is the only feasible strategy when there is no suitable area for a species in the future. Climate change must be a fundamental consideration in conservation management, and selection of new protected areas and management plans for existing areas need to account for its projected impacts.

Economic implications

The economic value of crop wild relatives to sustainable agriculture is large. The contributions of CRW to crop yield and quality of US-grown or US-imported crops were calculated to be over $340 million a year in the early eighties (Prescott-Allen and Prescott-Allen 1983), and this figure is likely to have increased since then. Our study has shown that many crop wild relatives of *Arachis, Solanum* and *Vigna* that have already been important for crop breeding programs are under threat from climate change. The importance of CWR genes to peanut breeding is clearly demonstrated by the fact that nearly half of new peanut cultivars and germplasm lines registered in the journal *Crop Science* between 2000 and 2005 contained CWR in their pedigrees. Breeding for resistance and tolerance in crops is essential to continue adaptation of farming systems to changed and irregular climate conditions.

Conclusions

The results presented in this paper provide a strong indication that climate change alone presents a significant threat to important agricultural genetic resources, specifically the wild relative species studied here, with 16-22% of species predicted to have no climatically suitable areas and perhaps go extinct by 2055. When the effects of climate change are combined with alteration of habitats and other anthropogenic impacts, the status of many of these species should be considered as highly threatened, and measures to conserve the genetic resources will need to be expanded. Conservation strategies should be complementary, combining both *ex situ* germplasm conservation and *in situ* conservation and management of populations.

The impacts of climate change have been shown to be heterogeneous in space, and variable depending on the geographic origin, habitat and migrational capacities of the species under question. This is evident in the difference in predicted extinction rates between the three groups of CWR, with 47-61% of *Arachis* species facing extinction compared to just 2-6% of *Vigna* species predicted to be facing extinction.

Although the data presented here are based on inherently uncertain model predictions, they clearly indicate that further investigation is needed to truly understand the potential impacts of climate change on plant species in the wild. In the case of wild *Arachis*, important uncertainty can be attached to the results presented here as little is known about the adaptation of the species in "new" climates not currently found in Latin America. Experimental studies could take advantage of *ex situ* collections and perform common-garden experiments of populations in different climatic environments (representing present *and* future climates) to gain a mechanistic understanding of the physiological basis of climatic adaptations.

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Another dimension to grazing systems: Soil carbon[1]

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Abstract

In 1998, Fisher et al. attempted to draw together published and anecdotal information to answer some of the questions raised by the findings of Fisher et al. (1994; 1995), that introduced pastures of African grasses on the eastern plains of Colombia accumulated large amounts of C in the soil. This review synthesises the work in both Colombia and Brazil over the last 7 years that answers some of the questions raised and speculations made by Fisher et al. (1998). The most important studies have shown that the rate at which litter decays at the soil surface has been grossly underestimated in the past. As a consequence, net aerial primary productivity (NAPP) was shown to be 33.3-33.5 t/ha/yr in well managed pastures of introduced grasses without either a legume component or N fertiliser. While data for soil C vary according to the past history and states of the pasture, well managed pastures do accumulate C in the soil to levels above that under the native grassland vegetation. Net primary productivity below ground was only slightly less than NAPP. Deficiencies of N and P are primarily responsible for the widespread degradation that occurs when introduced pastures are overgrazed and not fertilised. Heavy stocking rates profoundly change the N cycle and lead to N deficiency and hence degradation in the bulk pasture area by concentrating N recycling from faeces and urine in rest areas and watering points. Here the pasture is so damaged by trampling that it cannot take advantage of the increased fertility.

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Introduction

Atmospheric carbon dioxide (CO2) concentrations have increased from 270 ppm before the industrial revolution to 367 ppm in 1999 (IPCC 2001) and are continuing to increase at an average rate of about 1.5 ppm/yr. Without action to limit global CO2 emissions, the concentration of CO2 in the atmosphere could reach 550 - 1000 ppm by 2100. CO2 is one of the main contributors to the so-called "greenhouse effect", which the Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report (IPCC 2001) concluded could lead to substantial warming of the global climate by 1.8 - 5.4○C by 2100.

In terrestrial systems, plants capture CO_2 from the atmosphere by photosynthesis. As dead plant material decomposes both within the soil and at the soil surface, plant C can be stored or sequestered in soil organic matter (SOM). The store of soil organic C (SOC) is almost 3 times that held in biota (1550 compared with 550 Pg) (*e.g.* Lal *et al.* 1995). Therefore, small increases in SOC could slow the increase in the concentration of CO_2 in the atmosphere (Schlesinger 1995), and in so doing have considerable effects on the global climate system.

African grasses introduced into savannas of the central lowlands of tropical South America can increase SOM and accumulate more C in the soil than the native grasses they replace (Fisher *et al.* 1994; 1995). In a review published in 1998, Fisher *et al.* explored the possible impact of this finding, and the role of "anagement options that can increase the potential of tropical pastures as a significant C sink to mitigate

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global warming." They went on to write, "Neither the extent of this finding in the Latin American savannas nor understanding of the mechanisms in the soil-plant system by which it occurs are yet known."

Over the 5 years to 2004, a project partly financed by the UK Department for International Development has allowed some of these issues to be addressed. In this paper, we attempt to update Fisher *et al.*'s (1998) review with recent information, some of which is unpublished or in the process of revision.

The potential of grasslands

Approximately one-fifth of the world's land, 3.4 billion ha, is covered by grasslands (Hadley 1993; FAO 1993), with about 1.5 billion ha in the tropics, of which Pearson and Ison (1987) considered as much as 0.7 billion ha to be "improvable grasslands". Houghton (1995) estimated the mean C content of the soils under tropical grasslands and pastures to be 48 t/ha, although it is not clear what depth of soil was used to obtain this estimate. Fisher *et al.* (1998) measured 1.5 - 5 times that amount of C in the soil to a depth of 1 m on the eastern plains of Colombia. The data on soil C stocks presented below, also to a depth of 1 m, are 2-3 times Houghton's figure.

Vegetation communities

Scholes and Hall (1995) estimated that tropical savannas, woodlands and grasslands occupy at least 11.5% of the global land surface. In calculating the C budget for these biomes, net annual C fixation in tropical tree-grass systems is about 7.6 Pg, which is about half of the net annual C fixation attributed to tropical forests, which have closed canopies and no herbaceous layer. The main factors that control C fixation are water, nutrient availability and vegetation composition and structure. The total C stock in tropical grasslands, savannas and woodlands is about 135 Pg, 80% of which is in soil (Scholes and Hall 1995).

Many of the generalisations about savannas have ignored the South American grasslands (for example, Parton *et al.* 1995), so it is worth describing them briefly. The area of central Brazil known collectively as "the Cerrados" covers 205 M ha. (In this paper, we use the terms with their common meanings. "Cerrados" refers to the lands in central Brazil and "cerrado *sensu strictu*" refers to the low scrubby vegetation that covers a large proportion of the Cerrados.) Fisher *et al.* (1998) asserted that most introduced pastures on the Cerrados were sown on the 24% (Haridasan 1992) that is either treeless or has only a few stunted trees and shrubs, concluding that: "It is on these lands that most of the 50 M ha (Sano *et al.* 2000) of introduced pastures are found." This now appears not to be the case, in that most introduced pastures were in fact sown on lands that formerly carried cerrado *sensu strictu* vegetation. Any calculations of net carbon accumulations on the central lowlands of tropical South America (Fisher and Thomas 2004) must discount figures for C accumulation by the amount of C that is lost when the cerrado *sensu strictu* vegetation is cleared. Since cerrado *sensu strictu* vegetation covers a continuum from communities with scant arboreal component to near open forest (Cochrane *et al.* 1985), it is no trivial exercise to calculate historic C stocks on the lands sown to pasture. While we draw attention to this anomaly, further discussion is outside the scope of this paper. The savannas of Colombia and Venezuela (about 32 M ha) have not had, from historical times, a significant tree component (Moreno and Moreno 1989). Since this area is vast, any intervention in the savannas of the central lowlands of tropical South America that will increase their net primary productivity, and hence the stock of C in the soil, could be large enough to be of global significance.

Net primary productivity above ground

Long *et al.* (1989; 1992) found net primary productivity (NPP), that is accounting for mortality of above- and below-ground organs, at 5 natural grassland sites in the tropics to range from 0.14 to 10 kg $/m^2/yr$ dry matter (DM), as much as 5 times greater than if they used the methodology of the International Biological Programme (Milner and Hughes 1968). Long *et al.* (1992) indicated that all 5 sites were potential sites of net C accumulation. In the absence of fires, their terra firma sites in Kenya, Mexico and Thailand accumulated 144 g/m^2/yr C, and 40 g/m^2/yr C with occasional fires (0.5/yr). They also found a net loss of 70 g/m^2/yr C with more frequent fires and drought, suggesting that the balance, in terms of the sites being a sink or source of C, was delicate. Their studies indicated, however, that the grass-dominated communities have the potential to act as significant sinks for C.

Rezende *et al.* (1999) carried out an experiment on lands cleared from the coastal Atlantic forest in southern Bahia state in central-eastern Brazil to determine the effects of introducing a forage legume (*Desmodium ovalifolium*) in pastures of *Brachiaria humidicola* at different stocking rates. At monthly intervals over 3 years, amongst other measurements, they collected data on the rates of plant litter fall and decomposition by measuring litter already on the ground and the rate of litter fall over the subsequent 14 days. Doubling the stocking rate from 2 to 4 head/ha caused a highly significant decrease in litter fall, but the legume treatment had little effect (Table 1).

Table 1. Annual means of existing litter, litter deposited in 14 days and litter decomposition parameters in pastures of *B. humidicola* in monoculture under three stocking rates of crossbred Brahman cattle in the period January to December 1995 at Ceplac station, Itabela. The values are means of 12 monthly evaluations, from 10 quadrats per paddock, and 3 replicate paddocks per treatment.

Stocking rate	Means of existing and deposited litter		Decomposition constant	Total litter deposited in 12 months		Consumption	Annual NAPP[3]
	Existing	Deposited in 14 days	k	Estimate[1] 14 days	Corrected[2]		
An/ha	g/m^2		g/g/d	t/ha/yr			
2	116.6	72.5	0.0706	18.9	29.7	7.8	35.5
3	105.8	66.4	0.0734	17.3	27.5	9.1	33.3
4	73.7	49.1	0.0797	12.8	21.3	12.4	30.6
Mean	98.7	62.7	0.0746	16.3	26.2	9.8	33.1

[1] Calculated from [(litter deposited in 14 days)/14] x 365.

[2] Allowing for losses during the 14 days of deposition (See Rezende et al. 1999 for details).

[3] Annual NAPP (net aerial primary productivity) = total deposited litter + forage consumption + change in standing biomass. The change in standing biomass during the year was -2.0, -3.3 and -3.1 t/ha for the stocking rates of 2, 3 and 4 animals/ha, respectively.

Data from Rezende *et al.* (1999) and Boddey *et al.* (2004).

Their data showed that 15 - 18 t/ha of litter DM were deposited annually. However, the amount of existing litter was always relatively small (annual means were 0.8-1.5 t/ha DM), suggesting that litter decomposes rapidly, with calculated half life of 22-33 days. Moreover, even this calculation must underestimate the true rate at which litter disappears, because a substantial proportion of it must have disappeared within the 14-day collection periods.

To resolve these issues, Rezende *et al.* (1999) developed an equation to correct for the loss of litter between sampling dates. The correction gave constants for litter decomposition of 0.037 to 0.097 g/g/d, equivalent to litter half lives of 9-20 days. They summed these data, together with estimates of animal consumption, to calculate net aerial primary productivity (NAPP) of the pastures at 30 - 36 t/ha/yr (Table 1). These are astonishing figures, even compared with Long *et al.*'s (1989) estimates, but are consistent with Fisher *et al.*'s (1998) reasoned hypothesis that NAPP of sown *Andropogon gayanus* pastures on the eastern plains of Colombia was likely to be as much as 43 t/ha/yr. It is also worth pointing out that Long *et al.*'s data came from naturalised grasslands, which usually have much lower NAPP than sown pastures of introduced species to which some fertiliser has been applied (Fisher *et al.* 1992).

Rezende *et al.* (1999) also experimented with litter bags, and a "covered litter" system, which allowed soil fauna to access the litter. This experiment showed that soil fauna had little impact on the rate at which litter disappeared. Moreover, these techniques, commonly used to estimate litter decomposition, actually underestimated true rate of litter decomposition at least tenfold, because, in contrast to litter bags, in the open field fresh litter is being added continuously. As this material consists of both easily degradable ("active") and recalcitrant fractions, the easily degradable fraction fuels an active microbial biomass that continuously degrades the less decomposable material. They noted in conversation that, when they went to the field in the early morning at Itabela, "the litter felt warm" (R.M. Boddey, unpublished data). In this seminal paper, they concluded that their approach gives more realistic, and much higher, estimates of the NAPP of tropical grasslands and pastures than the techniques used until now.

The approach by Rezende *et al.* (1999) used a mathematical adjustment to take account of presumed degradation losses during the 14-day measurement interval, which may not be accepted by all. The result could be confirmed, albeit rather laboriously, using the techniques of tissue turnover developed by Hodgson and his colleagues at the former Hill Farming Research Institute in Scotland (Hodgson 1990). The method depends on determining the rate of leaf emergence coupled with taking a census of the number of tillers and the number of leaves on each. In many cases, the number of leaves per tiller is constant (5 or 6 in many *Brachiaria* species), implying that old leaves must die at the same rate as new ones appear. Data of mean mass of newly fallen leaves, multiplied by tiller density per unit area and multiplied by the rate of leaf appearance, would provide an independent estimate of litter fall ($g/m^2/d$).

Net primary productivity below ground

Although Long *et al.* (1989; 1992) broke new ground by including roots in their estimates of NPP, they limited their measurement of roots to the surface 15 cm. At the time, this was thought reasonable, because most measurements of plant behaviour were dominated by studies on sown crops (Fisher *et al.* 1998). However, the emphasis in the Tropical Pastures Program of the Centro Internacional de Agricultura Tropical (CIAT) for many years was to select tropical grasses with deep and abundant root systems, that can exploit nutrients and water at depth in the soil. In many environments, especially in the semi-arid tropics, deep roots can also confer ecological advantages, for example, adaptation to drought. Fisher *et al.* (1994) speculated that deep-rootedness was at least part of the mechanism by which C was accumulated[2] by pastures of introduced grasses in the neo-tropical savannas. However, there are few measurements of the contribution of grass roots at depth to NPP.

Trujillo *et al.* (2005) estimated the net below-ground primary productivity (NBPP) on the eastern plains of Colombia. They assessed the rate of root decomposition and calculated the annual input of soil organic carbon under native savanna vegetation (NS), a degraded pasture of *B. humidicola* (Bh) and well managed pastures of *B. dictyoneura* alone (Bd) and in mixture with the legume *Arachis pintoi* (Bd+Ap). Standing root biomass in Bd (8.6 t/ha) was about 3 times that in NS (2.9 t/ha), reflecting the low growth rates reported for the savanna species (Fisher *et al.* 1992). NBPPs of the well managed pastures were 30.0 and 31.3 t/ha/yr for Bd and Bd+Ap, respectively, compared with only 12.5 t/ha/yr for NS. Turnover losses of Bd and Bd+Ap were 1.5 – 2.5 times those in either NS or Bh (Tables 2 and 3). The decomposition constant of roots of Bd was lower than that of either NS or Bd + Ap, which resulted in a longer residence time for Bd roots. The amount of NBPP remaining in the soil after one year of decomposition under well managed pastures was about 2.3 times that under NS.

[2] Soil carbon is often described as "sequestered". Since we do not know the exact form of the newly accumulated C, we prefer to refer to it as "accumulated". Where we quote from earlier work, in which the authors used the term "sequester" and its derivatives, we have substituted the alternative of "accumulate" enclosed in square brackets [ ].

Table 2. Mean net below-ground primary productivity calculated from ingrowth tubes of a native savanna (NS) grassland compared with a degraded *Brachiaria humidicola* pasture (Bh) and well managed pastures of *B. dictyoneura* alone (Bd) and in association with the legume *Arachis pintoi* (Bd+Ap). Data from Trujillo *et al.* (2005).

Parameter	NS	Bh	Bd	Bd+Ap
		t/ha/yr		
Sum of short-term tubes	2.42 c[1]	5.33 b	9.74 a	9.99 a
Last long-term tube	1.22 c	2.89 b	8.03 a	7.91 a
Peak in long-term tubes	2.88 b	3.47 b	8.63 a	8.96 a
Turnover	5.88 c	5.11 c	11.06 a	7.66 b
Last long-term tube + Turnover	7.10 c	8.00 c	19.09 a	15.57 b

[1] Within rows, treatment means followed by the same letter did not differ significantly ($P>0.05$).

Table 3. Mean net below-ground primary productivity of a native savanna grassland (NS) compared with well managed pastures of *Brachiaria dictyoneura* alone (Bd) and in association with the legume *Arachis pintoi* (Bd+Ap), calculated from a compartment-flow model. Data from Trujillo *et al.* (2005).

Parameter	NS	Bd	Bd+Ap
		t/ha/yr	
Change in live roots	3.14 b[1 2]	7.28 a	7.92 a
Change in dead roots	1.82 b	6.32 a	5.16 a
Amount of decomposition	7.50 b	16.41 a	18.26 a
Turnover	9.32 b	22.72 a	23.42 a
BNPP	12.46 b	30.00 a	31.34 a
Inputs of SOC	4.99 b	10.30 a	11.58 a

[1] Within rows, treatment means followed by the same letter did not differ significantly ($P>0.05$).

[2] The figure in Trujillo *et al.* (2005) is 1.92, which is a typographical error. The correct value is 3.14 (W. Trujillo, personal communication, 29 January, 2007).

In a complementary study, Trujillo *et al.* (2006) estimated macro-organic matter (> 150 µm, MOM) in the soil under the same pastures described above. They separated the MOM into light (LF), intermediate (IF) and heavy fractions (HF), using solutions of differing specific gravity, and analysed each fraction for C and N. The C:N ratios of the MOM fractions decreased in the order LF > IF > HF in all pasture treatments (data not presented). While the MOM fraction in NS and Bh accounted for a small percentage (8%) of the total SOC pool, the contribution increased to 21 % under Bd+Ap and 30% under Bd. Trujillo *et al.* (2006) concluded that the MOM represented only a small percentage of the total soil organic carbon pool, because it turns over rapidly as indicated by the decrease in C:N ratios as the density fraction increased. They further pointed out that the amount and C:N ratios of the LF were most sensitive to differences in soil depth, vegetation type and pasture management.

Relation between root mass and pasture health

Embrapa-Agrobiology have measured root mass under pastures in various states from productive to degraded. Degraded pastures in the Cerrados are commonly identified as having a discontinuous grass cover, invasion of shrubby and other weeds and many termite mounds. The data seem to show that root mass increases as fertility declines up to a critical point, after which there is a cataclysmic decline in root mass as the roots disappear and the area becomes infested with termite mounds. They speculate that the dead roots are feed for the termites.

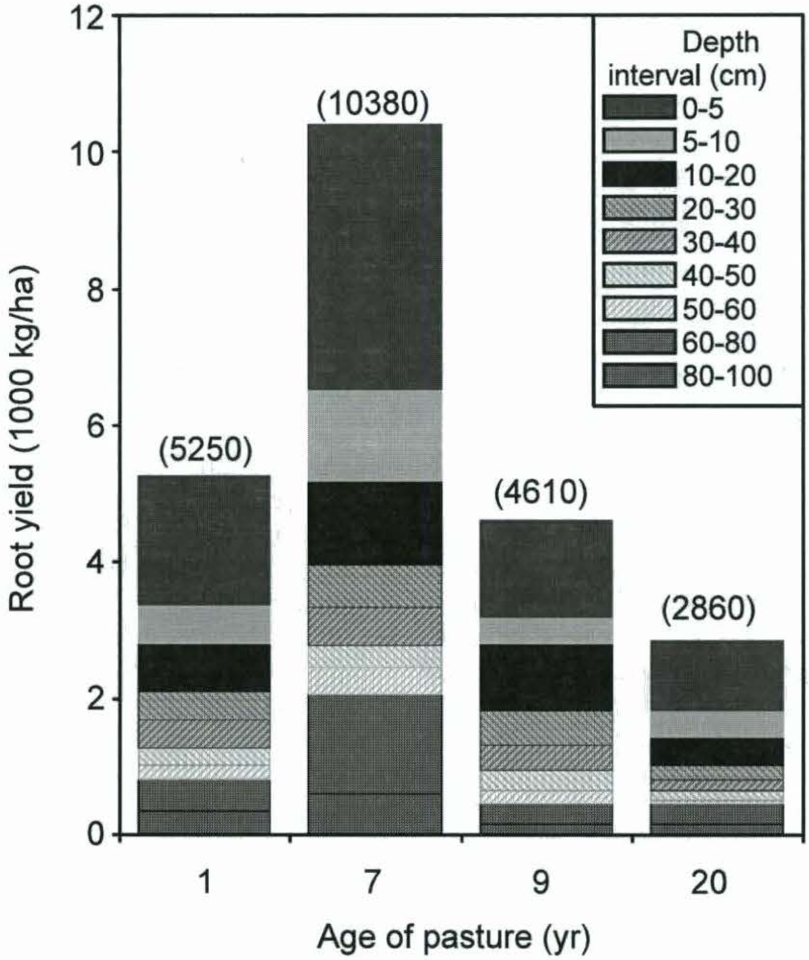

Figure 1. Root stocks in three *B. brizantha* pastures of increasing age and a 20-year-old degraded pasture of *B. decumbens,* Fazenda Barreirão, near Goiânia. Data are means of 4 replicates. Values in parentheses above the stacked bars are the total root stocks (kg/ha DM) to 100 cm. Renato, personal communication.

In severely degraded pastures, root biomass is often far lower than in productive pastures. In a chronosequence of *B. brizantha* pastures near Goiânia, a 7-year-old pasture had a larger root-stock (10.4 t/ha DM to 100 cm) than either a pasture established 1 year before (5.2 t/ha DM) or a heavily utilised pasture established 9 years previously (4.6 t/ha DM, Figure 1, Renato, personal communication). A 20-year-old heavily degraded *B. decumbens* pasture showed the lowest root-stock of only 2.9 t/ha DM.

Oliveira *et al.* (2004) studied 3 pastures established under well controlled conditions at the Embrapa-Beef Cattle Centre near Campo Grande. The root-stocks to 40 cm were compared in a newly established pasture and two 13-year-old pastures (all *B. brizantha*), one of which had been well fertilised including additions of N, and one grazed without fertiliser application since its establishment. The results showed that the unfertilised 13-year-old pasture had the highest stock of roots (Table 4).

Table 4. Root biomass (t/ha) in soil under *Brachiaria brizantha* pastures at Campo Grande site. Data are means of 4 replicates.

Depth (cm)	Treatment		
	4 months	Fertilised	Not fertilised
0-10	3.2	8.3	12.2
10-20	0.7	1.9	2.4
20-40	0.7	1.9	3.1
Total in profile	4.6 b[1]	12.1 c	17.7 a

[1] Means followed by the same letter are not significantly different (P> 0.05).

A further study (R. Schunke, personal communication) at Fazenda[3] Ribeirão, Chapadão do Sul in a large grazing experiment with *B. decumbens* pastures regularly fertilised with P and K (but not N), showed that increasing stocking rate from 0.6 to 1.0 animal units/ha (1 AU = 450 kg live weight) had no significant effect on rooting density (g root DM/kg soil). A further increase to 1.4 AU/ha increased rooting density by approximately 50 % (data not presented). These data suggest that, as soil fertility declines or demand on the pasture increases, initially the grasses increase their root mass, presumably to increase their capacity to capture nutrients from the soil. We hypothesise that finally the photosynthetic apparatus of the plants is unable to support such a large root system and there is a massive shedding of roots, leading to the low values typical of severely degraded pasture.

Table 5. Root biomass (t/ha) in soils under a chronosequence of recuperated *Brachiaria brizantha* pastures of different ages (5 months, 4, 6 and 9 years), Fazenda Barreirão, near Goiânia. Data are means of 4 replicates.

Depth (cm)	Pasture age			
	5 months	4 years	6 years	9 years
0-10	13.6	13.5	34.5	8.8
10-20	1.7	2.0	2.3	1.2
20-40	2.0	1.6	2.9	1.4
Total in profile	17.3 a[1]	17.1 a	39.7 b	11.4 c

[1] Means followed by the same letter are not significantly different (P> 0.05).

[3] Fazenda is the Brazilian equivalent of the US ranch or the Australian station.

Oliveira *et al.* (2004) also monitored root biomass under a range of pastures at the Fazenda Barreirão near Goiânia (Table 5). A newly established pasture of *B. brizantha* showed a total root biomass to 40-cm depth of about 17 t/ha DM, which was very similar to a 4-year-old pasture at the same site. However, a 6-year-old pasture had more than double this root biomass (39.7 t/ha), while a 9-year-old pasture had only 11.4 t/ha. These are on-farm data and not from long-term experiments. Grazing pressure on the different pastures was not monitored nor was it necessarily the same for each pasture. Despite these limitations, the data are broadly consistent.

With the ongoing decline of pasture productivity, there may be important consequences of this behaviour of roots for the understanding of C accumulation under grazed pastures. While the application of generous levels of fertiliser to *Brachiaria* pastures almost certainly results in increased aerial productivity and allows increased stocking rates, root biomass may well be lower than in pastures that receive little or no maintenance fertiliser. This conclusion is certainly surprising, likely to be controversial, and needs confirmation from long-term experiments and studies of root turnover, *i.e.*, NBPP.

A further conclusion would be that, for under-fertilised (or as is most usual, completely unfertilised) pasture, root biomass, and presumably inputs of C derived from roots, will increase with time. Root biomass should reach a peak, followed by a large deposition of dying roots as the system collapses. Under this hypothesis, the maximum rate of C deposition will occur at this time, but subsequently C stocks will gradually decline, and, if the area is not cultivated or fertilised, the C stocks will decline to levels below those originally present under the native vegetation.

The role of introduced grasses in C accumulation

Fisher *et al.* (1994) reported that African grasses introduced into the savannas of Colombia could accumulate organic carbon at depth in the soil compared with the native savanna vegetation. They reported that SOC from 0 to 80 cm depth in a grass-legume and a pure grass pasture exceeded that in savanna by 7.04 and 2.59 kg/m^2 C, respectively. More than 75% of the additional soil C was found below 20 cm, or below the plough layer. They concluded that "this C should therefore be less prone to oxidation, and hence loss, during any cropping phase that might be undertaken in integrated crop and pasture systems. Indeed, such systems should be able to accommodate rotations with annual crops and still contribute to C [accumulation]."

Total amounts of SOC to 80 cm depth ranged from 19.7 kg/m^2 C under the native savanna to 26.7 kg/m^2 C under *B. humidicola-A. pintoi* grass-legume pastures (Fisher *et al.* 1994; Figure 2). These values of SOC represent the upper range for tropical soils including oxisols, which generally range from 2-22 kg/m^2 C (Moraes *et al.* 1995 and the references therein).

Tarré *et al.* (2001) reported the use of stable C isotope (^{13}C) analysis to determine the source of soil C in the 20 years following clearing of the Atlantic forest vegetation at a site in southern Bahia state of east-central Brazil. Eleven years after clearing in 1977, *B. humidicola* was established and subsequently regularly fertilised with P and K. After 9 years of pasture, soil (Typic Paleudult) C levels under the original forest and under the sown pasture were similar, but that the source of the C had changed, with 9 t/ha of the original C lost from the 0-30 cm layer and replaced with C derived from the sown grass. Stocks of soil C to 100 cm (corrected for compaction caused by grazing by calculating the C stock in a mass of soil equal to that under the forest – Neill *et al.* 1997) under the sown grass were not significantly different from those under the forest.

Where the legume *Desmodium ovalifolium* had been introduced into the sward, the mean rate of accumulation of soil carbon almost doubled from 0.66 to 1.17 t/ha/yr C. Although these rates are far lower than those reported by Fisher *et al.* (1994) on the Colombian Llanos, the results confirmed the positive effect of the legume. However, the ^{13}C abundance data showed that little C derived from *B. humidicola* was deposited below 40-cm depth. This suggests that, in this biome where rainfall is fairly evenly distributed throughout the year, *B. humidicola* did not root deeply. This contrasts with the deeper rooting of the same grass species in the Llanos of Colombia (Rao 1998), which has a higher annual rainfall (~2200 mm) than Bahia (~1400 mm), but also has a strong 3-4 month dry season.

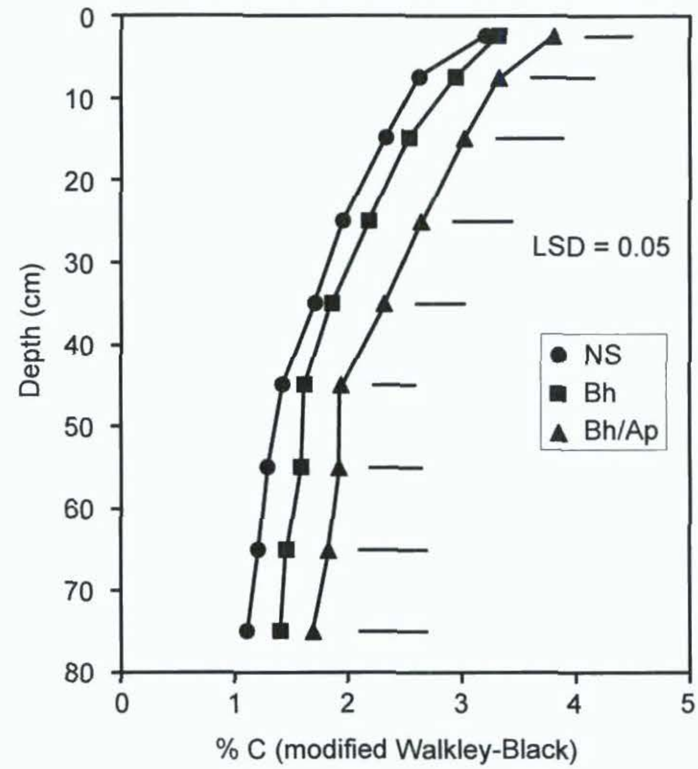

Figure 2. Soil organic C distribution by depth in introduced pastures of the grass *Brachiaria humidicola* alone (Bh) and with the legume *Arachis pintoi* (Ap) compared with native savanna pasture (NS) on a clay loam Oxisol at Carimagua on the eastern plains of Colombia. From Fisher *et al.* (1998).

Until recently, very few studies from the Cerrado region of Brazil had evaluated the impact of substituting pastures of *Brachiaria* spp. for native vegetation. Corazza *et al.* (1999) studied the soil C stock under a *B. decumbens* pasture established in 1976 on an Oxisol (49 - 59 % clay) near Brasília. In 1982, a single crop of soybean was planted with intensive tillage and the pasture was then resown. The stock of soil C was found to be 150 t/ha to a depth of 100cm, 16.6 t/ha C more than that under the cerrado *sensu strictu* community, although this may be an overestimate, as no correction was made for differences in soil bulk density in the 2 profiles (Neill *et al.* 1997).

Freitas *et al.* (2000) compared the stocks of C to 40-cm depth under the native vegetation and a productive and a degraded sown pasture on an Oxisol (36 - 46 % clay) near Goiânia. They presented data for bulk density, but did not correct the data for equal soil mass between the 2 pastures. Recalculating the data shows that both sown pastures had less soil C than was originally present under the cerrado *sensu strictu* vegetation. The correction for compaction by grazing animals shows the importance of correcting for equal mass of soil in the profiles (Table 6).

Table 6. Carbon concentration, bulk density and C stocks (as presented and corrected for equal mass of soil) in an Oxisol (36 - 46 % clay) near Goiânia under cerrado *sensu strictu* vegetation compared with productive and degraded pastures. Means of 9 replicate samples per depth in each plot. Adapted from Freitas *et al.* (2000).

Depth	Carbon	Soil bulk density	Soil carbon stock (t/ha C)	
(cm)	(g/kg)	(kg/dm^3)	Presented[1]	Corrected[2]
NVC Native vegetation of the Cerrado[3]				
0-10	22.6	1.19	26.9	26.9
10-20	19.6	1.24	24.3	24.3
20-40	13.7	1.12	30.7	30.7
0-40	---	---	81.9	81.9
PP– Productive pasture				
0-10	22.0	1.10	24.2	25.6
10-20	16.1	1.32	21.3	19.9
20-40	10.8	1.33	28.7	24.2
0-40	---	---	74.2	69.8
DP – Degraded pasture				
0-10	19.0	1.10	20.9	22.4
10-20	16.4	1.23	20.2	19.9
20-40	12.2	1.23	30.0	27.3
0-40	---	---	71.1	69.6

[1] C concentration x soil bulk density x depth.

[2] Corrected for same mass of soil to 100 cm as under native vegetation (Neill *et al.* 1997).

[3] The term used by Freitas *et al.* 2000; cerrado *sensu strictu* vegetation in the terminology we use here.

A third, very recent study compared the soil C stocks under an area of cerrado *sensu strictu* vegetation and 6 areas of different forage species on an Oxisol at the Embrapa-Cerrado Centre near Brasília (da Silva *et al.* 2004). The area of native pasture, which was regularly grazed, contained 99.7 t/ha C to a depth of 100 cm. The carbon stocks, also to 100 cm, under:

- Grazed *Panicum maximum* established 7 years before sampling,
- A grazed mixed pasture of *Stylosanthes guianensis* with *B. brizantha* established 3 years before sampling, and
- Two ungrazed fields of *B. brizantha* and *Paspalum atratum* established 4 years before sampling and used for seed production.

All showed significantly increased soil C stocks, which reached 110 - 113 t/ha C. No significant increase in C stocks was observed under a *B. decumbens* pasture, nor under a mixed legume-*Andropogon gayanus* pasture, both of which were grazed, but which had been established for only 3 years. Considering the short period of this study, and that soil C stocks are generally significantly reduced at the time of land clearing and pasture establishment, these data indicate a considerable potential for accumulation of soil C under productive pastures.

The source of the accumulated C

The C accumulated in the soil must originate in the C fixed by the pasture, that is, it must come from the pasture's NPP. Fisher *et al.* (1998) pointed out that, unlike the synchronised development of short-cycle annual crops, pastures have a continuous cycle of initiation, growth and death of individual units (tillers in grasses and branches in legumes). As the volume of herbage in a pasture increases, the rate of senescence and death of the older units also increases until finally they equal the rate of initiation of new units, leading to the so-called maximum yield that is commonly measured by agronomists and others.

Unless there is some environmental constraint (drought, nutrient deficiencies, pests or diseases) or the grasses flower, which they rarely do in well-managed sown pastures under grazing in the central lowlands of tropical South America, primary growth probably continues at something close to the maximum measurable rate for the whole growing season. Fisher *et al.* (1998) estimated that yearly NAPP of *A. gayanus* on the Colombian eastern plains, where rainfall is abundant (~2200mm annually with at least an 8-month growing season) and temperatures are uniformly high throughout the year, may be 4.3 kg/m^2. We emphasise that these conditions are for the central lowlands of South America and may not be typical of other regions with less favourable climates.

On the Colombian Llanos, Rao (1998) estimated standing root biomass during the growing season under grazing of introduced pure grass and grass-legume pastures at 570 and 380 g/m^2, respectively, compared with 140 g/m^2 for a native savanna. Root turnover in pure grass pasture was estimated to be twice and in grass-legume pasture 3 times that in native savanna. Based on these data, Fisher *et al.* (1998) concluded that, "we can safely assume that roots turnover at about the same rate as above ground material, and apply that to the maximum measured yield of roots [to estimate NPP]".

Fisher *et al.* (1998) then attempted to estimate C inputs to the soil of pastures under grazing, assuming that plant dry matter is 40% C. They concluded that total C inputs from shoots and roots in a grazed pasture on the eastern plains of Colombia were likely to be about 2.6-3.2 kg/m^2/yr. We can now draw together the experimental data of Rezende *et al.* (1999), Boddey *et al.* (2004) and Trujillo *et al.* (2005), discussed elsewhere in this paper, to obtain revised estimates of C inputs under grazed pastures. The data for litter fall of *B. humidicola* plus faeces return under the lower 2 stocking rates in the Itabela experiment were .1-3.2 kg/m^2. NPP of roots on the eastern plains of Colombia for the *B. dictyoneura* pasture was 3.0 kg/m^2. Summing these and converting them to C, we may safely estimate the total C inputs under reasonably well managed *Brachiaria* pastures to be about 2.4-2.5 kg/m^2/yr, only slightly less than the lower end of Fisher *et al.*'s (1998) 'back-of-the-envelope' estimates. Moreover, because the present data come from widely distributed experiments, we can be confident that they apply more generally to the central lowlands of tropical South America.

Are there differences among tropical grass species?

All grasses that show a capacity to accumulate more C in soil than the native grasses are of African origin (Thomas and Grof 1986). Fisher *et al.* (1998) quoted data of sampling from pastures of *B. decumbens* in the Cerrados near Brasilia that showed little or no C accumulation (J. Duxbury, personal communication; since rendered somewhat moot by the data of da Silva *et al.* 2004 summarised above). However, they added that, in the Llanos of Colombia at Carimagua Research Station, SOC accumulation to 100 cm depth in 13-year-old pastures of *B. decumbens* and *B. decumbens-Pueraria phaseoloides* was 25.6 and 34.1 t/ha C, respectively, greater than under native savanna vegetation.

Fisher *et al.* (1998) speculated that possible explanations for differences amongst species might be related to differences in the composition of litter, which in turn would affect their rates and patterns of decomposition. For example, the C:N ratios of leaf litter ranged from 88 for *B. decumbens* to 130, 126 and 117 for *A. gayanus*, *B. dictyoneura* and *B. humidicola,* respectively (Thomas and Asakawa 1993). Data from roots indicate a range of C:N ratios of 159-224 (Thomas, Ayarza and Celis, personal communication), and although these differences were not reflected in short-term decomposition constants (Thomas and Asakawa 1993), they may affect longer-term decomposition and conversion to recalcitrant forms of SOC. Fisher *et al.* (1998) continued, "The lower contribution of *B. decumbens*-based pastures to C [accumulation] may in part be explained by higher rates of decomposition of shoot and root litter of *B. decumbens* due to lower C:N ratios. Therefore the ability to [accumulate] C in soil may be species specific as noted for tree species (Sánchez *et al.*, 1985)." There does not appear to be any recent work that clarifies these speculations.

Demands on additional N supply

Fisher *et al.* (1998) discussed this issue in some detail, but because of the lack of data, much of it was speculation. We have summarised their arguments below. Boddey *et al.*'s (2004) paper on detailed studies of the N cycle of grazed pastures is broadly relevant to this topic, but they addressed the C cycle only indirectly. Boddey *et al.*'s (2004) paper, which gives understanding of the processes of pasture degradation, is discussed below in the section on grazing management.

Fisher *et al.* (1998) drew attention to anomalous C:N ratios of the soil organic matter under the grasslands of the Colombian eastern plains, which at 21.5 are much wider than the 10-12 found elsewhere (Schlesinger 1995). They pointed out that litter of introduced grasses in the sown pastures has extraordinarily wide C:N ratios (75-194 for above-ground litter and 158-224 for root litter), and that after only 9 years of a sown pasture on the eastern plains of Colombia, 6 of them with the legume *Arachis pintoi*, the C:N ratio to a depth of 80 cm had increased to 33.2. They concluded that further work was needed to develop an "understanding of the processes of breakdown of plant material of high C:N ratios".

Fisher *et al.* (1998) went on to speculate on the possible source of N to allow the accumulation of C at depth in the soil. By using known inputs of N from the legume component and associative fixation to be 200 kg/ha/yr N in grass-legume pastures and 40 kg/ha/yr N in pure grass pastures, they reasoned that the C:N ratios of the newly acquired SOM must be around 200, which is close to the values of the root and shoot litter. They concluded that this "suggests that the newly-acquired SOM is particulate plant material. How it gets to depth in the soil is unknown at present, but deep rootedness is a clear possibility". Boddey *et al.*'s (2004) study on N cycling in grazed pastures, discussed below, is broadly consistent with this conclusion, although they did not address the issue of C:N ratios of SOM.

Relationship with soil moisture

Fisher *et al.* (1998) quoted Brown and Lugo's (1982) study of tropical forest soils, in which they reported a positive relationship between the amount of soil C and moisture, which was also associated with different plant communities and soil types. They further concluded that, "Soils in wet climates exhibited greater variations in soil C content with changes in land use, in terms of both loss and recovery, than did soils in dry climates (Lugo and Sánchez, 1986)." There have been no recent studies that provide further evidence on this topic.

Management options to increase C accumulation

Introduction of forage legumes to improve N supply

In pure grass pastures on the eastern plains of Colombia, the amount of C accumulation is remarkably constant at about 3 t/ha/yr, and is 2.5 - 5 times this rate with a legume component (Fisher *et al.* 1994). The constant rate of C accumulation by pure grass pastures suggests that the process is rate-limited, and the increased rate with a legume suggests that the limitation is N. If this is so, sowing a legume component in pastures will clearly increase their capacity to accumulate C. If there is a new equilibrium value for the maximum amount of C that can be accumulated in the soil, increasing the rate of accumulation will mean that the equilibrium value will be reached sooner. However, the new equilibrium value is unknown, so that the role of increasing the rate is uncertain. There are other options to increase the N supply to a pure-grass pasture, such as application of modest amounts of N fertiliser and seeking means to increase associative N fixation (Fisher *et al.* 1998). The same arguments would also apply to them, except that there is a C cost in producing N fertiliser.

Use of fire

Much of the native tropical grasslands or savannas (as opposed to sown grasslands) are burned as frequently as annually, and they are rarely fertilised. Therefore, Long *et al.* (1992) suggested that soil C is at an equilibrium that is less than it would be if pastures were not burned and if some fertiliser was applied. Greenland (1995) hypothesised that, with these simple management options, the tropical savannas could be an even greater sink for C than is presently forecast. However, it is doubtful whether traditional sedentary or nomadic users of tropical grasslands would change their management practices without some strong economic incentive to do so. It is outside the scope of this paper to discuss the topic further.

It is worth noting that introduced pastures are rarely burned, except by accident, at least until they have become seriously degraded and invaded by undesirable woody weeds.

Increased activity of soil macro-fauna

Lavelle *et al.* (1994) pointed out that pastures usually have greater populations of soil invertebrates than other forms of land use and that these organisms require significant amounts of energy. An active earthworm community may consume the equivalent of 1.2 t/ha/yr C (Lavelle 1996), although, given the data that we quote in this review, this is only about 5% of NPP of a well managed *Brachiaria* pasture. On the other hand, Martin (1991) determined that rates of carbon mineralisation in earthworm casts may be 70% less than that of the bulk soil. In the acid soils of the eastern plains of Colombia, mass of soil macro-fauna in pastures of *B. decumbens* was 5 times, and in *B. decumbens-P. phaseoloides* was 10 times, (up to 60 g/m^2, Decaens *et al.* 1994) that in the native savanna. Earthworms dominate the soil fauna population and can ingest up to 10 times their body weight in soil each day, leading Fisher *et al.* (1998) to calculate that, within 3 years, 60 g/m^2 of earthworms have the potential to pass the whole of the soil volume to 1 m depth.

Fisher *et al.* (1998) postulated that earthworms must have considerable impact on the processes for moving C from the surface to depth in the soil, although there are no data to determine whether they are the only vehicle or whether other processes are involved. It is known that earthworm casts have substantially different properties from the bulk soil, with more water-stable aggregates due to cementing of the soil particles (Guggenberger *et al.* 1996). Fisher *et al.* (1998) concluded "We do not know for example if the benefits brought by earthworms in terms of soil improvement (*e.g.*, macro-aggregation, nutrient cycling) and hence increased NPP of the pasture, will outweigh the costs, in terms of carbon, of supporting the activity of earthworms. Available evidence indicates differences depending on the fauna species that dominate the populations (Lavelle *et al.*, 1994)." In this regard, Decaëns *et al.* (1999) showed that the casts of the large aneic (surface-feeding) earthworm *Martiodrilis caramaguensis* can account for the accumulation of as much as 8.6 t/ha/yr C.

Grazing management

Most studies on grazed lands have focused on aspects of animal production, herbage production and utilisation with little attention being paid to impacts on the soil resource base (Fisher *et al.* 1998). Fisher et al. (1998) concluded that results of evaluations of the effects of grazing on SOC are inconsistent, both increases and decreases being reported with increased grazing pressure, and that many factors are involved in the response of SOM to grazing (soil type, sward type, nutrient status etc.). They further asserted that there is a need to develop an indicator or some parameter of system state that reflects the overall result of the different factors involved in determining actual or potential C accumulation. They speculated that the concept of sward "steady-state" as described by Hodgson (1990), which can be used to optimise growth, productivity and senescence in terms of a simple measurement of sward height in temperate ryegrass pastures, might be used in tropical pasture systems. They thought that such an estimate of sward state could be linked to the concept of Spain *et al.* (1985) in terms of the management of tropical pastures within a "grazing envelope", which ensures sustainability of production and could optimise net accumulation of SOC. They added that, "This work is in its infancy for tropical pastures and requires much more attention."

From the few investigations that have been performed, and from a theoretical point of view, it is evident that, if pasture productivity declines, which almost invariably occurs because landowners rarely apply maintenance fertiliser and frequently overgraze their pastures, soil C stocks will be reduced. To this end, Embrapa-Agrobiology are engaged in studying soil C stocks under *Brachiaria* pastures of contrasting productivity compared with those under neighbouring native vegetation.

It is extremely difficult rapidly to assess the productivity or "degree of degradation" of pastures. Traditional soil fertility analysis does not reveal the difference between productive pastures and even those in a fairly advanced state of decline. Lilienfein *et al.* (2003) made an intensive comparison of soil properties between 3 sets of areas of native vegetation, productive pastures and degraded pastures, all within an area of 100 km^2. They sampled the soil solution at 5 depths (5 replicate suction cups per depth) down to 2.0 m at weekly intervals through 2 wet seasons (October - April). All samples were analysed for P, K, Al, Ca, Mg and Na as well as Fe, Mn, Zn, NH_4^+, NO_3^-, total organic C and total S. There were no significant differences in the concentrations of these various elements/ions between the productive and degraded pasture with the exception of Ca, K and Mg. The authors suggested that the higher grass productivity in the productive pasture was due to the significantly higher concentrations of these 3 nutrients and concluded that maintaining constant productivity "requires the regular application of Ca, K and Mg."

This conclusion contrasts strongly with the consensus amongst pasture agronomists working in the Cerrados that N and P are the 2 nutrients that principally limit pasture growth in this region (Carvalho *et al.* 1990; Zimmer and Correa 1993; Macedo 1995). In Lilienfein *et al.*'s (2003) study, P and $NH4^+$ concentrations in the soil solution were below the limits of detection of their analytical techniques (0.2 and 0.05 mg/L, respectively) as were many analyses of NO_3^- (limit 0.01 mg/L). Furthermore, there was no significant difference between the productive and degraded pastures for the measurable values of NO_3^- in the soil solution.

Oliveira *et al.* (2004), working on a chronosequence of pastures of 2, 4, 7 and 17 years of age, could not rank their state of productivity using traditional analysis of either soil fertility or plant tissue. While soil mineral N was not evaluated, available P (Mehlich-I) in the soil under all pastures was at 1.0 or less mg/kg. However, these same authors had previously shown at 3 different sites in the Cerrados that, while degraded pastures did not respond to P, K, S or micronutrient fertilisers and responded weakly to N application, most responded strongly when N was supplemented with P or full fertilisation with NPKS and micronutrients (Oliveira *et al.* 2001). In summary, these results vindicate the belief that generally P and N deficiency are the principal causes of pasture decline (Boddey *et al.* 2004), and furthermore the extremely high affinity of the dense mat of roots for P, NO_3^- and NH_4^+ means that, even in productive pastures, the concentrations of these elements/ions in the soil solution are extremely low, as they are absorbed by the roots as soon as they become available from mineralisation of soil organic matter.

The lack of simple analytical tests for evaluating the relative productivity of *Brachiaria* pastures on-farm was a major obstacle in the effort to determine the effects of pasture productivity on soil C stocks at a farm level. Cattle farmers often cannot provide accurate information on grazing history, as they normally rotate their animals through many paddocks during a single season. For this reason, Oliveira *et al.* (2004) investigated dynamic/biological indicators of the state of decline/degradation of pastures in the Cerrados.

Their best indicators of pasture health, which should preferably be used together for more certainty in the assessment, were:

1. Rate of regrowth after cutting,
2. Rate of litter fall after clearing all litter from the soil surface,
3. Microbial biomass C, and
4. Light-fraction of the soil organic matter,

which is consistent with Trujillo *et al.*'s (2006) conclusions.

The work now in progress at Embrapa-Agrobiology will examine different chronosequences of productive and degraded pastures on neighbouring areas for their apparent productivity using these indicators, and C and N stocks to a depth of 1 m and to identify the origin of the soil carbon (derived from C_3 native vegetation or from the C_4 *Brachiaria*) by evaluating the ^{13}C natural abundance of the C at each sampling depth.

Preliminary results are now available for 2 of these sites:

a) Fazenda Palota (soil 80% clay), near Luz in Minas Gerais state and,
b) Fazenda Ribeirão (soil 18% clay), near Chapadão do Sul in Mato Grosso do Sul state.

Both regrowth after cutting to a height of 5 cm and the rate of litter deposition were measured after 28 days (Table 7). The results confirmed the initial classification of the productivity of the pastures at both sites.

Table 7. Forage re-growth and litter deposition in putative productive and degraded pastures at two sites in the Brazilian Cerrados. Means of 4 replicate plots per pasture.

Site	Forage re-growth		Litter deposited on soil surface	
	Productive pasture	Degraded pasture	Productive pasture	Degraded pasture
	(g/m^2 DM in 28 days)			
Fazenda Palota, Luz, MG	264** [1]	119	37*	27
Fazenda Riberão, Chapadão do Sul, MS	235ns	206	114**	35

[1] ** P<0.01, * P<0.05, ns P>0.05.

At Fazenda Palota, the area had been used for growing coffee since the 1930s and subsequently for extensive grazing, probably of *Hyparrhenia rufa* and *Melinis minutiflora*. While these grasses (also African introductions) are much less vigorous than *Brachiaria* spp., they are also C_4 and so have high ^{13}C abundance similar to *Brachiaria* spp. The productive pasture (*B. brizantha*) was established in 1995 with tillage and the application of lime and P fertiliser on an area that had been under *B. decumbens* since the 1970s. The area sampled was only lightly grazed and used as a reserve of forage in the dry season. The degraded pasture (*B. decumbens*) was established in an area of *H. rufa* and *M. minutiflora* in 1995, immediately after a crop of limed and fertilised upland rice, but was heavily grazed and at sampling had been heavily invaded by weeds. The soils were sampled in 2003.

The C stocks differed markedly between the vigorous and the degraded pasture, being 164.6 and 138.0 t/ha C (corrected for equal mass of soil to 100 cm depth under the native vegetation, whose C stock was

117.0 t/ha). The distribution of the C derived from the native vegetation and from the *Brachiaria* pastures for the 2 pastures and the native vegetation is shown in Figure 3.

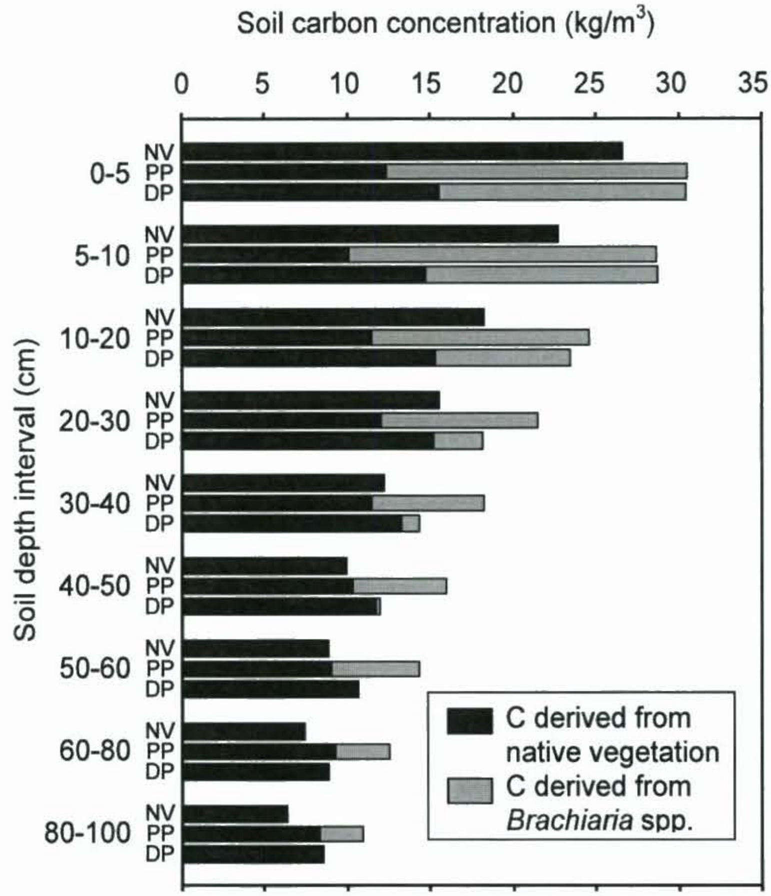

Figure 3. Carbon derived from C_3 native savanna vegetation and from C_4 *Brachiaria* spp. in a stand of cerrado *sensu strictu* vegetation (NV) compared with a productive *B. brizantha* pasture (PP) and a degraded *B. decumbens* pasture (DP). The soil has 80% clay and NV has 117.0 t/ha C to a depth of 1 m. Data are means of 4 replicates. Fazenda Palota, near Luz in Minas Gerias state. Note that the scale of the abscissa is about twice that of Figure 4.

At Fazenda Ribeirão in both pasture areas, the native vegetation was originally cleared at the start of the 1980s and sown to *B. decumbens*. The productive pasture is on an area that was cropped to soybean in 1991-94, and then sown to *B. brizantha*, which is well managed. The degraded pasture was an area, which remained in *B. decumbens* with indifferent management.

The C stocks (0-100 cm) under these 2 pastures were, respectively, 62.6 and 53.1 t/ha C, the latter under the degraded pasture being lower than that under the neighbouring native vegetation (57.1 t/ha C). Distribution of the C derived from the native vegetation and the *Brachiaria* down the profile for the 2 pastures and the native vegetation is shown in Figure 4.

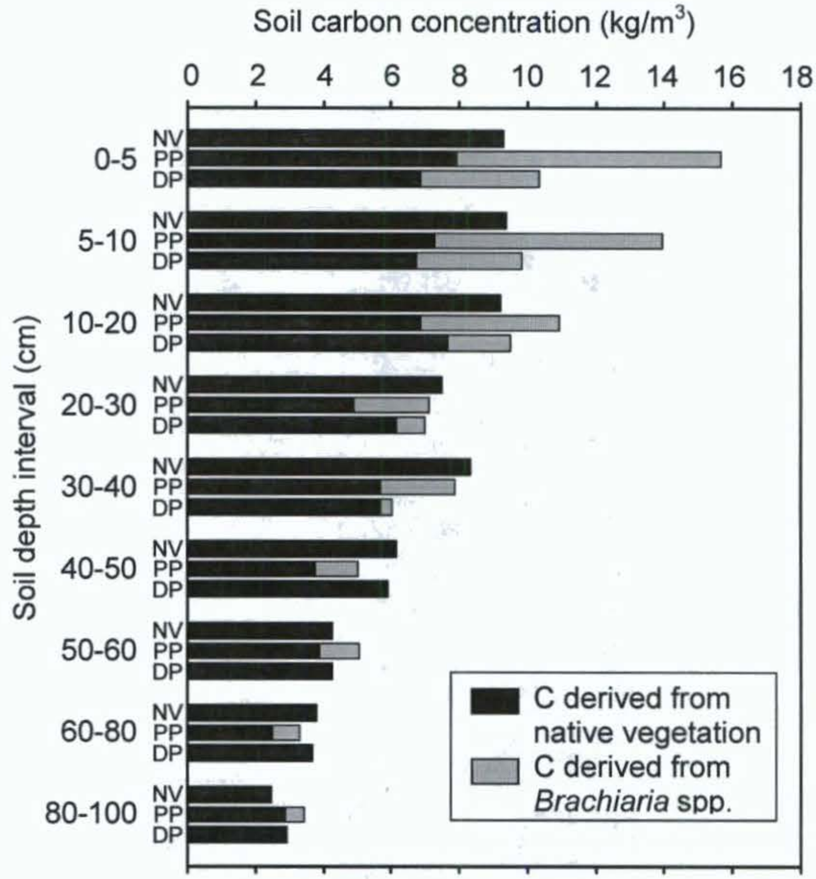

Figure 4. Carbon derived from C_3 native savanna vegetation and from C_4 *Brachiaria* spp. in a stand of cerrado *sensu strictu* vegetation (NV) compared with a productive *B. brizantha* pasture (PP) and a degraded *B. decumbens* pasture (DP). The soil has 18% clay and NV has 57.1 t/ha C to a depth of 1 m. Data are means of 4 replicates. Fazenda Ribeirão, near Chapadão do Sul in Mato Grosso do Sul state. Note that the scale of the abscissa is about half that of Figure 3.

Three tentative conclusions can be made from these preliminary results:

1. Productive, lightly grazed pastures on soils high in clay content can eventually accumulate considerable quantities of soil C, well above the stocks under the cerrado *sensu strictu* vegetation.
2. Under productive pastures, considerable quantities of C can be stored at depth, as deep as 100cm.
3. When pasture productivity falls due to lack of maintenance fertiliser and inappropriately heavy grazing, C derived from the grass is lost and appears to be almost entirely eliminated from depths greater than 40 cm.

Grazing management and pasture degradation

Pasture degradation, which is widespread on the Cerrados, has a profound influence on soil C stocks. Fisher and Thomas (2004) attempted to estimate the total contribution of introduced pastures in the tropical lowlands of tropical South America. They included the Amazon, which is not relevant to this review, so comments will be limited to the Cerrados and the Orinoco basin of Colombia and Venezuela. They used the figure of 0.44 M km^2, recently updated to 0.50 M km^2 (Sano *et al.* 2000), of the treeless grasslands of the central lowlands that have undergone substantial conversion from the native vegetation to pastures, mainly *Brachiaria* spp., in the last 30 yr. By using the extensive descriptions of the land systems of the central lowlands of Cochrane *et al.* (1985), they extrapolated data for C accumulation in the soil under introduced pastures on the eastern plains of Colombia (about 3 t/ha/yr C) to similar soils and topography elsewhere to estimate the probable change in C stocks as a result of conversion to pasture in the grasslands as a whole. They pointed out that losses of above-ground C on conversion of the former treeless grasslands are negligible.

Fisher and Thomas (2004) addressed the issue of pasture degradation, and by using a simple model of a declining ramp function (Figure 5) to calculate mean rate of C accumulation for a number of scenarios, they calculated a "degradation index" (DI). DI is the time-averaged amount of C accumulated in pastures that degrade and are recuperated compared with well managed pastures that do not degrade, expressed as a percentage. They concluded that, if pastures were recuperated soon after they degraded, they probably accumulated as much as 50% of the C of a well managed pasture (DI=50), and that "It requires draconian mismanagement of rapid degradation and long-delayed renovation for the [DI] to fall below 30."

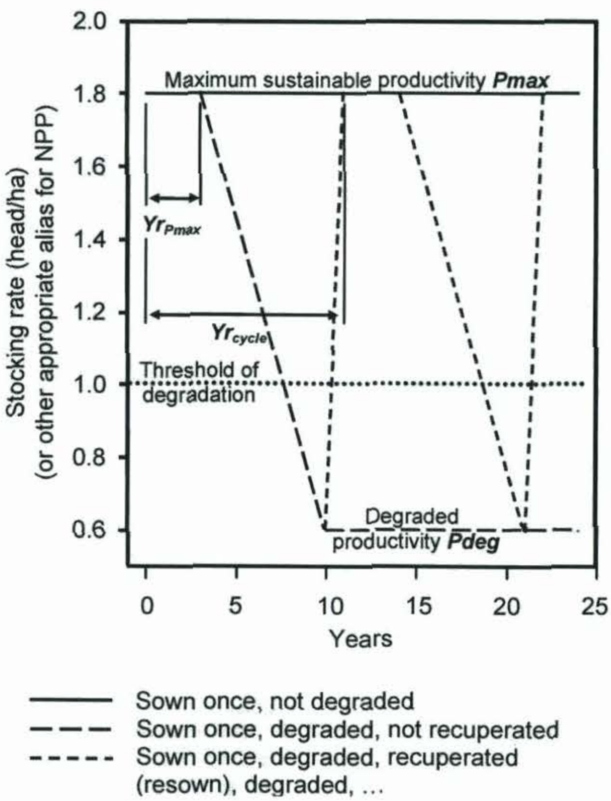

Figure 5. A conceptual model of pasture degradation expressed in terms of stocking rate of beef cattle. The pasture is assumed to remain at its maximum productivity *Pmax* for Yr_{Pmax} years and to decline linearly to a degraded state whose productivity is *Pdeg* at which stage it is recuperated and returns to productivity *Pmax*, which completes the cycle of Yr_{cycle} years. The cycle is then repeated. The time-averaged productivity is the integral of the area under the curve over the period Yr_{cycle}. From Fisher and Thomas (2004).

Fisher and Thomas (2004) estimated the mean time since land conversion started in the tropical lowlands and discounted the calculated C accumulation with a mean DI of 50. They concluded that introduced pastures on the former grasslands have been a net sink for about 900 M t C. Although there were many uncertainties in the study, the authors detailed all assumptions made. With more reliable data, the study can be readily updated.

Although only broadly concerned with soil C, a recent paper by Boddey *et al.* (2004) gives the first definitive understanding of the processes involved in pasture degradation. Since degradation so profoundly affects soil C, it is appropriate to discuss it in some detail here. Boddey *et al.* (2004) studied the effect of increasing stocking rate on the fluxes of nitrogen (N) though the animal (forage consumption, production of faeces and urine) and through the plant pathways of growth and senescence in *B. humidicola* pastures grazed by beef cattle in the Atlantic forest region of the south of Bahia state in Brazil. The experiment was the same one reported in the study of NAPP by Rezende *et al.* (1999).

As stocking rate increased from 2 to 4 head/ha, liveweight gain decreased from 153 to 120 kg/head/yr but overall weight gain per hectare increased from 305 to 360 kg/yr. N exported in the animal weight gain increased only from 7.3 to 8.6 kg/ha. Pathways of N cycling were radically changed by increasing the stocking rate from 2 to 4 head/ha (Figures 6 and 7). Total N consumed by the animals increased from 94 to 158 kg/ha/yr, which resulted in increases in N deposited as urine and dung in the pastures from 50 to 90 and 37 to 59 kg/ha, respectively. N in plant litter deposited on the soil decreased from 170 to 105 kg/ha.

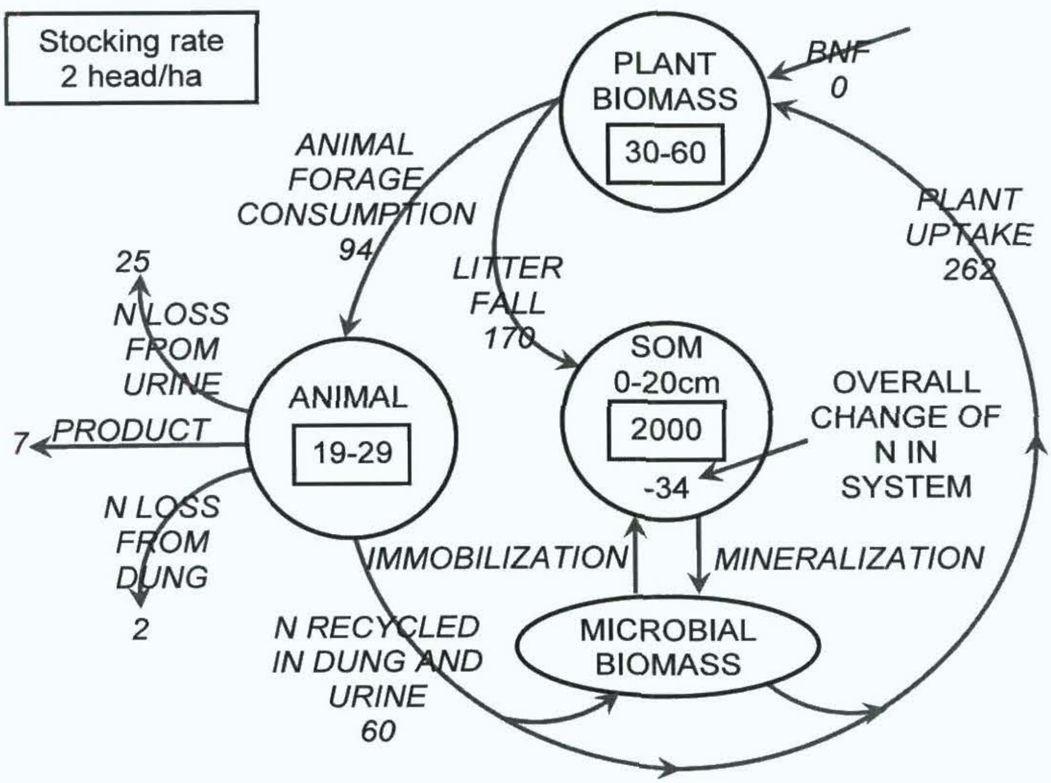

Figure 6. Schematic diagram of the nitrogen cycle in a *B. humidicola* pasture grazed by crossbred Zebu steers at a stocking rate of 2 head/ha. Values in rectangular boxes are pool sizes (kg/ha N) and other values are annual fluxes of N in kg/ha/yr. SOM is soil organic matter. Redrawn from Boddey *et al.* (2004).

A large proportion of the animal excretions was deposited in rest areas and around drinking troughs, where the grass was so trampled that it could not take advantage of the N and other nutrients they contained. Data from complementary studies showed that N losses from urine could be 35 - 80%, being much higher in areas without vegetation. Boddey *et al.* (2004) concluded that pasture decline is hastened by increasing stocking rates because of these losses of N and the decrease in N and other nutrients available for grass growth over the pasture as a whole.

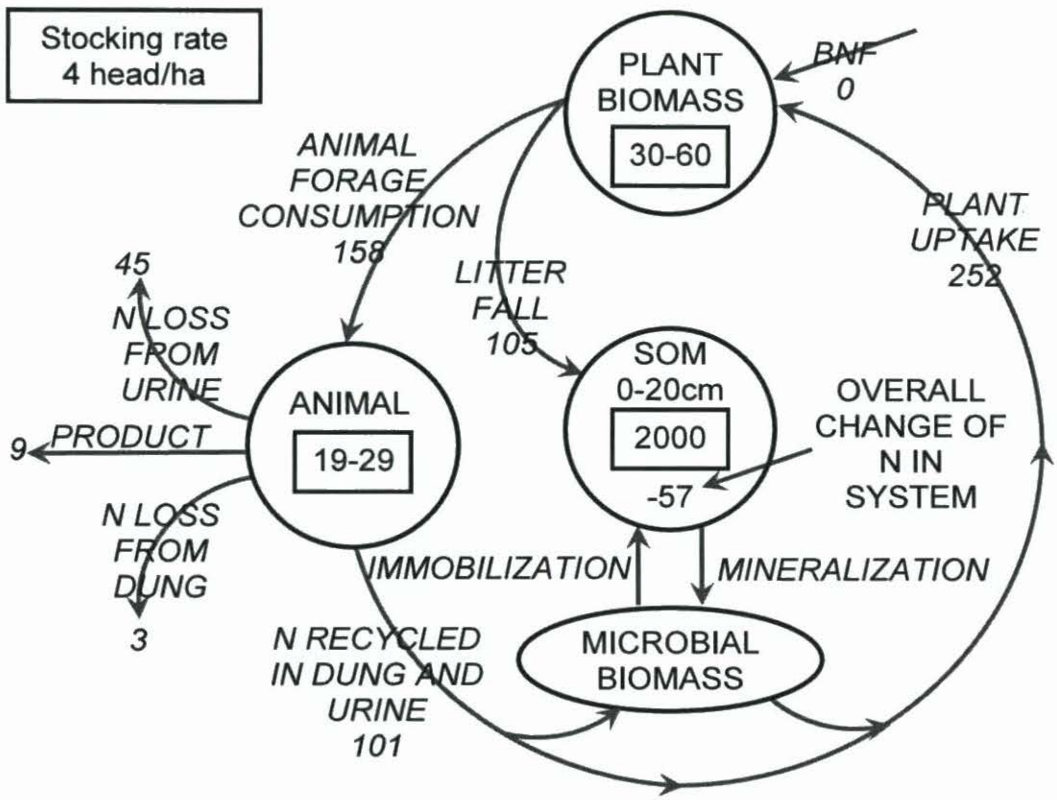

Figure 7. Schematic diagram of the nitrogen cycle in a *B. humidicola* pasture grazed by crossbred Zebu steers at a stocking rate of 4 head/ha. Values in rectangular boxes are pool sizes (kg/ha N) and other values are annual fluxes of N in kg/ha/yr. SOM is soil organic matter. Redrawn from Boddey *et al.* (2004).

Fertiliser management

In small plot experiments referred to above (Oliveira *et al.* 2001), conducted at 3 widely separated sites in the Brazilian Cerrados on degraded pastures of either *B. decumbens* or *B. ruziziensis*, there were no growth responses to P, K or S, alone or in combination, in the absence of N, nor were there more than minor responses to N alone. However, the application of NPK fertiliser with micronutrients gave good recovery, suggesting that pastures may be rejuvenated by the use of chemical fertilisers alone. Moreover, one can conclude that the cause of degradation in the first place is principally nutrient deficiency.

Very little fertiliser is applied to sown pastures in the neo-tropical savannas. In contrast, in mixed agro-pastoral systems, fertiliser is applied to crops, which need higher levels of fertility than do pastures. The pastures can then make use of the residual fertility from the cropping phase (Thomas *et al.* 1995). In this context, it is the crop, not the pasture, that bears the financial and environmental costs. As Fisher *et al.*

(1998) noted, "In agro-pastoral systems, then, the use of fertilizer to increase both agricultural production and C accumulation may be economically viable and a "win-win" option."

Summary and Conclusions

In the 7 years since Fisher *et al.* (1998) reviewed the questions of carbon accumulation by introduced pastures on the acid soils of the grasslands of the central lowlands of tropical South America, a considerable amount of work has been done to overcome the uncertainties and fill the knowledge gaps they identified. We know now that:

1. Litter is a key component of net aerial primary productivity that was previously seriously underestimated;
2. The NAPP of introduced African grasses in the tropical lowlands of South America is much higher than previously thought;
3. NBPP is about three-quarters of NAPP, data that were previously only surmised.
4. Pasture health is a key component of C accumulation in the soil and degraded pastures in general have soil C stocks little different from the native vegetation that they replace.

On the other hand, well managed pastures of *Brachiaria* species almost always have more soil C than native vegetation communities. Soil C accumulation under introduced pastures in Brazil is substantial, but a maximum of half that measured on the eastern plains of Colombia. To date NAPP on the Colombian eastern plains has not been measured, so we can only speculate that climatic differences may be responsible. The eastern plains of Colombia have uniformly high temperatures throughout the year, in contrast with southern Bahia, which has a cool season April to October.

We have gained valuable insights into the reasons for pasture degradation, which is so common in introduced pastures in the central lowlands of tropical South America. It is primarily caused by over-utilisation of the pasture, which fundamentally alters the nitrogen cycle. We conclude that this is not an inevitable process, but with judicious application of fertiliser and prudent grazing management it could be averted.

It seems possible to rejuvenate degraded pastures simply by the application of fertiliser, although at present we do not know how widely useful this may be. However, there may be a requirement to recuperate pastures periodically in some version of the ley-farming practices of temperate systems. These so-called agro-pastoral systems have received attention in the last decade and appear to be as successful on the tropical lowlands as they are elsewhere (Guimarães *et al.* 1999). There are no definitive data of their impact on C accumulation in the soil, but by recuperating a vigorous pasture it should be substantially positive.

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THEME 2:

REALIZING THE POTENTIAL OF SPATIAL AND TEMPORAL VARIABILITY OF PLANT-ENVIRONMENT INTERACTIONS

Systematic agronomic farm management for improved coffee quality

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Introduction

International markets for differentiated agricultural products are growing. As *per capita* income increases, diets can diversify; and the proportion of expenditures for higher-quality food stuffs relative to staples often increases (Coyle *et al.* 1998). Product differentiation occurs when consumers see a product as different from its competitors in terms of perceived or real differences (Dickson and Ginter 1987). Differentiation of agricultural products can be material or intrinsic to the product, symbolic or based on reputation, and based on producer-consumer relationships (Daviron and Ponte 2005). Many attributes can determine product quality, which in itself has much to do with personal preferences. In fact, such preferences give rise to markets for differentiated agricultural products. Wine with its *terroir* concept is the classic case of a differentiated product (Wilson 1999). Olive oil and cheese are similar examples (van de Kop *et al.* 2006). There is also growing interest of international markets in differentiated products from the tropics (Hellin and Higman 2003, Lewin 2004). Coffee is a tropical crop of relatively high value. That value is increasing as consumer demand in developed countries for specialty and higher-quality coffee has grown. Such growth, in turn, has created a need to understand the determinants of quality. Beverage quality in coffee has been defined in terms of fragrance, aroma, flavor, acidity, body, sweetness, and aftertaste. Value relative to these qualities is added to green coffee by intrinsic attributes; and long-term sustainability is achieved through quality management (Kilian *et al.* 2006).

The expression of intrinsic coffee quality attributes results from interactions among environment, genetic make-up of the plant, and management practices. Management practices include pre- and post-harvest processes and roasting. The latter two do not improve intrinsic quality, but conserve it (Fajardo-Peña and Sanz-Uribe, 2003). The impact of environment on quality has been demonstrated in various studies (Avelino *et al.* 2005; Buenaventura-Serrano and Castaño-Castrillón 2002). Methods to identify the impact of specific environmental factors have been developed (Läderach *et al.* 2006). The interaction of genotype with the environment for the expression of product characteristics has also been shown (Cortez 1997, Fajardo-Peña and Sanz-Uribe 2003). Management also determines the expression of product quality (Bertrand *et al.* 2004, Muschler 2001, Vaast *et al.* 2006). Research in precision agriculture on the temporal and spatial dynamics of crop responses suggest that impacts are very location specific and generalizations are practically impossible generalize into blanket reccommendations (Blackmore 2003).

Smallholders do not easily benefit from emerging markets for higher-valued quality products; and their integration into the supply chain has become increasingly difficult (Reardon 2002, 2005). We hypothesize that there is a real opportunity for smallholder coffee growers in favorable growing environments. Smallholders can benefit from emerging markets by capitalizing on the natural resource variability in their production systems and from the knowledge that they have about this variability. They could then systematically employ particular management practices in order to consistently obtain the desired product attributes.

The objective of this paper is to illustrate the process of how systematic targeting of management practices can be implemented by smallholder growers and their supply chain partners using the case of specialty coffee. We first present the conceptual background and then illustrate the process of targeting management practices with case studies using data from Colombia and Mexico. The study looked at some of the environmental, biophysical and management variables that influence coffee quality. We examined the importance on coffee quality of aspect, slope, soils, choice of varieties, fruit thinning, harvest by level on the plant, and harvest care. The paper also briefly discusses the implications of these findings for small-scale coffee producers.

Conceptual Background

The approach is based on cycles of analysis and learning to find better ways of doing business. In this context, the strategy is to identify and establish on-farm agronomic and processing practices and monitor their effects on product quality to enable growers' participation in the supply chains for quality differentiated products. Cook and Bramley (1998) adapted this approach to precision agriculture (PA). The objective of PA is to improve the control of input variables such as fertilizer, seed, chemicals and water with respect to the desired outcomes of increased profitability, reduced environmental risk or better product quality. The practice can be viewed as comprising 4 stages: information acquisition; interpretation; evaluation; and control (Figure 1).

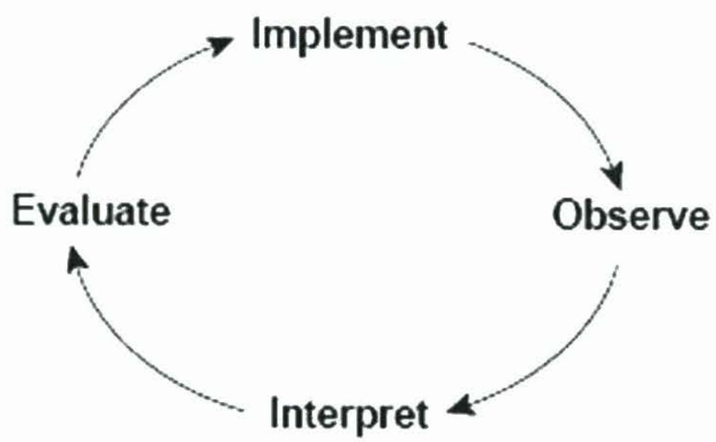

Figure 1. The use of information in repeated cycles of observation, interpretation, evaluation and implementation as developed by Cook and Bramley (1998)

For almost two decades, PA has offered a paradigm shift in agricultural research that has been directed almost exclusively through technology to farmers in the developed world. Cook *et al.* (2003) argue that the fundamental nature of the paradigm shift exists not in the technology but in the change in agricultural decision making enabled by the technology. They described the importance of this paradigm shift for agricultural research in developing countries.

The notion of managing variation is intuitively appealing to growers who are experts in identifying locally variability in their resource base (Oberthür *et al.* 2004). In explicitly recognising spatial variation, the approach of PA differs from conventional reductionist agricultural research. We argue that the likely gains from explicit definition of spatial variation are sufficient to justify greater efforts to apply the principles of PA to the problems of agronomic management for product quality in developing countries. PA enables three fundamental changes that are applicable to a broad range of natural resource management problems:

- Spatial information enables a more systematic approach to management of natural resources (Cook 2001). Spatial insight enables farming to be analysed as a controllable *system*, rather than a disaggregated set of agronomic factors and helps agronomists to adopt a systemic approach to management.

- Spatial information enables analysis of specific, rather than generalized, decisions, taking into account the context in which they are made and their consequences. Assuming, reasonably, that decision-makers do not choose willfully to take damaging decisions, the main source of error is uncertainty about the outcome of decisions in specific instances. Decision theory helps characterize this problem as a choice between two very simple options: action (for example, change fertilizer rate) or inaction (do not change it). The correct decision to act results in a positive outcome. The correct decision *not* to act avoids a negative outcome. These decisions are subject to two errors: failing to act when benefit would have occurred (Type I error) or ill-fated action (Type II error). Both errors can be reduced by information directed specifically to the problem in question.

- Spatial information helps to resolve the specific uncertainty caused by spatial and temporal variation. Acquiring information about this variation is justified *if* the benefit of improved certainty is perceived by decision-makers to be significantly greater than its cost. This can be paraphrased through questions faced by the decision-maker as: 'What are the controllable factors in the system?'; 'What is the nature of uncertainty for specific decisions about these factors?' and 'How much uncertainty can be removed by the use of spatial analysis?'.

While PA has tended to focus on field-scale variables as factors, such as application rates of fertilizer, agrochemicals or seed, the range of controllable factors can include choice of crop, land-use system, application of labor or investment of capital. The scale at which these are varied can expand to meet the scope of specific decisions, and include field-to-field, farm-to-farm, district-to-district or even larger-scale variation. In this paper, we describe the application at the field-to-field scale.

Information reduces uncertainty that causes loss-making decision errors (Lindner 1987). An example of type I error, often seen in agriculture, is the failure to apply adequate fertilizer for a given growing season because of uncertainty that the crop will receive sufficient rainfall. A widespread example of type II error is ill-advisedly reducing the fallow phase of slash-and-burn cultivation, resulting in the long-term decline of soil fertility. In both cases spatial information would improve the decision if it provided actionable insight. In the first example, it could be used to confirm the value of fertilizer for specific instances. In the second it would confirm the where fallow is essential to maintain soil fertility.

The benefit of acquiring information depends on the practical significance that the decision-maker assigns to the uncertainty it removes. This is determined firstly by the variance of the outcome that is caused by the controllable factor. Factors that cause large variation are likely to be controlled before those that cause small variation. To sufficiently value, the information about variance must also be novel, for example, farmers hardly need quantitative information to tell them that upslope areas tend to be drier than downslope areas. To identify the actionable factors for quality Pareto's Principle is relevant. The Pareto Principle implies that causes and effects are not linearly and proportionally related. In other words, a few causes produce the majority of effects, also known as the 20-80 law, that is, 20 percent or fewer causes produce 80 percent of the effects (Bhote 2000). Pareto's Principle thereby facilitates the identification of a few but important controllable factors. For example, Laderach *et al.* (2006) showed that at regional scale only two environmental factors of the eleven analysed factors had important impacts on coffee quality.

In summary, we consider the agricultural system as one with inputs and outputs (Figure 2). The grey box describes the biophysical function of land. Inputs can be either controllable, such as fertiliser, seed or spray, or uncontrollable, such as incident radiation, pests or rainfall. The entire system is subject to noise, which is thought to be non-controllable and ill-defined.

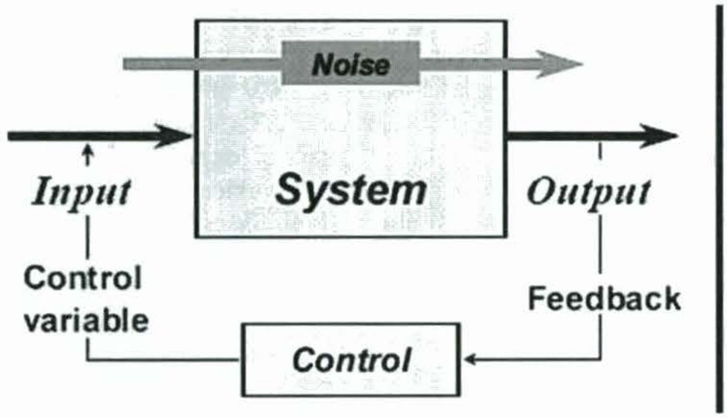

Figure 2. The farming system illustrated as a partially controllable system (Cook and Bramley 1998).

The challenge is to obtain enough knowledge, even if that knowledge is incomplete, about the relationship between inputs and outputs to enable the farmer to vary the controllable inputs in such a way as to maximize beneficial and minimise harmful outputs. In our case of coffee, specific information is required about the relationship between factors of agronomic management and product quality. This information is often not available on farm.

Traditionally growers used PA to increase yields, something that they could easily determine on their own farms (horizontal information flow). In the case of coffee, our producers are unaware of the potential for producing a coffee with particular desirable characteristics that coffee buyers are seeking. Farm products that are differentiated by quality not only require specialized production systems, but also novel strategies for providing information about product quality to the producer. Quality-based product differentiation requires mechanisms to feedback information that includes the targeted markets (vertical information flow).

The new business and trading models that have been developed to handle smaller quantities of differentiated products (compared to, say, wine) are built on information flow of product characteristics and product availability. In these models, constant dialogue and information flow along the supply chain is essential to ensure that the final consumer can purchase a product with the desired specific characteristics. The functionality of the dialogue can also be used by the producer and the purchaser working together to improve the quality of the product. The current revolution in information technology (cheap radio frequency identification , RFID, "smart tags", which can be read remotely) means that many of the well-established principles of modern supply-chain management can now be applied to smallholder agriculture where there are a large number of small production units geared to supplying markets with differentiated high-value products. Interactive information platforms such as Cinfo (Oberthür *et al.* 2006) are now more frequently in place to feed information in vertical supply-chain networks.

Materials and Methods

Site selection and characterization

The philosophy of the approach is that farmers manage only those factors that make good sense environmentally and commercially. This can be one or several factors depending on the particular farm and farmer. We have therefore conducted our studies at commercial farms that provided diverse conditions for the implementation of various managerial scenarios, which differed in their complexity. The farms were included based on the interest of growers and their supply-chain partners to take part in the research.

Specifically, the study examined two estate farms (> 25 ha) and 62 small farms (0.5 – 5.0 ha) in Colombia; and two farms of about 5 ha in Mexico (Figure 3). The estates in Colombia were located one in the municipality of Concordia (longitude -75.89; latitude 6.03; 1870 masl, Department of Antioquia) and one in the municipality of Piendamo (longitude -76.57, latitude 2.75, 1640 masl; department of Cauca). The small farms were located in the municipalities of Inza (33 farms, longitude -75.99 to -76.02, latitude 2.47 to 2.53, 1630 to 1990 masl; department of Cauca). The two Mexican farms were located in the state of Veracruz. One farm was in the community of El Encinal (longitude -96.82, latitude 19.21, 890 masl) in the municipality of Totutla and the other in the community of Auxcuapan (longitude -96.98, latitude 19.20, 1490 masl) in the municipality of Tlaltetela. Departments in Colombia represent the same administrative level as the states in Mexico but communities in Mexico are one administrative level lower than the municipalities in Colombia.

To resemble commercial farm operations as closely as possible, the sampling units in all farms were management units (MUs). MUs are land areas that can be independently managed by the grower during all production stages, including post-harvest processing of batches of beans. Depending on the technical infrastructure, an MU can therefore be a single individual field, a group of fields or a complete small farm. All farms and their MUs were assessed by means of interviews with the growers and general field descriptions.

The two estate farms in Colombia represented intensive, shade-free coffee-production systems. In the Concordia estate slope varies from 0 to 15° and the MUs have a wide range of aspects, which vary their exposure to the sun. Annual precipitation is 2300 mm, mean annual temperature is 19.3°C and the soils are Entisol-inceptisols. In the Piendamo estate the slopes range from 0 to 23°. Annual precipitation is 2200 mm, the annual mean temperature is 19.2°C and the soils are Inceptisols. The small farms in Colombia varied widely in terms of shade levels, slopes, and aspect. Slopes ranged from 3 to 35° and averaged 20°. Annual precipitation ranges from 1580 to 1760 mm; and annual average temperature is about 18°C. The soils are principally Entisols-inceptisols. The Mexican sites have flat topography. In El Encinal, annual precipitation is 1200 mm with an mean annual temperature of 21°C. Soils are Cambiosols. Axocuapan has an annual precipitation of 1800 mm and an annual average temperature of 18°C. The soils are Andosols.

Selection of biophysical variables and management practices

The different biophysical variables and management practices selected are shown in Table 1. The estate farms in Colombia provided the widest choice of management options. The growers identified five different management units in each estate that presented northern, western, southern and eastern aspect. In addition, one plateau MU was selected. In the MUs with different aspects, two sites were chosen on the upper and lower parts of the slope to give contrasting levels of soil fertility; growers contend that the upper slopes are less fertile than the lower slopes.

Table 1. The different biophysical variables and management practices examined at the various case-study sites. Note that not all variables and practices were represented at all sites.

	Biophysical variables and management practices						
	Aspect[1]	Soil fertility[2]	Varieties (#)	Shade	Fruit thinning	Canopy level[3]	Harvests (#)
Concordia	5	2	1	None	50%	3 levels	2
Piendamo	5	2	1	None	50%	3 levels	1
Inza small farms	VNA5[6]	VNA[5]	1	VA[4]	None	Whole tree	VNA[5]
El Encinal	Flat	1	4	VA[4]	None	Whole tree	1
Axcocuapan	Flat	1	2	VA[4]	None	Whole tree	1

[1] Aspect (north, east, south, west and flat; in Concordia northwest instead of north).

[2] Soil fertility level (fertile is lower slope position, infertile is upper slope position).

[3] Number of horizontal strata harvested.

[4] VA = variable analyzed here.

[5] VNA = variable not analyzed here.

In each of the nine identified sites different harvesting strategies were implemented. These practices were selected after consultation with the growers and included harvesting fruits separately from different tree canopy levels (low, middle, high; in Concordia), fruit thinning (in Concordia and Piendamo) and harvest time (Piendamo). The first canopy level included the upper orthotropic nodes and comprised leafy primary plagiotropic branches with few fruit-bearing nodes. The middle region comprised primary plagiotropic branches with a large majority of heavy fruiting nodes but with few leaves. The lower canopy region comprised plagiotropic branches that had already produced the previous years and bore secondary and tertiary branches that had few fruiting nodes. The fruit thinning consisted in removing 50% of the fruits nine weeks after the main flowering from 25 previously-labeled trees. At this time the fruits have initiated the bean filling stage and have reached about 10% of their final size (Arcila-Pulgarín *et al.* 2002). The harvest in Piendamo was divided into an early harvest on 12 May and in a late harvest on 9 June. Other management practices were implemented by the growers using their usual standards. Managing so many different factors was impossible in the small Colombian farms. Farm owners identified one MU in each small farm for the inclusion in this study. Shade levels were defined in each of these management units. The other agronomic management practices were very similar in all small farms. In Mexico aspect, variety and shade levels were determined for eight management units in El Encinal and four management units in Axocuapan. The other agronomic management practices followed local commercial standards but were similar in all Mexican MUs.

Harvest and processing

Twelve kg of ripe berries were harvested by hand during the peak of the 2006 harvest. The maturation index of Marín *et al.* (2003) was used as guidance. In the estate farms, berries from 50 trees for each management practice and each biophysical variable were harvested by estate workers. For comparison, berries also were harvested from 25 control trees for each different bio-physical variable that were not subjected to fruit thinning and harvest at various canopy levels. Samples in the small farms in Colombia were harvested by the farmers from trees in a previously delimitated 30 m x 30 m area within the identified MU. Before processing, damaged, green and infected berries as well as stones, leaves and other artefacts were removed.

Immediately after harvest, samples from both the estates and the small farms were delivered to a mobile, truck-mounted processing unit. In the unit the berries were de-pulped and the mucilage removed using a J.M. Estrada Model 100 unit. The beans were subsequently fermented in 10 l buckets using only the water attached to the grains. The samples were then dried using the integrated dryer of the processing unit. The dryer consists of a metal closet with four shelves each containing four individual drawers, which are perforated on the bottom. The dryer thus has the capacity to process 24 samples of 1-1.5 kg at the same time. Air, heated to 45°C by a gas burner, is blown into the bottom of the closet and ascends through the closet drying the beans. The most recent samples are placed in the top drawers and moved down to the next lower level when new samples are added, thereby emulating the process of industrial dryers. Samples are dried until the parchment beans reach a humidity of 10% to 12 %, which occurs normally after 14 to 16 hours.

The samples were then placed in sealable plastic bags and stored at 18° C until the cupping process. Samples from Mexico were harvested during the peak of the 2005/06 harvest. The samples were processed the same day according to the wet local method which included de-pulping, fermentation, washing, and drying in a standardized manual manner. The slightly different procedures used in Mexico and Colombia did not present a problem in the data analyses because there is no direct comparison of Mexican and Colombian samples. There is also no direct comparison of the results from the assessments of samples from the Colombian estates and small farms.

Physical assessment ad beverage quality evaluation

The parchment beans were milled and the percentage and weight of bean and husks determined. The density of the beans was calculated after humidity was measured. Thereafter beans with primary and secondary defects were quantified, and their weight and percentage recorded. Any beans with defects were then removed by hand. The defect-free beans were sieved and the bean size distribution determined using standard sieves from 14/64 inch to 18/64 inch. Physical assessment data were recorded but not used in the analyses presented here.

The objective of this study was to understand the impact of selected biophysical field variables and management practices on the beverage quality. All the Colombian samples 250 g of beans were roasted in a laboratory roaster the day before the beverage assessment. All samples were roasted for about 11 minutes with an initial temperature of 200 °C to a standard reddish-yellow color. Exact roasting time was recorded. Roasted beans were ground to the recommended intermediate particle size immediately before the beverage quality assessment using a precision grinder. Sensory beverage quality assessment was done by cupping of the coffee liquid prepared for each sample: water (150 ml at 97 °C) was poured on 10 g of ground coffee in each of five cups. This produces coffee with a range of 1.1% to 1.3% soluble solids. The five cups were treated as replicates for the sensory beverage quality assessment.

The sensory attributes evaluated were fragrance, aroma, acidity, aftertaste, body, flavour, sweetness, preference and final score. Fragrance is the sensation of gases released from ground coffee. Aroma is the sensation of gases released from brewed coffee. Fragrance and aroma were assigned one value. Acidity is a measure of the intensity of acidic sensation. Aftertaste is the taste that remains in the mouth after having tasted the brewed coffee. Body is the oral feeling of viscosity. Flavour is the taste perception of the coffee beverage on the tongue. Sweetness is the detection of soluble sugars on the tongue tip. Preference represents the overall impression of the coffee by the cupper. Final Score is the sum of the attributes evaluated plus three times their average. The attributes were rated on a scale of 1 to 10 with 0.5 point increments, using the cupping protocol of the Specialty Coffee Association of America (SCAA, Lingle 2001). A score of one implies many defects, two some defects, three implies a very deficient coffee, four a deficient beverage, five is a standard coffee, six is a good coffee, seven very good, eight refers to an excellent coffee, and nine to exceptional quality.

The estate samples were cupped by one cupper of high international reputation. The samples from the small farms were assessed by a national panel of several cuppers of which only the results of the most consistent cupper were included in the analyses. Cupper consistency was assessed using statistical discriminant function analyses (Hair 1992). The national panel assigned on average lower values than the international cupper so that the results could not be analyzed jointly with the estate samples. The Mexico samples were assessed by a panel of seven cuppers in the cupping laboratory of Café-Veracruz, A.C also according to SCAA standards. As suggested by the official Mexican norm only the attributes fragrance, aroma, aftertaste, acidity and body were assessed. Mexican cuppers used a scale that ranges from 0-15, 0-5 being low quality, 5-9 medium quality and >9 high quality. The different scales used did not present a problem in the statistical analyses because there is no direct comparison of Mexican and Colombian samples.

Acquisition of environmental information and statistical analyses

Geographic location was determined using a Trimble Pro-XR global positioning system (GPS) with Omni-STAR real-time correction. Aspect in degrees (°) was measured with a compass. Hemispherical imagery to describe shade levels was taken with a NIKON Cool-Pix E4500v1.3 digital camera using a fish-eye lens with a field of view of 180°. The imagery was then processed using Win-SCANOPY (Regent Instruments 2005) software to derive illumination parameters. First the pixels of the imagery were classified in canopy and sky, the output of this process is a black and white image. The second step is the analyses of the canopy which comprises the analyses of the canopy structure and the radiation analyses. The canopy structure variable derived for the present analyses was the gap fraction. Gap fraction is the number of pixels classified as sky region divided by total number of pixels. The shade percentage is simply the numerical complement (100% - gap fraction).

In the radiation analyses the average direct and diffuse photosynthetically active radiation (PAR) over (PPFDO) and under (PPFDU) the shade tree canopy were estimated in MJ m^{-2} d^{-1}. PAR radiation is assumed to be constant over time and is a percentage of solar energy flux. This value is 0.51 J/m^2s. Atmospheric attenuation is inversely proportional to atmospheric transmittance at zenith and relative path length to the zenith. As common in meteorological studies incident radiation was cosine corrected to account for the radiation angle of incidence with respect to the receiving surface. The preceding formulae are used by WinSCANOPY to compute direct radiation above the canopy for the selected sun track, which is created automatically by WinSCANOPY for a specified period of time. These calculations are a function of latitude and longitude, and the defined growing season and time zone.

PAR under the canopy was calculated the following manner: For all sun positions on a sun track the instantaneous radiation value below canopy varies between zero and the direct radiation value above canopy in function of the pixels value in the image under the sun tracks at the moment. When the pixel is classified as sky it is assumed that all radiation is intercepted so the value below is zero. When the pixel is classified as sky, it is assumed that all radiations above canopy passes unimpeded so it is equal to the radiation level above canopy. These parameters include the average direct and diffuse photosyntetically active flux density over (PPFDO) and under (PPFDU) the shade tree canopy measured in MJ m^{-2} d^{-1}.

All field measurements, product quality assessment data and other information related to management practices were entered into Cinfo (Oberthür 2006). CINFO is an interactive, online spatial data-management system for supply chains of higher-value agricultural products. Data were exported for statistical analyses in spreadsheet format and summary statistics were computed. These, the ANOVA analyses and the Duncan tests were done using the S+ package (Insightful 2001).

Information of sensorial beverage quality are on a quasi-interval scale (1 to 10 with increments of 0.5 giving 20 available points), which is analogous to a Likert scale. These data are usually analyzed using interval procedures in parametric statistical methods (e.g. Decazy *et al.* 2003; Avelino *et al.* 2005; Vaast *et al.* 2006). In a review of the literature, Jaccard and Wan (1996) concluded, "for many statistical tests, rather severe departures (from intervalness) do not seem to affect Type I and Type II errors dramatically." They suggest, provided the scale has at least five, and preferably seven categories, the assumption of normal distribution can be assumed to be valid.

Results

Summary for all sites

Table 2 summarizes the results of the coffee beverage sensory analyses.

Table 2. Descriptive statistics for all sites including the two Colombian estates (Concordia, Piendamo), the small farms of Inza in Colombia and the two Mexican farms (El Encinal, Axocuapan). Samples for all biophysical variables and management practices are included in the analyses.

		Aroma fragrance	Acidity	After-taste	Body	Flavor	Sweet-ness	Prefer-ence	Final score
Piendamo n=139	Minimum	4.00	5.00	3.75	7.00	4.00	6.00	4.00	59.8
	1st quartile	7.00	7.00	6.50	7.50	6.75	7.25	6.75	74.4
	Mean	7.53	7.60	7.04	7.90	7.33	7.83	7.08	78.1
	Median	7.75	7.75	7.00	8.00	7.50	8.00	7.25	80.0
	3rd Quartile	8.00	8.00	8.00	8.00	8.25	8.25	8.00	84.3
	Maximum	9.00	9.25	9.50	9.00	9.25	10.00	9.75	91.5
	Std devn.	0.91	0.81	1.24	0.46	1.13	0.71	1.43	7.56
Concordia n=76	Minimum	5.00	6.25	5.00	6.00	6.00	5.00	6.00	63.5
	1st quartile	7.25	7.50	7.00	7.75	7.00	7.50	7.00	79.0
	Mean	7.64	7.82	7.43	7.99	7.85	8.13	7.83	82.3
	Median	7.75	8.00	7.25	8.00	8.00	8.00	8.00	81.9
	3rd Quartile	8.00	8.25	8.25	8.50	8.50	8.75	8.00	85.1
	Maximum	9.00	9.25	10.00	9.00	10.00	10.00	10.00	92.0
	Std devn.	0.72	0.64	0.98	0.58	0.86	0.92	0.94	5.03
Inza n=33	Minimum	2.00	3.00	4.00	3.00	4.00	2.00	3.00	39.0
	1st quartile	5.00	5.00	5.00	5.00	5.00	2.50	5.00	49.0
	Mean	6.05	5.78	5.77	5.56	5.77	2.83	5.37	54.6
	Median	6.00	6.00	5.00	5.50	5.00	3.00	5.50	54.0
	3rd Quartile	7.00	6.00	7.00	6.00	7.00	3.00	6.00	58.0
	Maximum	8.00	8.00	8.00	9.00	8.00	5.00	8.00	77.0
	Std devn.	1.43	1.19	1.11	1.29	1.05	0.70	0.98	8.58
El Encinal n=97	Minimum	8.50	6.10	na[1]	4.80	na	na	na	na
	1st quartile	9.20	7.50	na	5.80	na	na	na	na
	Mean	9.73	8.27	na	6.00	na	na	na	na
	Median	9.70	8.30	na	6.05	na	na	na	na
	3rd Quartile	10.20	8.80	na	6.30	na	na	na	na
	Maximum	11.40	10.40	na	7.20	na	na	na	na
	Std devn.	0.58	0.89	na	0.42	na	na	na	na
Axocuapan n=48	Minimum	8.20	6.70	na	4.70	na	na	na	na
	1st quartile	9.10	8.00	na	5.87	na	na	na	na
	Mean	9.52	8.81	na	6.07	na	na	na	na
	Median	9.50	8.80	na	6.10	na	na	na	na
	3rd Quartile	9.90	9.42	na	6.50	na	na	na	na
	Maximum	11.10	11.40	na	7.00	na	na	na	na
	Std devn.	0.58	1.09	na	0.50	na	na	na	na

[1] na = not available

The two Colombian estates have average values between seven and eight for the sensory characteristics. Concordia tends to have higher values and also results that are less variable as indicated by the smaller ranges and lower standard deviation of the data. Concordia reaches an average final score of more than 80 points, which is remarkable. The highest final scores for the both estates were more than 90 points. The Inza farms had relatively low values between three and six for the sensory characteristics which was expected due to the different quality preferences of the panel. The results indicate highly variable product quality coming from the 33 farms. The results from the two Mexican farms indicate that the quality of the coffee is very similar in both farms, although results from Axocuapan tend to be slightly more variable.

Biophysical variables

On the Concordia estate the best quality coffee comes from south-facing slopes with a final score of 83.9. Berries harvested from the plateau also achieve very good results with a final score of 83.4. The east-facing slopes have generally the lowest values albeit with a still acceptable final score of 80.8 (Table 3). The situation presents itself very different in the Piendamo estate where east-facing slopes score second best after the plateau site. South facing slopes perform badly compared to all other aspects and achieve only a final score of 72.8. This represents an astounding difference of almost eight points between the best and the least performing site.

Table 3. Effects of aspect and position in the slope on coffee beverage quality on samples from the Concordia and Piendamo estates based on one-way ANOVA and t-test. Data for the same attribute followed by the same letter are not significantly different according to Duncan's multiple range test ($P<0.05$, aspect) and t-test ($P<0.05$, slope position).

Aspect	Aroma fragrance	Acidity	After-taste	Body	Flavor	Sweet-ness	Prefer-ence	Final score
			Aspect Concordia estate ANOVA					
North	7.83 a	7.81 a	7.10 b	7.94 a	7.81 ab	8.16 a	7.75 a	82.1 a
East	7.57 a	7.62 a	7.27 ab	7.57 a	7.45 b	7.81 a	7.60 a	80.8 a
South	7.42 a	7.94 a	7.93 a	7.94 a	8.25 a	8.40 a	8.18 a	83.9 a
West	7.79 a	7.29 a	7.22 ab	8.08 a	7.91 ab	8.25 a	7.88 a	82.0 a
Flat	7.67 a	8.12 a	7.67 ab	7.92 a	7.97 ab	8.05 a	7.70 a	83.4 a
			Aspect Piendamo estate ANOVA					
Northwest	7.28 b	7.73 a	7.31 a	7.86 a	7.55 a	7.75 a	7.30 a	79.8 a
East	7.50 ab	7.78 a	7.66 a	7.93 a	7.66 a	8.12 a	7.47 a	80.6 a
South	7.15 b	6.89 b	6.00 b	7.54 a	6.45 b	6.99 b	6.33 b	72.8 b
West	7.57 ab	7.41 ab	6.88 a	7.83 a	7.37 a	7.62 ab	7.30 a	78.0 ab
Flat	7.54 ab	7.88 a	7.36 a	7.98 a	7.69 a	8.05 a	7.41 a	80.7 a
			Slope position Concordia estate t-test					
High	7.63 a	7.70 a	7.52 a	7.90 a	7.79 a	8.22 a	7.85 a	82.4 a
Low	7.63 a	7.62 a	7.28 a	7.86 a	7.86 a	8.07 a	7.84 a	81.8 a
			Slope position Piendamo estate t-test					
High	7.45 a	7.69 a	7.09 a	7.50 b	7.41 a	7.83 a	7.22 a	79.7 a
Low	7.31 b	7.26 a	6.93 a	8.07 a	7.18 a	7.45 a	7.05 a	76.3 a

As we noted above, farmers believe that the lower slope positions are more fertile than the upper slopes. Coffe quality was indeed influenced by slope position with the higher slope positions generally performing better in coffee-quality characteristics. Once more the differences were greater on the Piendamo estate than on the Concordia estate; with a difference of three points' in the final score compared to less than one point. In Concordia only flavour appears to be better in coffee harvested in the lower positions. In Piendamo only body is perceived better than berries are harvested in lower positions on the slope. It is not clear how fertility differences could bring about these differences.

It is noteworthy that aspect and some slope values in the Piendamo estate were considerably greater than for Concordia estate, or, put another way, slope and aspect are important at Piendamo in Cauca but are only slight consequence at Concordia in Antioquia. It is not clear why this should be as the altitudes and rainfall differ only slightly and coffee is grown without shade on both estates. Clearly the interactions between aspect and quality are more subtle than might be expected.

Variety choice

Quality characteristics differed between varieties in the two Mexican sites. In El Encinal the Red Caturra variety had highest values for fragrance/aroma and acidity, followed by Mundo Nuvo for both characteristics. Only when body is considered do Typica and Yellow Caturra achieve higher values (Table 4). In Axocuapan Typica performs best for fragrance/aroma and for body, and Red Caturra gives the highest values for acidity.

Table 4. Effect of variety on beverage quality at the El Encinal and Axocuapan farms in Mexico, based on one-way ANOVA (El Encinal) and t-test (Axouapan). Data for the same attribute followed by the same letter are not significantly different (P<0.05 t-test or Duncan's multiple range test for ANOVA).

Variety	Aroma fragrance	Acidity	After-taste	Body	Flavor	Sweet-ness	Prefer-ence	Final score
			Varieties El Encinal ANOVA					
Typica	9.45 a	8.03 a	na	6.1 a	na	na	na	na
Red Caturra	10.17 b	9.02 b	na	5.9 a	na	na	na	na
Mundo Novo	9.78 ab	8.22 a	na	5.9 a	na	na	na	na
Yellow Caturra	9.57 a	7.80 a	na	6.0 a	na	na	na	na
			Varieties Axocuapan t-test					
Typica	9.81 b	8.70 a	na	6.2 b	na	na	na	na
Red Caturra	9.22 a	8.95 a	na	5.8 a	na	na	na	na

Shade management

To understand the impact of different shade management on coffee-quality characteristics, sites were grouped into two classes, one with relatively high-shade coverage and one with relatively low-shade coverage. At Inza, the mean shade level of the 17 sites in the low-shade class was 37%. The fifteen sites with denser shade averaged of 61 % (Table 5). Shade coverage ranged from 26.% to 49. % and from 52% to 79% in the low- and high- shade classes respectively (data not presented in tabular format). The coffees brewed from berries that were harvested under denser shade generally scored higher than coffees derived from berries grown under lower shade levels. These differences are consistent for all quality characteristics, except sweetness, albeit only statistically significant for body. The individual characteristics result in final scores of 53.2 for lower shade density and 56.3 for the higher shade class, a difference of a little over three points.

Table 5. Effect of shade level on beverage quality using samples from in Inza, El Encinal and Axocuapan. Data for the same attribute followed by the same letter are not significantly

Shade descriptor (%)	Aroma fragrance	Acidity	After-taste	Body	Flavor	Sweet-ness	Prefer-ence	Final score
				Inza, t-test				
37	5.89 a	5.55 a	5.50 a	5.13 b	5.41 a	2.97 a	5.18 a	53.2 a
61	6.18 a	6.06 a	6.07 a	6.06 a	6.21 a	2.67 a	5.21 a	56.3 a
				El Encinal, t-test				
68	9.79 a	8.36 a	na	6.1 a	na	na	na	na
87	9.68 a	8.19 a	na	5.9 b	na	na	na	na
				Axocuapan, t-test				
68	9.68 a	8.96 a	na	6.2 a	na	na	na	na
87	9.39 a	8.96 a	na	5.9 b	na	na	na	na

Consistent differences were also found in Mexico. Shade coverage on average was much higher in Mexico. In both communities the lower density shade group had an average of 68.2% coverage and the more densely shaded areas had an average of 87%. Contrary to the results from the Inza farms in Colombia beverages prepared from berries harvested under less shade performed better in Mexico than their dense-shade counterparts. Differences are however not statistically significant at the $P<0.05$ level.

Average direct and diffuse photosyntetically active flux density measured under the shade canopy (PPFDU) during the growing season was 9.10 MJ m^{-2} d^{-1} in Inza. A correlation analyses illustrated that PPFDU was negatively correlated with all quality attributes except for fragrance/aroma. The correlation coefficients for aroma/fragrance, acidity, aftertaste, body, flavor, sweetness, preference and the final score were 0.05, -0.25, -0.44, -0.47, -0.44, 0.12, -0.32 and -0.18 respectively.

Harvest management

Three different harvest management practices were considered in the two estates in Colombia including manual fruit thinning, different harvest date and harvest from different coffee tree canopy levels (Table 6).

Table 6. Effect of fruit thinning (samples from estates in Concordia and Piendamo), harvest time (samples from Piendamo estate) and harvest in different canopy levels (samples from Concordia estate) on beverage quality. Data for the same attribute followed by the same letter are not significantly different (P<0.05 t-test or Duncan multiple range test for the ANOVA analyses).

Treatment	Aroma fragrance	Acidity	After-taste	Body	Flavor	Sweet-ness	Prefer-ence	Final score
Fruit thinning (%) at Concordia estate, t-test								
0	7.76 a	7.94 a	7.91 a	8.06 a	8.20 a	8.50 a	8.50 a	84.8 a
50	7.72 a	7.71 a	7.33 b	7.33 a	7.72 a	8.15 a	8.12 a	81.8 b
Fruit thinning (%) at Piendamo estate, t-test								
0	7.32 b	7.37 b	6.99 a	7.75 a	7.25 a	7.68 a	7.15 a	77.8 a
50	7.62 a	7.71 a	7.14 a	7.89 a	7.52 a	7.70 a	7.27 a	79.2 a
Harvest time at Piendamo estate, t-test								
May 12	7.47 a	7.72 a	7.27 a	7.86 a	7.53 a	7.25 a	7.89 a	79.89 a
June 09	7.83 a	7.51 b	6.88 b	7.83 a	7.17 b	6.95 a	7.69 b	77.5 b
Canopy level harvest at Concordia estate, ANOVA								
Low	7.29 a	7.81 a	7.72 a	7.97 a	7.89 a	7.83 a	8.31 a	82.8 a
Medium	7.67 a	7.96 a	7.14 a	8.05 a	8.01 a	7.57 a	7.96 a	81.7 a
High	7.65 a	7.21 a	7.07 a	8.10 a	7.48 a	7.75 a	7.73 a	80.47 a

Fruit thinning by 50% resulted in consistently higher values for all quality characteristics in the Piendamo estate, giving final scores of 79.18 points for coffee from trees where the fruit load was reduced compared to 77.79 points from trees with full fruit load. In the Concordia estate differences were also found but the better-scoring coffees were from berries harvested from trees that had no manual fruit thinning. The final scores in Concordia for the reduced and full fruit load were 81.79 and 84.75 points respectively, a difference of three points.

Early harvest (May 12) was generally more favorable than late harvest (June 09) for the coffee-quality characteristics apart from aroma/fragrance. Final scores for early and late harvested coffees were 79.79 points and 77.52 pints respectively, a difference of a little over two points.

Harvesting from different canopy levels in the Concordia estate also produced differences in beverage quality. Berries from the lower levels had the highest final score for the beverage. However the differences were not consistent with different coffee-quality characteristics giving the highest scores for different canopy harvest levels. For example, body was best in coffees brewed from berries that were harvested in the higher-level canopy but acidity and flavor were best from coffees brewed using berries from the middle-level canopy.

Discussion

Is systematic management viable?

The case studies show that targeting biophysical characteristics in coffee farms for separate management and the appropriate choice of agricultural practices can have impact on the attributes of coffee beverage quality. These differences are not consistent across sites and they are not always statistically significant.

The impacts of the same biophysical variable and / or management practice can be negative at one site and positive in another site. The site specific nature of the impacts is obvious.

While it provides helpful guidance, formal statistical tests of the significance of measured differences mean relatively little to growers in a commercial production situation. The information provided by growers' on-farm experimentation with biophysical variables and management practices has to be evaluated as to whether it generates commercial benefits. The cost-benefit ratio of generated information and the gains realized from decisions based on that information is the key yardstick for growers. In discussions with growers, the management implications were assessed in terms of resources (labor, yield, and quality evaluation), ease of implementation (knowledge and logistics), the potential for improvement of the beverage quality and the value added from the intervention (Table 7).

Table 7. Evaluation of management interventions by their statistical significance, ease of implementation, likely improvement of quality, resource intensiveness, and added

Management	Satistical signigicance	Ease of implementation	Improvement of quality	Rsource intensiveness	Added value[1]
Aspect	Medium	Easy	High	Low	High
Variety	Medium	Medium	Low - medium	High	Low – medium
Soils	Low	Medium	Low	Medium	Low
Shade management	High	Easy	Medium	Medium	Medium
Fruit thinning	Medium	Difficult	Low-medium	High	Low - medium
Harvest time	High	Easy	Medium	Low	High
Harvest by levels	Medium	Easy	Medium	Low	Low

[1] Benefit – cost.

Aspect often has a statistically significant and consistent impact on beverage quality: in Concordia south-facing aspects scored the highest or second highest and in Piendamo south-facing aspects scores the lowest while east-facing aspects and flat sites scored the highest for the majority of quality attributes. The investment of harvesting the sites separately has only minor logistical implications and does not add much to the cost of the production process. The quality differences are remarkable taking into account the sites with varying aspect were only a few hundred meters apart. Trees in upper slope positions score slightly higher than trees on lower position on the same slope. The differences are not substantial in the data presented here.

Varieties have significant impacts on quality characteristics as shown at the sites in El Encinal and in Axocuapan. However, the change of varieties in a farm is resource-demanding and is likely not to be recommendable in many cases. Obviously this is an option when farm renovation is being considered anyway. When a certain variety is identified that performs substantially better under specific environmental and management conditions there may reason for change. For example, the variety Geisha that traditionally is not being grown in Panama has been planted recently by a few growers. Intelligentsia Coffee Roasters Chicago sells a half-pound of roasted Panama Hacienda La Esmeralda Geisha (a repeated competition winner) beans for US$52, an outstanding premium.

Shade management has been shown to have substantial impacts on quality on both the Colombian and the Mexican sites. Shade is an easy and cheap farm management practice and a viable practice not only for the improvement of coffee beverage quality but shade trees can also provide an additional source of income. Fruit thinning had a favorable influence on coffee beverage quality in the estate of Piendamo, but fruit thinning is not easy to implement and is labor intensive.

For the interpretation of the results, 80 points are usually considered the entry ticket to specialty coffees and coffees with more than 85 points can generate substantial premiums for growers. For example, during the 2006 Cup of Excellence® competition in Colombia[2] the winning 23 farms had final scores ranging from 84.33 to 91.48 points. In the subsequent online auction Maruyama Coffee for the Mikatajuku group, Stumptown Coffee Roasters and Intelligentsia Coffee Roasters Chicago bid US$12.05 per pound to secure the winning lot. Prices ranged from US$3.05 to US$12.05 respectively for a pound of these green coffees. For comparison. during 2006 the average price at the New York Board of Trade (NYBOT) for mild Colombian coffees was US$1.18 per pound of green coffee.

The Colombian estate coffees in this study were assessed by Mr Geoff Watts of Intelligentsia Coffee Roasters Chicago. Watts is one of the leading international cuppers and specialty green coffee buyers. Intelligentsia uses their triple AAA pricing scheme where high quality coffees are rewarded AAA, intermediate specialty coffees AA and entry level specialty coffees A. The price premiums are US$1.35 for a pound of an A coffee with 80 to 84 points final score, US$1.55 per pound for an AA coffee with 85 to 87 points, and at least US$1.85 per pound for an AAA coffee with a final score around 88 to 93 points. For boutique coffees of highest quality Intelligentsia very often pays more than US$3 per pound of green coffee. An additional 35-40 cents per pound have to be added to Intelligentsia farm gate prices to obtain the FOB price.

If this scheme is applied, for example, to the results of the different aspects in the estate farms then this biophysical variable becomes commercially very interesting for separate management of fields with aspects that are likely to produce high-quality berries. The difference in the final score between the highest and lowest scoring aspect is 2.66 in the Concordia estate and 7.87 in the Piendamo estate. In Concordia the highest scores qualify as an AA premium. In Piendamo coffees from the south, east and northwest aspects can be sold as conventionally traded coffees at NYBOT prices while the eastern aspect coffees and the plateau coffees would qualify for an A premium.

Reducing the fruit load obviously reduces the yield level of coffee trees. Vaast *et al.* (2006) estimated for 50% reduction of flower buds an actual yield decrease of 25%. The best-performing sites reached an average green bean yield of 4.1 pounds per tree when flowering buds were reduced by 50%. The grower could therefore expect about US$4.84 per tree if sold to the NYBOT. Considering an additional labor cost of 20 cents this translates into an actual loss of US$1.85 per tree when compared to the income of US$6.49 per tree without manual thinning. Sold at Intelligentsia with an A premium, the tree would generate US$5.34, with an AA premium US$6.16 and with an AAA premium US$7.39 income for the grower. In the rare occasion that a boutique coffee would be produced due to the thinning of flowering buds, the grower could expect a return of US$12.10 per tree. Positive effects from fruit thinning were also shown in Costa Rica, where reduced fruit load significantly improved preference and acidity score. Bitterness and astringency decreased with decreasing fruit load (Vaast *et al.* 2006). Fruit thinning allows a plant to concentrate energy in fewer fruits and permits an increased accumulation of carbon, sugar, acids and other components. The effect of fruit thinning is also shown for kiwifruit (Smith *et al.* 1992), apples (Palmer *et al.* 1997), and peaches (Corelli-Grappadelli and Coston 1991, Souty *et al.* 1999).

Different harvest times also generate large quality differences, as we showed here. Managing separately batches harvested at different times presents no logistical problems. Harvesting from different canopy levels may also be possible, although it requires very thorough briefing of the pickers and probably strict supervisory control during the harvest.

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[2] www.cupofexcellence.org/CountryPrograms/Colombia/2006Program/FirstHarvest/WinningFarms/tabid/234/Default.aspx

Can information for systematic targeting be delivered?

One of key problems in precision agriculture is not information acquisition but its interpretation and the feed-back mechanisms that deliver the information in a usable form to growers (Cook and Bramley 1998). The dynamics and complexity of food systems and their supply chains require the use of new technologies to realize the opportunity to differentiate products based on their quality. This means that along the supply chain information must be shared vertically in both directions.

Several recent developments in low-cost RFID technology systems make it possible to track and trace agricultural products (grain, fruit and meat) from farm to fork (Information Society and Media DG 2005, Society and Media DG 2004, The Board of Trustees of the University of Illinois 2004, IDTechEx 2005). GeoTraceAgri is a user-friendly system that allows interested people to track the origin of products on the Internet. GeoTraceAgri, tracks and traces European agricultural products at all stages of production processing, storage, and distribution. They use a variety of different platforms, languages, databases, mapping engines and spatial processing libraries. The data can be geo-referenced and visualized on the Internet using geo-portals such as Google Earth (Information Society Technologies 2005).

Until recently, small- and medium-sized companies and producers in rural areas have remained outside the advanced, integrated supply networks because the information technology solutions enabling this transparency in supply chains was expensive and unaffordable for them (Kärkkäinen and Ala-Risku 2005). With the Internet as a medium to deliver real-time information to consumers on the quality status of the products, the methodology now appears feasible for them and worthy of investigation. Oberthür *et al.* (2006) have recently presented the concepts that govern the provision of innovative information within agriculture supply chains with small holder producers.

Can systematic targeting generally be applied?

For the proposed concepts to be applicable elsewhere, we assume heterogeneity of growing conditions and a varied response to uniform management and technologies. Under these conditions, blanket recommendations for regions or zones do not optimize management for specific crops directed to particular markets. Although initial improvements can be obtained by using widely adapted technology, later improvements can come from more site specific technology (Evenson 1981, Cock and Luna 1996, Cassman 1999, Cock 2000). Farmers have long been aware of the differences among sites and constantly try out new options and adopting practices suited to their conditions. Due to the limited number of treatments that any one farmer can try and to the effects of variations in climate and other management practices, it may be difficult for a farmer to filter out the best option.

Supply chain management (SCM) for differentiated higher value crops emphasize the overall and long-term benefit of cooperation and information sharing by all chain members. Relevant information for better decisions can be provided to growers. Chain integration has been shown to improve the information flow concerning customer preferences (Trienekens *et al.* 2003). Our literature review examined the widespread applicability of such chain integration.

Aspect has been reported to have an impact on quality in Costa Rica (Avelino 2005). Soil fertility is often quoted as a basic factor affecting coffee quality (Barel and Jacquet 1994, Camargo *et al.* 1992; COFENAC 2003, Illy 2001). It is generally accepted that volcanic soils produce the best quality coffee (Njoka and Mochoge 1997). These soils positively influence coffee acidity and body (Griffin 2001). Pochet (1990) found positive relationships between quality characteristics and low soil fertility. It has long been maintained that shade was only a key factor for coffee plantations in sub-optimal growing zones (Beer *et al.* 1998). More recently it has been shown that shade is beneficial in optimal coffee growing zones under a range of conditions in Costa Rica (Vaast *et al.* 2005), in Nicaragua (Lara-Estrada, 2005), and in Honduras (Decazy *et al.* 2003).

In the Piendamo estate, early harvest significantly improved beverage quality. In Costa Rica, coffee quality from early and peak harvest was significantly higher than for late harvest (Vaast and Bertrand 2005). In the Concordia estate, the lower and medium canopy level scored higher than the higher canopy regions. Bertrand et al. (2004) demonstrated in trials in Costa Rica that there was a significant difference between upper canopy region and middle and lower canopy regions. Also other variable management practices that have not been considered here would benefit from the outlined concepts: for example harvesting beans with different maturity grades has been shown to impact coffee beverage quality (Barel and Jacquet 1994). Furthermore, for wine it has been demonstrated that selective harvesting provides for substantial benefits from systematic management of variation (Bramley *et al.* 2003).

Conclusions

We have shown that biophysical and management factors have a variable impact on coffee beverage quality. There were statistically significant differences between:

- Slope aspect in Piendamo;
- Varieties in Mexico;
- Times of harvest in Piendamo;
- Shade in Inza; and
- Slope position in both Concordia and Piendamo.

Possible interventions vary in terms of their ease of implementation, the likely improvement of quality that they cause and the resource intensiveness they require. However, together they provide distinct potential for added value of the product. Aspect and harvest date have high potential to add value, shade management has medium potential, while fruit thinning and choice of varieties have medium to low potential. Soil fertility and harvest separation by canopy level had only low potential to add value on the sites that we studied.

Optimum management appears to be highly site specific so that it is not possible to make any blanket recommendations. But by recognizing that quality is highly site-specific, by means of continuous cycles of implementation, observation, interpretation and evaluation each farmer can improve his management over time. By this means the farmer will be able to target the product to the dynamic requirements of a dynamic market. But to make this happen, it is necessary to interlink supply chain actors more closely, to facilitate data analyses and interpretation for farmers, and to develop appropriate feed-back mechanisms. Systematic targeting of agronomic farm management is a promising opportunity for farmers to improve their livelihoods by producing coffees with added value.

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Geographical analyses to explore interactions between inherent coffee quality and production environment

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Abstract

In recent years, research has focused on the interactions of coffee cup quality and its production environment. Nevertheless, there has been a lack of methods and tools to extrapolate the findings of mainly controlled experiments to wider geographic areas. We present spatial decision support elements based on Bayesian statistics and geographically-weighted regression methodologies to identify niches, map quality response attributes, and determine their interactions with the environment. To do so, we use two case studies from Cauca, Colombia and Nicaragua. With the Cauca data set, we introduce the niche concept and test the predictive approaches. With the Nicaragua data set, we demonstrate the value of spatial analyses in assessing the variability of the response of the variables that determine coffee quality to the environmental factors that influence them.

Resume

Récemment, la recherche sur le café s'est concentrée sur les interactions entre la qualité en tasse du café et l'environnement. Cependant, il manquait des méthodes et des outils pour extrapoler les résultats de la plupart des expériences contrôlées à des aires géographiques plus étendues. Nous présentons un outil basé sur des méthodologies de statistiques de Bayes et de Régression Géographiquement Pondérée (GWR) pour cartographier les caractéristiques de qualité du café et pour identifier leurs interactions avec l'environnement. Pour cela, on utilise deux cas d'étude. Avec les données du département du Cauca au sud de la Colombie, nous introduisons le concept de niche et testons l'outil présenté. Avec les données du Nicaragua, nous démontrons la valeur des analyses spatiales pour évaluer la variabilité des caractéristiques de qualité du café et des facteurs environnementaux qui les dirigent.

Introduction

Usually, due to high resource inputs, agricultural research is conducted in few experimental sites, findings and generated knowledge is thereafter rolled out and applied to wide areas often without taking into account the changes of the environment over space. The development of tools and methodologies for extrapolating findings that are site and environment specific is required. Spatial decision support tools can help to extrapolate findings and identify niches where a specific coffee trait is likely to be found (Laderäch *et al.* 2006). Niches are clusters of sites with environmental characteristics that favor product qualities of similar nature. Spatial decision support tools give insights on interactions between species performance and the environment. We use two case studies to demonstrate the utility of geographical analysis. With a data set of Cauca, southern Colombia, we introduce the niche concept and test a spatial decision support tool, and with a data set from Nicaragua we demonstrate the value of spatial analyses to assess the variability of coffee quality response variables and their determining environmental factors.

Methodology

A spatial decision support (SDS) tool, that is, a software tool based in geographical information science (GIS) to assist users in decision-making was developed. The tool, CaNaSTA (crop niche selection in tropical agriculture), employs Bayesian statistics. Bayesian methods provide a "formalism for reasoning under conditions of uncertainty, with degrees of belief coded as numerical parameters, which are then combined according to rules of probability theory" (Pearl 1990). A simple Bayesian model defines prior and conditional probability distributions and combines these to calculate posterior probabilities for each possible outcome. The probability distributions may be derived from data, set by experts or defined from a combination of data and expert opinion. The CaNaSTA algorithm (O'Brien 2004) creates conditional probability tables of all predictor variables against response variable categories. In the case of coffee, predictor variables include climate and topographic factors, and the response variable can contain sensorial, physical or biochemical quality attributes. The primary model output is a probability distribution at each location. The probability distribution consists of the probability that the response variable is in one or other of each potential state. This information can be used to create maps showing the most likely response value ('most likely').

The values in the probability distribution can also be weighted to produce a suitability value ('score'). Finally, an indicator of reliability (certainty value) can also be displayed as a map ('certainty'), and can assist in the interpretation of the results. Once locations have been identified where a particular response is likely, further analysis can be carried out to determine which predictor variables are important; a significance indicator is used to compare the importance of the factors. These factors can be either quality enhancing or reducing, and help with the analysis of specific conditions required for specific coffees. Geographically weighted regression (GWR) assumes that "... the relationships between variables measured at different locations might not be constant over space" (Fotheringham 2002). We use GWR to illustrate that the interaction between the environmental factors and coffee quality attributes vary in space. GWR is a spatial statistical method employing moving windows for regression (Fotheringham 2002) used to describe the spatial variability of coffee quality attributes. Evidence data used for the predictions and analyses consisted of generated climatic factors with a resolution of 1 km and terrain attributes with a resolution of 90m.

Climate data were generated using 30 arcsecond (about 1km at the equator) resolution WorldClim (Hijmans *et al.* 2005) and 10 arcminutes (about 18km) resolution MarkSim data (Jones and Thornton 2000, Jones *et al.* 2002). The WorldClim data layers were generated on through interpolation of average monthly climate data from 15,000 to 47,000 weather stations during the years 1950 to 2000. Variables extracted from WorldClim were monthly total precipitation, and monthly mean, minimum, and maximum temperature. Annual average precipitation, annual average temperature and dry month per year were then calculated. Average annual precipitation was obtained by summing all monthly total precipitations, average annual temperature by averaging the monthly mean temperatures, and dry months were defined as months with less than 90 mm of precipitation. Annual average diurnal temperature range was calculated from WorldClim. As relative humidity varies diurnally and also between seasons, we mapped dew point, which is the temperature at which air becomes saturated and produces dew. Dew point is a direct measure of the absolute amount of water vapour in the atmosphere. Dew point maps were calculated by the method of Linacre (Linacre 1977) from the WorldClim dataset. Mean annual insolation, which is the solar radiation that reaches the surface of the earth, was calculated from the MarkSim daily data (MJ m^{-2} d^{-1}). Terrain attributes such as elevation, aspect and slope were generated and mapped from the digital elevation model

(DEM) of the Shuttle Radar Topography Mission (SRTM) using geographical information systems (GIS) methodology (Jarvis 2004).

Case Studies

We present two case studies, one using a data set from the Colombian department of Cauca where coffee is widely grown and a second one from the Nicaraguan coffee-growing departments of Matagalpa, Jinotega, Nueva Segovia and Región Autónoma del Atlántico Norte.

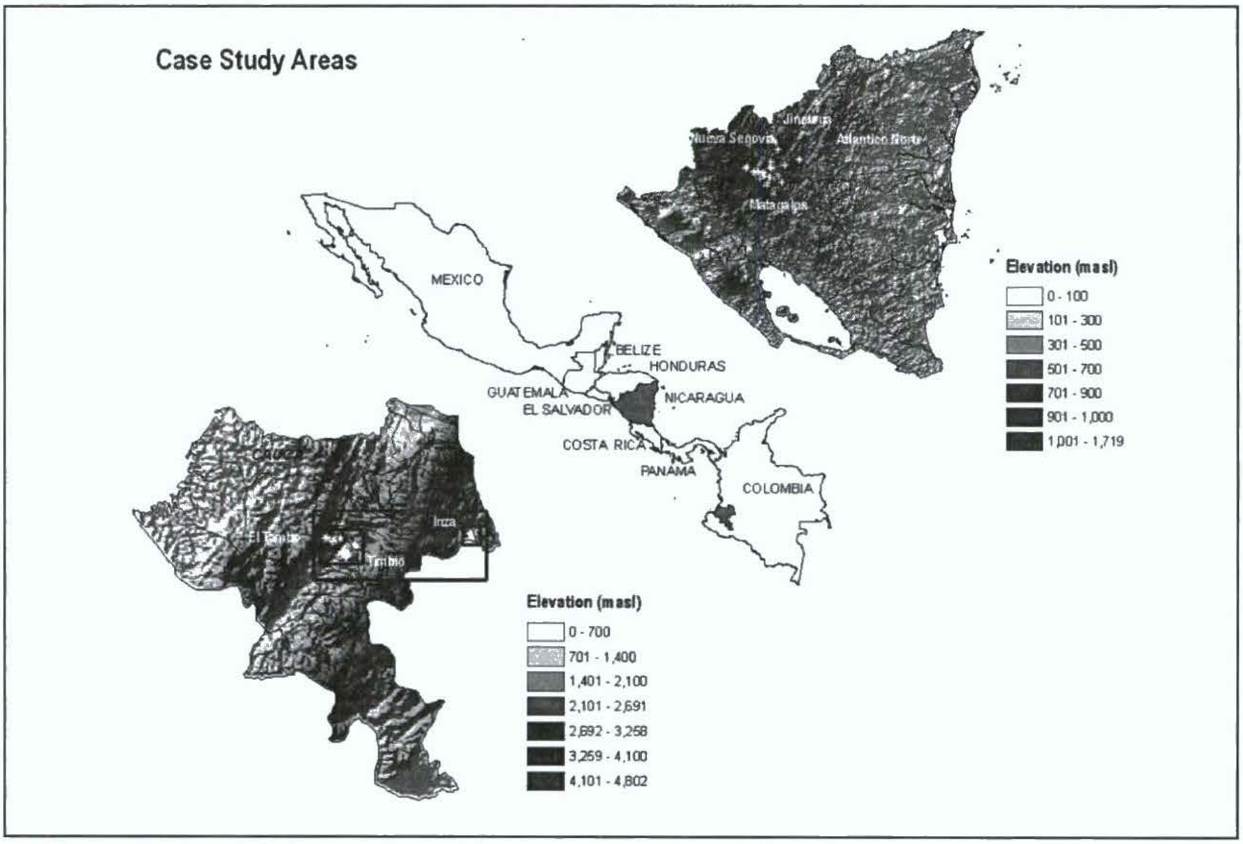

Figure 1. Location of the case studies in Cauca and Nicaragua. For Cauca the window of the "driving factor" analyses is shown: The large rectangle represents the entire study area (775,866 ha), the medium the niche of El Tambo-Timbio (160,765 ha), and the small niche of Inza (16,005 ha).

The Cauca case study data set consist of 88 sample points, 44 from sites in El Tambo-Timbio, 27 from Inza and 17 from other municipalities. Coffee was harvested in May and June, 2005 in homogeneous and geo-referenced farmers' plots, and standard post-harvest processes were applied with a mobile processing unit.

The sensorial quality was assessed by an international cupping panel in August, 2005. The sensorial evaluation was conducted according to Specialty Coffee Association of America (SCAA) standards and with an adapted cupping form assessing ten sensorial attributes: fragrance/aroma, flavor, aftertaste, acidity, sweetness, body, balance, uniformity, clean cup, and cuppers score. The probability of high final score (Figure 2), the sum of all the sensorial attributes minus the defects, was predicted with CaNaSTA.

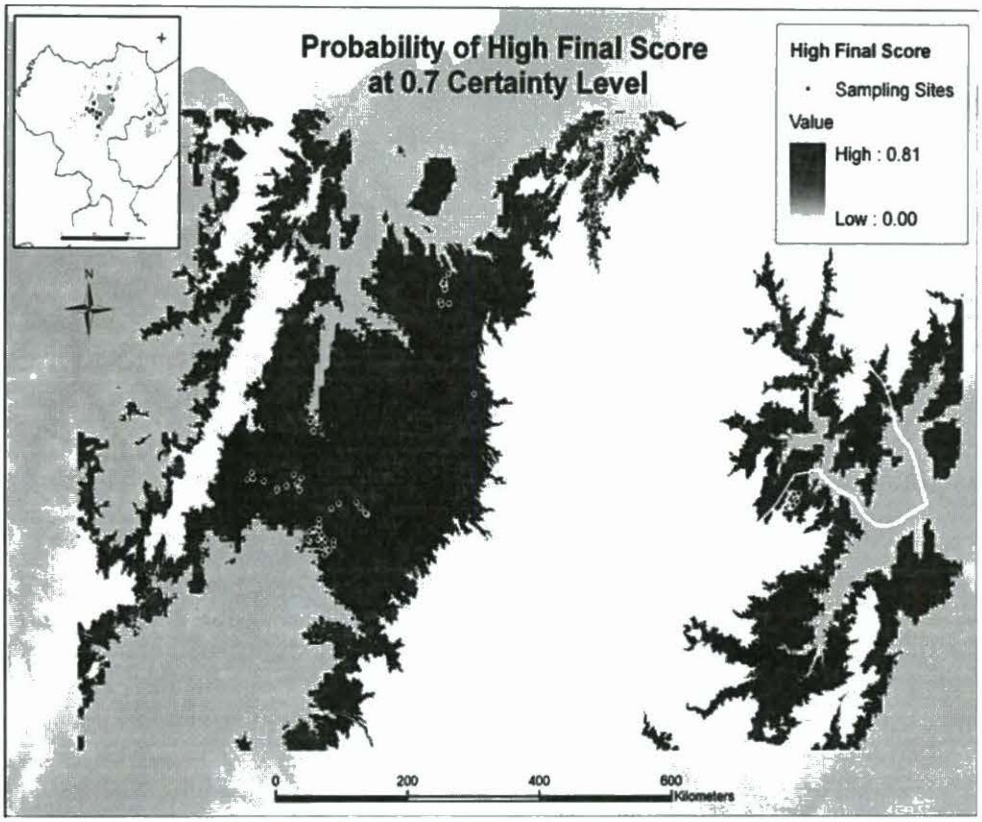

Figure 2. CaNaSTA "score" analysis; the likelihood of high final scores at a 0.7 certainty level are shown. The areas of El Tambo-Timbio and Inza are identified as potential niches for high value coffee.

To validate CaNaSTA, three different tests and training sets were used with 25/75, 50/50 and 75/25 percent of the data accordingly to predict and test the model, respectively. Each set was repeated 10 times with predicting and testing sites selected at random. The final score of a SCAA quality class is the sum of ten evaluated sensorial attributes, each having a score between 1 and 10. Because the emphasis is on quality coffees, only those samples scoring in the range of 70-90 were used in the evaluation. The likelihood ratio of the dependency of the quality class on the predictor scores was tested using the chi-square test. The test method uses a conformity matrix where the axes represent the quality classes and predictor ranges and the cells of the matrix cells show the agreement between them. "Driving factor" analysis was then applied to determine the factors most impacting on sensorial coffee quality. The analysis was conducted on the two different environmental niches and on the entire Cauca data set (Figure 1). The Inza niche covers 16,005 ha, El Tambo-Timbio 160,765 ha, and the sampled municipalities of Cauca cover 775,866 ha.

The data set from Nicaragua consists of 67 sample points collected and analyzed by Lara-Estrada (2005). The samples, all of the Caturra variety, were picked and processed using standardized methodology and physical, bio-chemical and sensorial attributes were assessed. The sensorial attributes including acidity, body, bitterness, aroma, cuppers preference, flavor, were determined in the cupping laboratory of Atlantic SA in Nicaragua. Bio-chemical attributes including cholorenic acids, caffeine, fat content, trigonelline, and sucrose content, were assessed by near infrared spectroscopy (NIRS) in CIRAD, France. We applied "score" analyses, an indicator of the likelihood to produce high quality, and combined with the "certainty" surfaces to Lara-Estrada's (2005) data. We calculated the cross correlations between pair surfaces (Nelson 2004) and conducted GWR analyses to quantify the spatial impact of the environmental factors on quality attributes.

Results

Niche concep

With the "Score" analyses (Figure 2) the areas of El Tambo-Timbio and Inza were identified as niches with high probability to produce specialty coffee. CaNaSTA was then validated, comparing prediction and evidence quality scores (Table 1), with the hypotheses being:

H_0 = Prediction and evidence scores are independent

H_1 = Prediction and evidence scores are dependent

In El Tambo-Timbio, the P-value decreases from 0.062 to 0.019 with increasing numbers of prediction points (Table1). With the 25/75 set, the null hypothesis is accepted, that is the prediction and evidence scores are independent. For the 50/50 and 75/25 sets, H_1 can be accepted with P=0.052, that is the prediction and evidence scores are dependent. For Inza P=0.014 for the 75/25 set and P=0.082 for the 50/50 set, likely because the number of samples was insufficient. When analyzing the entire area no pattern is distinguishable, 50 and 75 percent of the data points predict the niches at P=0.056 and 0.13 respectively, which are reasonable p= values, recalling that the CaNaSTA methodology uses site data combined with the relevant environmental data to predict areas that are suitable for any particular germplasm. In the case of Cauca, this implies that predictive relationships derived for Inza is used to predict qualities in El Tambo-Timbio and vice versa. It is also obvious that the niches cannot be identified at a high degree of confidence, but the methodology still serves for a general identification of niches that can thereafter be refined by concentrating the analysis window at the niche scale, in other words, include a smaller window to define the niche more closely.

To illustrate the site specificity of the interactions of environmental factors with quality, the "driving factor" analysis was run for the entire data set and for the two niches separately (Tables 2 and 3). For the entire data set, only one enhancing and three reducing factors were identified having a significance value (c) > 2. As stated previously, by running a general analysis, we predict areas that produce high-quality coffee based on evidence data from distinct environmental conditions and insights of interactions with coffee quality are only of a general nature. When analyzing niche by niche, a more detailed set of responsible factors can be obtained.

Table 1. P values of the likelihood ratio chi-square for the entire area and for the two niches.

	25 / 75	50 / 50	75 / 25
Cauca	0.43	0.056	0.13
El Tambo-Timbio	0.062	0.051	0.019
Inzá	0.86	0.081	0.014

Table 2. Quality enhancing factors impacting on the final score attribute of the niches Inza, El Tambo-Timbio and the whole Cauca sampling area. The significance indicator *c* is shown in parentheses.

Quality enhancing factors	Entire data set	Inzá	El Tambo-Timbio
Altitude (masl)		1750 – 1800 (2.02)	1652 – 1725 (2.32) 1725 – 1798 (2.39)
Average annual dew point (°C)		11.9 – 12.2 (2.43) 12.3 – 12.6 (2.07)	12.3 – 12.8 (2.38)
Average annual temperature (°C)		17.7 – 18.1 (2.55) 18.0 – 18.4 (2.21)	17.8 – 18.9 (2.32)
Average annual precipitation (mm)	1760 – 1934 (2.31)	1645 – 1674 (2.2) 1587 – 1616 (2.1)	

Table 3. Quality reducing factors impacting on the final score attribute of the niches Inza, El Tambo-Timbio and the whole Cauca sampling area. The significance indicator *c* is shown in parentheses.

Quality reducing factors	Entire data set	Inzá	El Tambo-Timbio
Altitude (masl)	1528 – 1623 (2.74)		
Slope (degrees)		22.4 – 25.6 (2.54)	34.5 – 40.9 (2.55) 21.6 – 27.9 (2.10)
Average annual dew point (°C)	12.8 – 13.5 (2.4)	11.5 – 11.9 (2.57)	14.3 – 14.8 (2.00)
Average annual temperature (°C)		17.3 – 17.7 (2.47)	20.0 – 21.0 (2.02)
Average annual solar radiation ($Mj/m^2/d$)			21.8 – 22.3 (2.32)
Average annual precipitation (mm)	1133 – 1587 (2.78)		
Dry months (mth/yr)		3 (2.81)	

For both niches, altitude, average annual temperature and average annual dew point enhance final score quality. The ranges are only slightly different between the two Cauca sites, Inza having lower temperatures and higher altitudes than El Tambo-Timbio. Average annual precipitation is an important enhancing factor in Inza and for the entire Cauca data set. In contrast, greater slope influences final score negatively in both niches. Dew point above and below the range identified as enhancing quality have a negative impact as does average annual temperature. The optimal annual average temperature in Inza is 17.7 – 18.4°C but is slightly higher (17.8 – 18.9°C) for El Tambo-Timbio. The results demonstrate variability in the environmental factors that impact on final score and the need to assess these factors according to their niches.

Variability in space

Recent studies show the interactions of environmental factors and coffee quality and the correlations between quality attributes for selected study sites: Vaast *et al.* (2005*a*) reported no differences in the caffeine content of high and low quality coffees while Avelino *et al.* (2005) did not find any strong correlation between sensorial characteristics and caffeine, trigonelline, fat, sucrose, cholorenic acids. Vaast *et al.* (2005*a*, *b*) showed that there is a strong relationship between high trigonelline content of coffee beans and higher bitterness and lower acidity of the coffee beverage; Decazy *et al.* (2003) found a positive relationship between bean sucrose content and coffee acidity and quality and also that high bean fat content related to good acidity and beverage preference. Little work has been done on the spatial variability of coffee attributes and their interactions with the environment. Our analysis of Lara-Estrada's (2005) study puts data on coffee quality in a spatial perspective. The correlation of the "score" response maps, for ten different quality attributes, demonstrated the variability in correlation between the responses (Table 4).

Table 4. Correlation coefficients of response variable pairs (Pref. = preference, Caff = caffeine, C.A. = cholorenic acids, F.C. = fat content, Suc. = sucrose, Trigo = trigonelline).

	Acidity	Aroma	Bitter	Body	Flavor	Pref.	Caff	C.A.	F.C.	Suc.
Aroma	0.72									
Bitter	-0.22	-0.08								
Body	0.69	0.76	0.17							
Flavor	0.82	0.64	0.06	0.74						
Pref.	0.82	0.74	0.00	0.82	0.90					
Caff	-0.13	-0.03	0.16	0.07	0.07	0.02				
C.A.	0.08	0.08	0.26	0.25	0.12	0.17	0.50			
F.C.	-0.24	-0.21	-0.17	-0.24	-0.24	-0.22	0.28	-0.04		
Suc.	0.33	0.44	0.03	0.42	0.28	0.35	-0.10	0.35	-0.23	
Trigo	0.18	-0.04	-0.23	-0.06	0.09	0.03	-0.37	-0.57	-0.31	-0.27

A single figure averaging the correlation of a pair of variables is often not meaningful. For example, sugar content and flavor are poorly correlated ($r = 0.28$); only when visualizing the r coefficient on a map, does the importance of the spatial variability become evident (Figure 3) and highly correlated areas (with values as much as $r = 1$ or $r = -1$) identified (Figure 3). The spatial correlation with window sizes of 3, 5, 9 and 17 grid cells, translates into 9, 16, 65 and 94 ha for each analyzed window. These correspond to individual farms up to 9 ha in size, groups of farms up to 16 ha, associations up to 65 ha and micro-catchments up to 294 ha.

The different resolutions give insight on the scale where correlation patterns emerge, which is valuable information for profile identifications of coffee quality and their marketing. The analysis also demonstrates to farmers' associations the strengths and weaknesses of their coffee qualities. Not only do quality responses vary in space, but environmental factors also impact on quality. A GWR analysis on the overall importance of environmental factors that impact on flavor result in flavor being significantly dependent on "number of average annual dry months" (DM) and "average annual diurnal temperature range" (DTR) at P=0.05 and P=0.01 respectively.

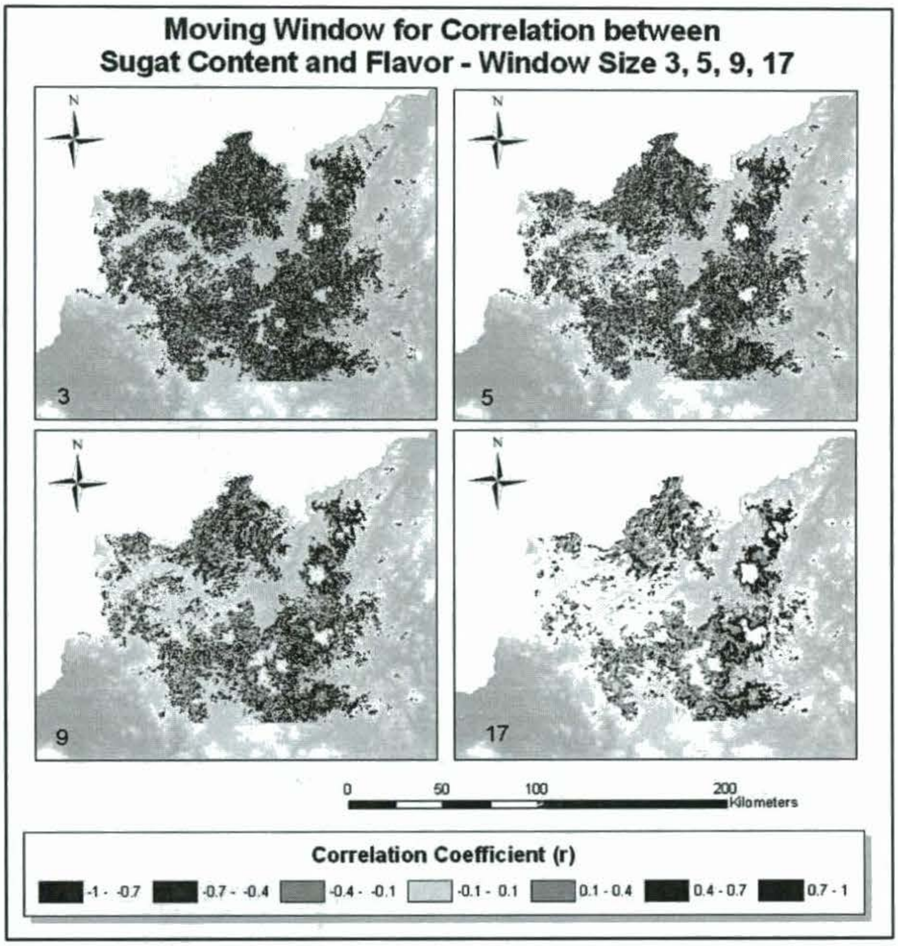

Figure 3. The variability of the correlation between sugar content and favor at different resolutions of moving window.

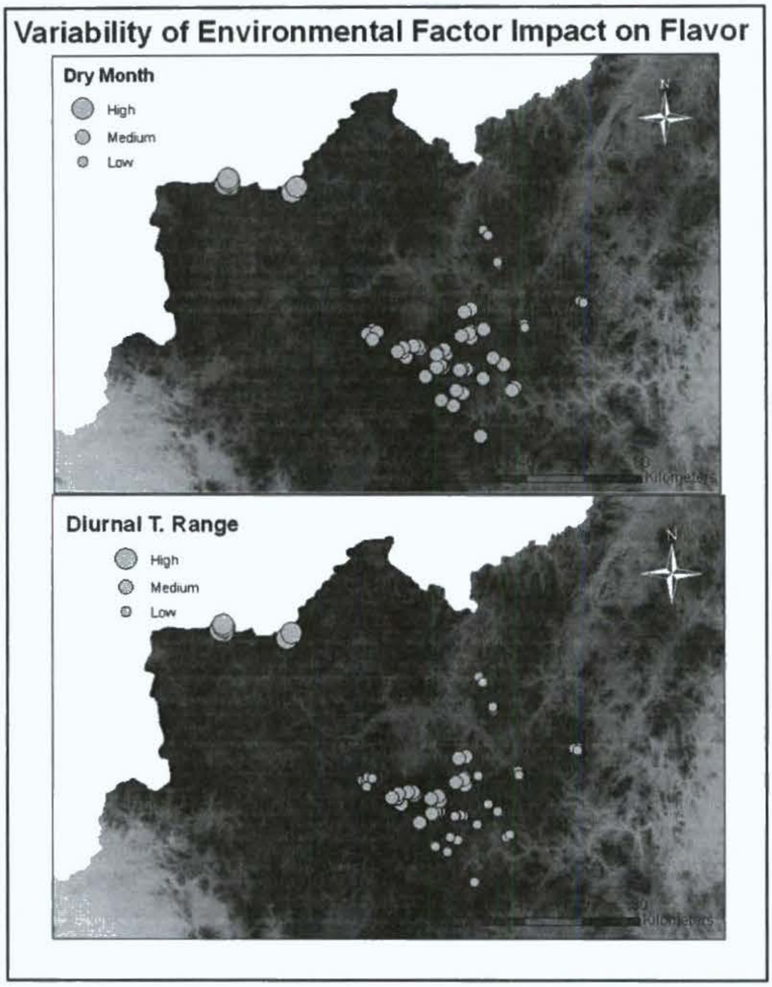

Figure 4. Variability of the impact on flavor for two decisive environmental factors (dry months and diurnal temperature range). Bigger dots are representing a larger impact on flavor than smaller dots.

Even though these two environmental factors are significant for flavor; their contribution at each site is distinct. Figure 4 shows the variable impact of DM and DTR on the flavor quality. Bigger dots represent a larger impact on flavor than smaller dots. The impact of these factors is very heterogeneous in space but there are clusters that form niches where either DM or DTR are more important.

Conclusions

CaNaSTA predicts niches likely to produce high final scores for coffee quality at confidence levels of P = 0.056 – 0.1 for an area of 800,000 ha in Cauca using only quality data from 88 sites. Within pre-defined niches, quality classes can be predicted at P = 0.019 – 0.051 for the El Tambo-Timbio niche (160,000 ha) and at P = 0.014 – 0.081 for the Inza niche (16,005 ha). The ranges of the factor-enhancing or -reducing quality in the two niches of Cauca are very different depending on the environmental envelopes predominating in the niche. The importance and utility of SDS tools and geographical analyses for assessing the variability of environmental factors and causal quality responses is shown in a case study in Nicaragua. These are very powerful tools that allow the extrapolation of point information to give information about a broader surface. Environmental factors and their impact on quality are very heterogeneous in space. Nevertheless geographical analyses allow the identification of niches with similar factor combination.

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THEME 3:

IDENTIFYING THE CONDITIONS UNDER WHICH ENVIRONMENTAL GOODS AND SERVICES CONTRIBUTE TO EQUITABLE AND SUSTAINABLE DEVELOPMENT

High-value agricultural products: Can smallholder farmers also benefit?

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Abstract

A rapidly changing agriculture and food economy threatens resource-poor smallholder farmers. Consumers throughout the world are shifting away from staple-based diets (grains and tubers) to energy-rich diets with increasing amounts of meat, especially poultry. In addition, consumers are eating perishable foods such a fresh fruits and vegetables that also require timely and careful handling. Smallholders often raise and cultivate these high-value agricultural products (HVAPs). Nevertheless, their products rarely reach such consumers or obtain high prices. The ambiguous term HVAPs can confuse development practitioners, industry professionals and policymakers in their efforts to support smallholders. Farm products acquire high-value by way of: (a) their inherent value arising from quality, scarcity or luxury attributes (e.g. specialty coffees and organic products), or (b) value-added activities that enhance consumer convenience (e.g. processing and packaging). Some HVAPs have both inherent value attributes and value-added activities. Marketing strategies enhance consumer awareness and their willingness to pay. For products with imperceptible attributes (e.g. organic, social or environmental benefits), marketing information is essential for authentication. While many smallholder farmers have comparative advantages in the production of HVAPs, research and development efforts may not be effective in fostering the marketing components. This paper outlines cost-effective investment strategies according to different production, market and policy contexts.

Introduction

Approximately two-thirds of people living on less than US$1 per day are smallholder farmers or landless workers. They face extensive changes in the global agricultural economy including:

a) A two-decade decline in real prices of commodities (Robbins 2003, FAO 2004);
b) The dismantling of marketing boards that had provided free or subsidized inputs such as credit and fertilizer as well as extension and training (Gill and Carney 1999, Byerlee and Echeverria 2002);
c) Increasing competition from liberalized international trade policies (Bannister and Thugge 2001);
d) Different consumer preferences for foods resulting from expanding and wealthier urban populations (Delgado, *et al.* 1999, Weinberger and Lumpkin, 2005); and
e) Increasingly stringent food quality and safety standards such as lower pesticide residues (Hill 2000).

These changing conditions can further marginalize the ability of smallholder farmers to participate in the market economy. Many resource-poor farm and landless families are by-passed by technology-based advances in agriculture production and marketing. In addition, smallholder producers often lack the supporting institutions (e.g. market information and transport networks) to compete in the marketing sphere (Mangisoni 2000, World Bank 2004). Unable to compete in the market economy, many smallholders will continue subsistence production or migrate to urban areas.

Food systems can no longer be viewed simply as a way of moving basic staples from farm to local plates (ODI 2003). Numerous farmers now produce to the demands of niche markets and according to specific grades and standards of sophisticated supply chains. In many regions, retail systems have spurred these changes, especially the growth and increasing concentration of supermarkets. For example, the share of supermarkets in Latin America has risen from a mere 10-20% of food retail in 1990 to 50-60% by the early 2000s. Small shops and open-air markets were displaced in the process (Reardon and Berdegué 2002). In China, no supermarkets existed in the late 1980s; food retail was nearly completely controlled by the government. Yet by 2003, supermarkets had captured a 13% share of national food retail sales and 30% of urban food retail sales (Hu *et al.* 2004).

Changes in the global agricultural economy provide rural producers with new opportunities. High-value agricultural products (HVAPs) are seen to be an attractive development option for smallholder farmers (USAID 2004, ADB 2005). Government, non-government and industry efforts can all contribute to smallholder involvement in HVAP markets. Confusion about what HVAPs are, however, creates misunderstandings amongst researchers, development practitioners and policy-makers regarding the actions needed to foster more lucrative and equitable HVAP markets for smallholder farmers at national, regional and international levels.

This paper provides a conceptual framework that characterizes different types of HVAPs, and identifies research, development, and policy efforts that facilitate farmers' participation in HVAP market chains. Such support ranges from training in production, processing, business development, organizational strengthening and marketing activities to institutional and policy changes.

Clearing up the misconception of HVAPs

What is a HVAP?

A good starting point is to state that HVAPs are not staple commodities. They are not homogeneous products, traded on the basis of price; nor are HVAPs the basic components of a diet. The first two words, 'high value', cause a strict definition to be elusive. High-value is a relative term, not only with respect to a dimension of being low-high, but also regarding the word value, which can be seen from either the consumer or producer perspective. Despite this ambiguous context, HVAPs can be defined as:

a) Products that return a higher net earning per unit of input (e.g. per hectare and/or per unit labor) than standard commodities; and/or
b) Products that have attributes for which consumers are willing to pay (WTP) a price premium.

HVAPs often require special skills for their cultivation or collection. Fruits, vegetables, meat, eggs, milk, fish and many non-timber forest products can be considered HVAPs (Gulati *et al.* 2006, Science Council 2005). An HVAP can also obtain value by its unique or scarce nature. Such "rare" products include spices, medicinal plants, and even crops that yield illegal drugs, e.g. coca and poppy (heroin). Scarcity value is also determined by time and place. For example, the value of fruits and vegetables increases outside the harvest season or production regions, despite the costs of transport or storage contributing to such higher prices.

Product value reflects a consumer's willingness to pay. The value of a product depends on its inherent attributes and how a consumer perceives them. Inherent attributes that differentiate products can be perceptible and imperceptible. Quality characteristics such as color, shape and size perceptibly distinguish a product. Less perceptible attributes include a product's origin, which can be cultural and/or geographic. Examples of cultural attributes are products from ethnic groups and/or smallholders that are in contrast to products of faceless corporate agriculture. Geographic attributes refer to production from certain known and delineated areas (Umbarger *et al.* 2003). Other intangible attributes include product safety, for example, having few pesticide residues or, to some, no genetically-modified organisms. Notwithstanding, a lack of safety can also generate higher values. Unsafe and risky products, such as illicit drugs, can have valued thrill-seeking characteristics.

Both marketing efforts and product standards and certification help to preserve and enhance product attributes. Intangible attributes become more tangible to the consumer and enhance WTP. Information management along the supply chain can preserve and validate authenticity of intangible product attributes. A certification process of product management practices, such as organic or environmentally-friendly production, can ensure HVAP attributes. Socially-equitable product attributes, such as fair-trade, also have certifications.

Specialized versions of commodities can also be HVAPs. Many agricultural products have been changed from commodities into HVAPs. The key to success of these initiatives has been the process of product differentiation accompanied with comprehensive product tracking and information systems. Tactics to authenticate product attributes and preserve their public perception will be discussed below.

High-value versus value-added

Confusion remains between the terms *high-value* and *value-added*. In the context of HVAP markets, *value-added* corresponds to post-harvest activities such as processing, transformation, packaging, and marketing. These activities tend to pertain to links placed further along the supply chain and away from rural areas. distinguishes the term *value-added* from *high-value* by using examples of coffee, maize, fruit and vegetables, and animal (e.g. chicken) products.

Table 1. A comparison of value-added and high-value products

Market	Product	
	Primary/Raw	Value-added
Commodity	Coffee Bulk maize Fruits and vegetables Whole chicken	Roasted coffee Maize flour Packaged fruits and vegetables Chicken parts
High-value	Shade-grown or denomination coffee QPM, non-GMO or organic maize (Organic) fruits and vegetables Whole chicken	Roasted denomination coffee Organic corn chips Packaged organic fruits and vegetables Chicken parts (and free range)

Value-added products are processed versions of primary or raw products. Post-harvest activities of roasting coffee and packaging rice, for example, add value to the primary products. Fruits, vegetables and animal products can be considered commodity products. In many countries, large-scale industrialized agriculture produces a majority of these products. The same products can also have added-value with additional post-harvest activities. Packaging and storage, for example, enables a product to be sold at a different times of the year; transport permits sales in different locations.

High-value products depend on their inherent attributes to obtain greater market prices. Unlike commodities, which are 'standard' value products sold in commodity markets, *high-value* products typically have specific niche markets. Some commodities have become HVAPs. Coffee is one of the most notable examples of the 'decommodification' of a commodity. Coffee was long characterized as a homogeneous product with falling terms of trade and volatile prices. Yet, in recent years, coffee has undergone growing product differentiation in final markets (e.g. shade-grown or origin denominated), with premium prices being paid (Kaplinsky and Fitter 2004). Decommidification examples exist for practically all commodities. To different degrees, differentiation has occurred with potatoes (Devaux *et al.* 2006), cassava (Best *et al.* 1994) and maize (Bender and Hill 2000).

Although the inherent attributes of HVAPs are acquired or managed before the harvesting of the product, post-harvest activities are often needed to maintain product identity and promote consumer awareness.

Facilitating higher earnings by smallholders

By addressing both farm management and post-harvest (e.g. processing and marketing) contexts of smallholder farmers, development support can become more effective.

Three of the six development support initiatives indicated below describe HVAPs: (1) specialized management and handling (fruits, vegetables and animal products), (2) product differentiation with perceptible quality attributes (color, size, shape, smell, taste), (3) product differentiation with imperceptible quality attributes (safety, origin, producer characteristics). Related to HVAPs, are initiatives that enhance (4) value-added activities (post-harvest processing and handling). In order to enhance and preserve consumer knowledge requires development efforts on (5) product and market and information. An enabling environment that 'levels the playing field' can be realized with development efforts that address (6) organizations, institutions and policies.

Figure 1 summarizes these development support initiatives. Overlaps amongst these initiatives demonstrate that support efforts are not necessarily mutually exclusive and coordinated effort can lead to greater impacts. Effective, or at least non-detrimental, organizations institutions and polices are a necessary condition to achieve development impacts. At nearly the same level of importance is product and market information. In order for products with imperceptible quality attributes to obtain higher prices, product and market information is essential. The initiatives are presented in detail below.

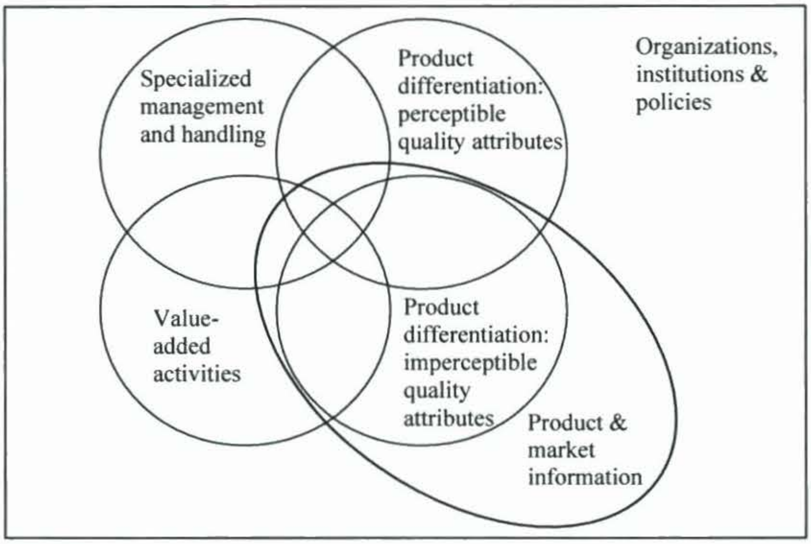

Figure 1. Development support initiatives for smallholder participation in markets

Specialized management and handling

A fundamental farm management decision is whether to continue producing lower-value but known agricultural products, or change to higher-value but riskier products. While fruits, vegetables and animal products can have higher profit margins, their cultivation and raising typically requires extra inputs and managed care. Numerous factors influence technology adoption decisions, ranging from the availability of inputs (e.g. land, fertilizers and pesticides) to contextual issues such as agronomic and market conditions, land tenure and infrastructure (Feder and Umali, 1993; Franzel et al., 2001). Fitting a technology into the agricultural system of the resource-poor farm is often required to assure technology adoption (Collinson, 1972; Zandstra, et al., 1981; Byerlee and Siddiq, 1994).

Family labor is one of the most important production inputs of smallholder farms (Schultz, 1964; Ruthenberg, 1976; Byerlee and Collinson, 1980). Nevertheless, farmers and economists have dramatically different perceptions regarding the value of labor, especially during peak demand periods such as planting and harvest (White, et al. 2004). Three conditions of market failure lead to this disparity. First, labor availability during peak demand is often insufficient; or in other words, labor supply markets are inelastic (de Janvry, et al. 1991). Although a farmer may wish to expand production, sufficient labor cannot be acquired despite the payment of higher wages. Second, resource-poor farmers rarely have sufficient financial resources with which to purchase labor. The seasonal nature of harvest sales and the lack of credit markets leads to cash flow constraints. Three, even if funds were available to purchase labor, numerous transactions costs exacerbate difficulties of obtaining and managing temporary laborers. In remote areas where many resource-poor farms are located, a rudimentary transportation and communication infrastructure inhibits the acquisition of additional labor. Together, these conditions of market failure (inelastic labor supply, liquidity constraints and transactions costs) restrict the ability of farmers to meet temporary labor demands and obtain higher farm earnings.

Value-added activities

Agro-enterprise and post-harvest systems can raise incomes of rural people. Such value-added activities (e.g. cooling, cleaning, sorting and packing) are labor intensive and generate value added earnings. Urban consumers are increasingly aware of and willing to pay for foods of consistent quality and safety. Compliance with conditions set under sanitary and phytosanitary regulations that accompany WTO negotiations are critical for the continued participation of smallholder farmers in international agricultural markets. The handling and treatment of agricultural products after they leave the farm gate largely determine the ability of agricultural products to meet the required conditions. Such food safety standards are non-tariff barriers not only imposed by importing countries but also by the private sector (Reardon and Farina, 2001). To participate in increasingly formal urban and export markets, producers need access to well-organized post-harvest chains that can adequately process and market agricultural products. Consequently, smallholder farmers will need to become more integrated with upstream processing of their produce (Minot, 2005).

Product differentiation with perceptible quality attributes

Consumers are often willing to pay more for color, size, shape, smell, and taste. Smallholder farmers are frequently not aware of the potential opportunities to market high quality - high value products. If smallholders are conscious of particular opportunities, they need to identify optimal production niches on their land that are most suitable for high-value crops. The differentiation away from standard mediocre quality agriculture products will most likely occur in environmental niches that provide the appropriate conditions for production and marketing of these products. The growth of the specialty coffee market is ample evidence that demand for higher valued quality coffees is increasing (Oberthür, 2004).

Product differentiation with imperceptible quality attributes

A growing emphasis on production methods (for example, organic production and fair trade) and end traits (e.g. non-GMO products), requires identity preservation (in some cases, segregation may be sufficient) and separate marketing channels. This marks a departure from the traditional bulk commodity focus based on blending and large volumes. Niche markets for non-GMO products may develop, similar to the present market for organic foods, which is characterized by separate identity-preserved marketing and associate premium prices. Marketing mechanisms, however, are generally not in place.

Maize is typically considered a commodity. An important obstacle currently impeding the widespread cultivation of value-enhanced maize is the lack of a widely recognized price mechanism for the specialty characteristics (Meng and Ekboir 2001). Maize can also be HVAP and an input for other HVAPs. In Brazil, the expansion of the feed and poultry industries has induced a transformation of maize producers into commercial farmers. The growth of demand for maize feed has had major implications for the opportunity to differentiate maize, including quality protein maize (QPM). QPM has been successfully introduced into Brazil and China for use as an improved livestock feed. QPM can serve as a fortification programme within local people's normal nutritional regime (Lauderdale, 2001).

Many HVAPs are more perishable than commodities. In order to ensure quality and consistent supply of perishable goods, supermarkets (and other retailers) are pushing the food marketing system toward more vertical coordination (Gulati *et al.* 2006, Boehlje 1999). Vertical coordination allows retailers to standardize quality, improve bargaining power, and achieve economies of scale. This vertical coordination has such profound impacts on smallholder farmers. Retailers traditionally procure products from traditional wholesale markets, which are aggregated from many producers. The growth in demand for HVAPs has been accompanied by a shift from exclusive reliance on commodity markets toward the use of specialized/dedicated wholesalers (Reardon *et al.* 2006). Specialized wholesalers are usually more responsive to quality, safety, and consistency requirements than traditional wholesalers.

Product and market information

Realizing production increases are not the only challenge facing smallholder farmers. To ever increasing degrees, management with respect to fertilizer and pesticide application, is coupled with proper harvesting, grading and processing in order to obtain higher prices. Although reputation can function in local and national markets, systems of information management are needed to ensure that producers obtain higher prices for their superior products. For example, markets for differentiated commodities exist in the developed world. They required the development of mechanisms and technologies to identify specialized traits and track the movement of the produce through the supply chains.[1] The key question is whether similar markets exist in the developing world and whether smallholder producers can access these markets.

Agricultural processors and traders face increasing pressures to certify the safety of production practices (such as to avoid pesticide residues in the final product), quality attributes, adequate supplies and on-time deliveries. To do so, they also must rely on a large number of independent small farmers. Vertical integration, contract farming, and traders' associations can address these problems by reducing the moral hazard of farmer non-compliance, which can compromise an entire supply chain. Informed policies and a conducive regulatory environment increase the incentives for agro-processors to use the produce of small-scale farmers as inputs, and improve their capacity to meet the product attributes required in a rapidly modernizing agricultural marketplace. (Minot, 2005)

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[1] See www.identifypreserved.com for examples from the United States and http://web.aces.uiuc.edu/value/ for specific examples from Illinois

Organizations, institutions and policies

The growth in high-value agriculture and the increasingly vertically-integrated chains associated with HVAPs has raised questions about governance and equity of supply chains (re-governing markets). Close linkages are needed between farmers, processors, traders, and retailers to coordinate supply and demand (Gulati *et al.* 2006). This integration focuses on increasing profits and product value and is usually led by the more powerful members of the chain, in particular, the retail sector. For smallholder farmers who manage to enter such lucrative markets, many find it difficult to remain due to an inability to withstand losses stemming from unexpected production and/or price decreases and cost of cultivation involved. The challenge for farmers is that HVAPs are typically associated with high transaction costs (Pingali *et al.* 2005).

If development practitioners wish to contribute to poverty reduction with HVAPs, a market-literate approach is required. Such an approach aims to promote the growth and improved performance (for example, competitiveness, productivity, employment, value addition, linkage coordination) of chains in ways that benefit poor small-scale producers (Hellin *et al.* 2005). The value chain analysis school (for example, Kaplinsky and Morris 2001), analyzes the segments of a supply chain, and in particular the relations between the segments of the chain. New institutional economic analysis refers to this process as organizational and institutional analysis of governance and coordination of the supply chain (Reardon 2005). An analysis of HVAP supply chains can reveal where inefficiencies in the chain exist and by bringing different stakeholders together, these chains can be made to work more effectively and efficiently through participatory approaches for example, the Learning Alliances (Lundy, *et al.* 2005).

A key issue that policy makers and development practitioners have focused on is farmer organization as a tool for collective action to bring about greater equity in HVAP supply chains (Hellin *et al.* 2006). Collective action and producer organizations are therefore not surprisingly one of the foci of the pro-poor market approach (e.g. DfID 2005). Another cause (and consequence) of increased vertical coordination in supply chains is the growth of private quality and safety standards as well as private enforcement of public standards. In particular, strict requirements will be in force in two areas: food safety, driven by recent food crises in Europe, and the traceability of the identity and origin of the product (Vellema 2004). Smallholder farmer are unlikely, unless they are very well organized, to meet many of these quality standards (Shepherd 2005).

Farmer organisation is not, however, a panacea. Research in Chile (Berdegué, 2002) and Meso-America (Hellin *et al.* 2006) demonstrates that only under certain market conditions do small farmers to engage in collective action in order to access markets. Such efforts imply significant costs and risks, but only occasionally have the potential to benefit farmers. Producer organisations are more effective amongst producers of HVAPs as opposed to producers of commodities. There is far less incentive for producers of commodities to organize themselves as the transaction costs associated with market access are relatively low: there are so many buyers and sellers that farmer organizations would have little impact on, for example, prices.

Strategies are, therefore, needed that enable producers to diversify or upgrade production, and to compete more effectively in markets where they have advantages. Making HVAP markets work for the poor involves strengthening competitiveness in the enterprises, supply chains and wider business environments on which rural producers depend. A key element is the provision of business development services (BDS). Once an enterprise has been established, there is an on-going need for it and other supply chains actors to access services of different types, both market and technical, that will allow it to grow and maintain its competitiveness (Best *et al.* 2005). The range of BDS includes: input supplies (seeds, livestock, and fertilizers); market information (prices, trends, buyers, suppliers); transport services; and support for product development and diversification.

Much debate surrounds identifying the role of the private and public sector in the provision of BDS (for example, Miehlbradt and McVay 2005). Traditionally, BDS to small enterprises (including agricultural supply chains) have been delivered with the support of donor and government subsidies. Critics suggest that this distorts market prices and undermines the provision of BDS by the private sector. The neo-liberal market paradigm in the provision of BDS delivery signifies a shift in thinking from subsidized supply-led BDS provision to market-determined demand-driven services. In many cases, however, the private sector has proven incapable of replacing previous state services due to high transaction costs, dispersed clientele and low (or non-existent) profits (Lundy *et al.* 2002).

Contract farming is an intermediate institutional arrangement, a form of 'vertical coordination' as well as a sourcing mechanism, that lies between commodity market purchases and commodity production on owned or rented land (Echánove and Steffen 2005). Under contract-farming arrangements, landowners or tenants have obligations with agribusiness marketing and/or processing firms, which specify prices, timing, quality and quantity/acreage of the produce to be delivered. Contract farming allows firms to participate in, and exert control over, the production process without owning or operating the farms (Key and Runsten 1999). In the developing world, contract farming has spread rapidly since the 1980s, especially in relation to HVAPs.

Conclusions

The global agricultural economy is changing, with significant implications for the vast number of smallholder farmers. Gulati, *et al.* (2006) posit that to significantly improve their incomes per capita over the next twenty years, farmers in Asia must either be part of the shift to HVAPs or increase the share of income they get from non-agricultural sources. Furthermore, unless smallholders become vertically integrated with processors and retailers, they will increasingly have difficulties in participating in high-value markets (Gulati, *et al.* 2006).

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Watershed management and poverty alleviation in the Colombian Andes

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Abstract

Watersheds, especially in the developing world, are increasingly being managed for both sustainability and equity objectives. How complementary are these objectives? In the context of a watershed, the actual and potential linkages between land and water management and poverty are complex and likely to be very site specific and scale dependent. This study uses multiple methods to analyze the importance of water in the livelihoods of the poor at multiple scales. At the household scale, the Stages of Progress method (SOP), a participatory approach for assessing poverty dynamics, is used to assess how poverty has changed over time in communities and to identify the assets, including land and water, and livelihood strategies associated with poverty and/or progress. The results are then interpreted in the broader economic and environmental context of the watershed, and the implications for potential poverty-environment tradeoffs are identified. In the case of Colombia, the results show that while many households do improve their welfare status by investing in improved water access, opportunities to lift households out of povetry via better water access alone are limited. Off-farm labor, mainly in mining and commercial dairy, were the major pathways out of poverty in the region. Since activities also contrinutors to environmental problems in the watersheds, the potential exists for poverty- environment tradeoffs. The results demonstrate potential of multi-scale analysis to contribute to the design of interventions that minimize tradeoffs between environmental and social welfare objectives.

Introduction

Watersheds, especially in the developing world, are increasingly being managed for both environmental and rural development objectives. The actual and potential linkages between land and water management and poverty are, however, complex and may be site specific and scale dependent (Swallow *et al.* 2006). Sorting out these relationships to arrive at policy- and management-relevant conclusions requires methods of poverty assessment that allow for complex relationships but are not too complex or costly to implement, since site specificity may limit the extent to which results can be extrapolated from one site to another.

This paper uses the stages of progress methodology (Krishna 2002) to assess the relationship between water and poverty in two watersheds in the Colombian Andes. The methodology includes both a participatory assessment of current poverty and an analysis of how household poverty status has changed over the last 25 years. Taken together, the two results capture both direct and indirect linkages between water and poverty. They identify situations where win-win solutions may be possible, and also where it is likely that trade offs will be required, not only between environmental, economic growth and equity objectives at the watershed scale, but also between households' welfare objectives and the strategies that they use to achieve them.

The paper is organized as follows. The next section summarizes the literature on poverty and watersheds, from the perspective of watershed management and diversification of livelihoods. We then describe the study watersheds, followed by the presentation of the SOP methodology. We then present and analyze the results, and conclude with a discussion of the implications for policy and practice, using examples from the watersheds.

Watersheds: The "missing middle" in livelihoods research

The complex relationship between watershed management and poverty alleviation rests on the fact that watershed management is not just about managing water, but is also about managing land, forests and other resources. The livelihood strategies of the poor interact with these resources in a range of ways. Even though they may not "own" them, the poor, even the landless poor, are often able to access and use resources, which means that changes in the rules that govern resource use can directly affect them.

In addition, livelihood strategies of rural households are increasingly diverse. Even in rural areas, households do not depend exclusively on agriculture or extraction of natural resources. Off-farm income from sale of labor or commercialization of products and services is important for household welfare of the rural poor. Therefore, the impacts of environmental, industrial, transportation and other policies that often are considered as coming under the ambit of watershed management may have significant implications for the their welfare.

Poverty and watershed management

The term watershed management refers to the use and management of inter-dependent resources—cropland, pastures, forests, wetlands, as well as water--within hump-backed "watersheds" that dispose water into streams and bowl-shaped 'catchments" that collect water into a common outlet (Swallow *et al.* 2001*b*, Kerr and Chung 2001). Because watersheds integrate diverse resources, environmental services, uses and users, an integrated approach to management that considers the goods and services they provide is essential. Often these goods and services, for example, soil stabilization, water catchment protection, agricultural land, pastures, forests, or wetlands have significant impacts on livelihoods of the rural poor who live both in upstream and downstream areas of a watershed.

The interconnectedness of upstream and downstream sections of watersheds has been extensively investigated by biophysical scientists studying hydrological cycles, stream flows, soil nutrient and sedimentation flows. In contrast, a similar unified analyses of livelihoods, poverty and land use along different points of the watershed are lacking. Many social and economic studies have focused on individual elements within a watershed such as agricultural land or forests, but not on the watershed as a system that is both biophysical and social, with two-way linkages between upstream and downstream (Swallow *et al.* 2006). Researchers are increasingly recognizing the watershed as the "missing middle" for research on land use and livelihoods (Swallow and Meinzen-Dick 2001), where land use and environmental services have impacts beyond the individual farms yet not at the regional or global level.

Some evidence exists that there may be a synergistic relationship between rural development and watershed management. A recent global review of watershed management projects implemented in the last 25 years indicates that projects that focused on individual farms rather than the entire watershed tended to be site-specific, isolated and dispersed, serving farmers superficially but reducing the potential of broader impact (Perez and Tschinkel 2003). In contrast, better integrated projects had scope for increasing ecological benefits while at the same time contributing to the economic development of poor rural communities (Grewel *et al.* 1999). For example a watershed management project in the Himalayan foothills in the northern states of India included various ecological restoration and conservation efforts as well as water development and breed improvement. It resulted in increased employment, increased maize and wheat yields and reduced drudgery of women, among other benefits.

A better understanding of the adaptive capacities of the rural poor to manage water supply and quality in light of their multiple needs and the multiple functions of watersheds is necessary in integrated watershed management programs (Fereres and Kassam 2003). It provides an opportunity for addressing natural resource management as well as important socio-economic problems.

Understanding livelihoods and their implications for watershed resource use

A livelihood comprises a household's 'means to a living', or its strategy to attain a level of material well-being, which can be reflected in income, consumption, satisfaction, health, longevity and other measures (Bezemer and Lerman 2004). For example, household livelihood strategies may involve different members of the family seeking and finding different sources of food, fuel, animal fodder, cash and support in different ways in different places (on farm, through commonly shared resources, or markets) at different times of the year (Chambers 1995). Livelihood strategies are complex and diverse, contributing to household incomes in ways that are not always immediately evident to an external observer.

Components of livelihoods that enable households to make a living include assests (natural, physical, human, social and financial) and the activities by which individuals gain to access these assets. The way that households combine these assets, the trade-offs they may make between assets at different times and the welfare outcomes are the subject matter of poverty and livelihoods analyses. However, De Haan and Zoomers (2005) encourage analysts to look beyond material aims and motives, and also to consider the structures and processes that may enhance or limit activities and assets. Property rights and power relations often influence the range of activities that individuals and groups can engage in. Similarly, geographical settings, seasonality and distance to markets all influence the set of opportunities and outcomes available to the poor (Zoomers 1999).

It has long been established that the rural poor engage in multiple livelihoods strategies. In eastern Zambia for example, Peterson (1999, cited in Gladwin *et al.* 2001) shows that while agriculture forms the basis of households' incomes, it is not the only source. Women are engaged in alternative cash-generating activities including beer brewing, sale of snack foods, vegetable production and processing and selling, performing *ganyu* (piece work), and petty trading. Men also are engaged in informal income-generating activities, including renting out oxen for plowing, made brick making, construction, selling firewood and various forms of petty trading.

These diverse activities are generally classified into those that generate incomes away from one's family farm (off-farm) and those non-farm activities that involve the processing of raw goods into secondary and tertiary products (such as flour milling, cheese production) or use labor for the production of services (Barrett and Reardon 2000). In general these portfolios can be measured, often by studying the allocation of resources, mainly labor, to different activities or in terms of household income shares. Although Africa is largely viewed as a continent of subsistence farmers, non-farm sources are growing in importance and account for up to 45% of household incomes (see Bryceson and Jamal 1997, Reardon 1997, Little *et al.* 2001 cited in Barrett *et al.* 2001). For a detailed distinction of rural livelihoods strategies and their different income returns 2000*b*), however non-farm incomes overshadow those based entirely on agriculture.

Multiple strategies, multiple motivations and effects on rural welfare

There are many reasons why individuals attempt to diversify their strategies (Barret, Reardon and Webb 2001). First, "push factors", which include risk reduction, response to declining returns to assets, and high transactions costs, push households towards self-provision. For example, African women farmers combine farm and non-farm income-earning activities to reduce risk and food insecurity where drought and pest attack reduce food security (Gladwin *et al.* 2001). Following the introduction of structural adjustment policies, small-holder farmers in Malawi resorted to micro-enterprise and closer integration with markets, which allowed them to adapt to increasing prices of organic fertilizer, loss in soil fertility and declining maize yields (Orr and Mwale 2001).

Second, "pull factors" include realization of complementarities between activities such as crop-livestock integration, specialization due to advantages offered by superior technology, skills or endowments. These push and pull factors do not operate at the household or individual level alone, but are often linked to structural-level constraints/opportunities. Weak or incomplete financial systems can create incentives for individuals to select activities that will smooth income and consumption in the face of climatic uncertainty, labor and land constraints. Similarly, proximity to urban areas can create opportunities for diversification in production- and expenditure-linked activities. In sum livelihood diversification can serve the function of risk mitigation (Turner *et al.* 2003) or be a coping/survival strategy (Wood 2003, Orr and Mwale 2001, Reardon *et al.* 2001) or even a pathway out of poverty (Ellis 2000).

But what are the effects on incomes and welfare of livelihood diversification on the rural poor? Does livelihood diversification, which is the consequence of individuals and households pursuing multiple livelihoods, have beneficial and unambiguous effects on rural livelihoods? A growing number of studies in different parts of the world suggest that indeed it does. In Nepal, farmers in the central and western mid-hill regions of are increasingly participating in off-farm wage labor to the point where it contributes significantly to farm income (Shivakoti and Thapa 2005). In Ethiopia, Block and Webb (2001) show that income diversification is positively linked to improved welfare, including nutrition. In Tanzania income shares in peri-urban areas rise with per capita food consumption (Lanjouw *et al.* 2001), while Barrett *et al.* (2001*a*) report a strong, positive association between greater income diversification and wealth in Cote d'Ivoire and in Kenya.

However, the gains of diversification are tempered by access to public services such as education, communication and transportation, which determine participation in nonfarm activities. In Uganda greater diversification increased income inequality. Poor, uneducated, women, recent migrants, and others lacking social ties enjoyed less access to new income-generating opportunities compared with educated males with strong social networks in the community (Canagarajah et al??? 2001). Moreover, the impacts of increased off-farm activities on land management practices are yet to be more carefully assessed. In the Honduran hillsides, for example, soil conservation is negatively associated with off-farm work; rather than use their off-farm income to boost their farming, farmers tend to practice minimally extensive farming because farming is now relegated to food security alone (Morera and Gladwin 2006). The authors suggest that off-farm work should be treated as one amongst many strategies as opposed to the main development strategy in the effort to resolve poverty.

The analysis of "off-farm" incomes is incomplete without including products and services that are accessed from areas that are off-farm but not necessarily in secondary or tertiary industries, typically on the commons. Such areas include common pool resources that may be held and managed under various property regimes such as common property or state property. These include forests, fisheries, pastures, swamps, roadsides that can be exploited for fodder, building material, food, game meat, fish, medicine etc.

A cross section of studies in different settings shows that the commons often have a positive contribution on the livelihoods of the poorer and marginalized members of communities. In certain parts of India, income derived from CPRs contributes about 12% to the household incomes of poorer households (Beck and Nesmith 2001), and 15-25% in other parts (Jodha 1986, 1995). Reddy and Chakravarty (1999) found that forest income was associated with small reductions in income inequality for a sample of northern Indian farmers. In Zimbabwe, the share of household income attributed to CPRs is close to 40% for the poorest income quintile (Cavendish 2001), thus contributing to redistributive equity. In Malawi, Fisher (2004) found that 30% derive incomes from forests, which results in 12% reductions in measured income inequality. Here, asset-poor households were more reliant both on both low- and high-return forest activities, compared with the better off. In southeastern Ghana the poorest households rely on sources to meet 20% of their food requirements during the lean season, compared to providing 2% and 8% of wealthy and middle-income households needs respectively (Dei 1992). Taken together, these studies show that products from the commons can improve the welfare of the rural poor by supplementing incomes and acting as safety nets when other opportunities are lacking, or even as ways to reduce poverty where earnings are high enough.

In considering the livelihoods strategies and their contributions to rural welfare it is evident that off-farm incomes are critical, but that the magnitude of benefits vary depending on prior distribution of assets such as education, social networks and on structural factors such as market access and also on gender; all of which are critical entry barriers. The category of off-farm income can also be expanded to include incomes derived from resources on the commons. These are important safety nets for the poor, do help to mitigate income inequalities and can under certain conditions contribute high earnings.

Description of the study sites

Lake Fuquene Watershed

The Fuquene Lake and Coello River watersheds are typical of the socio-environmental situation in the Andes (Ramírez and Cisneros 2006). Fuquene Lake watershed (Fuquene), which encompasses the valleys of Ubate and Chiquinquira in the state of Cundinamarca, Colombia (Figure 1), has an area of 187,200 ha and a population of 229,000 (Rubiano 2005), about 59% of which is rural (DANE 2005). The altitude ranges from 2300-3300 masl, with an annual rainfall range of 700 and 1500 mm.

Fuquene is located about two hours from the Colombian capital, Bogotá, on a good all-weather road. The area of influence of the watershed includes 17 municipalities in the states of Cundinamarca and Boyaca[4]. For the municipalities in the watershed, the 2003 life condition index, a measure of welfare, ranges between "very low" and "high" (Sarmiento et al, 2006), reflecting the socioeconomic heterogeneity in the zone.

[4] The municipalities that belong to the Fuquene watershed are Carmen de Carupa, Ubate, Tusa, Sutatausa, Cucunuba, Suesca, Villapinzon, Lenguazaque, Gacheta, Fuquene, Susa y Simijaca in Cundinamarca and San Miguel de Sema, Raquira, Caldas, Chiquinquira y Saboya in Boyaca.

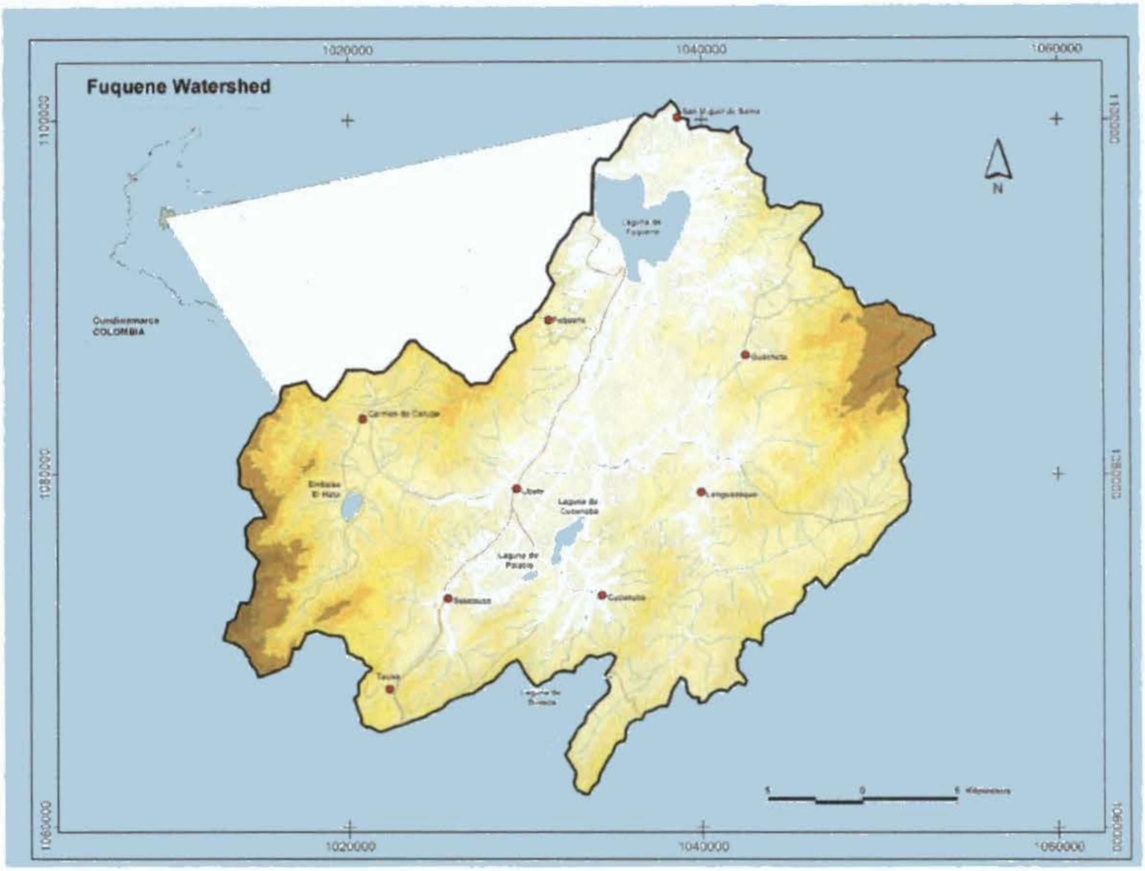

Figure 1. Fuquene watershed, Colombia

The largest land use in the watershed is pasture (59%), followed by agriculture (26%), forest (4%), paramo (2%) and lake (2%) (Rubiano *et al.* 2006). Land degradation is important, with 13,000 hectares classified as severely eroded and 40,000 as moderately eroded. In the past, major investments were made in soil conservation activities, however aside from stabilizing fragile areas, the impact of these investments on productivity has not yet been rigorously assessed. Conservation tillage has been widely promoted, however adoption has been limited until recently when payment for environmental services (PES)-type schemes have begin to promote it.

The principal economic activities in the watershed are livestock, agriculture and mining. Livestock are mainly raised in the lower part of the watershed, in highly productive, high-input, medium- and large-scale dairy farms. Crops are grown in the upper and middle parts of the watershed. Land ownership is generally by smallholders, however in the higher areas appropriate for potato cultivation, much of the land is rented out to large-scale producers who are willing and able to take the risks associated with a crop like potato whose production costs are high and whose market price is highly variable.

Because of the potential profitability of potato, significant cultivation occurs in the paramos, which are ecologically fragile and play a key role in maintenance of ecosystem function, especially supply and regulation of water flow (Rangel, 2006). Destruction of páramo is a concern for communities in the upper areas as well as downstream. Agricultural production on these ecologically important areas is restricted by law, however there are problems with implementation. By law, municipalities are mandated to buy land in upper watersheds to protect water sources, and this is beginning to happen in some areas.

The middle part of the watershed is mainly occupied by small farms producing grains and legumes. Decades ago, these were productive family farms, however a combination of massive soil degradation, changing rainfall patterns, and the opening of markets to external competition significantly reduced the relative profitability of grain farming. Some large-scale soil conservation and reforestation project were implemented, but with little effect. As a result, the middle part of the watershed has experienced large-scale out-migration of young people, and those who stay depend mainly on off-farm work and transfer payments.

The lake, located at the bottom of the watershed, is at the center of environmental controversy and is the issue driving change in the watershed[2]. In the past, government policy was to drain the lake to make more land available for agriculture (Mayorga 2003). The policy was reversed, however the surface area of the lake continues to decline due to of eutriphication and an explosion of water hyacinth caused by in part to agro-chemical run off from both crop and dairy farms and untreated domestic waste water.

The national government and the regional environmental authority have placed high priority on resolving the problems of Fuquene, and after large-scale flooding downstream of the lake in the spring of 2006 was attributed to reduced capacity of the lake, the President called for a Consejo Nacional de Política Económica y Social (Conpes), a special initiative to address an urgent problem of national significance. (DNP, 2007)One option is to focus on a technical solution such as dredging the lake, however this is likely to be very costly and unsustainable unless the underlying causes of watershed degradation are addressed. Addressing them is complicated by the fact that any policy changes could have implications for farm profitability and, by extension, land values. Cities downstream of the lake rely on it for drinking water supplies, however they have not yet perceived the threat and mobilized in response to it.

Mining is also an important economic activity in some municipalities in the Fuquene watershed, and has increased in recent years due to the record high prices of coal (team Scales Projec, 2005a, 2005b). The industry consists of both large-scale, regulated mines and small, informal operations, the latter having increased dramatically with the increases in price. Mining is an important source of income and employment and draws migrants from other regions; however it is also a major contributor to water pollution (team Scales Projec, 2005a, 2005b).

The environmental authority for the Fuquene watershed, the Corporacion Autonoma Regional de Cundinamarca (CAR)[3] ,is in charge of allocating water permits and collecting water charges, and has participated in conservation activities. However, there is widespread discontent with the fact that the CAR has yet to develop and implement a management plan that addresses the issues facing the watershed. Local municipal governments have some responsibility for resolving water conflicts and for undertaking conservation activities. While some are more active than others, they are limited in what they can achieve given their purely local scope.

Coello River Watershed

The Coello River watershed, located the state of Tolima in the central Andean Cordillera (Figure 2)[4] has an area of 190,000 ha, ranging from 280 to 5300 masl. Annual rainfall ranges from below 1000 mm to more than 3970mm. The watershed includes ecosystems ranging from dry forest to páramo to snow-capped peaks, and is home to national parks and private reserves (team Scales Projec, 2005a, 2005b). The population of the watershed was 622,395 in 2005, including the city of Ibagué (pop. 425,770). Only 16% of the population is rural; excluding the municipality of Ibague, urbanization rates are still above 50%. The life condition index for municipalities in the Coello watershed ranges from medium low to medium high, a

[2] See http://www.livinglakes.org/fuquene/.

[3] See http://www.car.gov.co

[4] The municipalities that make up the Coello River watershed are Ibague, San Luis, Rovira, Cajamarca – Anaime, Espinal, Flandes, Valle del San Juan y Coello.

slightly narrower range than for Fuquene. While indicators are generally higher in Ibague, in the rural municipalities there are problems with basic coverage of primary and secondary schools (Sarmiento *et al*, 2005).

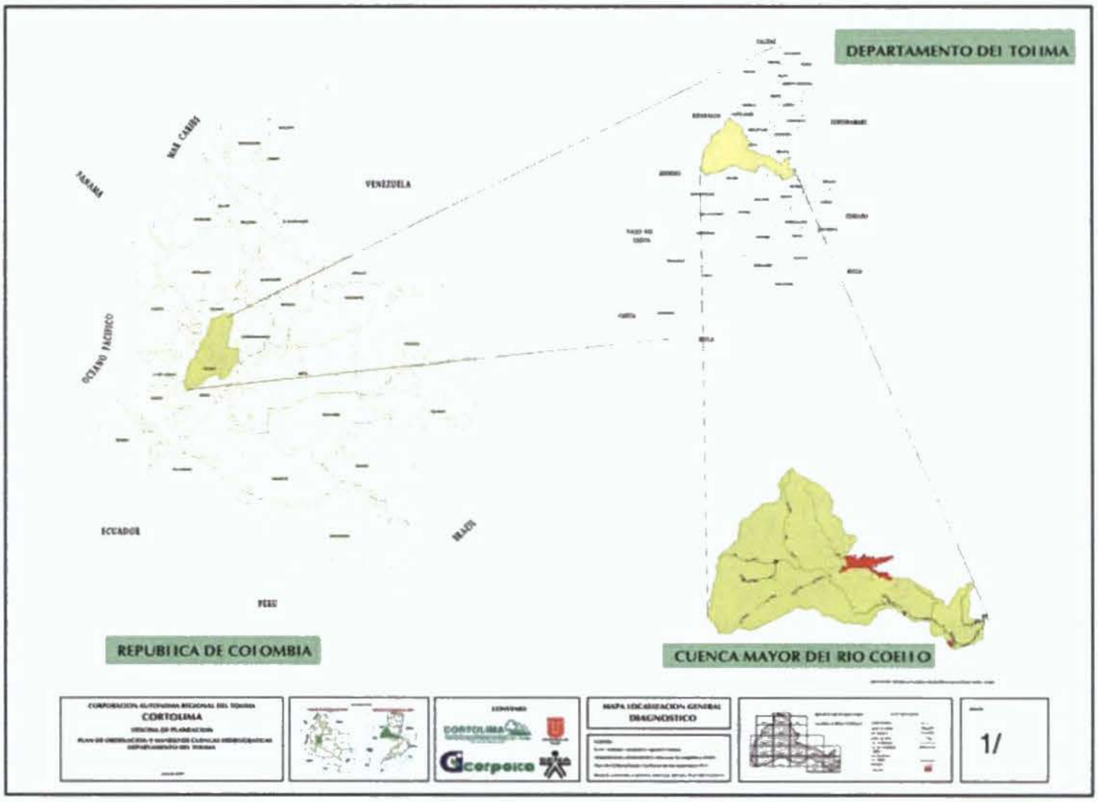

Figure 2. Coello watershed, Colombia

Principal economic activities in Coello include agriculture and livestock. The upper part of the watershed is mainly forested, however land there is increasingly being converted for livestock, coffee and horticultural crops. In the middle altitude areas, sugar cane and fruit trees are common, and the lower part of the watershed includes 30,000 ha of large-scale, irrigated rice, cotton, and sorghum. Landownership is highly unequal (team Scales Projec, 2005a, 2005b), however small-scale agriculture is more viable in Coello than in the middle part of Fuquene because the land is less degraded.

The Panamerican highway passes through the watershed, generating economic activity but at a cost of soil erosion and air pollution.

In the upper parts of the watershed, there is presence of actors in Colombia's armed conflict, something which is not true in Fuquene. The security situation is much more serious in Coello, and there is significant internal displacement.

Water has not traditionally been scarce in Coello, however there is growing awareness that inappropriate land use in the upper watershed combined with growing demand for irrigation, domestic water and hydroelectric power in the lower areas are rapidly leading to a situation that is not sustainable. Water quality is also an issue as contamination is increasing due to agrochemical use, and domestic and industrial waste.

The environmental authority in Coello is the Corporacion Autonoma de Tolima (CorTolima (http://www.cortolima.gov.co), and as in Fuquene the local governments also have important responsibilities. There is a wider range of actors in Coello than in Fuquene, including environmental NGOs, universities, the irrigation district, and agricultural producer associations.

Poverty dynamics and the stages of progress (SOP) methodology

While national-level poverty rates are often slow to change, for many of the rural poor, poverty is not a static situation. It changes according to various influences such as seasonality, climate variability, household-level shocks (such as illness and death) and lifecycle changes, and public policies. In addition, the group of poor people is itself constantly changing, individuals and households can escape from poverty but they can also descend further into poverty. There is therefore a need to track the movement into and out of poverty and to explain it. A longitudinal analysis of household welfare can foster a better understanding of the conditions that keep people in poverty and those that move them out in order to identify general patterns and to assist policy targeting (eg Sen 2003, Barrett, Carter and Little 2006). It provides us with better insights into the processes that lead to patterns of disadvantage and inequality, but also different ways by which the poor may improve their welfare. In both cases, public policy can be tailored to include protection for the most vulnerable without pulling back those that are escaping.

The stages of progress (SOP) methodology (http://www.pubpol.duke.edu/krishna/methods.htm) were developed to assess the dynamics of poverty and the causes behind them. SOP is a participatory methodology that relies on community definition of poverty at a household scale. The poverty level of each household in the community is assessed, and explanations sought of the causes behind changes in poverty level over time. The method takes its name from the stages or steps that each household passes through as it makes its way out of poverty. To define the stages, the group must first come to agreement on a definition of the "poorest family in the community." Once this is done, the group successively answers the question "What would this family do with a little more money?" until they reach the point at which the household is considered prosperous. Because they are defined locally and in reference to a particular poor family, they vary by community and reflect the specific conditions and values of the community.

Once the stages are identified, the group then assigns each family in the community—based on a census which must be obtained or constructed— to the stage where they currently are and the stage where they were at some point in the past, usually 10, 20 or 25 years ago. Families are then categorized as follow:

A – Poor in the past, poor now
B – Poor in the past, not poor now
C – Not poor in the past, poor now
D – Not poor in the past, not poor now

For a randomly-selected sub-sample of families, the community then identifies the reasons for any change in stage. The final stage in the methodology is to conduct follow-up interview with a sample of families to confirm the results of the community analysis and to gather more information on specific issues. In the case of this study, interviews included questions on water use, conflicts, and management at the household and community scale.

Using this methodology, studies in India, Kenya and Uganda reveal that factors associated with decline are distinct from those associated with escape. Generally, decline is associated with ill-health and high cost of healthcare, while escape from poverty is most commonly associated with income diversification through trade and employment (Krishna, 2006, 2004; Krishna *et al.* 2006; Krishna *et al.* 2004). However there are variations. In Rajasthan, high-interest private debt, and large social and customary expenses constitute major additional reasons for households declining into poverty. In Andhra Pradesh, drought, membership in a scheduled tribe and large family size were additional factors that contributed to decline into poverty.

Irrigation and access to non-traditional crops were further reasons associated with escape from poverty in Andhra Pradesh. While land and the uneconomic subdivisions are seen as a primary concern among declining households, access to land was found to be critical for those that escaped poverty in Uganda.

A quantitative and qualitative analysis of poverty across two time periods in Uganda identified asset ownership and access as major factors that influence poverty transitions and persistence. Education, land and cattle are the primary assets identified, while increasing household size and high dependency rates were seen as key factors in decline. Non-agricultural activities provide an important escape route in rural areas, however, this is determined by levels of human capital.

Data and results from two Colombian watersheds

For this study, the SOP methodology was applied in 13 communities (veredas) in six municipalities in the Fuquene watershed, and ten communities in five municipalities in the Coello watershed during the first half of 2005 (Table 1). Sites were selected in the upper, middle, and lower parts of the watershed, on the basis of prevalence of poverty and the expected intensity of water conflicts. Site selection was based on available secondary data and on extensive interviews with key informants in the region. Information gathered in each community consisted of quantitative data from the SOP methodology—including movement in and out of poverty and their main causes—as well as qualitative data from interviews with households and key informants, and from observations by project staff in the field.

Table 1. Sites where the SOP methodology was applied

State	Municipality	Community	# of households
Fuquene	1 Tausa	Ladera Grande	53
		Rasgata Bajo	41
	2 Sutatausa	Chipaquin	94
		Palacio	59
		Peñas de Cajon	69
	3 Guacheta	Gacha	128
		La Isla	92
		La Puntica	90
	4 Fuquene	Centro y Guata	182
		Chinzaque	39
		Nemoga	119
	5 Cucunuba	Chapala	86
	6 Carmen de Carupa	Apartadero	43
Coello	1 Cajamarca	La Leona-APACRAQ	
		El Rosal	
		La Alsalcia	
		Minidistrito La Leona	
	2 Ibague	Coello COOCRA	
		San Cristobal-Honduras	
	3 Espinal	Dindalito	60
	4 Coello-COCORA	Potrerillo	
		Chaguala Adentro	
	5 Rovira	La Ocera	

The importance of water in the definition of poverty and stages of progress

The poorest families in the communities were identified as landless day laborers who lacked quality housing, health care and other services, and who were unable to send their children to school. Non-material dimensions of poverty were also mentioned. In both watersheds, non-participation in community activities was also considered to be an indicator of poverty. Half of the communities in Coello included this in their definition of the poorest family. In Fuquene, participation in community activities was considered to be a component of well being.

The number of stages that communities defined ranged from 7 to 24, and the number of stages below the poverty line ranged from 3 to 10. As expected, shortages of the basic necessities such as food, education, clothing and housing were the most common early stages in nearly all communities. As household welfare increased, the items mentioned in the stages began to diverge with some communities focusing more on agriculture-related investments, others on services and others on durable goods (Table 2).

Table 2. Frequency of categories of items that appear as stages below the poverty line, in order of importance.

Description	Order	Frequency
Food	1	20
Education	2	18
Clothing	3	12
Housing	4	15
Small animals	5	14
Land	6	8
Services	7	8
Appliances	8	8
Health	9	4
Crops	10	4
Other	11	2
Transportation	12	2
Savings/Investment	13	1
Recreation	14	2

Some communities were much more demanding than others in terms of what a household must have in order not to be considered poor. Often the communities that were better off on the basis of objective well-being measures were more demanding. For example, some communities required only food, education and shelter, while in others households were considered poor until they had land, television sets or the means to engage in recreational travel. This led to the more demanding communities being classified by SOP as having higher levels of poverty than other communities, which by objective measures were likely to be poorer[5].

As such, these results will not necessarily be consistent with national poverty statistics, nor will they be comparable across communities. It is important to keep in mind that the purpose of a subjective poverty assessment such as the SOP is not to identify uniform indicators, but rather to classify families in a way that local people understand and that will allow them to carry out the analysis of the dynamics of poverty. The fact that the poverty measures may not be consistent does not invalidate the results regarding livelihood strategies that are associated with poverty and/or progress.

[5] For a detailed analysis of the SOP poverty lines, their components and their relationship to other poverty measures, see Peralta *et al.* 2006.

Access to water is clearly an important element of well being since 23 of the 25 communities mentioned access to water as a stage, either directly or as part of sanitation services. In only one community (Chinzaque in Fuquene) was agricultural use of water specifically mentioned. While acquiring water usually means getting a household connection to a potable water system, domestic water is often used for productive, income-generating activities as well. In Fuquene, for example, small-scale cheese processors must have access to potable water in order to get certification to sell their products.

In eleven communities (44%), water was included in categories below the poverty line while in 56% it was either not mentioned or was in categories above the poverty line. One reason that water is in categories above the poverty line is that in many cases households have good access to water from natural sources such as wells or springs or from shared taps. Thus, a home connection is somewhat of a luxury. Where water is in categories above the poverty line, improving access would improve livelihoods but would not reduce poverty. In three communities (12%), water was the included in the stage just below the poverty line, which means that improving access could literally get households out of poverty. Ranked from most to least demanding, the three communities where water is the last stage before getting out of poverty occupied 5th, 15th and 20th places.

What this means in terms of how many poor households could actually be helped by better access to water in these two watershed depends on how many still do not have it. According to the data, 13% of households are without water in communities where access to water is included in categories below the poverty line. Of these 4% are at the limit where getting access to water would get them out of poverty. Of the remaining households, only 8% are without water however by community standards they are not considered poor. The remaining 78% of households already have water.

Thus it seems that improving household access to water would not be an effective way to address poverty in these watersheds. There are specific cases of households and communities that would benefit significantly from improved access to water, but in general this is not the case. As Table 2 suggests, interventions to improve access to food, education, clothing, housing, small animals or land would be better targeting towards helping the poor.

Role of water in the dynamics of poverty

According to the results of the categorization of families (Table 3) poverty declined in nearly all communities over the last 25 years. In 1980, roughly 70% of families in both watersheds lived in poverty. Between 1980 and 2005, 30% of the families in Fuquene escaped poverty (Category B), while only 3 percent fell into poverty. In Coello, the results are even more dramatic; 59% of families got out of poverty while only 3 percent became poor. These results clearly show that people in rural communities perceived important advances in their quality of life in recent decades. Nonetheless, over 40% of families in Fuquene and 10% of families in Coello continued to be poor in 2005.

Table 3. Changes in poverty status from 1980 to 2005 (% of families per category).

Vereda	N	CatA Poor-poor	CatB Poor-not poor	CatC Not poor-poor	CatD Not poor-not poor	CatE New arrival
Fuquene						
Ladera Grande	53	66	8	17	4	6
Rasgata Bajo	41	24	22	2	5	46
Chipaquin	32	34	41	13	13	0
Palacio	59	37	47	0	2	14
Peñas de Cajón	69	17	61	0	0	22
Gacha	81	38	26	6	28	1
La Isla	92	40	30	3	25	1
La Puntita	90	39	32	0	4	24
Centro y Guata	82	90	1	0	1	7
Chinzaque	39	23	46	3	28	0
Nemogá	119	13	29	4	46	8
Chápala	86	83	13	0	0	5
Apartadero	43	30	70	0	0	0
TOTAL	886	42	30	3	14	10
Coello						
Apacra	13	0	31	0	69	0
El Rosal	13	0	77	8	15	0
La Alsalcia	14	21	57	0	21	0
Minidistrito La Leona	11	45	55	0	0	0
Cocora	18	6	22	0	44	28
Dindalito	26	15	46	8	31	0
San Cristóbal-Honduras	19	5	47	5	42	0
Potrerillo	31	0	100	0	0	0
Chaguala	14	29	57	7	7	0
La Ocera	16	6	75	0	19	0
TOTAL	175	11	59	3	24	3

For each family in the survey, up to three causes were identified to explain the change in poverty category between 1980 and 2005. A total of 25 causes were identified (Table 4). Among the causes that were mentioned in first place for each family, the most important was off-farm employment (20%), followed by inheritance (17.2%), help from family and friends (9.4%), day labor (7.8%) and help from the government (7.5%). These results are consistent with diversification of rural livelihoods.

Table 4. Principal causes of change in poverty status (% of families)

Cause	Mentioned as first cause (n=361)	Mentioned as second cause (n=284)	Mentioned as third cause (n=133)	All (N=778)
Government help	7.5	4.9	14.3	7.7
Help of family and friends	9.4	16.2	8.3	11.7
Unexpected loss	0.3	0.0	0.8	0.3
Unexpected benefit	0.3	0.0	0.0	0.1
Education/training	1.9	3.5	8.3	3.6
Off farm employment	20.0	20.1	8.3	17.0
Day labor	7.8	9.9	5.3	8.1
Small or low quality landholding	0.8	0.7	0.8	0.8
Credit	0.6	2.5	3.0	1.7
Illness/accident	3.6	1.8	2.3	2.7
Large family	1.4	0.7	0.8	1.0
Small family	0.0	1.1	3.0	0.9
Newly established family	3.9	1.1	0.8	2.3
Agriculture	6.1	7.7	11.3	7.6
Livestock	1.7	3.2	8.3	3.3
Good money management	0.6	2.1	0.8	1.2
Bad habits	3.3	2.1	0.0	2.3
Legal or family problems	3.0	1.1	1.5	2.1
Inheritance	17.2	6.3	6.8	11.4
Savings/investment	3.3	10.6	9.8	7.1
Old age	0.8	0.4	0.0	0.5
Pension	4.4	2.1	2.3	3.2
Community work/collective action	0.6	1.4	3.0	1.3
Fishing	0.8	0.7	0.8	0.8
Migration	0.8	0.0	0.0	0.4
Total	100	100	100	100

While not related to one's own farm, off-farm employment in these watersheds usually refers to steady work that is agriculture- or natural-resource-based. The dairy sector in Fuquene generated significant employment, ranging from administrators who manage farms for absentee landlords to milkers, mainly women and often heads of households. Small and medium scale agro-enterprises based on production of value-added dairy products, such as cheese and yogurt, were also common in Fuquene. The sale of services such as machinery rental to farmers and in the commercialization and/or transportation of agricultural products such as fruit, coffee or livestock were common in both watersheds. Mining was also an important source of off-farm employment in some municipalities in Fuquene as was the collection and sale of sand and other materials from the river in Coello.

Among secondary causes, off-farm jobs and family help continue to be important, however other causes such as agricultural production and savings and investments also were mentioned. Government assistance and agriculture were the most important third causes.

The results are similar for Fuquene and Coello, with the important exception that agricultural production was much more important in Coello than in Fuquene (Tables 5 and 6). In Coello, agriculture is the most frequently mentioned first cause, followed by off-farm labor and day labor as the second and third causes for changes in poverty status.

Table 5. Principal causes of change in poverty status, Fuquene (% of families)

Causes	Mentioned as first cause (n=251)	Mentioned as second cause (n=187)	Mentioned as third cause (n=71)	% of all causes mentioned
Government help	6.4	4.8	7.0	5.9
Help of family and friends	8.4	15.0	9.9	11.0
Unexpected loss	0.0	0.0	1.4	0.2
Education/training	1.2	2.1	4.2	2.0
Off-farm employment	23.9	23.5	11.3	22.0
Day labor	7.2	8.0	4.2	7.1
Small or low quality landholding	0.4	1.1	1.4	0.8
Credit	0.0	0.0	4.2	0.6
Illness/accident	4.0	1.6	4.2	3.1
Large family	1.6	0.0	1.4	1.0
Small family	0.0	1.6	4.2	1.2
Newly established family	5.6	1.6	1.4	3.5
Agriculture	2.4	4.3	5.6	3.5
Livestock	0.8	3.2	8.5	2.8
Good money management	0.4	1.6	0.0	0.8
Bad habits	3.6	2.7	0.0	2.8
Legal or family problems	2.0	0.5	0.0	1.2
Inheritance	18.7	9.1	11.3	14.1
Savings/investment	3.6	14.4	14.1	9.0
Old age	1.2	0.5	0.0	0.8
Pension	6.0	3.2	4.2	4.7
Community work/collective action	0.4	0.0	0.0	0.2
Fishing	1.2	1.1	1.4	1.2
Migration	1.2		0.0	0.6
Total	100.0	100.0	100.0	100.0

Table 6. Principal causes of change in poverty status, Coello (% of families).

Causes	Mentioned as first cause (n=110)	Mentioned as second cause (n=97)	Mentioned as third cause (n=61)	% of all causes mentioned
Government help	10.0	5.2	5.2	7.1
Help of family and friends	11.8	18.6	18.6	15.8
Unexpected loss	0.9	0.0	0.0	0.4
Unexpected benefit	0.9	0.0	0.0	0.4
Education/training	3.6	6.2	6.2	5.1
Off-farm employment	10.9	12.4	12.4	11.8
Day labor	9.1	13.4	13.4	11.6
Small or low quality landholding	1.8	0.0	0.0	0.7
Credit	1.8	7.2	7.2	5.0
Illness/accident	2.7	2.1	2.1	2.3
Large families	0.9	2.1	2.1	1.6
Agriculture	14.5	14.4	14.4	14.5
Livestock	3.6	3.1	3.1	3.3
Good money management	0.9	3.1	3.1	2.2
Bad habits	2.7	1.0	1.0	1.7
Legal or family problems	5.5	2.1	2.1	3.5
Inheritance	13.6	1.0	1.0	6.2
Savings/investment	2.7	4.1	4.1	3.6
Pension	0.9	0.0	0.0	0.4
Community work/collective action	0.9	4.1	4.1	2.8
Total	100.0	100.0	100.0	100.0

As expected, in the majority of cases specific causes are associated with either progress or poverty. Regressing cause dummy variables (1=cause was mentioned for the household, 0=no) on a dummy for whether the household was poor in 2005, we can see the contribution of each cause to poverty (Table 7). According to the results (Table 8) the probability of being poor in 2005 was reduced for families with stable jobs (-37%), agricultural production[6] (-35%), government help (-30%), pensions (-27%), help from family and friends (-23%), livestock (-23%), savings and investment (-22%), or inheritance (-17%). The probability of being poor in 2005 was increased by family problems (+62%), health problems or accidents (+37%), or starting a new family (+25%).

[6] In Coello, no agricultural households were ranked as poor in 2005.

Table 7. Impact of major causes of change in poverty status on whether household was poor in 2005 (n=359).

Cause	Coef.	Std. Err.	z	P>|z|	95% Conf. Interval		Mean
Fúquene	0.8294	0.2606	3.18	0.001	0.3185	1.3402	0.6953
Government help	-0.7866	0.2522	-3.12	0.002	-1.2809	-0.2923	0.1662
Help from family and friends	-0.8534	0.2246	-3.8	0	-1.2935	-0.4133	0.2521
Education	-1.2576	0.4380	-2.87	0.004	-2.1161	-0.3992	0.0776
Off-farm employment	-1.2735	0.1983	-6.42	0	-1.6621	-0.8849	0.3934
Health/accident	0.9861	0.4466	2.21	0.027	0.1108	1.8615	0.0582
New families	0.6794	0.4182	1.62	0.104	-0.1402	1.4990	0.0499
Agriculture	-1.8283	0.3797	-4.82	0	-2.5725	-1.0842	0.1634
Livestock	-1.0400	0.4285	-2.43	0.015	-1.8799	-0.2001	0.0720
Family problems	1.7996	0.7036	2.56	0.011	0.4207	3.1786	0.0443
Inheritance	-0.5756	0.2077	-2.77	0.006	-0.9827	-0.1684	0.2465
Savings and investment	-0.8336	0.2399	-3.48	0.001	-1.3037	-0.3635	0.1773
Pension	-1.3996	0.4045	-3.46	0.001	-2.1925	-0.6067	0.0693
Constant	0.3137	0.2703	1.16	0.246	-0.2162	0.8435	

LR chi square (13) 205.8, log likelihood = -128.48344, pseudo $R^2 = 0.4447$.

Table 8. Influence of cause on probability of being poor

Cause	Delta P(Poor2=1) without cause (i) - P(Poor2=1) with cause (i)
Off farm employment	0.3650
Agriculture	0.3503
Government help	0.3041
Pension	0.2666
Education	0.2569
Help from family and friends	0.2343
Livestock	0.2310
Savings and investment	0.2182
Inheritance	0.1673
Fúquene	-0.2368
New families	-0.2517
Health/accident	-0.3706
Family problems	-0.6243

In spite of being an important cause, day labor did not significantly affect the probability of being poor in either watershed. Where families depend on day labor as a primary livelihood strategy (that is where it is given as their first cause), it seems to be associated with poverty. However, when day labor is a complementary livelihood option, it can contribute to progress.Accidents and illness were relatively rare among families in both watersheds, indicating that families are not as vulnerable as might be expected to external shocks. Rather, their challenge is to find and take advantage of opportunities. In Coello, failure to progress is due almost exclusively to bad habits or family problems[7]. This contrasts with SOP results from

[7] In Coello, there were cases of families who had fled the zone due to political violence, but, because they were no longer in the community, they were not considered in the analysis.

other countries, as mentioned in section 4. Though consistent with the relatively higher living standards in Colombia, such explanations should always interpreted with caution since they may constitute a superficial explanations for deeper problems that would not be recognized by the community. Lack of importance placed on illness suggests that indirect links between poverty and water quality via health are not important in these watersheds.

While water was not mentioned specifically as a cause, several of the strategies mentioned have obvious links with the environmental issues of the watersheds. For example, dairy farms and mines are important sources of employment in Fuquene, but they also contribute to problems of water contamination. If measures to improve environmental outcomes were to reduce the profitability of these industries and reduce their demand for labor, poverty could worsen in Fuquene. A similar argument could be made for small-scale agriculture, especially in Coello.

Degradation of the upper watersheds for potato cultivation and extensive ranching appears to present less of a poverty-environment tradeoff since the day labor that is generated either by potato cultivation or ranching does not contribute significantly to poverty alleviation the way that labor does in other sectors.

Discussion

These results suggests that in these two watershed, the indirect relationships between poverty and water via employment and income linkages may be more important than direct linkages via domestic supply. This is consistent with the diversification of rural livelihoods and the importance of off-farm income in poverty reduction. Interventions to enhance domestic supply may have big impacts in a few specific communities, but would not generally contribute much to poverty alleviation. Interventions that would reduce employment in industries like dairying or mining in Fuquene or profitability in small scale agriculture in Coello, could have significant impacts on poverty, since these have been important pathways out of poverty over the past 25 years.

Interventions aimed at reducing the destructive impacts of agriculture and ranching in the upper watersheds would appear to be a better options for improving the environment without adverse effects on poverty since the day labor generated in potato cultivation is not associated with poverty reduction. In Fuquene, a payment for environmental services scheme based on promoting conservation agriculture among potato farmers is an example of such an intervention (http://www.condesan.org/Andean/projects.htm).

Colombian legislation allows for stakeholder participation in watershed management decisions. While it is increasingly recognized that stakeholder participation is an important part of integrated water resources management (IWRM), effective participation presumes a good understanding of the issues, especially the socio-economic and biophysical linkages within watershed systems. Results from studies such as these can contribute to improving the community knowledge base, and therefore to helping stakeholder groups better identify the issues that are important to them, and their potential allies in reaching their goals. Such interests may cross the deep sectoral, socio-economic and cultural divides that exist in Andean watersheds.

Even though these results suggests that the poor are not a homogenous block of people whose interests are necessarily opposed to those of better-off groups, they do show that one thing the poor do have in common is that they tend not to participate in community level processes. Participation is considered to be a component of wellbeing, and in many communities the poor are identified as being those who do not participate. Therefore, in addition to technical and institutional interventions to change land use, efforts should also focus to build willingness and capacity of the poor to participate in community activities. In both Fuquene and Coello, local NGOs are leading such a process. Using the results from this study and those from biophysical studies could be used to build awareness of the upstream-downstream linkages and their implications for equitable and sustainable watershed management.

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Dynamics and definition of poverty in the Colombian Andes: Participative vs. objective approaches

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Abstract

The objective of this study is to examine the consistency of results of a participatory poverty assessment methodology applied in two Colombian watersheds with those from more objective approaches. The results suggest that there is a set of elements that are considered basic to both types of poverty assessment; however at the same time there are others that depend on household and community preferences. Moreover, the results indicate that the concept of poverty is context-specific that is a household that is considered poor in one community may not be considered poor in another. The results of the participatory methodology are useful to identify who the poor are, why they are poor, and provide a better understanding of the nature and dynamics of poverty. However, it may not be appropriate to generalize on the basis of the results of such methodologies since they may differ in both nature and magnitude from the results off objective poverty measurements.

Keywords: Poverty, rural analysis, participatory methods, Colombia.

Introduction

Although reduction of poverty is one of the major challenges of the Millennium Development Goals, there is still no clear definition of what poverty actually is. The standard definitions of US$1 or US$2 per day, unsatisfied basic needs (UBN), life-condition index (LCI) and so on, do not recognize that poverty is complex and includes both material and non-material dimensions.

In response to these limitations, participatory methods have been developed that allow local perceptions to be included in definitions of poverty. These methods, usually applied at the local scale, provide a level of detail that goes beyond the objective quantitative measures to show the dynamics of poverty. Therefore, they can be very useful in the design of interventions to reduce the problems of exclusion and poverty. However, because they are based on local perceptions, the results of participatory assessments from different places are not necessarily comparable. It may therefore not be appropriate to use information from such assessments to design regional interventions. Similarly, the generalization of conclusions based on such local results may not be appropriate.

This document attempts to validate the internal and external consistency of data on poverty obtained using a participatory method based on local community perceptions for two watersheds in the Colombian Andes. The principal research questions were:

Are the definitions and results obtained consistent with objective measures of poverty?
Are the results consistent with the condition of the study communities?

The results seek to contribute to a better understanding not only of what poverty is, but also how to use and interpret different types of poverty data. It was of particular interest to identify the conditions under which different types of information on poverty do or do not give consistent results.

The next section summarizes some of the issues raised by different types of poverty measurements, and considers the methods currently used in Colombia. We then describe the study watersheds, and go on to present the findings of the poverty analysis. We also examine the community-level data on which these findings were based, specifically the community-level definitions of poverty and poverty line (described below). We then summarize and discuss our conclusions.

Empirical aspects and measurements of poverty in Colombia

Objective and subjective approaches to poverty, the methods used and their advantages and disadvantages

Poverty is a multi-dimensional phenomena as the wide range of concepts in the literature illustrates. In concept, poverty can be objective or subjective, for example the need for people to have adequate diets contrasted with peoples' preference for specific foods independent of their nutritional value. It can be absolute or relative, based on the lack of income or of earning capacity. It can be chronic as a consequence of structural problem in an economy or temporary when caused by a short-term economic malfunction. Finally, poverty can be related to inequality, vulnerability and exclusion within a society. The use of these different concepts determines the way that poverty is measured and also influences the nature and implementation of policies and programs to alleviate it (Lok-Dessallien 1995).

Objective measures define poverty from the perspective of a group of normative criteria that define what is required to overcome poverty. In general, objective assessment emphasizes quantitative data, which are simple to record and to compare. In contrast, subjective measures consider poverty from the point of view of individual preferences and the value individuals place on goods and services. Subjective assessment mainly uses qualitative criteria to describe the intrinsic characteristics of what is being measured, although it is necessary to translate them into some quantitative form to be able to aggregate them (Lok-Dessallien 1995). Objective measures of poverty can be either non-monetary or monetary, and, in turn, the latter can be absolute or relative (Figure 1).

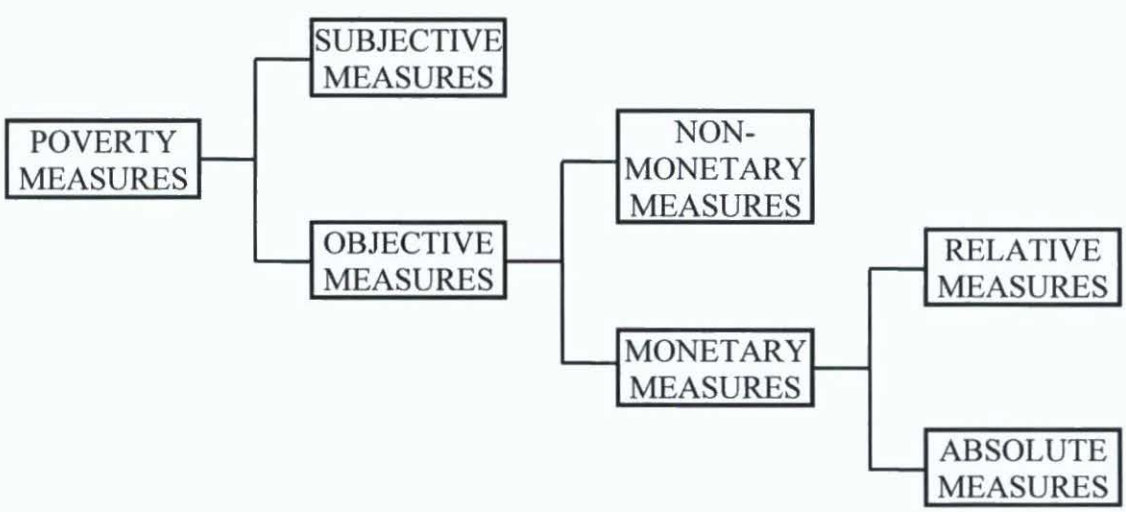

Figure 1. Diverse measurements of poverty. Source: MERPD (2006).

Now we describe the characteristics of the methodologies commonly used for the study of poverty, and discuss their advantages and disadvantages. In doing this, we adapted the methodologies developed by the Mission for the Design of a Strategy for the Reduction of Poverty and Inequality (MDERPD 2006).

The commonly-used indicators of subsistence are US$1 income per person per day (PPD) for indigent peoples. US$2 PPD is used to define poverty in purchasing power parity (PPP) in Colombia.

> "although somehow illustrative for effects of international comparisons, [these indicators] are not conceptually bound to the idea of poverty as a lack of basic necessities, this is because the values of the poverty line do not represent a specific basket of goods and services that a society considers indispensable to live a worthy life, according to its culture, geographical conditions and socioeconomic level. Also, clearly, one or two dollars PPP is not enough to cover the necessities that a country of medium income [such as] Colombia could consider as basic" (MDERPD, 2006, p. 21).[1]

The measure of absolute poverty called the poverty line is based on the value of a minimum basket of representative goods such as food, clothing, transport, etc. For any reference population this corresponds to the poorest 25%. The monetary value of the poverty line changes as the contents of the basket and/or the sources of information are modified (MDERPD 2006).

The most commonly used non-monetary objective indicators are the human development index (HDI), the index of unmet basic necessities (UBN) and the condition of life index (CLI). Another index used in Colombia is the system for the selection of beneficiaries of social programs (*el sistema de seleccion de beneficiarios para programas socials*) SISBEN, which we shall not consider further because of its similarity to the CLI.

The HDI is not exactly an indicator of poverty because in addition to a per capita income index it also includes an index of life expectancy at birth and a compound education index. Actually, the concept of human development is wider and more complex than captured by the HDI because it only three of the multiplicity of elements of human development. For example, participation in society was highlighted in the Human Development Report 2004 as an important part of human development; however this variable is not included in the HDI (MDERPD 2006).

> "The indicator of unsatisfied basic necessities [UBN] is sometimes [used] as an alternative measurement of poverty; it considers as poor those households or people that have at least one unsatisfied necessity out of the five defined (poverty for [UBN]) and as in misery those households or people that have at least two unsatisfied necessities (misery for [UBN])" (MDERPD 2006, p. 15).

The criteria in the UBN are inadequate housing, housing without services, overcrowding in a household, non-attendance at school and high economic dependence. The UBN determines which of the criteria are not met and of those which is the most common in households in a given location. However, it hides how many people are in poverty and misery, because it uses the household as the unit of evaluation, ignoring the number of people that comprise it. Moreover, important aspects, such as nutrition, are not included in the UBN (MDERPD 2006).

Finally, the CLI, developed by the Social Mission of the National Department of Planning (NDP) of the Colombian government "tries to give a more integrated and more informative coverage of the satisfaction of basic needs and quality of life than the UBN." (MDERPD, 2006, p. 17). It incorporates indicators of physical goods, present and potential human capital, and composition of the household, each variable included in these indicators has an assigned weight. The CLI is an indicator that is not used to determine

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[1] In 2004 U$1 a day PPP was equivalent to 24,137 Colombian pesos (COP) a month, while U$2 a day PPP to COP48,274 a month (MDERPD, 2006, p.20). The minimum legal monthly salary for 2004 was COP324,000.

which homes are poor and which are not, but it allows comparisons to be made at a given time and place. However, the weights that it assigns to the variables contradict what the society might consider desirable, for example, for garbage disposal it assigns a score of 2.59 to people who throw their garbage in a river and 1.59 to those who burn or bury it (MDERPD, 2006).

The subjective measurements of poverty that are used in Colombia are obtained from the answers to the questions of the survey of quality of life (SQL) about the perception of poverty by households. The following is a sample of such questions:

1. Do you consider yourself poor?
2. Presently, how the life conditions of your household are?
3. What do you consider should be the monthly minimum income that your household requires to satisfy its necessities appropriately?
4. What level of income would you classify as excellent? Bad?

These questions are not very clear about what is being referred to when speaking of poor in 1, of life conditions in 2 or of minimum income required by the household in 3. For that reason the results are not the most appropriate to determine strategies for programs of poverty relief. For example, in accordance with the calculations of the MERPD based on the question 1 in SQL 2003, 36% of the households in the fifth quintile in urban areas are considered poor (MDERPD, 2006).

There are participatory methodologies available, which have been used in Colombia and in other developing countries to generate profiles of poverty based on the local perceptions of communities. The World Development Report 2000/2001 gathered experiences of qualitative participatory studies on poverty carried out in 50 countries. A comparative study of 23 countries was made, with the objective of including the perceptions of the poor in political proposals for poverty reduction. As a result of this investigation, the World Bank published a methodological guide that created participatory profiles of well-being to be used in work groups with representative members of the communities.

For Colombia, we have the development of regional profiles of poverty (Ranvborg 1999) that determine the levels of well-being of the households in a given community. Workshops convened of representative members of the community classify households into the different levels of well-being. In this way average levels of well-being of all households in the community are also determined[2].

We applied Krishna's (2002) methodology in the present study. This methodology uses community participation to determine qualitative poverty lines and defines stages of progress within the community. The objective is to determine what stage households were in 25 years ago and what stage are they in now. This provides information on the dynamics of poverty and what were the causes of any changes. The method has been applied in India, Kenya, Uganda, Peru and the United States (Krishna 2004*a*, Krishna *et al.* 2004*b*, Krishna *et al.* 2004*c*, Krishna *et al.* 2005*a*, Krishna *et al.* 2005*b*, Krishna *et al.* 2006).

This methodology attempts to understand the dynamics of poverty at a disaggregated level, in both the communities and households. Although economic growth stagnated during the last decades in some developing countries, there were internal dynamics that allowed the poor to improve their situation or caused it to worsen. The knowledge of how some people escaped from poverty can be useful to help those did not (Krishna 2004*a*, Krishna *et al.* 2004b)[3].

Commonly-used objective measurements of poverty apply a series of normative criteria to determine which are the best for people. Studies carried out based on this information generally use nations as the unit of

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[2] For more detailed information see http://www1.worldbank.org/prem/poverty/voices/index.htm

[3] For more detailed information see http://www.pubpol.duke.edu/krishna/index.html

measurement. They require the availability of data collected over a substantial period of time and moreover that the data collected at different times are both comparable and complete. If the data do not fulfil these requirements, the studies will give questionable results and simply should not be carried out. In addition, this type of study lacks those elements that allow understanding of people's perceptions about poverty and the strategies that they develop to confront it. Moreover, they are expensive in that they require that time-series data are available. For all these reasons, the poverty dynamics method is a superior alternative (Krishna 2004*a*, Krishna *et al.* 2004*b*).

Stages of progress methodology and poverty line

The stages of progress methodology (SOP) was applied in 23 communities (*veredas*) of the municipalities of the watersheds of Fúquene Lake in Cundinamarca (Fúquene) and in the Coello River (Coello) in Tolima between March and July of 2005. The communities were selected in consultation with the mayors of the municipalities and were based on information of the relevant indicators in the municipal Outlines of Territorial Classification (EOT). The sites chosen were poor villages with water sources, near the *paramo* and in the hillsides. Workshops were held with the participation of 886 households Fúquene and 175 in Coello. The numbers of participants in Coello was limited because of security problems. Although the sample in Coello was not representative from a statistical viewpoint, we believe that it was essentially representative of the rural villages in the watershed.

Prior to the workshops, we agreed the concept of what constituted a household and what constituted a community. A household is the group of people that shares food "from the same pot or kitchen." A community is a compound group of 25 to 60 households with similar geographical and environmental conditions as well as similar access to markets. Furthermore, the households in the community must know each other and have remained in the community for at least the last 25 years.

The research team made an initial visit to each community and had discussions with local officials and other key people such as the presidents of meetings of communal action and community leaders. The characteristics of each community were described, including history, socio-economic characteristics, infrastructure and migratory movements of households. Where immigrants were more than 25% of population, the community was deleted from consideration.

Next the steps that were undertaken were (Team of the project Escalas CPWF 2005a):

I. **Convene representative groups:** A representative group was convened in each community, including members of different households, members of the poorest households and those that were not land owners or who were not entitled to use land. The invitees were 50 or more years old and had lived for more than 25 years in the community. In addition, youths born in the community and some representatives of the local authorities were also invited. The Team sought to have gender equality, trying to have equal numbers of men and women.

II. **Explain the objectives:** Members of the Team and of the institutions involved were introduced to the communities and explained the objectives and the process of information gathering. To avoid any possibility of encouraging false expectations among the participants, the Team emphasized that this was entirely a scientific exercise. The Team also explained clearly what the timetable of the workshop would be so that people would stay until the end of the process.

III. **Collectively define stages of progress and determine the poverty lines:** The objective was to arrive at a common understanding of poverty within each community and what it means to be considered poor. To avoid any prejudicial atmosphere, alternative words were used to define poverty. The following questions were asked in each community: On what does an extremely poor household spend any money that it obtains? What is the first expense that they cover? If the household obtains a little more money, what do they spend it on? And later, what would be the third expense? The fourth? And so on. In this way, people defined the stages without referring to money as such, for example, by asking, "If that poor family was a little better off or if they obtained stable work, what would they do? What material or non-material things would the household have that the very poorest do not? Each stage was described as specifically as possible for the workshop participants, for example education would be either elementary school or high school and for housing both the size and the material were specified.

Based on this information the poverty lines were described in each community. In each case, the participants were asked, "At what stage would a household no longer be considered poor?". The poverty line was identified by means of progressive questions, such as, "If a household has food but does not have clothes, does it continue to be poor?" until consensus was established among the participants.

IV. **Identify events that occurred 25 years ago, and determine the current situation and the situation 25 years ago:** To establish what a 25-year timeframe means, each community was asked to identify historical events that all could easily identify. Three events were chosen:

The Popayan earthquake in 1983;

The Nevada del Ruiz eruption and lahar (mud flow) that overwhelmed Armero in1985; and

The assault on the Palace of Justice by the armed forces in 1985.

This 25-year time frame was chosen to emphasize the changes that take place within a generation. In each community, the workshop participants evaluated the list of households in their community and estimated the stage they were at 25 years before and agreed the stage that they currently are at.

V. **Group households in four categories (A-D below) and to choose a random sample of households in each category:** Using the results of the previous step, each household was allocated to one of five groups:

- Category A. Households that have remained poor (that were below the poverty line all the time during the last 25 years).
- Category B. Households that have escaped from poverty (they were below the poverty line 25 years ago but at the moment they are above it).
- Category C. Households that have fallen into poverty (they were above the poverty line the 25 years ago but at the moment they are below it).
- Category D. Households that have remained non poor (they have been above the poverty line all the time in the last 25 years).
- Category E. Households who were not in the community 25 years ago.

The next steps in the workshops were to establish the reasons why some households escaped from and why some others fell into poverty. The Team visited those households to enquire more deeply into the causes. Because we shall not be referring to this information in this paper, we shall not present detail about these two final steps.

Description of the study sites

The SOP methodology was applied in thirteen communities in six municipalities of the Fuquene Lake watershed (Fuquene) and in ten communities in five municipalities of the Coello River watershed (Coello) (Table 1).

Table 1. Watersheds, municipalities and communities where the stages or progress (SOP) methodology was applied. Source: Progress Stages Project Scales, CPWF.

Watershed	Municipality		Settlement	
Fúquene	1	Tausa	1	Ladera Grande
			2	Rasgata Bajo
	2	Sutatausa	3	Chipaquin
			4	Palacio
			5	Peñas de Cajón
	3	Guachetá	6	Gacha
			7	La Isla
			8	La Puntica
	4	Fúquene	9	Centro y Guata
			10	Chinzaque
			11	Nemogá
	5	Cucunubá	12	Chápala
	6	Carmen de Carupa	13	Apartadero
Coello	1	Cajamarca	1	La Leona-APACRAQ
			2	El Rosal
			3	La Alsalcia
			4	Minidistrito La Leona
	2	Ibagué	5	Coello COOCRA
			6	San Cristóbal-Honduras
	3	Espinal	7	Dindalito
	4	Coello-COCORA	8	Potrerillo
			9	Chaguala Adentro
	5	Rovira	10	La Ocera

Fuquene Lake Watershed

Fuquene Lake watershed (Fuquene) is located in the Eastern Cordillera of the Andes north of Bogota, in the Ubate and Chiquinquira valleys, with an altitudinal range of 2300 to 3300 masl (Figure 2). It includes 17 municipalities in the departments of Cundinamarca and Boyaca. The population of the municipalities of the watershed in 2005 was of 232,000, 59% of which is rural (DANE population projections). The CLI for 2003 (Sarmiento *et al.* 2006) in these municipalities varies from low to high. The percentage of households with UBN for 2002 varies from 7 to 47%, which emphasizes the heterogeneity of living conditions, which is characteristic of the Andean basins. Moreover, the distribution of rural land in the watershed is inequitable with an average Gini[4] index for rural property of 0.59 in 2002.

[4] The Gini index measures the extent to which the distribution of income among households within a country deviates from a perfectly equal distribution. A value of 0 represents perfect equality, a value of 1 perfect inequality. http://hdr.undp.org/reports/global/2003/indicator/indic_126_1_1.html

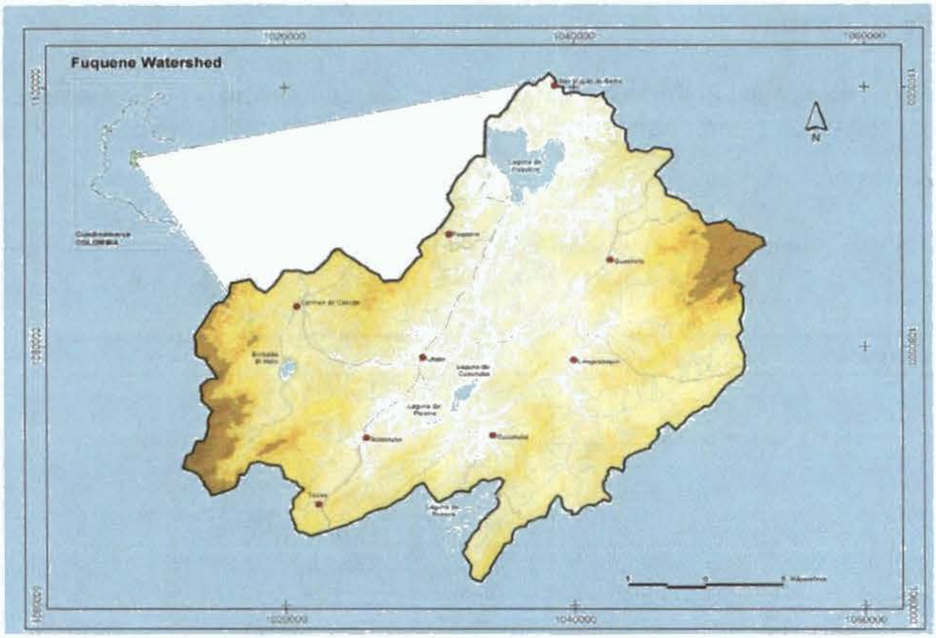

Figure 2. Map of Fuquene Lake watershed. Source: Ramirez and Cisneros (2006).

There are problems with legal title to property in the communities we surveyed. Moreover, according to the data in the *Esquema de Ordenamiento Territorial* (EOT) for the municipalities, unemployment in the communities reaches 70% or more, which causes migration to nearby urban centers. The communities have low levels of education (Team Project Scales CPWF, 2005*b*).

The main economic activities in the region are cattle, agriculture and mining. Cattle are the most important economic activity, mainly dairying for the production of milk; the area produces a large proportion of the national total. The most important crops are potatoes, wheat, peas and maize. Agricultural activity has quite a severe environmental impact. Cultivation is increasingly moving to steeper slopes, increasing soil loss by erosion, and to the *paramo* and forested areas, with the destruction of both ecosystems. Finally, mining is for coal, as well as stone quarries and river sand as construction materials. All three have negative environmental impacts by causing both water and air contamination (Team Project Escalas, 2005*b*, Ramirez and Cisneros, 2006).

In the communities, there are also landholders who do very little farming, instead working off-farm because of high costs of production and advanced land degradation. Dairy farmers produce milk either for household consumption or for sale to milk companies. There are some sheep for sale as meat and family vegetable gardens support household food security. The Regional Autonomous Corporation (*Corporación Autónoma Regional, CAR*) promoted acacia and eucalypt plantations in some areas, mainly in the hillsides, to stop soil erosion (Team Project Scales, CPWF, 2005b).

In the upland areas, land is commonly rented for potato production. Poor access to education and medical services occasionally forces people to move to other communities or to nearby urban centers. Public services are inaccessible and poor quality, especially access to water / water supply, although the latter is not always a problem (Team Project Scales CPWF, 2005*b*).

This is a very important watershed because of its biophysical and socioeconomic characteristics. It is representative of the basins of the Andes in terms of the environmental problems, the disparities between the amount available and the demand for water, the topography, the inequalities in the distribution of resources and the social conflicts. The results of the analyses of this basin can be extrapolated to similar basins in the Andes.

Coello River watershed

The Coello River watershed (Coello) is located in the north central section of the Tolima department, on the eastern slope of the Central Cordillera and includes an important portion of Tolima (Figure 3). The total number of inhabitants of the area (including Ibagué) in 2005 was of 622,000 people of which 16% were rural (projections DANE). More than 56% of the populations of most Coello municipalities are urban. The indices of life conditions range from medium-high to medium-low and health from medium to medium-low. The average years of education range from high to medium-low with most of the high in Ibagué (the department's capital). In the other municipalities there are problems of coverage of and access to educational centers, both elementary secondary schools (Sarmiento *et al.* 2006).

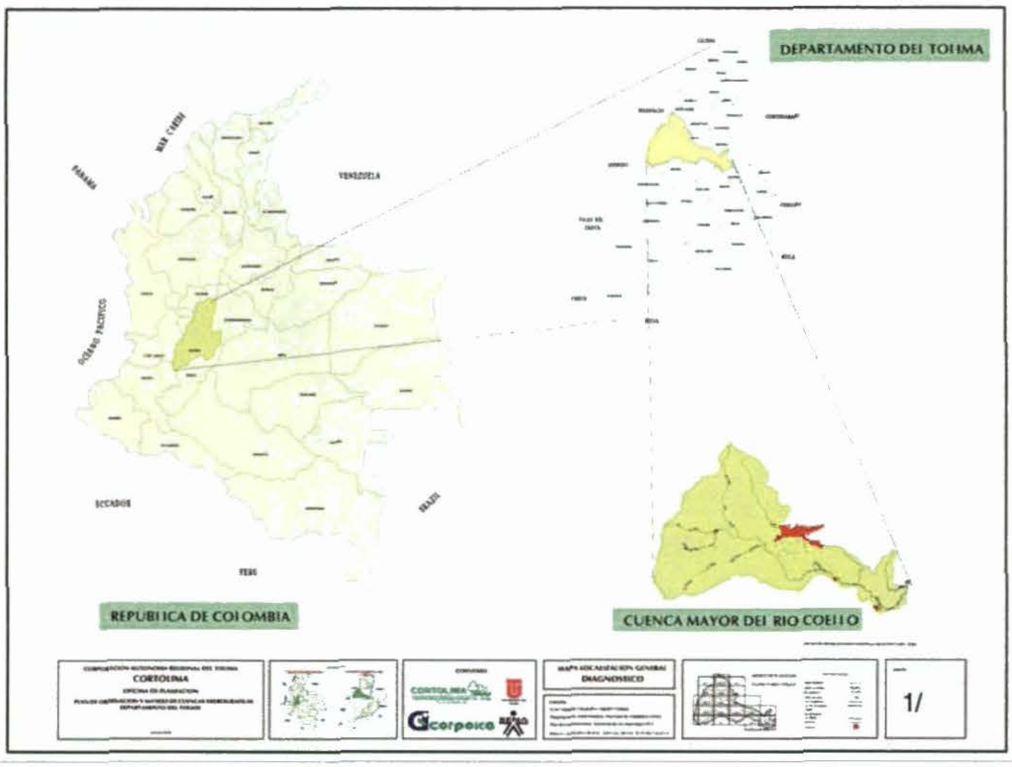

Figure 3. Map of Coello River watershed. Source: Project Scales, CPWF (2005).

In the communities we studied the most important economic activities were agriculture, livestock breeding and mining. The main permanent crops in the region are coffee, sugar cane for production of *panela*, and fruits (mainly mango, followed by lemon and *guanabana*). The annual crops of the region are cotton, rice, sorghum, soybean and sesame. Mining is mainly stone quarries and river sand as materials for construction. Access to public services in rural areas is good, with almost 100% coverage by reticulated electricity. In contrast reticulated the water supply has problems of quality and continuity, and the sewage service has severe coverage problems (Rodriguez and Rubiano 2005).

There is migration to nearby urban centers of Ibague, Armenia, Bogota, Cajamarca, El Espinal and Rovira, with the objective of seeking work. The communities are farmers either from the zone or who immigrated from the departments of Quindio, Cundinamarca, Tolima and Boyaca. In the communities of Coello-

Cocora, Dindalito, Gualanday and Chaguala Adentro there are city immigrants. Property ownership is characterized by inequality, absence of communal land, predominance of a few large holdings and many small ones (Rodriguez and Rubiano 2005, Team Project Scales, 2005*b*).

The main environmental problem is due to the Panamerican highway in that people living near it are affected by severe respiratory diseases. Furthermore, tunnel construction in *La Linea*[8] causes soil erosion and sedimentation. As well, there is the pollution by residual waters from towns, inadequate livestock and agricultural management, including agrochemical contamination on the riverine plain, deforestation to increase the areas cropped to rice, illegal crops, commercial forestry plantations and mining. It is important to note that there is increasing conflict in access to water between small landholders in the upper catchment and large-scale rice growers and the hydropower company in the lower catchment (Rodriguez and Rubiano 2005, Team Project Scales 2005*b*).

Results

Results of the application of the SOP methodology

The results the SOP study show how households in the sampled communities perceive their livelihoods in 2005 compared with 25 years ago (Table 2). The column A + C is the percentage of poor households in 2005, while B + D is the percentage who ar not poor. At the present 45% of the households in Fuquene are poor, with the highest numbers in Ladera Grande, Centro y Guata and Chapala, where 83%, 90% and 83% respectively of households are poor. In contrast, only 13% of households in Coello are poor and 84% are not poor. It is noteworthy that between 55% and 100% of the households in the ten communities surveyed are classified as not poor.

[8] The colloquial name for the Panamerican highway between Ibague on the eastern and Pereira on the western sides of the Central Cordillera.

Table 2. Results of the stages of progress (SOP) methodology, Fuquene Lake and Coello River watersheds, 2005. Source: Project Scales CPWF (2005), DNP-UNDP (2006).

Watershed	Municipality	Community	CatA[1] %	CatB %	CatC %	CatD %	CatE %	A+C %	B+D %	CLI 2003[2]
Fúquene watershed	Tausa	Ladera Grande	66	8	17	4	6	83	11	M
		Rasgata Bajo	24	22	2	5	46	27	27	
	Sutatausa	Chipaquin	34	41	13	13	0	47	53	
		Palacio	37	47	0	2	14	37	49	M
		Peñas de Cajón	17	61	0	0	22	17	61	
	Guachetá	Gacha	38	26	6	28	1	44	54	
		La Isla	40	30	3	25	1	43	55	M
		La Puntita	39	32	0	4	24	39	37	
	Fúquene	Centro y Guata	90	1	0	1	7	90	2	
		Chinzaque	23	46	3	28	0	26	74	M
		Nemogá	13	29	4	46	8	17	75	
	Cucunubá	Chápala	83	13	0	0	5	83	13	LM
	Carmen de Carupa	Apartadero	30	70	0	0	0	30	70	LM
	Total		**42**	**30**	**3**	**14**	**10**	**45**	**44**	
Coello watershed	Cajamarca	La Leona - Apacra	0	31	0	69	0	0	100	
		El Rosal	0	77	8	15	0	8	92	M
		La Alsalcia	21	57	0	21	0	21	79	
		Minidistrito La Leona	45	55	0	0	0	45	55	
	Ibagué	Cocora	6	22	0	44	28	6	67	MH
		San Cristóbal-Honduras	5	47	5	42	0	11	89	
	Espinal	Dindalito	15	46	8	31	0	23	77	MH
	Coello	Potrerillo	0	100	0	0	0	0	100	LM
		Chaguala	29	57	7	7	0	36	64	
	Rovira	La Ocera	6	75	0	19	0	6	94	LM
	Total		**11**	**59**	**3**	**24**	**3**	**14**	**83**	
Grand Total			**37**	**35**	**3**	**16**	**9**	**40**	**50**	

Categories (2005–25 years ago): A poor–poor, B poor–not poor, C not poor–poor, D not poor–not poor, E recent immigrants.

[2] The condition of life index (CLI) is aggregated by municipalities for rural and urban zones. L = low, M = medium, H = high.

Comparing categories A and B shows how household poverty has evolved in the last 25 years. In Fúquene as a whole, 42% continue to be poor while 30% have escaped from poverty. However, we saw extreme and intermediate cases in the communities we studied. Ladera Grande, Centro y Guata and Chapala have stagnated, with between 66% and 90% of households that have always been poor. In contrast, in Peñas de Cajon and Apartadero 61% and 70% of households have escaped from poverty. In Coello as a whole only 11% of households continue to be poor and 59% have escaped poverty, an important advance. More than half the households in nine of the thirteen communities improved their situation; the outstanding ones were Potrerillo, El Rosal and La Ocera with more than 70% of their households escaping from poverty in 25 years.

The SOP results for current levels of poverty contrast with the CLI assessments made by the NDP for the year 2002. For Fuquene, where there was a high incidence of poverty according to SOP but the levels of CLI were medium. For Coello, with a smaller incidence of poverty in each community and where there was greater progress according to the SOP evaluation, there were municipalities with low to medium CLI[9]. Some differences are noteworthy, such as Chápala in Fúquene. According to SOP most of the population is poor, but the UBN of 6.7 in 2002 for Cucunuba municipality, where the Chapala community is located, indicates the opposite. Although worrying, these comparisons are not conclusive because the data are not disaggregated for urban and rural communities.

It is important to keep in mind that the SOP evaluation depends on the poverty line defined by each community and that these poverty lines can differ, making comparisons across communities difficult. For example, a household considered to be poor in one community according to its poverty line may be above it in another community with a different poverty line. This leads us to analyze the poverty lines of the different communities: the elements they include and the number of stages there are to break out of poverty, together with the level of difficulty to overcome each of them.

At this stage it is important emphasize the utility of information obtained by the SOP methodology, especially compared with the indicators calculated by official state organizations. The participatory method used here obtains information of both current and former living conditions in the areas under consideration in an opportune way. In contrast, obtaining information at the rural level from official sources is difficult, because official data are calculated from samples that are not representative when disaggregating departmental and municipal data into urban and rural components. Moreover, collecting data it is time-consuming and expensive.

Definition and variability of the stages

During the participatory process of the SOP, each community set its own poverty lines and defined the stages of progress out of poverty. The communities defined 7 to 24 stages in total and, in turn, decided which of them it was necessary to overcome to escape from poverty. They variously settled on from three to as many as ten stages. The stages of progress of the communities within the same municipality were different in both the actual stages that comprise the poverty line as well as in the number of the stages and their order. This difference was especially notable in Sutatausa, Guachetá, Fúquene, Cajamarca, Ibagué and Coello (Table 3). There were differences in the definition of the poverty line between communities, which affect the particular community's perception that, to escape from poverty, both the stages and the order in which they must be achieved are important.

[9] The CLI in 2003 for Fuquene was 76.6 and for Coello was 73.4.

Table 4. Categories of Poverty Line in order of importance and frequency of mention.
Source: Calculated from data in Project Scales CPWF (2005).

Description	Index	Order	Frequency
Food	0.84	1	20
Education	0.55	2	18
Clothing	0.41	3	12
Housing	0.41	4	15
Small animals	0.35	5	14
Land	0.23	6	8
Utilities	0.22	7	8
Appliances	0.20	8	8
Health	0.12	9	4
Cultivations	0.10	10	4
Other	0.08	11	2
Vehicles	0.06	12	2
Savings/investment	0.04	13	1
Recreation	0.03	14	2

The index *I* measures the relative importance of each category in accord with the position that each community gave it in the stages required to overcome poverty. Moreover, one can deduce how difficult it might be to escape from poverty in a specific community by summing the relative weights given to each of the stages mentioned by that community. Those communities that mentioned larger number of stages to overcome to escape from poverty may be thought to be "more demanding" and are discussed in more detail below (Figure 4).

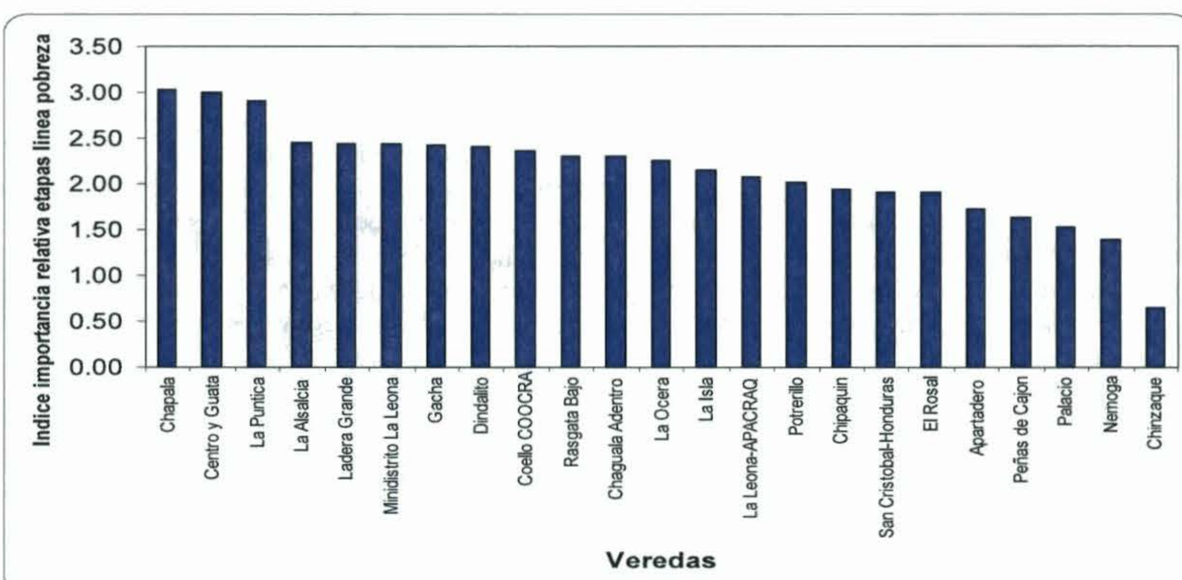

Figure 4. Level of demand for the poverty lines for each community. Source: Based on data in the Project Scales CPWF (2005). X axis = Communities, Y axis = Index of relative importance of the poverty line.

In Peñas de Cajon, Apartadero, Potrerillo and La Ocera a large proportion of households escaped from poverty over the last 25 years. They mentioned three to five stages, including food, education, clothing, health, small animals, housing, land and crops. Not only do these communities mention fewer stages compared with the more demanding ones, but the stages are less complex.

In contrast, the definitions of poverty in those communities where a large percentage of households have remained poor for the last 25 years implied more stages to overcome and more complex stages. In Fuquene, the households of Chapala and Centro y Guata needed to overcome 10 and 8 stages respectively. In Chapala the initial stages included access to secondary education, a plot of land and housing with walls, roof and bathroom. In Centro y Guata the initial stages included improved crops by means of constructing a reservoir, while in La Puntica the poverty line has eight stages of which the seventh is entertainment by making trips. In those communities there are many stages to overcome, implying making investment to acquire and improve land and housing, and being able to access secondary education or entertainment.

If the households that are considered poor in "more demanding" (poorer) communities like Centro y Guata and Chápala moved to some of the "less demanding" communities, like Peñas de Cajon or Apartadero, they would no longer be considered as poor.

In Chapala, youth migration has led to a population that is dominantly adult with few households having children under twelve. As a result the community mentioned high school education as a component in the poverty line. In Chapala, La Puntica and Centro y Guata agriculture is not a productive activity, only garden plots for self-consumption. In Chapala, the main activity is coal mining with emigration of mainly young people to work the mines.

In Peñas de Cajon, most households are involved with coal mining. Good incomes from mining (up to COP1,500,000/month in 2005) has influenced the perceptions of the inhabitants of the communities, so that they consider entertainment and the possession of appliances inside the poverty line. Although miners' wages are good, it is not clear why the poverty lines for these communities include fewer elements than elsewhere. In contrast, in Apartadero, Potrerillo and La Ocera, most households are devoted to the agriculture and cattle, and these communities mentioned land and crops.

The definition of poverty lines of each community is based on the local perceptions, which depend on social, economic and cultural factors that seem quite relative. We determined the most (or least) common categories in the definitions of poverty line in the communities using multiple correspondence analyses. This showed that services, food, education, and housing were the most common, with savings/investment and other the least common. We therefore eliminated the latter categories because of their low discrimination capacity. We then used a conglomerate analysis on the reduced data set to generate the first two principal components to cluster communities in accordance with the elements that comprise the poverty line each (Figure 5).

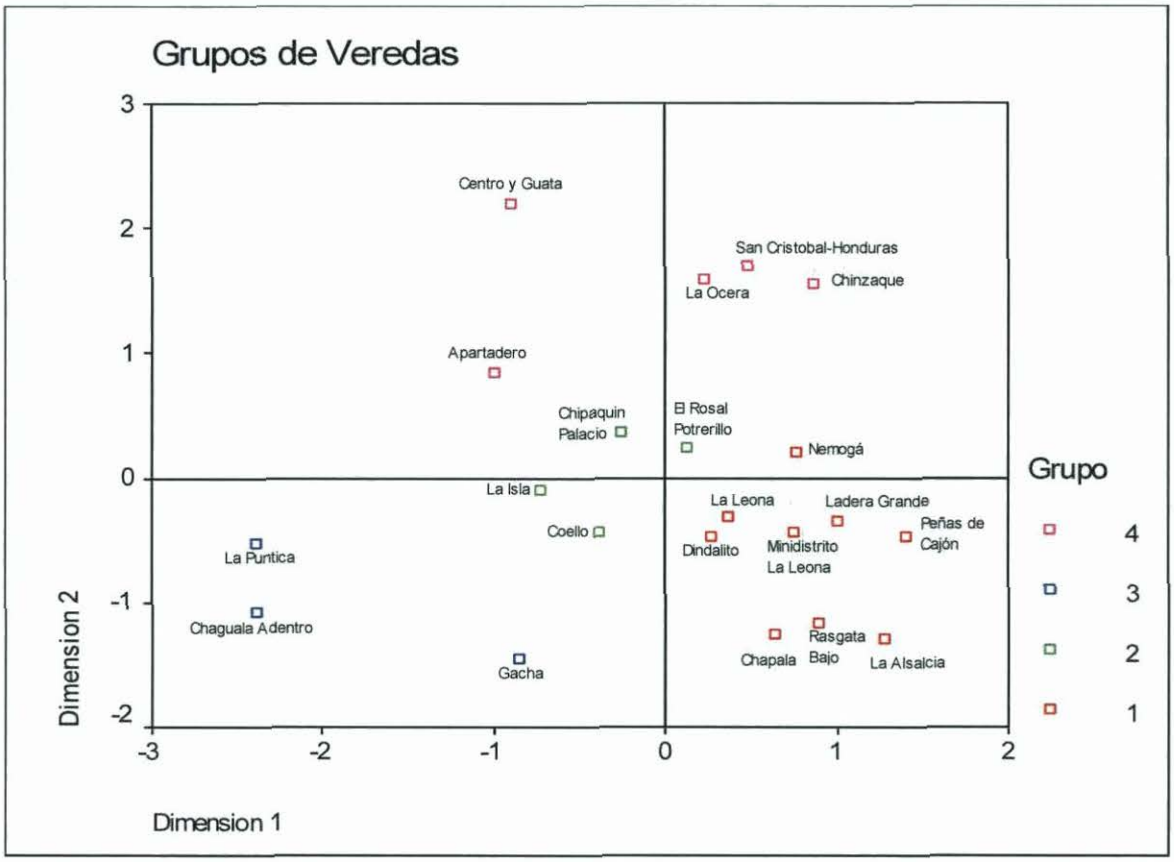

Figure 5. Cluster analysis of the elements of the poverty line by Community. Source: Based on the information of the project Scales CPWF (2005).

There are four groups, the poverty lines of which include one or more variables that was not mentioned by the other three groups. Group 1 includes land and appliances, Group 2 small animals and clothing, Group 3 vehicles and recreation and Group 4 crops. No pattern was detected for watershed or municipality. The communities of Group 1 are dominated by small holdings, which explains the inclusion of land as an important component of the poverty line. In contrast, Group 3 did not include land as the communities have large holdings for dairy cattle.

The poverty lines in all communities include certain basic elements such as food, education, housing and public services. Once the poverty line is overcome, communities tend to emphasize improved access to, and quality and quantity of, these basic elements. The conformation of the four Groups shows that there are some items that are fundamental to one group, but are unimportant to the others.

There are not enough elements to allow us to determine why a group includes a particular element. Nevertheless, it is likely that factors that influence those activities that generate income such as land and some institutional factors, influence people's perceptions. For the communities of Group 2, the main source of income is off-farm work as most work in construction, tourism or in flowers production. Households involved with cattle find it easier to satisfy some food needs (milk and cheese) than those growing crops. In the case of Group 4, agriculture is the most important source of income, which explains why crops are included as an element of the poverty line.

In both Groups 2 and 4, households participated in both cooperative activities and women Colombian Institute of Family Welfare, (*Instituto Colombiano de Bienestar Familiar ICBF*), there is no explanation for the inclusion of the elements small animals, clothing and crops.

The elements included in the poverty line in studies in other countries (Krishna 2004, Krishna *et al.* 2004*a*, Krishna *et al.* 2004*b*, Krishna *et al.* 2005*a*, Krishna *et al.* 2005*b*) do not differ in any important way from those in our study (Table 5). The poverty lines in each are made up of four to seven stages. However, some elements that are part of the poverty line for the Colombian communities are not included in the poverty lines of other countries, but we cannot say whether because these elements are not below the poverty line in these countries or because the communities do simply not consider them. For example, appliances, health, recreation and services do not appear for Peru, Kenya, India or Uganda.

A possible explanation is that the number of communities and households in Colombia were smaller than in the other countries. If this is so, we confront two possibilities if we enlarge the study universe in Colombia. We may find more differences in the stages defined by the communities or, alternatively, we may find more commonalities in the group of stages that comprise the poverty line that would enable us to generalize more widely to Colombian rural communities.

Table 5. Stages of progress for Colombia and other countries. Sources: Source: Krishna 2004*a*, Krishna *et al.* 2004*b*, Krishna *et al.* 2004*c*, Krishna *et al.* 2005*a*, Krishna *et al.* 2005*b*.

Stage	Coello-Fúquene	Kenya	Perú	Uganda	India
1	Food	Food	Food	Food	Food
2	Education	Clothing	Clothing	Clothing	School for children
3	Clothing	Home improvement (roof)	Basic home improvement	School for children	Clothing
4	Housing	Elementary school for children	Smaller animals	Repair existing house (roof)	Pay debts
5	Small animals	Buy chickens	Elementary school for children	Buy small animals	NA[1]
6	Land	Buy sheep	Buy land	Buy small land	NA
7	Utilities	Buy local livestock	Smaller livestock (sheep, alpaca, llama)	Buy a bicycle for transportation	NA
8	Appliances	Home improvement (furniture)	Buy more land	Buy more land	NA
9	Health	High school for children	Home Improvement	Buy a permanent house	NA
10	Cultivations	Buy land	Bigger animals	Start a small bussiness	NA
11	Other	Buy livestock	High school and higher educaton	Buy a car or start a bussines	NA
12	Vehicles	Buy land	Small business		NA
13	Savings / investment	Build a permanent house	Buy a house in the city		NA
14	Recreation	Invest in a bussiness			NA

[1] Information not available.

The stages of poverty highlighted in blue are those included in the poverty line created by the communities in each of the case studies.

There are elements common to the poverty line in all countries (Table 5). Food is in first place in all cases, with clothing, housing, education, small animals, land or crops, generally included, although in different order. Although the results from the different countries are not strictly comparable, from the perspective of the social, economic and cultural contexts, there is a group of material assets that are part of the necessary stages to overcome poverty in rural areas in all countries. Most importantly, these are not presently considered by any other type of measurement.

We can compare the elements included in the poverty line with those of the traditional measurements of poverty such as the UBN and the CLI (Table 6). It is noteworthy that food, considered the most important in the poverty line is not is not included in either of the other two indicators. Moreover, there is a group of assets, such as small animals, land and crops that were included by the communities in this study that are not included in the so-called objective measurements of poverty, like the UBN and the CLI. In the case of rural communities, assets such as these contribute to food security of the household and the survival of its members.

Table 6. Elements included in the poverty line compared with the UBN and the CLI indicators. Source: MERPD, PNUD (2006).

Poverty line	UBN	CLI
1. Food		
2. Education	*Non-school assistance:* A household with children from 7 to 11 years old who do not go to school.	*Education and human capital* Proportion of children from 5 to11 years old in school Average schooling level for a 12-year-old or older Proportion of youths from 12 to18 years old that go to high school or university Maximum schooling level of the head of the family
3. Clothing		
4. Housing	*Inadequate housing:* House with earth floor or flimsy wall material. House without utilities, a home with no water in urban areas and no connection to sewerage system or septic tank	*Quality of the house* Main floor material. Main material in the walls. Water source. Oil for cooking. Garbage collection.
5. Small animals		
6. Land		
7. Utilities		
8. Appliances		
9. Health		
10. Cultivation		
11. Other	*Critical overcrowding:* Number of people per room more than 3. *High economic dependency:* A household with more than 3 dependent members, where the head of the family has a maximum of 3 years' basic education.	Size and composition of the household Overcrowding in the house. Proportion of 6-year-old or younger children.
12. Vehicles		
13. Savings/investment		
14. Recreation		

If in the UBN and the CLI for rural areas included these types of assets, they may be more relevant to the real world situation in rural Colombia, in that households with these assets would have more favourable poverty scores than those that lack them. On the other hand, access to education, is a most important element, in the poverty line as well as in both the UBN and the CLI. The latter two are very specific about access to the education. In the UBN attendance at school of children between 7 and 11 years old is the criterion. The CLI takes a more sweeping view considering not only school attendance by children of school age, but as well the years of education of the household's head and of the other members of the family, that is it measures the accumulated human capital of the household.

In the poverty line determined by the communities in this study, both elementary and secondary education for the children was of great importance, as well as the capacity of the household to buy the supplies that are required to attend school. This seems reasonable, because parents generally consider that their children must first be fed, then have school supplies, and only then attend school. They also considered access to technical training for adults when this was identified as a means to overcome poverty.

Neither the household size nor the dependence rate were elements of the poverty line. In contrast, both the UBN and the CLI take account of the rate of economic dependence, together with overcrowding and the size and composition of the household. For the poverty line, only in El Rosal community in Fúquene was the second stage investment in family planning, although this is not the only community where women participate in programs of the ICBF. In the other cases the size of the household is not mentioned as a factor that has an impact in poverty, although the maintenance of more people does requires more effort of the household.

Finally, most of the elements of the UBN and the CLI are related with the material attributes of quality of the housing, or with the accumulation of human capital in the household. Neither considers the availability of food nor the holding of other types of material assets, which contribute to the livelihoods of the rural poor. Moreover, holding other assets is also indirectly related to adequate food availability; which can mark the difference between being or not being poor.

Conclusions

Existing methodologies for the measurement of poverty have to face the challenge of trying to express, in a synthetic way, a complex and multidimensional phenomenon. The so-called objective methodologies (UBN and CLI, amongst others) require standard procedures to allow comparisons between the data that are obtained at different times, and they favour the use of quantitative data to fulfil this objective. The standards determined by these measurements are absolute, and on occasions they are out of context. The standardized elements lack explanatory power for the sake of simplicity and comparability. They also exclude some elements that are considered important by society, and in doing so generate contradictions and ambiguities in the definitions of poverty.

In contrast, the subjective and participative methodologies we used here allow poverty to be understood in a given social, economic and cultural context. The context can be quite relative, particularly in conditions of heterogeneity and inequality, like in the watersheds we studied. But it is precisely because of these features that the capacity to make comparisons among communities is lost, as much in the temporal as in the spatial environment, due to their specificity to the place where they were determined. Therefore, the objective and participatory methodologies are complementary, which can lead to definition of better standards that include those elements that are important to people, and in this way allow more effective policies and poverty relief programs.

On the other hand, subjective methods provide opportune information on the livelihoods in an area or region, when it is not possible to have up-to-date objective standards on a regular basis.

It is worth emphasizing again that objective data obtained by the official organizations takes time and is costly, particularly for rural areas.

The results of the poverty lines defined by the methodology such as the stages of progress used here, include elements that are basic from the point of view of the objective measurement of poverty (food, housing, health, services, education). As such they are not in principle inconsistent with the objective standards. However, the elements that are basic to the objective measurements were not the only ones considered to be necessary in the community for a household to be classified as not poor. The additional elements perceived as important depend on the preferences of the households of a particular community and define the differences of the stages between communities.

The state of poverty from the perspective of the communities we studied depends on the context in which individuals form their conception of it, not only from the point of view of what is understood as being poor, but also by considering how complicated it can be to overcome poverty. For this reason there is a lot of variability regarding the location of the poverty line. One has to be very careful in considering the elements related to individual preferences and with their order, because it is not possible to make comparisons of the state of poverty between the different communities. This is because poverty lines differ as much in their composition as in the order of their elements.

The results we present show that we know little about what causes the definitions of the poverty lines to differ, because we found no pattern within the stages and their characteristics among the communities. We noted elements that could be associated with the possession of material assets, but in fact, they were not enough. Therefore, to deepen in the social and cultural characteristics of the communities it is necessary to understand, for example, why elements like recreation and owning a television are part of what a group of individuals can consider as essential stages to overcome poverty.

The comparison of the stages obtained within Fúquene and Coello with the stages set by the communities of other developing countries, suggests that there is more work to do. We need: to carry out the stages of progress exercise with more households and with other poor communities in Colombia to determine if there is some commonality in the stages, and what characteristics of the different communities influence the poverty lines that each of them builds. Furthermore, the question arises whether we could make some generalizations of what is needed to overcome poverty. For example, what material assets are needed and what kind of human capital is required for rural communities to escape poverty. These generalizations are needed to focus the government's poverty alleviation programs in meaningful ways.

We can conclude that the stages of progress methodology provides important information on the elements necessary to allow a household to overcome poverty. In the case of the rural areas we studied here, possession of material assets such as small animals, land and crops that contribute to food security would improve the situation of many people. Equally, the possibility to send children to school and to provide the requirements to increase the levels of school attendance are high-priorities in the programs of poverty relief in the areas we studied.

Participative methodologies like the stages of progress, can be very useful to identify how the dynamics of progress out of poverty in an area have been, since the definition of the poverty lines describes the evolution of households' welfare over time. We must caution, however, that defining poverty is complicated by the specificity of the context of what it means to be poor.

The methodology of stages of progress can be used to focus on the poorest population in a given area. However, we recommend that not only the categories be used but also the type of stages that the communities have not yet overcome. This will provide a sound description of the differences between the communities in terms of elements that are lacking. For example, it is not the same thing that a household is considered to be below the poverty line because it does not have the economic capacity to make recreational trips, compared with another household that is also below the poverty line because it does not have adequate housing.

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Agricultural water productivity: Issues, concepts and approaches

Basin Focal Project Working Paper no. 2a

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Challenge Program on Water and Food

Introduction

The world has finite water resources, which are under increasing stress as the human population and water demand per capita both increase. These problems are not new but are now becoming more widespread and their impacts more devastating. This has provided additional impetus for the search for solutions to problems arising from the mismatch between demand and supply in terms of water quantity, quality and timing. Increasing water productivity has been identified as one of the global challenges that requires urgent attention.

This document examines issues, concepts and approaches to assessing water productivity in agriculture. Section 2 presents a set of concepts and issues for improving our understanding of the complexities associated with assessing and improving water productivity. Section 3 presents approaches in assessing agricultural water productivity and highlights the challenges in quantifying and valuing inputs and outputs. Section 4 presents the rationale for increasing water productivity from the global, basin, irrigation system and farm level perspectives.

Concepts and issues

Water scarcity: a driver for increasing water productivity

Although globally there are adequate water resources to meet the needs of the current and future world population, locally there are many areas experiencing water scarcity (see Box 1).

Box 1: Symptoms of growing water scarcity

Declining dry season river flows have become a common phenomenon in many rivers. The ecological implications of decline in dry season river flows include (a) insufficient quantity of water to flush sediments leading to siltation problems; (b) insufficient quantity of water to dilute water pollutants leading to permissible pollution levels being exceeded; (c) reduced flows into estuaries result in a rapid advance of a saline front, which extends the extent of the estuary, damages the aquatic ecosystem and threatens bio-diversity. When such ecological changes occur, livelihoods of downstream communities are adversely affected leading to conflicts.

Groundwater depletion. Studies in the Indo-Gangetic plains of northern India show that groundwater tables are dropping by 0.5 to 0.7 meters a year and that 25 per cent of India's grain harvest is threatened by unsustainable use of groundwater. Postel (1999) estimated that globally groundwater is overused by 200 km3/year. The most serious over pumping occurs in India, the United States, Mexico, the Mediterranean countries and China. Over-depletion of groundwater in the coastal areas of Gujarat state in India has lowered the groundwater levels to a point where salt water intrusion is contaminating the supplies of drinking water (Postel, 1993).

Water pollution arising from agricultural and non-agricultural sources is a major contributor to water scarcity. Water erosion transports soil particles and nutrients and deposits them in water bodies contributing to loss of reservoir capacity and eutrophication of water bodies. Intensification of crop and livestock production systems is a major contributor of pesticides and fertilizer pollutants of surface and groundwater resources. Discharge of untreated or partially-treated waste water into river systems aggravates the problem with some rivers becoming virtual sewers. For example, Yamuna river, which passes through New Delhi, receives 200 million litres of untreated sewage per day and has coliform counts as high as 25 million per 100 milliliters (Clarke, 1993).

Inequitable allocation of water resources, combined with poor enforcement of permitted water withdrawals leads to conflicts among uses and users of water.

Water scarcity exists when the demand for water exceeds the supply and it can be classified based on the context as: (a) physical water scarcity in which water availability is limited by natural availability; (b) economic water scarcity when human and financial resources constraints availability of water; (c) managerial water scarcity where availability is constrained by management limitations; (d) institutional water scarcity where water availability is constrained by institutional short-comings; and (e) political water scarcity where political forces bar people from accessing available water resources (Molle and Molinga 2003). These types of scarcity can occur concomitantly, increasing both the severity and impacts of water scarcity.

Molden *et al.* (2003) estimated that by 2020 approximately 75% of the world's population will live in areas experiencing physical or economic water scarcity. Most of these areas happen to be where most of the poor and food insecure people live. Meeting their food needs with locally produced food presents enormous challenge. Hence, the need is to increase water productivity of agricultural production systems that the poor people in water scarce areas depend on.

Production function and technical and allocative efficiency

Agricultural production involves the combination of inputs to produce agricultural outputs. For each agricultural production system a generic production function (input-output relationship) can be derived:

$$O = f(I1, I2, I3, \dots In) \quad (1)$$

Where O is the output and I1, I2, I3, and In are the production factors (land, labor, water, capital, energy and other inputs used in the production).

As production resources become scarce, producers seek ways to enhance the productivity of the resources and of the entire production system. Understanding the production function is a pre-condition for identifying opportunities for improving the performance of a production system. Increases in productivity can be achieved by two approaches: (a) by increasing technical efficiency through more efficient utilization of production inputs; and (b) increasing allocative efficiency by producing outputs with the highest returns. Here below, we illustrate how these two approaches can be used in identifying opportunities for enhancing productivity.

The level of output produced when production resources are used most efficiently defines the technical efficient limit. For example, in Figure 1 the line A-B defines the limits of technical efficiency. Points below the curve are technically inefficient because the same level of yield could be attained with less water. Points above the line are not technically feasible. The single factor production function presented in Figure 2 denotes the production possibilities for a given level of technical efficiency and of other production inputs. From Figure 2, we note that the output per unit input decreases at higher levels of input. In the case of crop production, a decrease in crop yield at higher levels of water input is mainly attributed to inhibited uptake of oxygen by the roots under water-saturated soil conditions.

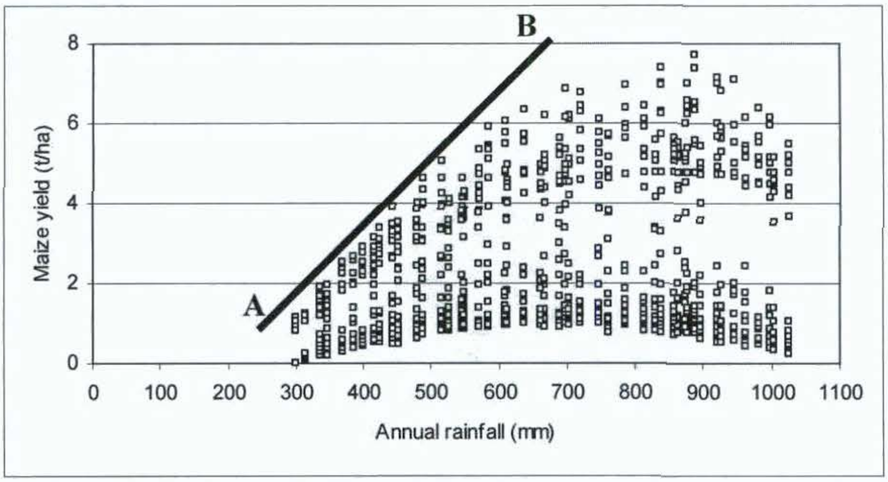

Figure 1. Maize yield as a function of annual rainfall in Ewaso Ngiro Basin Kenya

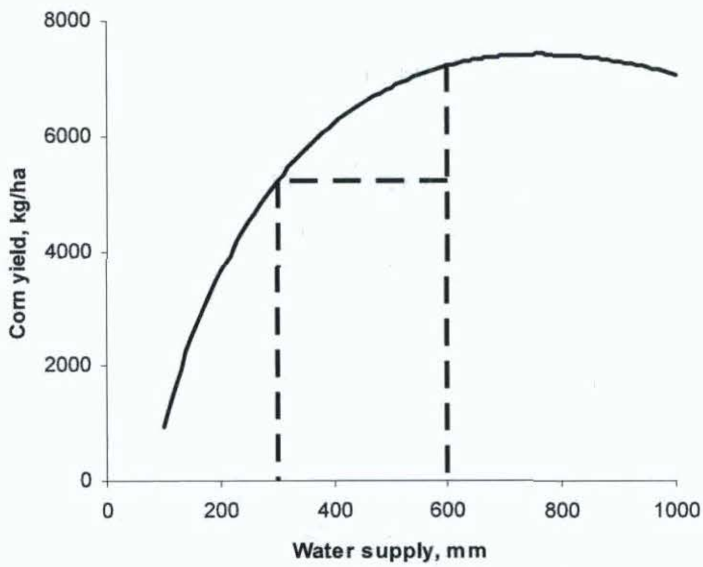

Figure 2. Crop-water production function for irrigated corn in Brazil. At point A, a yield of 5210 kg/ha was achieved with the application of 600mm water. The technically efficient water application for this yield is 300mm. Data from Frizzone *et al.* (1997).

An analysis of a single factor production function enables us to assess opportunities for maximizing returns from the use of this factor. Let us take a case where the only way of increasing crop yield is by increasing the water input. To optimize the production system, one must understand how output increases with increase in water input. The contribution of water to the production process can be described on both average and marginal (incremental) basis as shown below at different levels of water input.

$$Average\ Product\ of\ Water = \frac{Output}{Water\ Input} \tag{2}$$

$$Marginal\ Product\ of\ Water = \frac{Change\ in\ Output}{Change\ in\ Water\ Input} \tag{3}$$

At low levels of input, marginal product is higher than average product and the average product is increasing. The average product equals the marginal product when the average product reaches its maximum. At high levels of inputs marginal product decreases and product concept can be used to aid farmers in deciding what is the optimal level of a given input to apply.

How much production input is allocated to competing uses? The production resources available to farmers are limited and have competing uses. The farmers therefore have to choose the most desirable mix of agricultural outputs that they can produce with the resources at their disposal and with their state of technical know-how. They know that some outputs can only be produced if they forego others in keeping with the opportunity cost principle (see Figure 3). Take a case of a farmer who has to allocate a given quantity of water W to producing two crops, product A and product B. The production possibility curve for this enterprise shows how much of product A and product B he/she can produce for a given level of water input. Increasing the output of product A can only be achieved by reducing product B for that level of water input and production technology. Increasing the amount of water input will enable him to produce more of product A and product B at a higher production possibility curve.

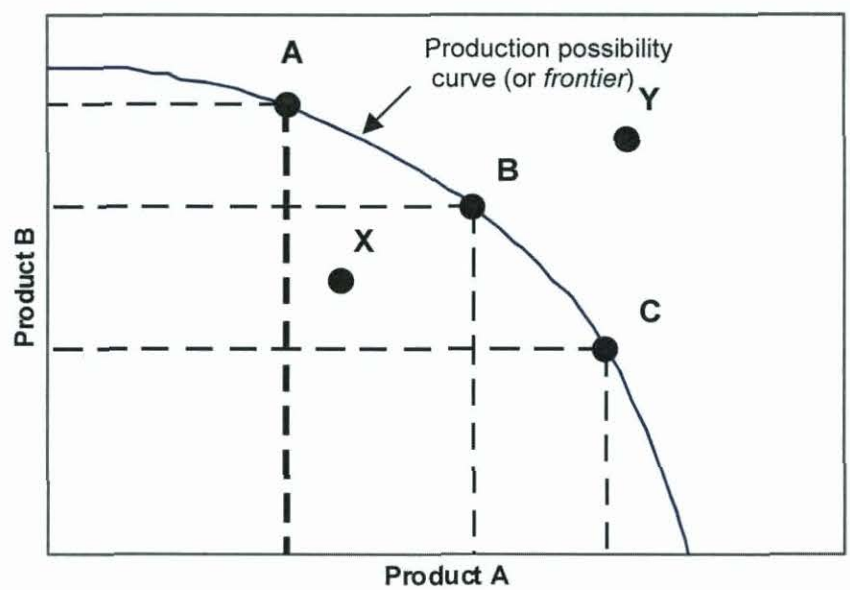

Figure 3. Product possibility curve (PPC), which depicts all maximum output possibilities for two (or more) goods with a given a set of inputs (resources, labor, etc.). The PPC assumes that all inputs are used efficiently. Points A, B and C all represent points at which production of both product A and product B is most efficient. At point X resources are not being used efficiently in the production of both products, while point Y cannot be attained with the given inputs.

The concept of allocative efficiency is used here to illustrate how a farmer could make a decision on what and how much to produce with a given level of input. The slope of the production possibility curve presented in Figure 3 is the rate at which crop A is substituted for crop B and is called the marginal rate of transformation (MRT). The farmer maximizes his returns if the marginal rate of transformation of crop A to crop B is equal to the price ratio of the two crops.

$$MRT_{AB} = \frac{P_A}{P_B} \tag{4}$$

What combination of input levels minimizes production costs? A given level of crop yield can be attained using different combination of production inputs. Hence farmers are confronted with the challenge of substituting one production input for another. The concept of marginal rate of technical substitution illustrates how this could be done.

Isoquants are curves that show all possible combination of inputs that yield the same level of output. An isoquant map is a combination of several isoquants in a single graph that describe how levels of output vary with different combination of input levels. Isoquant maps are used to assess input substitution as the slope of the isoquant indicates how the quantity of input can be traded off against the quantity of other inputs, holding the output constant. This slope is called the marginal rate to technical substitution (MRTS). As more and more of one input replaces the other, its productivity decreases as that of the other input becomes more productive. For example, the marginal rate of technical substitution (MRTS) of fertilizer for water in a crop production system is the amount by which the input of water can be reduced when one extra input of fertilizer is used, holding the crop output constant. MRTS tells the farmers the nature of the trade-offs involved in adding fertilizer and reducing the level of water input. The decision on how much water and how much fertilizer to use depends on the relative cost of these inputs. Optimum production is achieved when the following conditions hold

$$MRTS_{FW} = \frac{MP_F}{MP_W} = \frac{P_F}{P_W} \tag{5}$$

Where P_F and P_W are the unit prices of fertilizer and water respectively and MP_F and MP_W are marginal products of fertilizer and water respectively. MP_F/P_F is the additional output that results from spending an additional dollar on fertilizer. Similarly MP_w/P_w is the additional output that results from spending an additional dollar on water. The above equation therefore tells us that the farmer would minimize cost by choosing the quantities of inputs so that the last dollar's worth of any input added to the production process yields the same amount of extra output. We illustrate this point with a numerical example.

Suppose that the unit costs of fertilizer and water are \$10 and \$2 respectively. If an additional unit of water would increase output by 20 units, then the additional output per dollar of water input is 20/\$2 = 10 units per dollar and an additional unit of fertilizer increases output by 4 units. Because a dollar spent on water is five (20/4) times more productive than a dollar spent on fertilizer, the farmer wants to use more water than fertilizer. If he reduces fertilizer and increases water, the marginal product of fertilizer will rise and the marginal product of water will fall. Eventually, a point will be reached where the production of an additional unit of output costs is the same regardless of which additional input is used. At that point the farmer minimizes his costs.

Producers versus social net benefits

Farmers seeking to maximize benefits will use water and other inputs at levels where the incremental value generated is at least equal to the incremental cost. Farmers choose cropping patterns that maximize net benefits over time subject to their resource endowment, relative input and output prices and market opportunities. In places where water is scarce relative to available land, farmers will choose crops that maximize net returns to their limited water supplies. The way that they manage the water resources will depend on the cost and availability of water together with the technologies and management practices available for improving water productivity.

From society's perspective, the goal for managing public water resources can be described as maximizing the present value of net benefits over time. Net benefits include farm-level net returns minus the cost of water delivery, while accounting for the opportunity cost and externalities. Opportunity costs are the incremental values water might have in alternative uses, for example the value that it might generate for a downstream user. In addition to the spatial dimension (is the water worth more somewhere else?), opportunity costs can also have a temporal dimension (would the water be worth more at some time in the future?) In these examples, opportunity costs must be discounted by the cost of conveying the water to the alternative site or the losses during storage. Society's objectives in increasing water productivity are to meet the ever-increasing demands on a finite water resource. They fall into the following categories:

- Food security for all;
- Poverty alleviation;
- Employment creation – jobs/m^3;
- Equity and
- Meeting environmental demands (for example, flows needed to maintain wetlands).

Externalities are the off-farm effects of water use that impose costs or benefits on other water users. Positive externalities are any benefits that accrue, for example the generation of usable runoff to a desirable wetland area. Negative externalities are short- and long-term damage caused by runoff and deep percolation, for example, waterlogging and salinization.

Performance assessment

Rationale for performance assessment

Under conditions of increasing scarcity of resources, performance measures can play an important role in identifying opportunities to improve performance. Performance measures of similar (sub-) systems in different geographic locations or those tracking the performance of a particular (sub-) system over time can provide answers to strategic questions, such as: "What types of systems get the most return from limited water and land resources?" At the same time, they provide a cost-effective means of tracking performance in individual systems and valuable information that can be used by:

- Planners to evaluate how efficiently and effectively land, water, labour and capital resources are being used;
- Agricultural producers and managers of water systems to identify long-term trends in performance for use in setting reasonable overall objectives and to measure progress;
- Researchers to compare systems and identify factors that lead to better performance; and.
- Policy makers and development facilitators (donor agencies, private sector and NGOs) to assess the impact of their interventions so that they can be designed to be more effective.
- One of the challenges to improve the performance of water in agricultural systems is to answer the questions:
- How well should a system be performing;
- How well is it performing; and
- How can its performance be improved in a cost-effective way?
- Such performance analysis implies the need for:
- Performance standards that will be used for comparison;

- Tools and methods for assessing performance and any shortfalls in performance that there may be; and
- The ability to analyze critically the performance data and the determinants of those performance shortfalls that are modifiable.

Challenges of evaluating highly diverse production systems

A river basin comprises of a mosaic of highly diverse agricultural production systems whose outputs include crop, tree, livestock and fish products and a vast multitude of ecological goods and services. The bio-physical, socio-economic and institutional settings under which these production systems operate and the multiple and sometimes conflicts goals of the key actors present additional challenges.

The decisions made by agricultural producers and managers of water systems determine the levels of technical and allocative efficiency of the water resources available in the basin. Their decisions are influenced by the policy and regulatory instruments and by the level of complementary interventions such as infrastructural development. We therefore consider increasing water productivity to be a shared responsibility, however here we focus on the perspective of the agricultural producers. They have multiple objectives upon which they assess the performance of their production systems, namely the productivity, profitability, stability, diversity and time-dispersion (see Box 2 for brief definitions of each). The relative importance of each of these objectives depends on whether their production system operates at subsistence level or is partially commercial or fully commercial.

Box 2. Multiple objectives of an agricultural producer.

Productivity: Ratio of output to input that serves as a measure of the relative suitability of a farming system or an activity within the system.

Profitability: Net benefit accruing from the farming system.

Stability: The absence or minimization of season-to-season or year-to-year fluctuations in the level and/or the value of output of a farming system.

Diversity: Risk minimizing strategy associated with: (a) diversification of the farming system– crop, livestock, trees, fisheries on a given farm; (b) diversity of outputs from a given farming system, for example milk, meat and draft power from cattle production; (c) diversity of the ways that the produce is used – consumed, sold, stored, processed; and (d) diversity of income sources.

Time dispersion: The degree to which production inputs, output and income are spread over time.

Adapted from McConnell and Dillon (1997)

The most important objective for a commercial farmer is to maximize profit. Productivity, stability, diversity and time-dispersion may be important underlying factors for achieving higher levels of profitability but are generally not taken as desirable objectives in themselves. Farmers generally view productivity as a necessary condition to achieve higher profits but not as a sufficient condition in itself (McConnell and Dillon 1997).

The most important objective for a subsistence farmer is a reliable and well-distributed source of livelihood. Subsistence farmers therefore put more weight on time-dispersion, diversity and stability of their farming system. Subsistence farmers tend to be more diversified and produce more numerous and important by-products, which invariably complicates assessment of productivity. Subsistence farmers diversify to reduce risk of income loss or food insecurity and/or to increase the level of output and profitability through better use of available resources. Increased diversity improves stability, but in some cases reduces profitability.

Water productivity and efficiency

Productivity is a measure of performance expressed as the ratio of output to input. Productivity may be assessed for the whole system or parts of it. It could account for all or one of the inputs of the production system giving rise to two productivity indicators (Molden 1997):

- total productivity – the ratio of total tangible outputs divided by total tangible inputs; and
- partial or single factor productivity – the ratio of total tangible output to input of one factor within a system. In farming systems the factors could be water, land, capital, labor and nutrients.

Water productivity (WP), like land productivity, is therefore a partial-factor productivity that measures how the systems convert water into goods and services (Molden *et al.* 2003). Its generic equation is:

$$Water\ Productivity\ (WP) = \frac{Output\ Derived\ from\ Water\ Use}{Water\ Input} \tag{6}$$

WP was introduced to complement existing measures of the performance of irrigation systems, mainly the classic irrigation and effective efficiency (Keller *et al.* 1996). Classic irrigation efficiency focuses on establishing the nature and extent of water losses and included storage efficiency, conveyance efficiency, distribution efficiency and application efficiency. These measures are particularly useful for managers of water system who use them to (a) assess how much water they were losing in the storage, conveyance, distribution, and application sub-systems; and (b) identify interventions to improve performance.

In assessing the performance of water use in a large system, a basin or sub-basin, classic efficiency fails to capture the water re-use aspect. It ignores the beneficial use put to water re-captured and re-used in one part of the basin as a consequence of deep percolation and/or runoff losses that takes place elsewhere in the basin. To address this problem, Keller *et al.* (1996) introduced the concept of effective efficiency defined as the ratio of the gross inflow to the field less the sum of the volume of usable surface runoff and of deep percolation divided by the net volume of water supplied to a field.

The introduction of measures of water productivity makes it possible to undertake a holistic and integrated performance assessment by:

- including all types of water uses in a system;
- including a wide variety of outputs;
- integrating measures of technical and allocative efficiency;
- incorporating multiple use and sequential re-use as the water cascades through the basin;
- including multiple sources of water; and
- integrating non-water factors that affect productivity.

Water productivity and water saving

Real water saving is defined as the process of reducing non-beneficial water uses and making the water saved available for a more productive use. In situations where water is scarce, reducing non-beneficial uses becomes one of the main ways for reducing water scarcity. Improving water productivity seeks to get the highest benefits from water and hence can be viewed as a major contributor to water saving.

Real water saving by reducing non-beneficial depletion can be accomplished through:

- Reducing flows to sinks and
- Reducing non-beneficial evaporation.

For example, improving irrigation efficiency is considered to be the most appropriate way to reduce non-beneficial depletion and save water. Before this can be done, it is important to understand the water pathways of non-beneficial water use and its re-use. For example seepage losses may be the main way in which shallow groundwater aquifers used for downstream irrigation and domestic water supply are recharged. By failing to take a basin perspective when planning and implementing water interventions, we run the risk of not achieving real water saving and of having a negative impact on water quality, drinking water supply, groundwater balance, and downstream human and ecological users.

Guerra *et al.* (1998) noted that in most cases the arguments regarding water saving do not address other important factors that determine water saving such as the cost of water development and recovery. Increasing water productivity often requires greater use of other resources such as labor, capital and management.

Hence, at the basin level it is important to address the following key questions:

- What happens to the water that is lost through runoff and deep percolation?
- What effect does reducing non-beneficial use have on systems that were dependent on the water that it provided?
- What happens to the water that is saved through reduced runoff and deep percolation losses?

Approaches in assessing water productivity

Assessing the water input

Water accounting is a pre-condition for assessing the water input into a production system. A water accounting framework tracks the water pathways and quantifies inflows, depletions and outflows. It uses a 'water balance' approach to quantify the amount of water entering and leaving a system. The inflows include precipitation, surface and groundwater inflow and any changes in storage. There are two main pathways through which water leaves the system; depletion and outflow (see Box 3). The amount of water used in production can be interpreted differently depending on the system boundaries and the level of detail. Based on a water accounting methodology developed by Molden *et al.* (2003), the denominator can be, in decreasing order of scale:

- Gross inflow into a given field or catchment area;
- Net inflow;
- Available water;
- Depleted water, which is the amount of water removed from the system by both beneficial and non-beneficial depletion.
- Beneficially depleted water, which is the amount of water depleted through process and non-process beneficial use; and
- Process depleted water, which is the amount of water depleted through process beneficial use.

Box 3: Definition of terms used in the water accounting framework. (Source, Molden *et al.* 2003; IWMI, 2006.)

Gross inflow is the total amount of water flowing into the study area from precipitation, rivers and subsurface sources (groundwater).

Net inflow is the gross inflow less any increases in storage in the surface soil or groundwater.

Available water represents the amount of water available for use that is the net inflow minus the committed and non-utilizable outflow.

Water depletion is a use of water within the system that renders it unavailable for further use.

Process depletion is that amount of water diverted for use that is depleted to produce a human-intended product.

Non-process depletion occurs when water is depleted, but not by a human-intended process.

Non-beneficial depletion occurs when water is depleted through evapotranspiration that is not beneficial. Classification as beneficial or non-beneficial requires a value judgment and is a good entry point for discussions with stakeholders.

Committed outflow is that part of outflow from the study area that is committed to other uses such as downstream environmental requirements or downstream water rights.

Uncommitted outflow is that part of outflow that is not committed and is therefore available for a use within the study domain, but flows out of the basin due to lack of storage or sufficient operational measures. Some of the uncommitted outflow can be non-utilizable.

The water-accounting framework is summarized graphically in Figure 4.

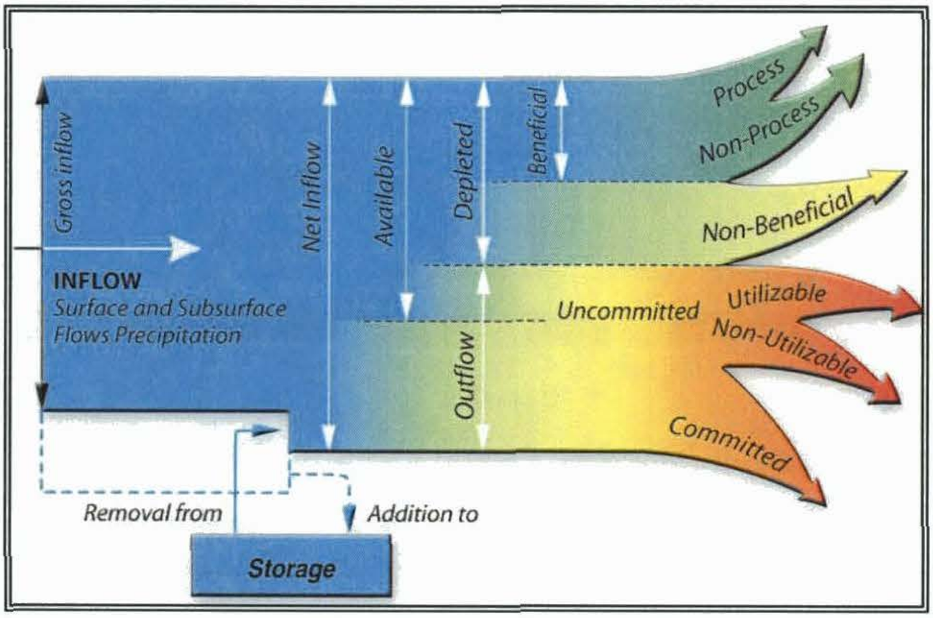

Figure 4. Water depletion accounting. (Source, Molden *et al.*, 2003.)

Assessing the outputs

Outputs in this context are benefits derived from using water. They can be quantifiable or non-quantifiable and can be generated either through depleting or non-depleting uses of water. Assessing different categories of outputs shown in Figure 5 is particularly challenging due to the following:

- Water provides a wide range of benefits, with quantifiable and non-quantifiable elements;
- No common objective measure applies to all water benefits;
- Water benefits reflect human value judgments that may vary from person to person and also over time;
- Benefits can be synergistic, for example income generation may improve health through adequate nutrition. Conversely, benefits may also involve trade-offs, such as the loss of ecosystem services that may occur as a result of excessive outtake of water for irrigation;
- In some cases, water may also cause harm through the introduction of hazards such as flooding, soil erosion, water-logging, salinization, as well as a wide the range of water-vectored health risks; and
- Benefits may be valued from different perspectives such as increased food security, reduced climatic risk, stabilization of income, etc.

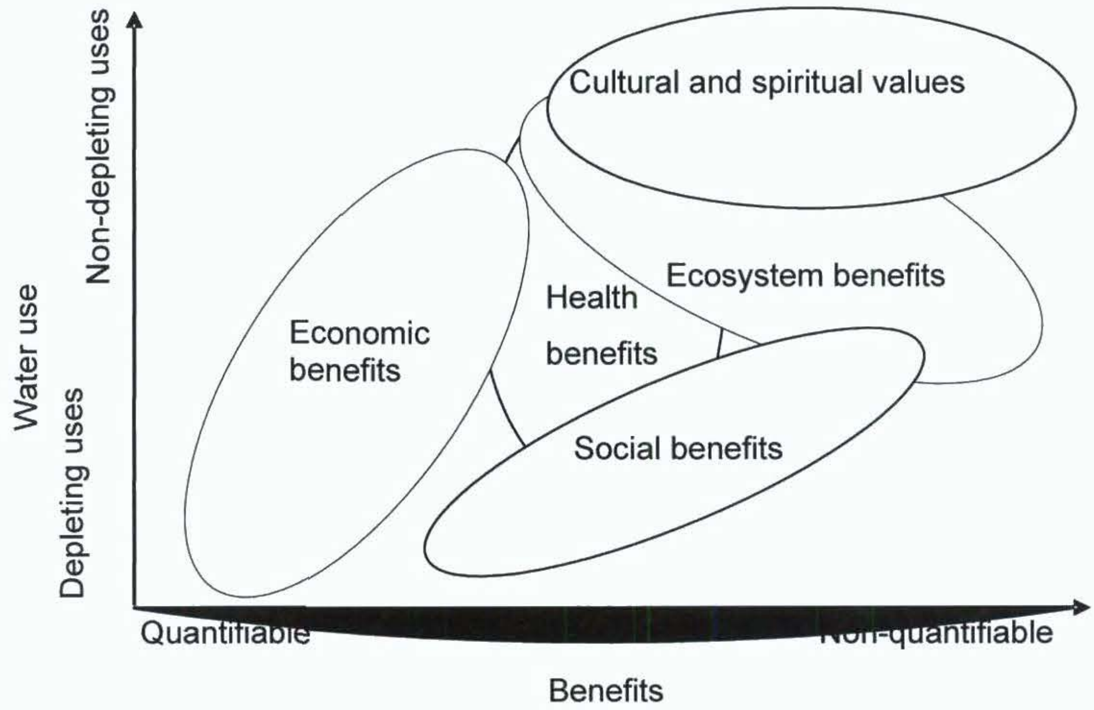

Figure 5. Water use and associated benefits.

An agricultural production system may be perceived as providing benefits of primary and secondary goods and services as shown in Table 1. Many secondary goods produced in agricultural systems are complementary to one another. For example, crop production systems may sequester carbon in some circumstances but in other circumstances they may release carbon. In most cases, the improved function of a system comes from complementarities in space and time. The difficulty is to compare parallel benefits from a range of water users.

Table 1. Some agricultural production systems and their benefits.

Agricultural production system	Benefits		
	Primary goods	**Secondary goods**	**Services**
Crop production	Harvestable yield	Crop residue for livestock feed	Soil cover to reduce erosion, enhancing agro-biodiversity, carbon sequestration
Livestock production	Meat, milk and eggs	Draft power, manure, leather	
Tree production	Timber, fuel wood	Food	Bio-diversity, water catchment protection, carbon sequestration
Fish production	Meat	Manure	Bio-diversity of aquatic ecosystems

We now focus on agricultural output, which can be evaluated for physical, nutritional or monetary benefit, within the bounds of the scale and time period being considered. Difficulties arise when outputs are difficult to value or when output quantities are expressed in different units. Crop production, for example, may produce a range of significant outcomes, including grain yield, fodder for livestock and organic matter for soil quality improvement. The first is measured in kg of grain/ha, the second in kg of gain in animal live weight/ha and the third in kg of organic matter accumulated/ha. It is little wonder then that past assessments of agricultural benefits have focused mainly on primary benefits of a given production systems and assessed the benefits as shown in Table 2. The table shows that even when focusing on primary output, there are still many ways in which the output can be quantified. This presents an enormous challenge when comparing total water productivity of different agricultural production systems.

Table 2. Agricultural production systems and their primary goods and indicators

Agricultural production system	Primary output	Indicator	
		Physical/nutritional	Economic
Crop production	Harvestable yield	• Total above ground biomass (marketable and non-marketable) at standardized water content (kg) • Total harvested product at the water content at which it is consumed (kg) • Nutritional content (kcal, or grams of protein, vitamin or micro-nutrient content)	Value of output or gross margin of output
Livestock production	Meat, milk and eggs	• Live weight of animal (kg) • Meat (kg) • Milk (kg or liters) • Eggs (number or kg) • Nutritional content (kcal, or grams of protein, vitamin or micro-nutrient content)	Value of output or gross margin of output
Tree production	Timber, fuel wood	• Timber (kg) • Fuel wood (kg)	Value of output or gross margin of output
Fish production	Meat	• Meat (kg) • Nutritional content (kcal, or grams of protein, vitamin or micro-nutrient content)	Value of output or gross margin of output

Current approaches to assessing the agricultural water-use benefits generally ignore secondary goods and services. In some cases these could be important. For example, in rainfed farming systems, grain is only one output of value to the farmer; others are green and dry fodder (grazing during early crop growth and straw and stubble after harvest). In pastoral systems, the value of green biomass varies at different stages of growth so that it is usual to convert green and dry biomass into digestible dry matter to account for this variability. Additionally, the value of a product may vary according to its position within often-complex farming systems.

These benefits often have relevance for broader water management goals and should be acknowledged in any attempt to define water productivity. Hence, the need to develope methodologies that take the following into consideration:

Non-grain benefits of water use in crop production such as the use of crop residues as fodder and/or mulch.

Benefits from by-products of livestock and fish production and their role as food supplements for livestock and fish production systems or as inputs to enhance soil fertility.

Benefits from ecosystem goods and services (biodiversity, ecosystem integrity, habitat maintenance) and socio-cultural benefits, such as aesthetics and cultural importance, derived from hydrologic flows in agricultural water use systems.

Indicators of water productivity

Water productivity is a very robust measure that can be applied at different scales to suit the needs of different stakeholders. This is achieved by defining the inputs of water and outputs in units appropriate to the users' indicator needs.

The numerator (output derived from water use) can be defined in the following ways:

- Physical output, which can be total biomass or harvestable product;
- Economic output (the cash value of output) either gross benefit or net benefit.

The water input can be specified as volume (m^3) or as the value of water expressed as the highest opportunity cost in alternative uses of the water.

The combination of the different numerator and denominator parameters yield a wide range of water productivity indicators as illustrated in Table 3.

Table 3. Range of water productivity indicators and the units that can be used.

Water input parameters	Output parameter					
	Physical measures		Physical/economic measures		Economic measures	
(m^3 or \$ value)	Biomass (kg)	Harvestable yield (kg)	Gross value (\$)	Net value (\$)	Gross value (\$)	Net value (\$)
Gross inflow	kg/m^3	kg/m^3	\$/m^3	\$/m^3	(\$/\$)	(\$/\$)
Net inflow	kg/m^3	kg/m^3	\$/m^3	\$/m^3	(\$/\$)	(\$/\$)
Available water	kg/m^3	kg/m^3	\$/m^3	\$/m^3	(\$/\$)	(\$/\$)
Depleted water	kg/m^3	kg/m^3	\$/m^3	\$/m^3	(\$/\$)	(\$/\$)
Beneficially depleted water	kg/m^3	kg/m^3	\$/m^3	\$/m^3	(\$/\$)	(\$/\$)
Process depleted process water	kg/m^3	kg/m^3	\$/m^3	\$/m^3	(\$/\$)	(\$/\$)

We now consider how the different indicators could be used to assess water productivity for a cropping system at different scales:

- **Crop scale**: is of interest to crop physiologists to assess how efficient a particular crop or cultivar of a crop is in converting water into biomass. At this scale the output can be quantified either as total biomass or crop yield (harvestable produce). The water input that is relevant for this assessment is the water used in transpiration, which here we call process depleted water.
- **Field scale beneficial use**: is of interest to the farmer, agronomist and water specialist to assess how efficiently a particular cropping system converts water into beneficial output. At this scale the output can be quantified as total biomass or crop yield and the water inputs are the amount of water that was used in process depletion (transpiration).

- **Field/farm scale beneficial and non-beneficial use**: is of interest to the farmer, agronomist and water specialist to assess the opportunities of saving water lost through non-beneficial use. At this scale the output can be quantified as total biomass, crop yield (kg), crop value ($) while the water input is the amount of water depleted from the system through (a) evaporation, (b) flows to sinks that are not recoverable, (c) pollution to levels that render it unfit for use and (d) incorporation into the product.
- **Irrigation system scale**: is of interest to the irrigation system manager in assessing how productively the water available to the irrigation system is being used. At this scale the manager takes into consideration both the amount of water depleted and that which is recaptured for re-use downstream. At this scale the output can be quantified in physical and economic terms and the water can be accounted for in either volume or in value terms.
- **Sub-basin scale**: is of interest to planners and river-basin managers in assessing options for increasing water productivity at this scale. The output can be quantified as either biomass or harvestable produce in kg or their cash value in $. The water input becomes the net inflow, which is difficult to value in monetary terms and therefore generally assessed as volume. It is particularly useful in assessing the opportunities for investing in water infrastructure.
- **Basin scale**: is of interest to river-basin managers and planners in assessing the productivity of the renewable water that enters the basin, mainly as rainfall. The output includes all the water benefits derived by water as it moves across the basin landscape and could even include the value of near-shore marine life.

Aggregating multiple outputs water productivity

One of the advantages of the water productivity concept is that it allows us to assess the productivity of multiple-use systems such fish production in irrigation canals, or where crop residue is an important source of livestock feed. Under such conditions there are multiple benefits arising from using the same quantity of water. To calculate water productivity of depleted water in a multiple-use system we could use the formula:

$$Waterprodu\ ctivity\,(WP)_{Depletedwa\ ter} = \frac{\sum_{j=1}^{p}\sum_{i=1}^{n} Y_{ij} A_{ij}}{\sum_{j=1}^{p}\sum_{i=1}^{n} W_{ij} A_{ij}} \qquad (7)$$

Where Yij is the amount of output for production system j on field i (kg/ha),
Wij is the amount of water depleted (m^3/ha),
Aij is the production area,
p is the number of production system and
n is the number of fields

Molden *et al.* (1998) proposed an approach for standardizing crop benefit by using the standardized gross value of production indicator within an area, computed as:

$$SGVP = \left(\sum_{i=1}^{N} A_i Y_i \frac{P_i}{P_b}\right) P_w \qquad (8)$$

Where A_i is the area cropped with crop i,
Y_i is yield of crop i,
P_i is local price of crop i,
P_b is the local price of base crop (the main locally-grown, internationally-traded crop) and

P_w is the value of the base crop traded at world prices and N is the number of crops grown.

Where data exist, SGVP for other agricultural produce (fish, livestock and trees) may be assessed using a similar procedure. The equation can also be expanded, at least in principle, to include the value of other goods and services. These might include value society places on other ecosystem services generated by the hydrologic flow of water through the system such as biodiversity, ecosystem integrity, habitat maintenance, aesthetics, etc.

Rationale for increasing water productivity

Global imperatives

The global population, which reached 6 billion in 1999 and is expected to reach 7.8 billion in 2025, is putting enormous pressure on the finite renewable water resources as the demand for food and other water-dependent goods and services increases. Irrigated agriculture, which accounts for 72% of global and 90% of developing countries' water withdrawal will have to increase its productivity to mitigate the growing water crisis (Cai and Rosegrant 2003). Other agricultural water uses will also have a role to play. It is estimated that increases of 30 and 60% in water productivity from rainfed and irrigated agriculture, respectively will be required to meet the demands for food security. To achieve sustainable agricultural growth necessary for food security, Kofi Annan, Secretary General of the United Nations in his Millenium Report to the General Asembly, April, 2000 and repeated in his report to the Millenium Conference in October, 2000 called for a "*Blue Revolution in agriculture that focuses on increasing productivity per unit of water – 'more crop per drop*" (Annan 2000). This formed the basis for setting global target for reducing water use in agriculture that is stated as (CPWF 2002):

> *"maintaining the level of global diversions of water to agriculture at the level of the year 2000, while increasing food production, to achieve internationally-adopted targets for decreasing malnourishment and rural poverty by the year 2015, particularly in rural and peri-urban areas in river basins with low average incomes and high physical, economic or environmental water scarcity or water stress, with a specific focus on low-income groups within these areas"*

Basin-level rationale

At the basin level, the rationale for increasing water productivity lies in the need to:

- Increase water availability to users and uses that are disadvantaged. For example the need to increase water productivity in the upper reaches of rivers so as to reduce water depletion and hence increase water availability in downstream reaches;
- Reduce overall water demand and develop additional water resources (dam development, groundwater exploitation and water transfers from regions with excess water to regions that experience water scarcity); and
- Increase total basin level water benefits through more productive use of the available water resources.

Several basins are exploring options for enhancing water productivity to achieve various social, economic and environmental goals. For example, the Yellow River basin, which is currently experiencing severe water shortages in the dry seasons[11], has set a target of reducing water use in agriculture by 4 billion m^3 by 2010 so as to meet the needs of urban development.

[11] In 1972, the river dried up failing to reach the outlet for 15 days. Since 1985, the lower reach has run dry each year, with the dry period and the length of the dry section getting increasingly longer. In 1996, the river dried for 133 days and in the drought year of 1997 for 226 days.

System level rationale

At the level of the irrigation system, increases in water productivity may be required to:

- Secure water for downstream farmers who experience water shortages;
- Reduce operation and maintenance costs associated with desilting and water outtake including the costs of pumping;
- Make water available for expansion of the irrigated perimeter where the cost of saving water through increasing water productivity is less than the cost of developing additional water resources; and
- Comply with water permit and pollution regulations to ensure adequate provision of safe water for non-agricultural users.

Farm level rationale

At the farm level, increases in water productivity are required to:

- Reduce water costs (costs of pumping, delivering water or water fees);
- Reduce loss of land productivity associated with soil erosion, waterlogging and salinization;
- Expand irrigated areas with the same amount of irrigation water available; and
- Increase agricultural output, food security and profitability.

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Water productivity: Measuring and mapping in benchmark basins

Basin Focal Project Working Paper no. 2

Francis Gichuki, Simon Cook and Hugh Turral

Challenge Program on Water and Food

Basic concept: Water productivity for agricultural production systems

The concept of water productivity (WP) is offered by Kijne *et al.* (2003) as a robust measure of the ability of agricultural systems to convert water into food. While it was used primarily to evaluate the function of irrigation systems – as 'crop per drop' - it seems useful to extend the concept to include other types of livelihood support, such as mixed cropping, pasture, fisheries or forests. The basic concepts and rationale for estimation are described more fully in the first working paper of this series.

The purpose of this paper is to present ideas of methods of estimating WP at a range of scales, and for different agricultural systems. Water productivity of non-agricultural systems is not considered.

A third paper in this series describes how estimates are used to define actionable goals of agricultural water management for poverty alleviation. For now, we assume two basic uses of WP estimates: firstly, WP provides a diagnostic tool to identify low or high water use efficiency in farming systems or sub-systems; secondly, WP provides robust insight into the opportunities for re-distribution of water within basins towards a goal of increased basin-scale and global water productivity.

In practice, measurement of WP over large areas requires approximations and assumptions that can introduce important errors. The subsidiary purpose of this paper is to enable developers to make judgments about how acceptable these errors are and what alternatives there may be to resolve the technical problems.

Basic expression:

Productivity is a measure of system performance expressed as a ratio of output to input. For agricultural systems, WP is a measure of output of a given system in relation to the water it consumes. Assessment may be required for the whole system or parts of it, defined in time and space.

$$WP = \frac{Agricultural\ Benefit}{Water\ Use}$$

Units:

It is normal to represent WP in units of kg/m^3. If production is measured in kg/ha, water use is estimated as mm of water applied or received as rainfall, convertible simply to m^3/ha (1mm = 10m^3/ha). Alternative notations include food (kcal/m^3) or monetary value ($/m^3).

Defining the system for which Water productivity is to be assessed:

Water productivity is estimated for an agricultural system or sub-system, defined within a given area and time period. The simplest purpose of WP is to enable rapid comparisons between water use systems in space and time; a WP of 1.5 kg/m^3 might be considered 'good' whereas one of 0.5 kg/m^3 might be thought 'bad'. For this purpose, it is preferable to restrict the concept to component parts of a system, rather than try to estimate overall productivity for the entire system.

Systems are defined by plot, field, sub-basin and basin. Estimates of WP for single activities are called partial WPs. WP of larger areas containing complexes of multiple land use requires integration of partial WPs for each activity contained within them.

Changes in water use in the hydrologic pathway will have impacts both upstream and downstream, so it is necessary to analyze the impacts of different interventions in a way that internalizes hydrologic feedback in terms of water quantity and water quality. The best way to do this is to integrate the production system, the hydrology and economics within one modeling framework. This can vary from simple spreadsheets, through suites of hydrologic, allocation and production models; to fully integrated hydrologic and economic models. The precise requirements and solutions will vary according to the basin context and data availability.

Defining the time period for estimation

The time period over which WP is estimated is determined by the cycle of agricultural production that drives the system. Normally, this would include at least one complete crop cycle, extended over a complete year to account for productive and non-productive water use. Assessment may be extended over several years to derive estimates of average, minimum or maximum water productivity within each season.

Complex agricultural systems may require assessment over several years to include all productive and consumptive phases. The value of product may vary according to its position within the farming system it is used, often in quite complex ways. For example, livestock systems in semi-arid regions have developed to cope with fluctuations in water availability in different seasons, so assessment in any one season may not represent productivity of the whole system. Cropping systems provide internal benefits in addition to yield, such as fodder or soil nutrition, which may significantly influence water productivity in subsequent years. Forest products may provide small but critically important gap-filling products.

The fluctuation over time of drivers of productivity such as climate or markets introduces a further source of estimation error. This is because the condition of WP will reflect the state of these drivers at the time of assessment, which may, or may not, be representative of the average situation.

Defining the area for estimation

The first step is to define the boundaries of the system for which WP is to be estimated. This is determined by the definition of production system (field-by-field, farm-scale, multiple administrative units) and the area for which water consumption can be defined (plot, field, sub-basin or basin).

There is a trade-off between accuracy of measurement over small areas and representation of a larger hydrologic system. Measurement of partial WP for a single crop at field or plot level is simplest. However, such an assessment will represent only part of the benefits generated within a farming system. Additional activities within the farming system such as livestock, trees or fish may need to be included to represent essential benefits, but will also introduce major uncertainties.

Yield data exist for many countries as secondary statistics, expressed crop-by-crop according to administrative boundaries. In these cases, manipulation in GIS is required to make the data spatially coherent with water-use data. Techniques of proportional areal estimation are described in standard GIS texts (see Davis, 2003 for a review of methods in relation to poverty mapping).

The effect of spatial scale on variation in water storage should also be considered. In rainfed areas, WP will vary spatially according to varying water storage capacity (Bouman, 2006), such that definition of a particular production system can be over- or under-represented within areas with a high or low storage capacity. Systems in which groundwater flows make a significant contribution to production (either via reemergent or extracted groundwater) need to be defined over an area large enough for this source of variation to be identified.

Production: Estimating the enumerator

The beneficial outcome of agriculture can be expressed in a range of forms, as yield (kg, Mg, t) or food equivalent (kcal.); income ($) or other agreed measure of well being derived from the goods and services coming from the agricultural system. The common forms of evaluation are listed in Table 1.

Table 1. Possible forms of the numerator for estimating water productivity.

Parameter	Numerator
Physical water productivity at field, farm or system level.	Yield (kg) of total biomass, *or* above ground biomass, *or* grain, *or* fodder.
Economic water productivity at farm level.	Gross value of product, *or* net value of product, *or* net benefit of irrigated production compared with rainfed production.
Economic water productivity at basin scale.	Any of the above valuations including those derived from raising livestock, fish or agro-forestry.
Macro-economic water productivity at regional or national scale.	Monetary value of all direct and indirect economic benefits minus the associated costs, for all uses of water in the domain of interest.

Physical measurement of productivity

The simplest option is to consider the water productivity of a principal crop, in kg or t, for an area of known extent for which there exist data on agricultural water use. Primary yield data may be generated from direct measurement or by crop survey. More commonly, crop production data will come from secondary statistics – as total tonnage for a given administrative area (convertible to t/ha if the area dedicated to each crop is known). In some cases, global or national level statistics can be manipulated to provide useful insight (e.g. Falkenmark and Rockström, 2004). This will enable partial water productivity of principal crops to be estimated for large areas. Raw production in kg may be converted to nutritional value (see Rockström *et al.* 2003).

Remote sensing provides a third option to estimate production over large areas. Wide area estimation of grain yield from the normalized difference vegetation index (NDVI) has been used successfully for basin or national scale estimation of biomass and crop yield for several years. Its accuracy varies widely, depending on the ability for an episodic estimation of reflectance to estimate biomass and final yield. Under good conditions, remotely sensed imagery correlates about 70% with final grain yield.

Local calibration seems essential since in some areas correlation between NDVI-based estimates and actual yield can be extremely low. Remote sensing has also been used to assess total feed value of pastures. In all cases, the accuracy of remote sensing techniques is highly dependent on the availability of timely imagery.

Remote sensing tends to be most successful in arid and semi-arid regions in which cloud-free imagery is available for the whole growing season.

Ahmad *et al.* (2005) propose a combined remote sensing approach to estimate water productivity at a regional scale, using a variety of scales of imagery (Landsat at 28.5 m pixel to Moderate Resolution Imaging Spectroradiometer (MODIS) at 1km (thermal) and 500m (visible, near- and medium- infrared wavebands)). Ground truth, crop histories, classification, biomass development and yield will be required to understand the relationship between net primary productivity and yield and better assess harvest index as a function of crop condition. Representative areas for survey can be selected from a preliminary analysis of satellite images, and local knowledge.

Economic measures of agricultural productivity

The simplest measure of economic productivity at a field scale is gross margin (GM) for a single product during a single phase of the crop rotation. The system may require estimates of GM from several seasons to cover all phases of a farming system.

For areas that contain different production systems, a composite measure is standardized gross value of product (SGVP) in which the price of the product is converted to the equivalent price of a standard crop, such as rice, then converted to the world market price. Expressed in a formula:

$$SGVP = \sum_{Eachcrop} (Area \times Yield \times \left(\frac{local\ price}{base\ price} \right) World\ market\ price)$$

The utility of SGVP may be questioned since it includes no estimate of costs, and therefore attributes average total benefit of all farming inputs to water.

The full range of economic benefits from agricultural production extends far beyond the simple measure of local production, to include indirect and broader impacts (Hussain *et al.* 2005). Multipliers of economy-wide farm / non-farm multipliers vary widely. Estimates in India suggest a multiplier as low as 1.2 for local schemes up to about 3 for the country as a whole. Multipliers tend to be larger in developed economies, estimated as high as 6 for Australia (Hill and Tollefeson, 1996).

Hussain *et al.* (2005) point out that the most meaningful measure is of marginal value, that is, the additional value that is created when water is added (or lost when water is not available). WP assessment is more directly linked to problems in water-scarce or water-costly situations than in systems which are supplied with plentiful, low value water. WP is most meaningful as an indicator as water resources become increasingly scarce. The range of productivity-based indicators is summarized in Table 2.

Table 2. Productivity indicators.

	Indicators
Water productivity-based indicators	Average product per unit of water
	Average gross value of product per unit of water
	Average gross margins per unit of water
	Average gross net value of product per unit of water
	Value of marginal productivity of water.

Note: Commonly used denominators for calculating water productivity based indicators are amount of water diverted/supplied, water applied, gross inflow of water (rainfall plus irrigation), and crop evapotranspiration (Et).

Estimates of marginal value may be necessary where assessment is needed to identify 'optimal' distribution amongst contrasting users. Oweis and Hachum (2003) cite the benefit of supplemental irrigation in these terms and demonstrate marginal WP of up to 2.5 kg/m^3. The concept of marginal value is reasonably standard in resource-based economies but data on which to evaluate it is difficult to find beyond research stations. It may be possible to derive crop production functions that estimate the contribution of water to productivity (see, for example, estimates for Rechna Doab in Pakistan; Ahmad *et al.* 2005).

Assessment to emphasize pro-poor outcomes might also weight assessment to account for the increased value of benefits in low income groups. This argument is made on the basis that

- Income has diminishing marginal utility in purely economic terms;
- If the intention is equitable income distribution, a dollar generated on behalf of a low income earner is worth more than one generated for a richer person and
- On a one-person, one-vote principle the per *person* benefit counts more than the per dollar benefit.

On the basis of this analysis, the relative value of fisheries and forests can be much greater than initial analysis suggests because they are often of great importance to the landless poor and marginalized people.

Non-economic measures of agricultural productivity

Non-economic benefits from water by agriculture can be significant factors to include in assessment of total WP. They can, however, be difficult to evaluate – each type demanding complex methodologies to assess complex benefits. Environmental benefits can include direct product (including protection of fish resources), indirect benefits (e.g. impact on carbon stocks) or environmental flows – namely, flows deemed necessary for proper function of basin processes (Smakthin *et al.* 2004). The potentials for payment for ecosystem services (PES) appear to be increasing as more effort is put into practical evaluation and implementation (Farber *et al.* 2002; Kozanayi, 2002). As explained in Paper 1 of this series PES exemplifies the benefit of building social capital through management of common water resources. The final non-economic benefit that we mention here is the political capital that accrues through agreements to share or trade water resources or their products (such as hydro-electric power). Analysis by Wolf *et al.* (2003) of reported events involving trans-boundary basins indicate these predominantly construct political capital.

Valuation systems are inextricably linked to the attitudes people have towards water, ranging from private, depleting uses to common, observable (non-depleting) attributes (Groenfeldt, 2003; Turner *et al.* 2004). Difficulties in quantification arise when outputs are difficult to value or when output quantities are expressed in different units. Some issues that may require specific attention include:

- Assessment of WP in complex livestock-based farming systems. This would need to include exchange of plant and animal products around the system (see, for example, Peden *et al.* 2002).
- Forest and agroforestry systems, which may provide ecosystem services, and be of unusual importance culturally or because of biodiversity considerations.
- WP of fisheries and other aquatic systems, for which both output and consumption may be very difficult to quantify, yet provide essential livelihood support to the world's poorest people.

One suggestion is to adopt a broadly-based indicator of water wealth that portrays the income per m^3 on a per capita basis. Per capita income, however, does not estimate the total support provided by water so ultimately does not relate to the problem that more food will need to be produced for more people with less water. For example in the Lakes region of Kenya and Uganda rainfed agriculture supports a very high density of people, each with a small per capita wealth. Total WP is far higher than per capita WP. Another approach may be to take account of the number of people supported by a given water resource and the level to which they are supported, using standard measures of livelihood support, such as Human Development Index (see Maxwell, 1999) or Basic-Needs Index (see Davis, 2003).

Estimating the denominator: Water consumed

A key distinction when computing WP is to differentiate between water input to an agricultural system and water depleted by it. WP is estimated from the amount of water directly consumed by the agricultural system (that is, evaporation and transpiration), not simply the amount of water supplied. This distinction is increasingly important as we move upscale from field to farm to basin, because water that is taken into a system, but not consumed, is available downstream and hence is excluded from calculation (see Molden, 1997). In measuring depleted water, we account for flows not used by the crop and returned to the hydrologic system.

Quality of downstream water is potentially an important factor. Activities that damage water quality effectively reduce or even remove water that would otherwise be available to downstream users.

Estimating water input can be confounded by not being able to define contributions from shallow or deep groundwater, although if available, water table modeling can assist. Another problem is not knowing the extent of run-on to rainfed lands from surrounding catchment areas. It is also possible that there will be varying amounts of soil water carried over between seasons, depending on the year and the timing of rainfall. For example, we would expect all soil moisture in the root zone to be depleted every year in the Karkheh basin, with its strong pattern of winter rainfall and very high rates of potential Et in the dry summer.

Water balance

The basic expression of water balance is (input – output), accounting for change in water stored in the system:

$$Q_{in} = Q_{out} + \Delta S \qquad (1)$$

Where: Q_{in} includes rain, groundwater and surface-supplied irrigation and run-on,
Q_{out} includes runoff, drainage and evapotranspiration, and
ΔS is change in soil water content.

At the field scale, the key term is evapotransiration, considered as:

$$Et = P + I + G + Q - \Delta S \qquad (2)$$

Where: Et = evapotranspiration, that is evaporation from soil and water surfaces plus crop transpiration
P = rainfall
I = irrigation inflow
G = net groundwater flow
Q = runon (positive) or runoff (negative)
ΔS = changes in soil water content within the root zone

Some components may not be relevant and be removed to simplify evaluation (e.g., no irrigation in rainfed farming, no run-on (incoming overland flows) or no capillary rise from high water table). Using both actual Et and net water supply as denominators can help define the context and options for management.

Direct and indirect measurement of Et

Et of crops is routinely inferred for large areas from more easily measured climatic variables (for details see Linacre, 1977; Allen *et al.* 1998).

Quantitative estimates of consumptive water use by crops over large areas is possible using the Surface Energy Balance Algorithm (SEBAL) method. This determines Et as a residual of the energy balance using routinely available weather data in conjunction with satellite-sensed thermal radiation.

Remote sensing offers the chance to represent land use and its spatial variation accurately, to determine actual Et (Et_a) and possibly to fill gaps that there may be in the coverage of rainfall data. Et_a is obviously a better measure of water consumption by agriculture than potential Et (Et_p), which assumes water is freely available and that the crop canopy remains fully developed and active. However there are a number of challenges to be addressed:

- SEBAL relies on cloud-free imagery of cropped areas,
- Sub-pixel disaggregation of land use (between crops and between cropped and fallow land), when using 1km or 500m pixel (MODIS or Advanced Very High Resolution Radiometer (AVHRR)) data,
- Corresponding sub-pixel disaggregation and attribution of Et_a to each land use, or alternatively to land use defined by higher resolution imagery (Landsat at 28.5m) and
- The SEBAL procedure needs improved calibration for rainfed, pasture and forest land covers. New research is providing some insight on the estimation errors.

Estimating consumptive water use by simulation modelling

It may be possible to represent the effect of climate variation on rainfed-crop WP by coupling a weather generator with crop simulation models. This has been done for large areas using the MarkSim procedure (Jones *et al.* 2002) coupled to the Decision Support System for Agrotechnology Transfer models (DSSAT, Hoogenboom *et al.* 2004) by Díaz-Nieto *et al.* (2006). Results can be spatialized in GIS using exhaustive parameterization of model inputs. An alternative approach is to establish the spatial distribution of a small number of 'typical' soil profiles for which more exhaustive modeling results exist (Pracilio *et al.* 2001). The purpose of this would be to identify theoretical benchmarks of crop WP from which may be identified intrinsic factors liable to reduce water productivity.

Allocation scenarios can be simulated by changing the balance of land under rainfed and irrigated conditions, or by adjusting water supply inputs through:

- Rainwater harvesting,
- Soil water conservation practices,
- Supplemental irrigation,
- Changing surface or groundwater allocations and
- Conjunctive use policy to balance demands for surface and groundwater.

The estimation of Et from water input data can be complicated by not being able to define contributions from high water table (although water table mapping will assist, if available) and not knowing the extent of run-on to rainfed lands from surrounding catchment areas.

The soil water storage term is normally assumed to make an insignificant contribution to seasonal water use. For example, we would expect all soil moisture in the root zone to be depleted every year in regions with strong patterns of winter rainfall and very high rates of potential Et in summer such as the Karkheh and upper Volta basins. However, it is possible that in some situations there might be carry-over of soil water between seasons in regions such as the Mekong basin, depending on the timing of rainfall between years.

More complex 2- and 3-dimensional modeling may be necessary to understand the consequences of land-use change on water availability and consumptive water use. Where the system is governed by surface water supply with limited groundwater, a simple node-link model like the Stockholm Environment Institute's water evaluation and planning (WEAP) system may be adequate to represent water budgets. If the system is dominated by rainfed agriculture, then a model like the USDA soil and water assessment tool (SWAT), which integrates land use and hydrology may be preferred, although there may be problems in representing groundwater and surface water diversions. Higher-dimensional hydrologic models such as TOPOG (Dawes and Hatton, 1993) may be used to represent water balance within spatially-variable landscapes. More complex process-based models (such as the Danish DHI Water & Environment MIKE-SHE model) integrate all process, but present very serious challenges in calibration and parameterization, due to extensive data requirements, often related to soil characteristics. There are intermediate solutions, such as the New South Wales Department of Land and Water Conservation integrated quality and quantity model (IQQM), which is basically a node-link model with more advanced hydrology options for catchment yield, ungauged inflows and storage (see Hameed and O'Neill, 2005).

A long history of development and application of such models can be found in the literature. However, the data requirements may be daunting. A major lesson seems to be 'proceed with caution', since propagation of error within data-hungry models can render complex results meaningless.

If there is significant groundwater use, and salinity is an important factor, then the integrating model should be a groundwater model, incorporating a salt transport module (e.g. the USGS modular three-dimensional groundwater flow model MODFLOW with the MT3D module). Creating groundwater models is a very time and data intensive exercise, and is usually limited to well-defined areas. It is highly unlikely that groundwater models can be built and calibrated at whole basin scale.

The recent publication by the International Water Management Institute (IWMI) on the Zayendeh Rud basin in Iran (Murray-Rust and Selemi, 2002) provides a good example of the integration of models at different scales using simple spreadsheets as links, although it is a little superficial on the integration of groundwater

Water accounting

The problem of estimating water consumption becomes more difficult for large, heterogeneous areas that contain complex mosaics of land uses. Discrepancy of meaning between WP of different uses can obstruct comparison of different water users within a single area. To simplify this, the method of water accounting may help track different flow paths of water depletion (Molden, 1997).

Water accounting tracks the movement of water volumes within a field, an irrigation system or a basin according to four basic designations (Figure 1):

- Water inflow (positive)
- Change in storage (positive or negative)
- Depleted water, that is water used or removed in either process (e.g. growing and processing food) or non-process (e.g. depletion by evaporation from soil surfaces and ditches, or deep percolation to groundwater that is non-recoverable) or non-beneficial (transpiration by weeds; washing motor vehicles).

- Outflow that is either committed as direct input into some downstream application or is available for use downstream (utilizable) or not (non-utilizable, as in the case of saline or contaminated water).

Volumes in each category are measured (e.g. irrigation inflows), inferred by modeling (drainage outflow) or inferred from other data (e.g. use of remote sensing to estimate Et).

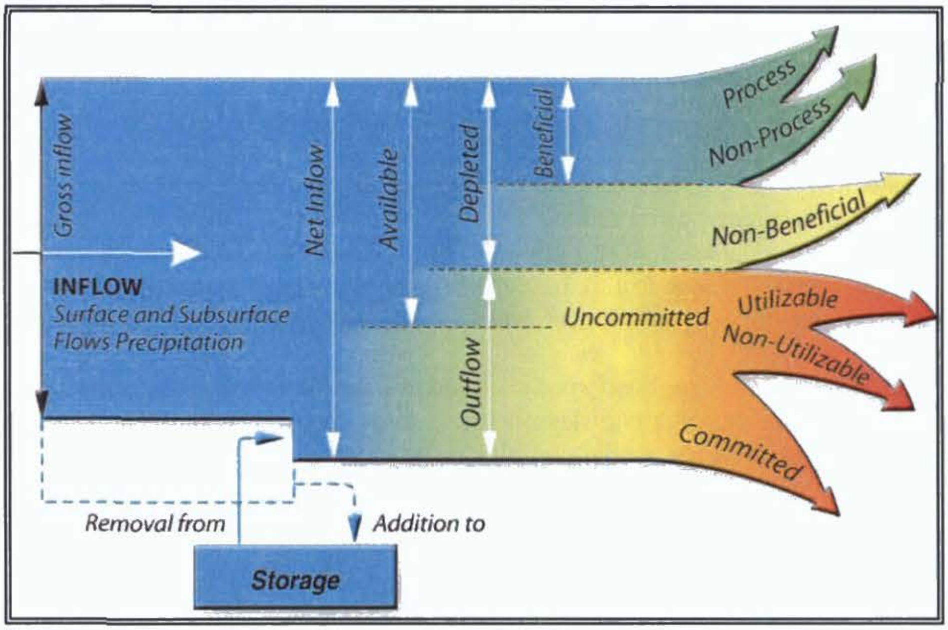

Figure 1. Water accounting framework (Molden *et al.*, 2001).

WP of rainfed cropping systems

Rockström *et al.* (2003) provide tables of consumptive water use for a range of tropical and temperate crops, based largely on observations from the 1950s to 1970s to compute WP from published values for crop water use efficiency (see also Rockström *et al.* 1999). Rockström *et al.* (1999) observe a wide range of WP around the universal average of about 0.7 kg/m^3 of green water. (non-irrigation water use by agriculture). Within-field variation in yield is even greater (hence WP), suggesting substantial scope for improvement of WP.

Water use efficiency of dryland crops has been studied for over 90 years. Yield data are widely available and in them attention is generally focused on estimating the denominator WP, the water consumed. At its most basic, consumptive water use (Et) is expressed as growing season rainfall and soil water changes:

$$Et = P_{\text{growing season}} + \Delta S \qquad (3)$$

No account is taken of losses/transfers of water by runoff, nor of losses through deep percolation beyond the rootzone, both of which will reduce WP at any given point. In dryland systems, changes in soil water at the beginning and end of growing season may be assumed to be insignificant, so that water consumption is simply estimated as rainfall during the growing season.

The compilation of results of water use by dryland cereal crops by Sadras and Angus (2006, Figure 2 below), shows several interesting features:

- An intercept of about 60mm (range 80-110 mm according to site characteristics), attributed to evaporative loss,
- An overall maximum conversion efficiency of about 22 kg_{grain}/mm_{water} (equivalent to WP of 2.2 kg_{grain}/m^3, somewhat higher than the estimates of WUE collated by Rockström *et al,* 1999) and
- A large spread of data below the maximum line, demonstrating the potential gains that could be achieved by better agronomic management.

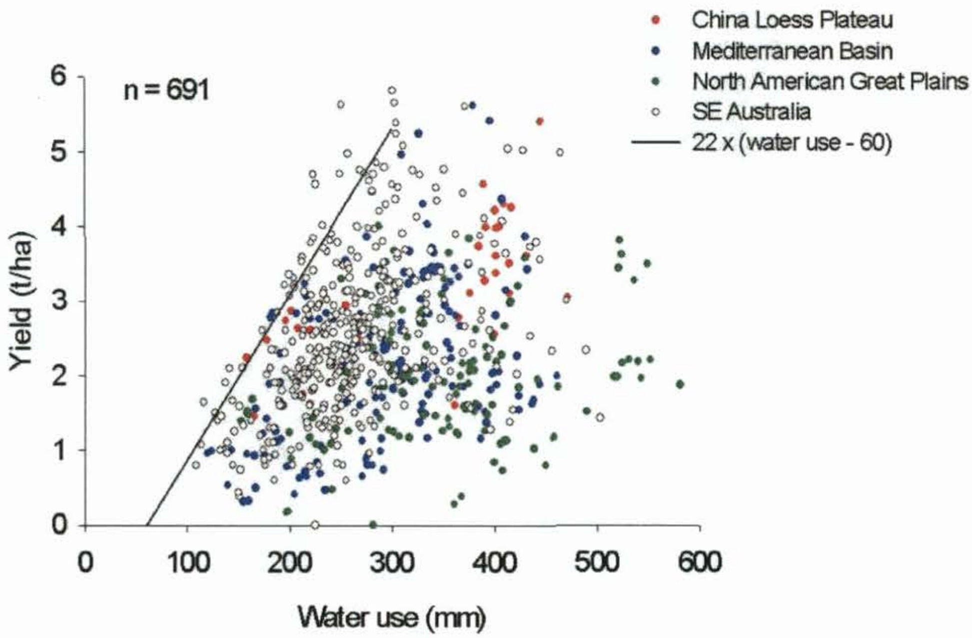

Figure 2. Yield of wheat as function of the amount of water evaporated and transpired (Source: Sadras and Angus, 2006)

WP of irrigated crops

Molden et. al. (2001) analyzed WP of two irrigated systems – Chishtian in the Indus basin in Pakistan and Bhakra in the Ganges basin in India. They showed that there are marked differences in yields, and hence WP, with the system in India reporting higher values (Table 3). They attributed the higher productivity of the Indian system to higher land productivity and deficit irrigation.

Table 3. Units and their values for indicators of agricultural water productivity.

Indicator of agricultural WP	Units	Indicator value	
		Bhakra	Chishtain
Cropped area	10^3 ha	2945.0	103.8
Wheat yield	ton/ha	2.3	1.4
Rice yield	ton/ha	3.0	2.1
SGVP	US$/ha	782.7	413.3
Wheat yield per unit Et	kg/m^3	1.1	0.6
SGVP per gross inflow	SGVP/Gross inflow	0.12	0.06
SGVP per available water for irrigation	SGVP/AW irrigation	0.15	0.06
SGVP per process consumption	SGVP/ETa	0.17	0.07

A procedure has been developed by scientists at IWMI for determining the water productivity of irrigated crops as follows:

1. Map irrigated areas and crop types within the surface water / groundwater system
   - Identify conjunctive use areas with the irrigation system
   - Map high water table areas (secondary data)
   - Obtain crop yield data through appropriate combinations of secondary (administrative or hydraulic district) data or from primary crop survey.
   - Obtain data on straw and green fodder production and utilization from irrigated crops, (usually from primary survey).
   - Determine livestock holdings and fodder use (by survey)
2. Overlay irrigation networks, and determine flow data for primary, secondary and possibly tertiary canals.
   - Select units for investigation, where sufficient water supply data exists
   - Estimate gross irrigation inflows
3. Obtain and spatially interpolate rainfall data. Using secondary data, determine typical values of effective rainfall (that retained in the root zone or as surface storage in the case of rice)
4. Obtain canal flow data and determine seasonal surface water supply. Where flow data are not generally available at lower levels of the distribution network, it is possible to develop and apply disaggregation techniques to estimate the net local supplies from canal head flows (Ahmad and Bastiaansen, 2003)
5. Survey groundwater pump locations, capacities and average operating hours to determine groundwater supplies.
   - Where necessary, apply more advanced procedures to estimate net groundwater contribution (see PhD thesis by Ahmad, 2002), using remote sensing and soil-plant-water models.
6. Estimate Et_a using SEBAL for each crop season (Droogers and Kite, 2001). Disaggregate Et_a by cropping system.
7. Calculate land productivity (LP) in terms of GVP and gross margin.

8. Calculate water productivities (WP), with respect to total supply and Et_a:
   - Physical production (kg)
   - Gross value (SGVP)
   - Gross margin
9. Identify innovative water use practices where WP is low but LP is high and vice versa.
10. Calculate water productivity at larger scales of irrigation system and basin, using the depleted and process fractions of water supply (Molden *et al.* 2001)
11. Determine system and basin average WP across all agricultural uses.

Livestock systems

Peden *et al.* (2002, Figure 3) illustrates the complexity of accounting for water use in livestock systems in Africa.

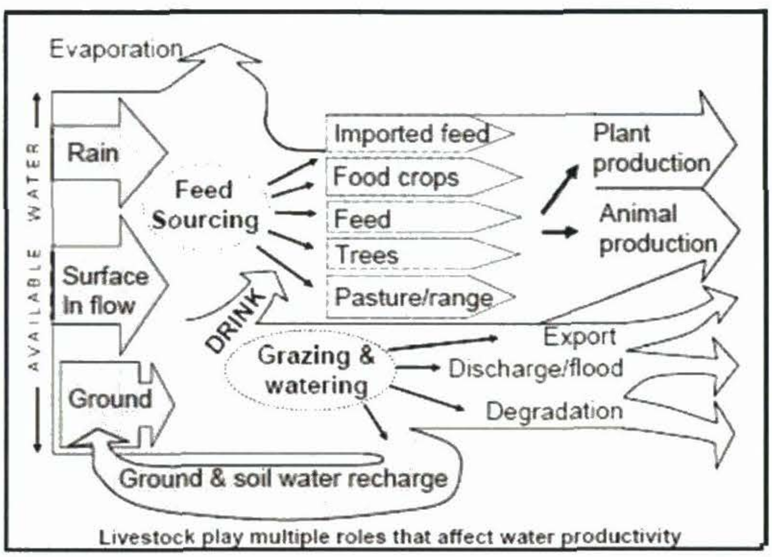

Figure 3. Framework for improving water productivity of livestock (From Peden *et al.*, 2002).

Multiple benefits of livestock systems include meat, milk, hide/wool, draught power, and drought protection. These benefits will be realized within complex farming system at different times (e.g. draught power is required for ploughing; the sale of animals to help buffer incomes is expected to occur only occasionally) and space (animals are moved large distances between grazing and between grazing, fattening areas and markets). Evaluating the transferred benefits within such systems is consequently difficult, and would require an estimate of net gain for the area for which water consumption is estimated.

Consumption of water occurs both directly through stock watering and making downstream water non-utilizable through pollution and indirectly through the production of feed as crop, sown pasture or as rangeland. In rainfed farming systems, grain is only one output of value to the farmer – others include green fodder and dry fodder (straw and stubble). In pastoral systems, the value of green biomass is optimal at a certain stage of growth and it is common to convert estimates of green and dry biomass into estimates of digestible dry matter (DDM). It may be possible to combine estimates of grain, green fodder and straw according to DDM basis, such that total production is expressed as:

Production (kgDDM) = Grain (kgDDM) + Green fodder (kgDDM) + Dry fodder (kgDDM)

Hill and Donald (2003) present a commercialized method of using satellite remote-sensing to quantify digestible pasture feed over large areas.

It may be necessary to estimate marginal value to evaluate WP fully, since it is uncertain whether the water consumed by pasture would be more productive if used elsewhere? Certainly the low stocking densities of rangeland will present low benefit per m^3 Et. The marginal value of pasture or rangeland vegetation is realized only when the feed resource is accessed by animals. Peden *et al.* (2002) examine options for alternative routes of water in livestock systems.

Fish production systems

There are few accurate assessments of the economic value of fisheries for most parts of Africa, Asia and Latin America (LARS2, 2003; Neiland, 2003). Furthermore, the special contribution of fisheries to food security and livelihoods is poorly represented in official statistics.

Valuation of benefits from fisheries

Methods to evaluate the full range of benefits from fisheries and aquatic resources are summarized by Bené and Neiland (2003) according to the following categories. These are specifically intended to address the complex issues associated with changes to fisheries and aquatic resources:

1. Conventional economic analysis
   - Economic efficiency analysis. Seeks actions which maximize social welfare in comparison with costs.
   - Total economic value. Acknowledges use and non-use values (see Figure 4).
2. Economic impact analysis: Assesses effect on specific variables
3. Socio-economic analysis: Distributional analysis of winners and losers from changes
4. Livelihood analysis: Broader analysis of multiple attributes that support sustainable livelihoods

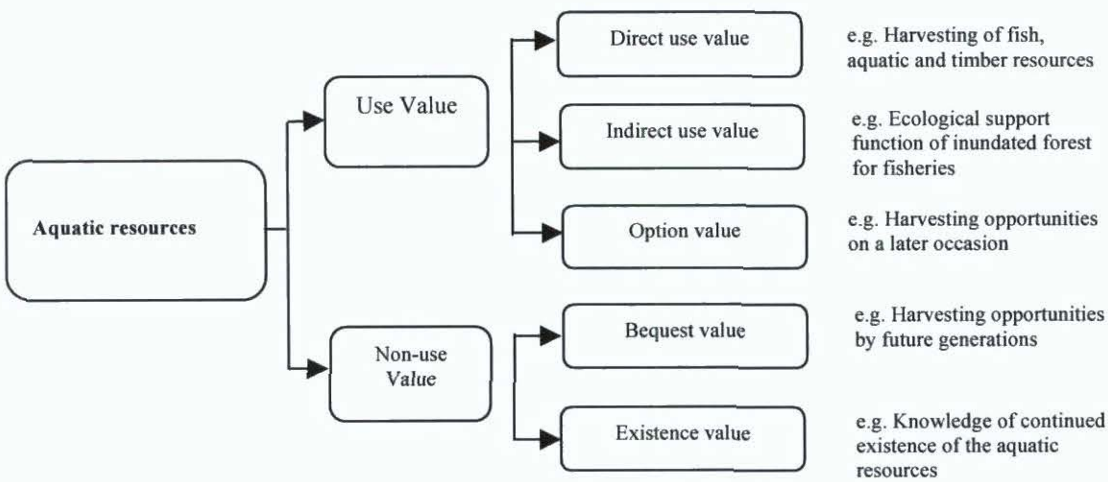

Figure 4. Total economic value and valuation methods (from Barbier *et al.*, 1997)

Demand for water by fisheries

Baran *et al.* (2001) related fish catches to water levels in the Tonle Sap river in the Mekong basin, calculating a loss of between 2500 and 5000 t of 'Dai' fish catch for each drop of 1 m in the average October levels of the river. The assessment of the denominator (water required to achieve a given outcome) for fisheries and aquatic resources is more complex than consumptive uses by crops, not least because – given the complex life cycles of both fish and their feed - several years' measurement are required to determine the actual requirement. Welcomme (2001), working in the Niger, concluded that at least 14 years are required to evaluate the impact of low flows on fish stocks. See Dugan *et al.* (2005) for more details.

Several issues are relevant to the demand for water by fisheries:

- River fisheries require substantial non-consumptive volumes of water to provide suitable environments for growth and breeding.
- There are opportunities for dual-use of irrigation infrastructure for fisheries (integrated agriculture-aquaculture - IAA), which can provide substantial supplements to both incomes and food security (Renwick, 2001).
- Development of rice-fish culture can significantly increase income and soil fertility in deep flooded paddy rice, without increasing water consumption. However, these gains have to be offset against increased cost of buying more water, especially if it is priced at its real cost to encourage more efficient water use.

Direct consumption of water by aquaculture occurs through evaporation and seepage. The former can be estimated from data of pan evaporation over the time required to produce a given weight of fish. For example, Brummett (2002) showed that integrated aquaculture in Malawi produced up to $264 g/m^2$ of footprint, approximating to evaporative consumption of between 0.2 and 0.7 m^3 of water for a 100 day production cycle (1.3 to 0.38 kg/m^3). This figure needs to be evaluated in relation to the price of fish products, which are normally readily available for traded products, and other costs of production that can be quite high. Impacts of intensive aquaculture on downstream water quality should also be considered.

Tree systems

Benefits from tree-based systems include both timber and non-timber products. Timber products are evaluated as m^3/ha, or \$/ha. Non-timber forest products comprise a wide array of animal and plant products, often of particular value to the poorest people that live in or on the margin of forests. Like fish resources, these tend to be under-valued by conventional economic analyses. It is possible that evaluation techniques similar to those used for fisheries could be used.

With respect to consumptive water use, a huge literature exists of forest hydrology, including some more recent evaluations that question the hydrologic benefits routinely attributed to forests (see Bruijnzeel *et al.* 2006, Mulligan and Burke, 2005). Space does not permit review of the methods of evaluating the scale of positive and negative hydrologic effects of forests.

Multi-scale estimation of WP

We envisage WP will be estimated at 3 scales[1]:

- Whole basin estimation of WP: Coarse-resolution estimation of WP using readily-available productivity data at national scale or administrative district level. Whole-basin estimates of well-

[1] Given the complexity of this subject, we propose it as the first of a series of technical papers to be developed during the life of the Basin Focal Projects of the Water and Food Challenge Program.

being derived from agriculture may be approximated from readily available data of crop production, rural population, the extent to which basic needs are met, the proportion of the population engaged in agriculture, etc., and compared with water consumption using Molden's (1997) water accounting methods. While useful for broad scale estimation, this will not provide the detailed insight necessary for further analysis.

- Small-area estimation of WP: Detailed estimation of WP is envisaged from small case study areas, where these exist. These will produce high-resolution crop, fisheries and livestock productivity/income data, which can be combined with detailed estimates of water balance. Such studies will provide valuable detailed insight into variations of WP within farming systems, and of the hazards and limitations that constrain increases in WP. Where reasonable, these estimates could be used to represent the WP of farming systems.
- Aggregated estimates of partial WP: Having estimated partial WP for contrasting disaggregated agricultural systems, it is necessary to consider how to estimate WP for aggregated farming systems at the sub-basin level or, to provide a detailed picture over whole basin or sub-basins. The following approaches are offered for consideration:
- Classification into sub-units: Sub-divide the area into *n* parcels of *i* classes, defined according to land use, agroclimatic zone or other classification. Aggregate individual estimates of WP for *n* land uses in a single measure for a larger area as $\sum(WP_i.A_i)$. This approach may work well for small or moderate areas, for which reasonably secure estimates exist of each WP. For larger areas, the approach is likely to prove difficult because:
- Many areas are likely to have missing data;
- Different land uses may use contrasting valuation systems;
- Estimation in some land uses will be seriously affected by seasonal variation and
- Spatial resolution will vary between different land uses, hence apparently equivalent land units will contain different degrees of uncertainty.
- 'Hot-spot' approach: Broad estimates of WP are offered, for regional comparison, supplemented by more detailed information about specific areas known to be of particular interest.
- An integrated approach, whereby coarse-resolution estimates of WP are used as a 'background' for overlays of more detailed estimates, resolved according to known variations of land use, agro-ecological zone, terrain position, erosion intensity or other factor that has a known (if approximate) association with WP. Coarse resolution and detailed estimates of WP may be combined using a probabilistic Bayesian Network approach (see Lacave and Diez, 2000).

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Analyzing water poverty: water, agriculture and poverty in basins

Basin Focal Project Working Paper no. 3

Cook, S.E., Gichuki, F., Turral, H. and Fisher, M.J.

Challenge Program on Water and Food.

Introduction: Why Analyze Poverty in Basins?

The purpose of analyzing poverty data within basins is to identify:

(a) How many people are affected adversely by poor availability or access to water, to what extent, and how this can be modified through improved agricultural water management, and
(b) Where low water productivity appears to induce poverty, and to what extent this is modifiable.

The analysable relationship between water, agriculture and poverty can be explained as follows: The total gain that people derive from water used by agriculture is a product of the amount of water they take and the productivity they achieve per volume consumed. In some cases the total gain is limited by water availability, through either problems of availability or distribution. Otherwise the total gain is limited by water productivity, and poverty will be related to other problems such as land degradation, lack of land tenure, poor access to markets, inadequate labour or capital.

All the above factors can be estimated at a range of scales within basins and used to analyze the existence of water-related causes of poverty. Such analysis is required within each basin to answer the following types of questions:

- How many people are affected by drought, and to what degree?
- How many could benefit from improved governance and infrastructure within a given irrigation domain?
- What are the consequences of soil erosion within an area on water productivity in the basin as a whole? How will this impact on livelihoods?
- What are the potential gains in water productivity within the basin?

Analysis is required to identify the incidence and depth of poverty associated with attributes of agricultural water management, and to provide a richer understanding of the nature of poverty and the degree to which it can be alleviated through improved agricultural water management. This is a necessary step for devising evidence-based, targeted interventions.

According to Black and Hall (2003) the water poor comprise[12]:

- Those whose livelihood base is persistently threatened by severe drought or flood;
- Herders, fishers and farmers whose livelihood depends on environmental services of water that are not dependable because of upstream factors beyond their control;

[12] Black and Hall (2003) also include those who are impoverished by lack of provision of water for drinking and sanitation, which are potentially indirect consequences of poor agrciultural water management.

- Those whose livelihood base is subject to erosion, degradation, or confiscation (e.g. for construction of major infrastructure) without due compensation;
- Farmers who cannot improve agricultural productivity because of the high risk and uncertainties of markets and rainfall, which could be reduced by a little water at the right time;
- Subsistence farmers who are constrained from higher value products such as fruit, vegetables or meat because of lack of access to water; and
- Those living in areas with high levels of water-associated disease (bilharzia, malaria, trachoma, cholera, typhoid, etc.) without means of protection.

Water-related poverty occurs because people are either denied dependable water resources or because they lack the capacity to use them, because they have insufficient land, degraded land, poor access to market, capital or other factor known to constrain development. Improvements in agricultural water management that offer poverty alleviation include:

- Provision of water resources to people who require it to sustain food production;
- Increases in water productivity at the field or farm level through removal of production constraints;
- Protection of environmental flows to increase dependability of supply; and
- Protection from water-related health hazards.

An important factor to consider is the collective vs. individual gains. Water is distributed within basins by surface and groundwater flows and irrigation infrastructure. Options to modify distribution include modification of the irrigation infrastructure and conservation of the soil and water resources. Other aspects of the water balance may be modified by changes in vegetation type as in converting native savanna to more productive sown pasture and/or increasing its growth rate as by correcting nutrient deficiencies. Net gain occurs when the benefit acquired by recipients exceeds the losses suffered by alternative users, where these exist.

Section 2 of this working paper clarifies the concepts that link poverty and agricultural water management. Section 3 outlines a methodology to analyze poverty at basin scale to determine the effects of agricultural water management.

Conceptual relationship between water, agriculture and poverty

Concepts that link water, agriculture and poverty

The linkage between water, agriculture and poverty is complex and non-linear; not all poor people lack adequate water resources. On the other hand, not all people who live in dry areas are poor. Water resource endowment alone does not explain the state of poverty within basins; it is a necessary, but of itself not sufficient basis for explanation (Castillo *et al.* 2006). The purpose of analysis is to determine to what extent agricultural water management explains poverty, in relation to other factors, and to what extent it can be improved.

Water is used in a variety of both productive and consumptive activities and contributes to rural and urban livelihoods in many different ways. Lack of access to drinking water is itself an indicator of poverty, but the role of water in human well-being is far more complex than simply access to drinking water. Food crop production, fishing, agro-processing, and health can all influence and are influenced by the quantity and quality of available water. Rural upper catchments largely contribute to livelihoods by providing valued primarily ecosystem services to downstream urban, agricultural, and industrial users. As the principal water user, agriculture offers important, if complex, opportunities for improvement of livelihoods for both consumers and 'producers' of water. Many of these issues are detailed by Castillo *et al.* (2006).

The complexity can be simplified. For example, Figure 1 shows the complex pathways of water within a livestock management system in sub-Saharan Africa (Peden *et al.* 2002). It seems reasonable to simplify this concept and see it as flow through three systems: a hydrologic system; an agricultural system and a livelihood support system. The well-being that people derive from water therefore depends on the interaction between:

(a) The water system, that determines availability and reliability;
(b) The agricultural system that converts the water into livelihood support, through food, income or other attribute – this is defined by water productivity; and
(c) The livelihood system that modifies access according to social relations, institutions or organizations (Allison and Ellis, 2001).

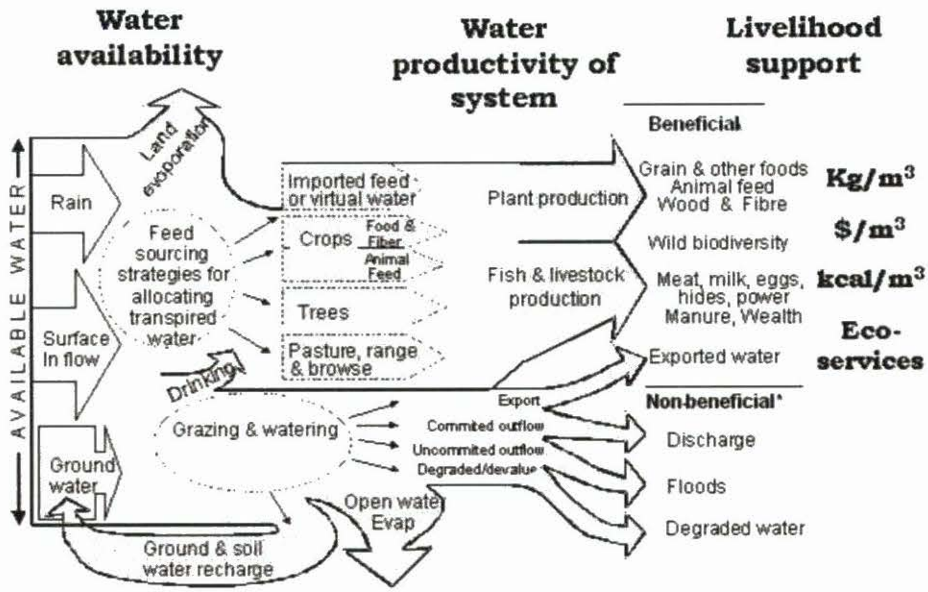

Figure 1. Framework for improving water productivity of livestock. (Modified from Peden *et al.*, 2002.)

The constraint that water places on well-being is attributable to two factors: its availability to people (as individuals or groups) and the agricultural system in which they use it. People will derive well-being through the interaction between the resource and the agricultural production system.

The objective of analysis, therefore, is to determine evidence for relationships within a three-variable system in which *poverty* (which we define for now as the lack of 'water wealth'), is a function of the *water availability* and the *water productivity* of the agricultural water management system that enables people to derive livelihood from it. We represent this in Figure 2

.

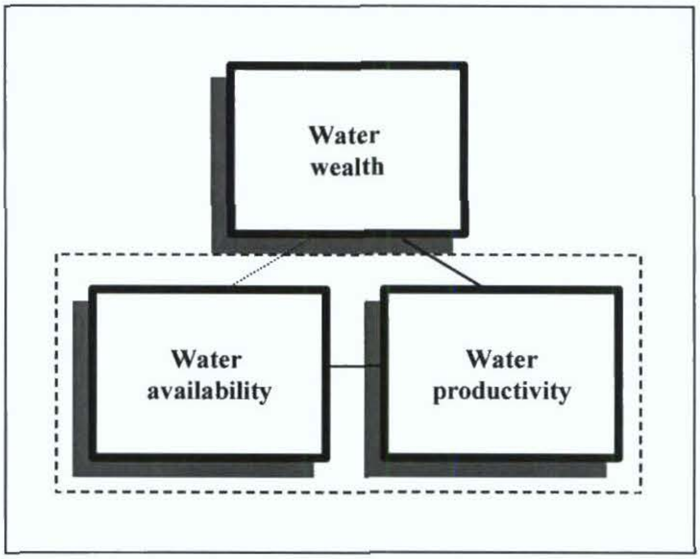

Figure 2. Representation of the components of water wealth.

The remainder of Section 2 provides information about the functional significance of different agricultural systems to poverty alleviation, indicating the ways in which productivity can be modified through agricultural water management.

Significance of agricultural water management to poverty alleviation

While water is the component that we seek to change, the reality is that change is effected through the agricultural system on which most of the world's poor depend. Nash (2005) reported that 63 percent of global population (and 73 percent of poor) live in rural areas. He further noted that even with rapid urbanization, more than 50% of the poor will remain in rural areas by 2035. For these rural poor, agriculture[13] is their main source of livelihood. For most poor countries, agriculture is a major economic sectors accounting for 30-60 percent of GDP. Agriculture growth contributes to poverty reduction through four main pathways:

- Household food self sufficiency for subsistence farmers, fishers and pastoralists;
- Low food prices, particularly for the urban poor for whom the cost of food accounts for a large percentage of their income;
- Employment opportunities and high wages; and
- Foreign exchange earnings that make it possible for governments to import goods at prices the poor can afford.

Water is one of the main factors that constrain their agricultural output, income and profitability. According to UNDP (1997), about half of the poorest people in the world earn their livelihood in areas where water constrains agricultural production.

Importance of crop production to the poor

Crop production is the main agricultural sub-sector in most countries. In most developing countries, crop production is carried out by smallholder farmers and is generally labor intensive. Low producer prices, low yields and high cost of inputs constraints its potential for getting farmers out of poverty. Agricultural

[13] In this paper, agriculture includes crop, forestry (plantation and tree crops), livestock and fisheries production.

laborers are amongst the most poorly-paid workers and are generally under-employed due to the seasonal nature of labor demand for crop production. Nevertheless, for lack of alternatives, it continues to be the main source of livelihood for most poor people.

Analysis of major farming systems in Sub-Saharan Africa illustrates the importance of crop production to the poor, as follows (IFAD, 2002):

- Cereal-root crop mixed and irrigated systems have low incidences of poverty mainly attributed to the higher yields and favorable prices for produce;
- Agropastoral and forest-based crop production systems have the highest incidences of poverty mainly attributed to low yield and remoteness of the farms;
- Mixed maize and agropastoral farming systems have high potential for poverty reduction mainly due to the high demand and the potential for yield increases; and
- Approximately 43 percent of the population in the region depends on maize mixed (16%), cereal-root crop (15%) and root crop (12%) farming systems, which occupy 10, 13 and 12% of the total land area in the region.

Crop production is constrained by biophysical, technological, socio-economic and institutional factors, water being one of the most critical factors. It is generally observed that crop yields are low in areas:

- Where soil nutrients are depleted by erosion and/or nutrient leaching;
- With low, erratic and unreliable rainfall;
- That are water-logged and/or have high levels of salinity.

In contrast, crop yields are high:

- Even in semi-arid areas so long as runoff is minimized and rainfall is well distributed; and
- In adequately irrigated land as compared to that receiving inadequate irrigation or none at all.

Importance of forest (tree) products to the poor

Forest products include timber products (sawn wood, building material, wood-based fibres, fuel wood and charcoal) and non-timber products (food-stuffs and medicine). Harvesting and processing these products is labour-intensive and is a significant source of employment. Forest and trees can also provide valuable ecosystem services.

Forest products are important sources of cash income and employment at certain times of the year and for certain groups of people. Forest values related to subsistence use, environmental services and other indirect benefits are generally not accounted for. World Bank forest strategy and policy document highlights the critical role that forests play:

(a) 1.6 billion rural people are dependent upon forests to some extent;
(b) 1 billion out of 1.2 billion extremely poor depend on forest resources for part of their livelihoods;
(c) 350 million people are highly dependent on forests;
(d) 60 million indigenous people are almost wholly dependent on forests;
(e) Production of wood and manufactured forest products contribute more than US$450 billion to the world market economy;
(f) The annual value of internationally traded forest products totals US$150-200 billion; and
(g) Globally, forest based industries provide about 47 million full time jobs (Nash, 2005).

Forests make a major contribution in the provisioning of water services, particularly to the poor. Forests buffer the effect of rainfall on stream flows reducing flood peaks and increasing dry season flows. This service is very beneficial to the poor who have limited water storage facilities and who live in flood plains.

Importance of fish to the poor

For poor communities with good access to aquatic resources, fisheries offer complementary livelihood strategies as illustrated below:

- High national importance as evidenced by (a) global trade of US$55-66 billion annually, with 50 per cent of the trade from developing countries; (b) national income from license fees; and (c) multiplier effect to the national economy; and
- Benefits to the poor as evidenced by: (a) the livelihood support for 30 million poor fishers and their families, employing an additional 150 million people in developing countries in associated sectors, e.g. marketing, boat-building; (b) main source of food security for 400 million poor people; and (c) high potential source of alternative employment for rural poor through aquaculture.

The poor engaged in fisheries comprise artisanal fishers and aquaculturalists. Artisanal fishers comprise approximately 8 million people of which more than half are engaged in sea fishing activities. They generally use un-motorized boats without decks and their activities are centered around landing sites from where they set out each day for sea or lake fishing. The following factors contribute to making them one of the weakest livelihood groups:

- Lack of control over the water resource on which their fisheries depend and of capital.
- Dangerous working conditions, which lead to high mortality rates. A profile of artisanal fishers in Benin indicated that malaria is endemic and diarrhoea and respiratory infections are common, especially in the rainy season when people are weakened by food shortages (FAO, 2000);
- Lack of investment capital and low profit margins hence low labour productivity. The southern Lake Volta fishing communities reported that increasing cost of production and transportation is eroding their profit margins. Their profit margins fell by 10-25% over a 10 year period (Pittaluga *et al.* 2003);
- Seasonal variation in fish availability and consequently uncertainty of income and food availability. The southern Lake Volta fishing communities reported that fishing contributes on average 70% of the household revenue and during the lean season (November-May) a large proportion of the families are unable to meet daily food needs (Pittaluga *et al.* 2003);
- Poor fisheries management, which can result in over-fishing and eventual loss of fish stock and
- Water pollution that degrades the aquatic ecosystem and reduces productivity.

Importance of livestock to the poor

Keeping livestock is one of the main livelihood strategies of the poor and food insecure and directly affects the livelihood of approximately 987 million poor people (Table 2). Livestock contributes to the livelihoods of the poor in many and diverse ways. The relative importance of these different ways varies between households, time of year and prevailing biophysical and socio-economic conditions. The main ones include:

- Livestock is the main source of income for the poor in semi-arid and arid areas. Most of the income in semi-arid areas is derived from small animals – goats and poultry. In Mali, it is estimated that 78% of the cash income on small-scale mixed farms comes from livestock (Sissoko *et. al.* 1992 quoted by Livestock in Development, 1999). A study in Bangladesh reported that 40% of the landless households owned cattle and a Pakistan study reported more than 50% of the landless households' income was derived from livestock (Subrahmanyam and Rao 1995, Kurosaki 1995, both quoted by Livestock in Development, 1999). The landless supported their livestock production through the use of crop residues, other waste material and feed resource found in communal land and roadsides.

- Livestock is a cherished way of storing cash as livestock can be accumulated in good times and sold off when the need arises. A study in Lesotho reported that in investing in livestock earned farmers the equivalent of 10% interest rate while a bank account lost 10% due to inflation (Swallow and Brokken 1987, quoted by Livestock in Development, 1999). This is also a good strategy in remote areas where banking services are not readily available.
- In mixed crop-livestock farming systems, livestock plays a key role in enhancing productivity of the farming system of the poor households through provision of draught power and manure. Draft animal power reduces drudgery associated with land preparation and transportation of water and other farm inputs and outputs, while manure returns soil nutrients for maintaining soil fertility.
- Livestock enhances livelihood security through diversification of the farming system. A diversified farming systems buffers the poor against shocks associated with drought, floods, diseases and market failures. A study in Nepal reported that the introduction of dairy buffalo into a village reduced the period of food deficit from eight to two months in a year. It also contributed to a reduction of the proportion of people in the village with inadequate food intake from 50 to 18% (Thomas-Slayter and Bhatt 1994 quoted by Livestock in Development, 1999).
- Livestock production enhances nutrition status as it is a source of high-quality protein and energy as well as essential micronutrients.

Assessing the contribution of water-related benefits through livestock is complicated by the multiple pathways, stores and products that link water to benefits through multiple uses (feed, direct consumption) and multiple benefits (meat, milk, eggs, hides, power etc). Quantifying the flow of water through intermediate benefits shown in Figure 1 can be extremely difficult, as can assessing the benefits of the products. Additionally, there are numerous constraints and livestock related hazards that obstruct the poor from benefiting from livestock. The main ones include:

- Regulations restricting the keeping of livestock production in urban areas;
- High cost of livestock and lack of credit facilities;
- High risk of diseases and drought;
- Availability of feed resources; and
- Low prices offered for livestock products.

Table 1. Distribution of the poor livestock keepers by agroecological zones. Source: Livestock in Development (1999).

Agroecological zone	Category of livestock producers		
	Extensive graziers	Poor rainfed mixed graziers	Landless livestock keepers
	(millions)		
Arid and semi-arid	87	336	
Temperate (including tropical highlands)	107	158	107
Humid, sub-humid and sub-tropical		192	
Total	194	686	107

Analyzing the Linkage Between Poverty and Agricultural Water Management in Basins

This section lays out a framework in which to analyze the linkage between poverty and agricultural water management within basins.

The analytical framework has three components:

(a) Measurement of poverty within the basin. This process includes mapping at best resolution feasible to improve analysis against biophysical and socio-economic attributes.
(b) Analysis of poverty variation against measurable attributes of agricultural water management within basins, and
(c) Modeling the current and future status of agricultural water management in basins with respect to poverty alleviation.

Measuring poverty within basins

Concepts of poverty

Lok-Dessalien (1998) provides an exhaustive review of poverty concepts and indicators. She argues that the distinction between different poverty indicators was important because poverty measurement and subsequent policy and program implications depend on the facets of poverty being addressed. For example, to address both temporary and chronic poverty, two sets of policies and programs would be required along with their indicators for establishing baseline conditions and monitoring progress.
Likewise the definition of poverty determined the appropriate poverty measures, policies and programs to address it and corresponding indicators. She highlights the following poverty concepts:

- **Absolute poverty** refers to inability to meet (food, shelter, education and health) needs that enable a person to enjoy a minimum acceptable standard of living. The needs define the required goods and services and the value of these goods and services used to define the minimum income needed to acquire them – the income poverty line.
- **Relative poverty** focuses on the inequality and uses income quintiles or deciles to compares the lowest and upper segment of the population.
- **Objective poverty** involves normative judgment of what constitutes poverty and what is required to lift people out of their impoverished state.
- **Subjective poverty** puts emphasis on individual utility in terms of how much people value goods and services. The subjective poverty approach has led to the development of participatory poverty assessment methodologies.
- **Physiological deprivations** concept is linked to the basic needs concept. Under this concept, people are poor because they lack income, food, clothing and shelter. Poverty-reduction strategies emerging from this approach focus on increasing income/consumption of the poor and their attainment of the acceptable levels of basic needs.
- **Sociological deprivation** perspective argues that people are poor because of the underlying structural inequalities, inherent disadvantages and other factors that constrain access of the poor to credit, water, common property resources and information. These structural inequalities thereby hamper them from using the resources at their disposal to climb out of poverty. Hence, poverty is not just low consumption but also the lack of opportunities to lead valuable and valued lives.

Poverty assessment

Poverty measurement exists for all countries. The nature and source of poverty data affects its ease of analysis and is detailed in Appendix II. Analysis against water-related variables is constrained by two further factors: date of sampling and spatial resolution.

The date of sampling may cause problems of analysis if the data are out of date and do not provide an accurate current view or are asynchronous with the data with which they are to be compared. Within trans-boundary river basins, data of different age (and probably different character) will need to be combined in a single data-set. Effects of droughts or flooding are likely to be partially date-variable, and so may not be visible if poverty is measured at a time when effects were minimal. Conversely, poverty measurement immediately after a crisis may over-emphasize an effect which is only of short-medium term.

The spatial resolution and definition of location may limit the quality of analysis against other factors that are highly variable spatially. Significant effects of localized biophysical factors, such floods, land-use potential, and groundwater availability or socio-economic factors, such as access to markets will be obscured if the resolution of poverty measures is at a regional level.

Poverty Mapping

Poverty maps (normally of absolute poverty measures) improve analysis with respect to water-related attributes within the basin, which are difficult to understand without acknowledging spatial variability. Poverty mapping has been developed in many countries and used to:

(a) Target public interventions by identifying where the neediest population live,
(b) Target emergency response and food aid programs, and
(c) Improve transparency of public decision making. Henninger and Snel (2002) highlight the value of spatial analysis to provide basin information on which to decide where, how, when to intervene.

A very important factor with respect to basin analysis is that maps provide a common data-framework on which to model socio-economic, agricultural and hydrological processes. Since many hydrological processes can *only* be represented effectively in spatial form, GIS provides a logical analytical platform to which other analyses relate.

Davis (2003) provides a comprehensive review of techniques of mapping poverty and food security, pointing out that at the time of writing there existed no gold standard of poverty mapping because of the wide array of applications. He groups the different methods according to:

- Small-area estimation of
    - Household level data
    - Community level data (Bigman *et al.* 2000)
- Weighted basic-needs index, using
    - Principal components analysis
    - Factor analysis
    - Ordinary least-squares
- Combined qualitative-plus-secondary data (detailed in section 3.3)
    - Primarily based on qualitative assessment, (WFP, 2006)
    - Primarily based on secondary data
- Extrapolated participatory approach
    - Calibrated participatory assessment (Ravnborg 1999, Kristjanson *et al.* 2005)
- Direct measurement
    - Household survey data
    - Census data

Analyzing poverty variation with respect to agricultural water management

The general process of analysis comprises the following:

- Definition of the hypothetical 'model' that links poverty variation with agricultural water management within the basin, on the basis of a theoretical and contextual understanding of the problem and an awareness of the data that are likely to be available. This step should also outline the method of analysis.
- Acquisition of poverty data for the basin, where possible using spatial analysis to improve the resolution and reliability of the data using methods of small-area estimation. Detail is provided above about the rationale and methodology of poverty mapping.
- In consultation with collaborators, assemble data of candidate explanatory variables.
- Analyze the general and site-specific relationship between the two variables. Coudouel *et al.* (2002) provides many useful suggestions (and cautions) to guide analysis, which commonly employs regression of poverty measures against 'explanatory' variables.

Conventional Poverty Analysis

Coudouel *et al.* (2002) provide a comprehensive review of conventional methods of poverty analysis. Analysis is intended to identify correlates against a range of poverty measures (e.g. income, consumption, inequality) that may help understand the general nature of poverty. Analysis normally uses a form of regression analysis to identify poverty effects for specific groups, by disaggregating data according to geographical region, age, gender, employment or other factor contained in the data.

Vulnerability analysis presents a special type of analysis, which looks at a measured decline in well-being that results from specific shocks.

Analysis is confounded by geographical variables that are not accounted for in the regression model. This could be reduced by including dummy variables of location, or map-derived variables of access to water, drought or flood incidence, market access etc., where these are considered to be candidate variables.

Analysis of poverty maps:

Why map? The effort to map poverty and its explanatory variables can be justified by the following:

(a) Improved data resolution by interpolation and small area estimation techniques
(b) Improved coincidence of socio-economic and hydrologic data on a common GIS data platform. These variables are generated through different sampling and estimation techniques.
(c) Visual representation of geographical patterns.

Experience in generation and use of poverty maps has demonstrated the potential value of looking at both spatial and temporal dimensions of poverty (Table 2). Poverty mapping at high spatial resolution has identified pockets of poverty amidst areas of prosperity. More importantly, it has enabled explanation of variations in poverty incidence by comparison with other spatial attributes such as drought incidence. This last feature can be crucial because the effects of agricultural water management are unlikely to be constant throughout an area and will require geographically localized analysis. Several other examples of spatial analysis of poverty against factors which include water-related attributes can be found in Hyman *et al.* (2005).

Trend or change analysis, that is, comparing data from two of more sampling periods, enables the dynamics of poverty to be assessed, for example where people have moved out of poverty or have been hit by natural or human-induced shocks. Figure 3 from Farrow *et al.* (2005) shows how poverty in Ecuador changed over the period 1991 to 2001. Areas in the Andes improved, in the face of drought stress (see Farrow *et al.*

2005), as a result of concerted action by organizations to ameliorate problems of isolation. Conversely, areas on the Pacific coast deteriorated as a consequence of El Niño damage to income-generating plantation crops. Pinpointing these variations enables us to interpret poverty within the basin-specific bio-physical, socio-economic and institutional settings and therefore get a better understanding of the causes and appropriate interventions.

Hazards that confront the unwary analyst include:

- Assumed correlation between measured and non-measured well-being variables, e.g. consumption vs. income measures (Coudouel *et al.* 2002).
- Use of the same information in explanatory and dependent variables, for example, if land quality is used in small-area estimation of poverty, it should not be used in analysis as an 'explanatory' variable.
- Complex variance structures may be hidden within data covering large areas: Geostatistical analysis by Farrow *et al.* (2005) revealed complex non-random patterns in poverty data that, if undetected, would have reduced the value of 'conventional' regression techniques. Analysis by Leclerc (2002) at department, municipality or village level shows that the level of disaggregation can significantly modify the advice coming from analysis.
- Non-stationarity of models: Conventional analysis of poverty may unjustifiably assume stationarity – leading to significant error (Coudouel *et al.* 2002). Analysis by Farrow *et al.* (2005) show strong geographically variation, with both positive *and* negative regression coefficients for the same explanatory variable at different locations. This may cause particular difficulties when ascertaining the geographical variation of significance of household level influences such as gender and age, which are unlikely to be analyzed at basin scale.

Table 2. Explanatory variables from poverty mapping in seven case studies. Source: Hyman and Imminck (2003).

Mexico	**Malawi**
Indigenous groups	Educational attainment
Education	Non-agricultural activities
Accessibility	Dependency ratio
Population density	**Kenya**
Ecuador	Soil resources
Accessibility	Rainfall and climate
Water availability	NDVI (vegetation growth rate)
El Niño	Access to education
Land tenure	Accessibility to towns
Nigeria	**Bangladesh**
Rainfall	Educational attainment
Vegetation (more analysis needed)	Availability of infrastructure
Sri Lanka	Land tenure
Access to land and water	Flood-prone lands
	Soil suitability for rice cultivation

Modelling the effects of changes in agricultural water management on poverty

The converse process is to predict poverty distribution on the basis of variation of attributes that represent the effects of agricultural water management. Davis (2003) provides a useful characterization of the two principal methods as used to map poverty:

- Combined qualitative-plus-secondary data (detailed below)
    - Primarily based on qualitative assessment
    - Primarily based on secondary data

Primarily qualitative information approach:

This method uses qualitative information such as a land-use map as a basis for 'first-cut' categorization of explanatory factors. Davis (2003) describes two examples. The first has been used successfully by the World Food Program Vulnerability and Mapping system (VAM) to target emergency aid. The method of Seaman *et al.* (2000) could be modified to map impacts of water-related interventions as follows:

(a) Define agricultural system zones for each basin (Dixon *et al.* 2001). System zones define areas containing similar combinations of agricultural activities.
(b) In each zone, define major categories of livelihood support.
(c) For each of these categories, determine information of the impacts of livelihood support of attributes of water-availability and water productivity known to be significant from analysis.
(d) Use the above as a baseline from which to estimate the possible impacts of changes in water availability and /or productivity resulting from detailed study of individual factors.

A second variant may be useful to focus on particular groups who are vulnerable within basins (e.g. fishers). In this method, mutually-exclusive, livelihood-strategy groups are defined by workshops of experts, following which the impact of changes in water availability and productivity would be estimated from institutional attributes.

Water poverty index

The water poverty index (WPI, Sullivan *et al.* 2003), subsequently modified to the water wealth index (WWI) attempts to define poverty that includes all factors relevant to the livelihood support provided to the poor by water resources in five dimensions:

- Per capita resource availability
- Access to water;
- Capacity to benefit;
- Water uses; and
- Environmental impact.

Maps have been produced at national scale and sub-national scale. The WPI has also been applied to analyse community-level characteristics, but the feasibility of more detailed mapping may be limited. This concept has undoubtedly broadened the scope of examination, but the rigid definition of relative weights reduces its value as an analytical tool, especially since some of the factors that could be used to help explain poverty variation are used within the index itself. WPI/WWI may provide greater value as a diagnostic indicator for subsequent analysis.

Falkenmark water stress index

The Falkenmark water stress index provides easily quantifiable measures that assume no direct association between poverty and water (Falkenmark and Widstrand 1992). This was modified by Ohlsson and Appelgren (1998) to include measures of social capital – that is, the ability and willingness of people to engage in activities that provide collective benefit - that seem likely to modify the ability to cope with stress. Useful as a broadscale indicator of the imperative for action, this makes no distinction between impact and condition.

Vulnerability

Several definitions on vulnerability exist. IFAD defines vulnerability as the probability of an acute decline in access to food or consumption, which leads to "inability to meet minimum survival needs". This definition captures two main elements that need to be present simultaneously: the exposure to risk, and the inability to cope with it. Kasperson *et al.* 2001 defined vulnerability as "the differential susceptibility to loss from a given insult". They argued that vulnerability has three dimensions:

- **Exposure** is a measure of the probability that a certain risk will occur. It is related to both the presence of the risk in a given location and to people being in that location.
- **Sensitivity** is influenced by both socioeconomic and ecological conditions, which together determines the degree to which a group will be affected by environmental stress. For example, people in poorer health condition are more sensitive to a health-affecting environmental stress than people in good health.
- **Resilience** is the extent to which an individual or a community utilize coping and adaptation strategies to help them retain their basic properties under stress, recover from damage, and enact change to prevent future damage.

The risk of severe poverty increases with membership in certain identifiable social and age groups that also suffer a higher risk of perpetuating poverty into the next generation. The strongest predictor of poverty is inability to perform or lack of access to paid work or lack of access to productive resources. The groups mostly affected by poverty are:

- Children, youth, and families with many children: The young face the highest risk of poverty and moreover the risk of poverty increases with the number of children in a family. Families with three or more children have a higher rate of poverty than those with fewer children, significantly affecting their long-term life prospects;
- Single parent families, particularly female-headed households in rural areas;
- Families with unemployed members;
- Agricultural families, particularly in areas of low productivity;
- Pensioners
- Homeless families; and
- Abused, neglected or abandoned children

Primarily secondary data:

The other hybrid method described by Davis (2003) is based on 'indicators' and is typified by the famine early warning system (FEWS) promoted by the USAID. The method (modified form Davis 2003) comprises the following steps:

(a) Determination of the principal water-related 'drivers' for which information exists over the basin;
(b) Selection and transformation of indicators over the basin;
(c) Weighting of indicators, based on analysis, expert judgment;
(d) Ranking according to summed scores of indicators; and
(e) Mapping of indicator scores.

Comparison of analytical and modeling activities

The analytical and modeling components contrast in the ways in which poverty is inferred to be related to agricultural water management:

- Identify the incidence of poverty and *infer* how much variation is associated with water management. This is called backward chaining: (*from* analysis of ***Y***, *infer* the influence of ***X***) and is useful to help explain the causes of poverty. An example is the analysis of poverty in relation to the intensity of drought in Ecuador (see Farrow *et al.* 2005).
- From information about biophysical and socio-economic characteristics in the basin *infer,* from modeling, the impact on poverty. This is forward chaining: (from ***X***, *infer* the likely status of ***Y***). This is useful to represent targetable problems on the basis of prior understanding. The approach is used to predict poverty effects of vulnerability (see the Vulnerability and Analysis Mapping reports of the World Food Program, WFP, 2006).

It is helpful to clarify the complementary use of these two processes. The first process helps to understand the causes of poverty that are related to agricultural water management, and to quantify, as far as the data allow, the relationship between the two. The result is a model that can be used – within limits of plausibility – to link explicitly the relationship between poverty and other measurable attributes in the basin. The second process takes the best current understanding of causes to portray where water-related poverty, and changes to it, is likely to occur within the basin, given data about the basin.

Summary:

The complete analysis and representation of *agricultural water management*-related poverty in basins depends on four assumptions.

The first is that poverty can be measured in sufficient detail to identify the effects of variations in agricultural water management, should these exist. In some areas, data are likely to be of insufficient spatial resolution to compare with short-range hydrologic features. Temporal resolution may be insufficient to define the effect of changes or extreme events.

The second is that agricultural water management is a major controlling factor on poverty. Logically, a wealth of evidence exists from case studies to support this view: agricultural production systems support the poor and agricultural production systems are influenced significantly by water availability and use. It seems crucial to separate the constraint of water availability on agriculture from the effects of other factors that influence the benefit people acquire from it.

The third assumption is that analysis of data from basins will reveal significant effects of agricultural water management on poverty within different parts of the basin. Many factors may confound such analysis: lack of high-resolution poverty measurement; spatial and temporal confusion of different data; poor quality data of 'explanatory' variables.

The fourth assumption is that the basin system can be modeled to represent the current condition of people living in the basin, together with the likely impact of changes targeted by the analysis. Analysis will be required to provide maps and tabular data to support assessment of the state of water-related poverty, and the degree to which it is modifiable.

Appendix I: Types and sources of poverty data

Data for poverty analysis can be obtained from two major sources: service records and surveys.

Service record data sets are the data collected by various government organizations such as: health service data on nutrition status, disease incidence, inpatient and outpatient visits; education data on school enrolment and performance; agricultural statistics on agricultural produce, prices and wages. Some of the limitation of these data sets include: limited coverage, questionable quality, not generally disaggregated and in most cases they are in a raw form requiring a lot of time to pre-process.

Household surveys are the basis for poverty data collection. Survey data contain information collected based on the needs of the study objectives and includes both quantitative and qualitative data. A poverty-study survey will in most cases yield a more comprehensive dataset than will other types of survey. Quantitative methods tend to define poverty in external terms such as need deprivation and focus on measurable and observable parameters. Qualitative methods tend to use an interactive process to understand both the constituents and their sources of well being. The surveys include:

- **Living Standard Measurement Survey (LSMS)** a large, multi-topic household survey comprising three sections: household, community and prices
- **Integrated Survey (IS)** is similar to LSMS and was designed to collect data for analyzing impacts of structural adjustment on household.
- **Priority Survey (PS)** collects data for identifying and monitoring population groups most affected by structural adjustment policies.
- **Household Income and Expenditure Surveys (HIES)** core data sets include: household characteristics (size, structure, composition and activities of its members); household income (both individual and collective, in-kind, in-cash, paid and self employment); and household expenditure (purchased goods and services, consumption of self-production). Depending on the coverage, the survey may also include: consumer prices, income distribution, inequality, poverty, savings, taxation, elasticity of demand for goods and services, and nutritional data.
- **Demographic and Health Surveys (DHS)** that focuses on maternal and child health, fertility and family planning, but also include education, occupation and knowledge data.
- **Consumer Price Surveys (CPS)** carried out to assess the comparative costs at current prices of the same basic basket of goods and services over time.
- **Labour Force and Employment Surveys (LFES)** that focus on the relationships between poverty and occupation and livelihoods.
- **Food Consumption and Nutrition Surveys (FCNS)** that collect information on:
  (a) type and severity of nutritional deprivation;
  (b) consumption and production of certain foods; and
  (c) consumption expenditure and effects of subsidy programs.
- **Agricultural Surveys (AS)** that cover:
  (a) comprehensive statistics of agricultural land, crops cultivated, irrigation, number and types of livestock;
  (b) benchmarks for improvements in crop and livestock production;
  (c) agricultural structure attributes such as size and distribution of holdings, extent of various forms of tenancy, agricultural resources, production facilities and practices;
  (d) agricultural machinery and inputs; and
  (e) food.

- **Other specialized household surveys** such as gender equity, education and literacy, housing, access to markets, schools and hospitals.

Poverty indicators and their derivation

Single indicators

Poverty line: The poverty line defines who are poor and who are not poor by establishing individual or household incomes or expenditures levels below which they are considered poor. Poverty lines are usually established using one of the following methods:

- The food energy method determines the consumption of a bundle of food items required to reach a minimum agreed caloric intake. Regression of caloric intakes with income or expenditure levels then determines the income at which the minimum energy intake is realized. This becomes the poverty line income or expenditure level. The method implicitly takes into account non-food expenditures.
- The US$1 per day per person poverty line was set up to facilitate comparison of poverty situations of different countries or of different areas in the same country in a uniform manner. The US$1 is converted to local currency using purchasing power parity (PPP) indices, which are derived from the costs in constant US dollars of a national average consumption bundle. The index therefore does not reflect the composition or the relative prices of typical consumption items of poor households but rather national averages compared to a world average. International comparisons are thus made on a fairly inadequate basis, and their results should be used with much caution.

Poverty incidence of a given area is computed as the percentage of the total population that is poor. This measure is intuitively understandable but fails to indicate the depth of poverty for different groups of people.

Poverty gap: Poverty gap captures the depth of poverty by assessing the income shortfall if all the poor had to have incomes equal to the poverty line. The poverty gap is defined as the income transfer required to lift the incomes of all poor exactly up to the poverty line and is expressed as the percentage of total income that needs to be redistributed.

Composite Indicators

Poverty index: Several poverty indices, (HPI, HDI, GDI, WPI) that combine different poverty indicators have been proposed (see table below).

	Component indicators		
	Longevity	Knowledge	Standard of living
HDI	Life expectancy at birth	Adult literacy rate: Combined enrollment rate	Adjusted income / capita
GDI	Female and male life expectancy at birth	Female and male adult literacy rate: Female and male combined enrollment ratio	Female and male earned income share
HPI	Percentage of people not expected to live to forty	Adult literacy rate	Percentage of population without access to safe water; Percentage of the population without access to health services Percentage of undernourished children under five

Human Development index

From a human development perspective, poverty is defined as deprivation of capabilities and opportunities essential for human development, which include material welfare, education, health, freedom of choice, and participation (Dzenovska, 2001). According to the 1997 Human Development Report, human poverty is the denial of choices and opportunities most basic to human development – to lead a long, healthy, creative life and to enjoy a decent standard of living, freedom, dignity, self-esteem and the respect of others. Lack of any or all of these capabilities and opportunities constitutes poverty because provision of these capabilities is a desired end of human development process. Hence, from measures of human development, poverty is pinned on two primary indicators – the human development index (HDI) and the human poverty index (HPI). HDI measures the conditions of human development and its fluctuations while HPI measures deprivation of human development and its fluctuations.

HDI encompasses: life expectancy at birth; literacy rates and combined primary, secondary and tertiary enrollment; and adjusted income. HPI for developing countries encompasses indicators for the percentage of people not expected to survive the age of 40; percentage adult literacy; and economic provisioning in terms of the percentage of people who do not have access to health services, safe water, and the number of malnourished children under the age of 5. These indices do not measure all aspect of development and poverty and are aimed at identifying potential problem areas and for comparing general trends among countries, regions or population groups at a very aggregated level. These indices therefore fail to capture the distribution of the deprivation across income groups, social and ethnic groups and regions. They also fail to provide information needed to interpret the data more broadly. For example these indices fail to illuminate the political and historical context, which may be imperative for understanding the trends of development or deprivation as well as devising policy solutions.

Human development approach challenges the assumption that economic growth is the primary vehicle for poverty reduction and asks what kind of economic growth is conducive to poverty reduction for all with a focus on quality and equity rather than quantity of economic growth. Technology-driven economic growth tends to favor the rich and increases income inequality among countries and within countries.

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Environmental and socio-economic evaluation of prototype forest plantations in Cordoba department, Colombia

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Introduction

This study identifies the economic and environmental benefits of different land uses. The analysis concentrates on reforestation, cattle raising and a silvopastoral system.

Córdoba department has high potential for forestry. According to the forest zoning of the Ministry of Agriculture, Córdoba has 946,400 ha suitable for forestry. Similarly the department has a total of 1,404,400 ha suitable for protected forestry or for restoration (Cruz and Franco 2006).

While agricultural and forest systems generate multiple environmental benefits, priority is given to the environmental benefit of carbon sequestration owing to two factors. First, it is possible to estimate the benefit (quantities of carbon sequestered in accordance with the growth of trees). Second, there is a growing market for carbon with clients prepared to pay (for example, the BioCarbon program of the World Bank). In contrast, the benefits in soil, water and biodiversity are difficult to identify given the relation between the supply and the benefit. Moreover, there is little market for these services within Cordoba.

Investment portfolios are presented based on this information of the environmental and economic benefits.

Methods

As well as timber products, reforestation produces environmental benefits such as carbon sequestration, soil protection and improvement, conservation of biodiversity and regulation of stream flows. Carbon sequestered in biomass was calculated for seven forest species.

A time horizon of 30 years was used for the financial analysis of the systems. This strategy allows accounting for the growth of the forest species that have different harvest intervals. Spreadsheets were created to represent growth behavior and financial aspects of the production systems such as inputs (e.g. costs of labor, administration, capital and fixed costs). These spreadsheets were based on previous work of CVS (plantations) and Corpoica (cattle production and silvopastoral systems). In addition, the analysis takes account of the different sources of income such as sale of milk, meat, wood and other income such as Forest Incentive Certificates (*Certificados de Incentivo Forestal*, CIFs) and Certified Emission Reductions (CERs).

The financial analysis allows adjustment of parameters to see the effect of different scenarios in the performance of the farm and/or plantation. The scenarios compare management strategies (for example, stocking rates of 0.8 or 1.5 head/ha), financial context (for example, interest rates), national programs (CIFs) and international programs (CERs).

Forest plantations

To facilitate comparisons between the seven forest species, the economic analysis reduces the number of variables that affect yield of biomass and wood. Biomass yield of trees depends on both environmental factors and management strategies. The majority of the species used in the economic study are long cycle, with the main exploitation occuring at the end of the time horizon, in this case 30 years. These species included: Roble (Pink Tecoma), Teca (Teak), Ceiba, Caoba (Mahogony) and Cedro (Spanish Cedar). While shorter periods could be used for the shorter-cycle species, the use of the same time horizon allows comparison of species performance (Figure 1).

Planting distance of the chosen species, with the exception of Acacia, is 3m x 3m giving 1111 trees/ha. The planting distance of Acacia is based on a plantation in Tierralta (2222 trees/ha). Acacia and Tambolero (a lesser known native species) are species with more than one cycle during the analysis horizon; their rapid growth allows harvest each ten years giving three cycles during the analysis. The plantations are assumed to be thinned twice, removing half the trees before the final harvest. Sixty five percent of the tree is assumed to be lumber and the remaining 35% is branches and felling losses.

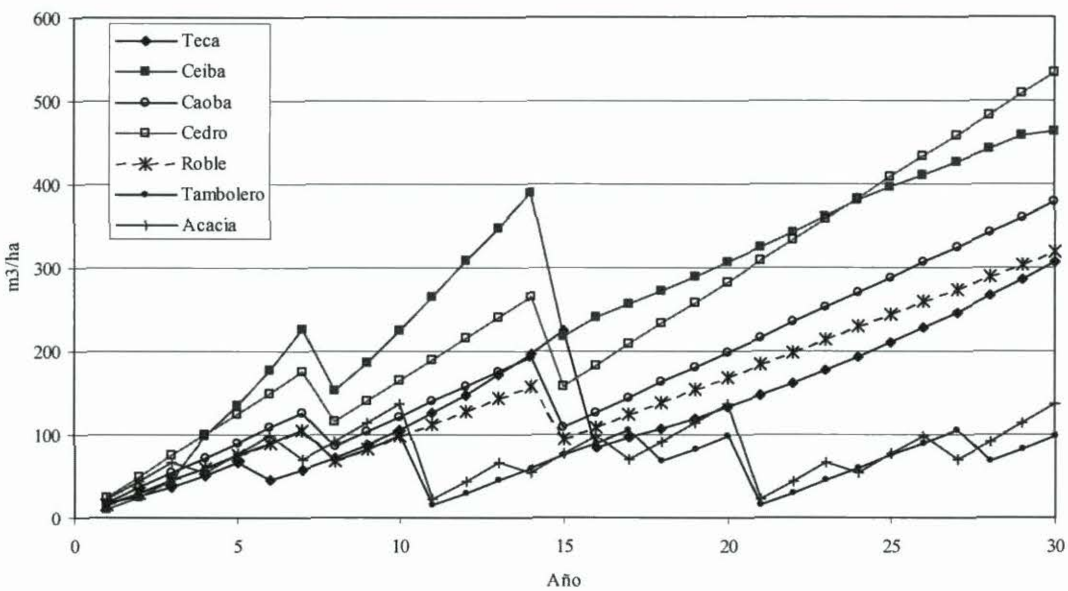

Figure 1. Estimated yields of trees (m^3) over 30 years

Carbon content is related to biomass. Carbon is estimated from wood density, yield and the length of the rotation (Table 1). Wood densities range from 0.39 t/m^3 for Ceiba to 0.6 t/m^3 for Teca. Furthermore, the volume of timber per ha takes account of the planting density and the level of thinning.

Table 1. Wood density, yield and harvest cycle of the forest species.

Common name	Scientific name	Word density	Yield (m^3/ha/yr)	Harvest frequency (yr)
Native				
Caoba	*Swietenia macrophylla*	0.43[a]	10 - 18	25 - 30
Cedro	*Cedrela odorata*	0.42[a]	11 - 25	20 - 30
Ceiba roja / Ceiba tolúa	*Pochota quinata* *Pachira quinata* *Bombacopsis quinata* *Bombachosis quinata*	0.39[b]	15 - 20	20 - 30
Roble	*Tabebuia rosea*	0.54[b]	8 - 15	20 - 30
Tambolero, frijolito	*Schizolobium parahybum*	0.40[b]	13 - 15	12 - 30
Introduced				
Acacia	*Acacia mangium*	0.3	22	10
Teca	*Tectona grandis*	0.4 - 0.6	15 - 17	20

Adapted from: CONIF (2001) In the Consejo Regional de Competitividad (2002).

Notes:

[a] Aróstegui, A. 1982 Recopilación y análisis de estudios tecnológicos de maderas peruanas. Documento de trabajo No. 2. Proyecto PNUD/FAO/PER/81/002. *Fortalecimiento de los programas de desarrollo forestal en selva central*, Lima. In: Baker *et al.* (2004).

[b] Proyectos Andinos de Desarrollo Tecnológico (PADT) en el área de los recursos forestales tropicales. 1981. In: Baker et al. (2004).

Wood products of the plantations also vary according to the species and the management strategy. A conversion factor of 0.65 was used to convert biomass to sawn lumber in the estimation of wood production.

The estimates of tons of CO_2 equivalent/ha was calculated based on the estimated volume/ha. This calculation takes account of the carbon content of wood of 0.46 giving a conversion factor of 1.6 and C to CO_2 of 3.67. Owing to the important quantities of carbon fixed in roots of the trees (Silver *et al.* 2004), its contribution was calculated at 0.2 above ground biomass. For Cedro, Ceiba and Caoba, the ratio of biomass and CO_2 is 1.3. For the dense wood of Roble, the ratio is 1.5 and for the fast-growing Acacia, 1.1.

Estimates of CO_2 are not always easy to calculate. For some species, the density of word is not constant throughout the life of the tree. In Teca, for example, it varies between 0.4 and 0.6 depending on tree age. Studies of physico-mechanical properties provide this information (Valero 2000). For this study, the ratio biomass to CO_2 varies from 1.36 to 1.86. As well as the age factor, wood density can vary according to geography, especially in Amazonia (Baker *et al.* 2004). The uncertainty of these assumptions draws attention to the need to refine the relation between biomass and CO_2 as a priority for forestry research.

The performance of storage of CO_2/ha (Figure 2) is similar to yield m^3 of the tree species. However, there are small differences owing to the species characteristics. For example, assuming equal growth (15 m^3/ha) of Roble and Tambolero, Roble has higher carbon storage because of its higher density. Moreover, it is notable that the density of Teca increases with age. Nor is the increase a straight line relationship, but an upward curve. Over the time horizon of 30 years, Ceiba has the highest average storage of carbon (353 tons CO_2 equivalent/ha). Cedro is about 328 followed by Teca 249, Caoba 233, Roble 226, Acacia 101 and Tambolero 69.

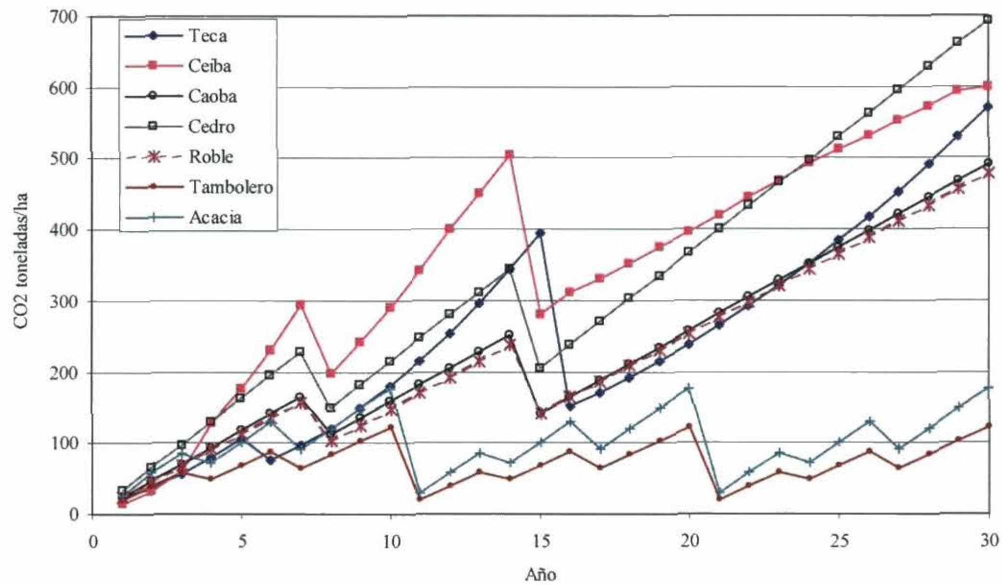

Figure 2. Tonnes of CO_2/ha in the forest species

Cattle production

The average annual inputs of the traditional system is $117,430[1] which includes the cost of posts, barbed wire, animal health and livestock (Table 2). The labor cost for maintenance and management has an annual average cost of $280,420. Inputs to the intensive system are greater, $215,836, and differ inasmuch as the cost of livestock, use of supplements, fertilizer and seed for improved pastures. The average annual labor cost of the intensive system is $282,520. The average annual indirect costs for both systems are $38,652 and $59,169, made up of transport and administration.

[1] 2006 Colombian pesos.

Table 2. Parameters for traditional and intensified cattle production.

Concepto	Tradicional	Intensificado
Stocking rate	0.8	1.5
Milk production (litre/yr)	600	1000
Meat production (kg/yr)	130	300
Inputs ($)	117,430	215,836
Labor ($)	280,420	282,520
Indirect costs ($)	38,652	59,169

Silvopastoral system

Corpoica's silvopastoral system uses dual-purpose cattle production with a stocking rate of 0.8 animals/ha (Cajas 2006, Convenio CVS-Corpoica-CIAT 2006, Corpoica 2006). This silvopastoral system stores an average of 119 tons CO_2 equivalent.

Prices

The analysis is based on actual data and estimates of the prices of the products, which are assumed to be at the farm gate. The value of meat is $2700/kilogram and milk $600/liter. The prices of forestry products are more diverse. As high-value species, Teca and Caoba command higher prices. In contrast, Acacia is a species of lower value (Table 3).

Table 3. Prices of firewood and lumber (,000 Colombian pesos)

Prices/values (units)	Caoba	Cedro	Ceiba	Roble	Tambolero	Teca	Acacia
Product of pruning or harvest (firewood)	150	150	150	150	150	150	100
Thinning 1, third class lumber (m^3)	350	250	200	250	250	300	5*
Thinning 2, millable lumber (m^3)	800	300	250	300	300	800	170
Final harvest, millable lumber (m^3)	800	360	360	360	360	1,018	180

*Poles per unit.
Sources: Interviews; CVS; Fedemaderas (2006).

The price of carbon from organic sources is about US$4 on the international market (Lasso 2005). From other sources such as the energy sector, the international price varies between $15 and $23. This low price reflects the uncertainty of sequestration in the long-term and the lack of precision in measurement of biological carbon. Moreover, it is unlikely that the plantation owner would receive this amount of money as multiple transaction costs, such as paperwork, local and international negotiations and monitoring of carbon storage diminish the cash return. For the analysis, it was assumed that the value of a ton of CO_2 equivalent has a value of $9,200 Colombian pesos (about US$4).

Costs

The revised land use (forestry, cattle production and the silvopastoral system) produces different economic benefits. These benefits may be interpreted in different ways since they depend on land productivity, management strategy, fixed costs, operating costs and the products themselves. This study concentrates on wood, meat, milk and carbon as products. The assumptions of the analysis are detailed below together with the results.

Like any investment, inputs are necessary to generate outputs. Forestry plantations need a variety of expenditures over the 30 years of the time horizon. The inputs for plantations include the cost of planting ($1,121,000/ha) for planting material and fertilizer. Fencing the land to protect the trees costs $731,000/ha, based on 163 lineal m. This includes the costs of posts, barbed wire and so on. The labor costs ($15,677,000/ha) includes planting (land preparation, digging the holes and planting), maintenance (weeding and pruning), thinning and final harvest. The labor cost for protective fencing is $143,000/ha over 30 years. The high variation in land prices because of the availability of access to infrastructure (roads, ports and so on), proximity to the centers of consumption, topography, quality in terms of fertility and availability of water etc.) affects the financial results and makes them difficult to compare. For these reasons, the cost of land was not taken into account in the analysis, assuming that whatever cost might be used affects the different plantations in the comparison equally and that, in general terms, the trends of the results will not change.

Costs of technical assistance are estimated at $558/ha over 30 years and include the costs of professional foresters, technicians and auditing. Indirect costs ($31,136) are calculated as a percentage of the other costs. These costs include tools (5% of labor costs) and transport of inputs (15% of the inputs). The silvopastoral system has an average cost of establishment and maintenance of $614,070.

Results: The investment portfolios

The land uses (that is cattle production, forestry plantations and the silvopastoral system) have different costs and incomes during the thirty years. A discount rate is applied because the value of income (and costs) in the future have less importance than those in the present. The financial results of the systems are sensitive to the assumptions and need interpretation.

Three measures are used to analyze the economic benefits (Table 4): net present value (NPV), internal rate of return (IRR) and cost-benefit ratio (CBR). Plantations of Teca, Caoba and Tambolero give better NPVs but their order changes according to the discount rate. With a rate of 15%, the silvopastoral system gives a better NPV than Teca. In contrast, Roble gives a lower IRR while Tambolero gives the best result by this measure because of its more frequent returns during the thirty years. The IRR is the rate of interest received on the investment over the time horizon of the analysis. For this reason, it is not a measure by itself of profitability. This result implies that the system is resistant to high interest rates. Profits can be less but still have a high IRR, such is shown by the cattle production system.

Table 4. Summary of financial indicators of plantations, catlle production and silvopastoral systems with CIFs and CERs (,000 Colombian pesos).

Financial results	Caoba	Cedro	Ceiba	Roble	Tambo-lero	Teca	Acacia	Traditional cattle	Intensified cattle	Silvo-pastoral
NPV 5%	71,083	43,763	43,227	22,268	52,341	70,621	20,655	3,619	12,051	23,371
NPV10%	24,468	15,084	16,013	6,379	26,372	22,413	8,339	1,818	6,635	12,258
NPV15%	9,644	5,952	6,786	1,539	15,074	7,695	3,234	977	4,075	7,091
IRR	31.6%	29.9%	31.3%	19.1%	75.4%	26.5%	22.9%	33.6%	64.4%	51.5%
CBR	12.5	8.1	7.6	4.9	4.6	12.9	2.6	1.6	2.5	5.2

The margin of preference of the systems, in terms of NPV, change according to the rate applied (Figure 5). With a rate of 5%, for example, Caoba and Teca have higher NPVs than the other systems. This scenario implies that the investor has the facilities to wait for profits in the long-term. Nevertheless, the result is different when a rate of 15% is applied. The differences in the NPVs are reduced and the order of preference of the options changes. With a discount rate of 15%, Tambolero shows a higher NPV because of the three harvests. Sale of wood that takes place in the future (for example Teca) is not so attractive as returns generated at various intervals during the time horizon of the analysis. This financial situation is typical for many small producers who are not easily able to wait for returns.

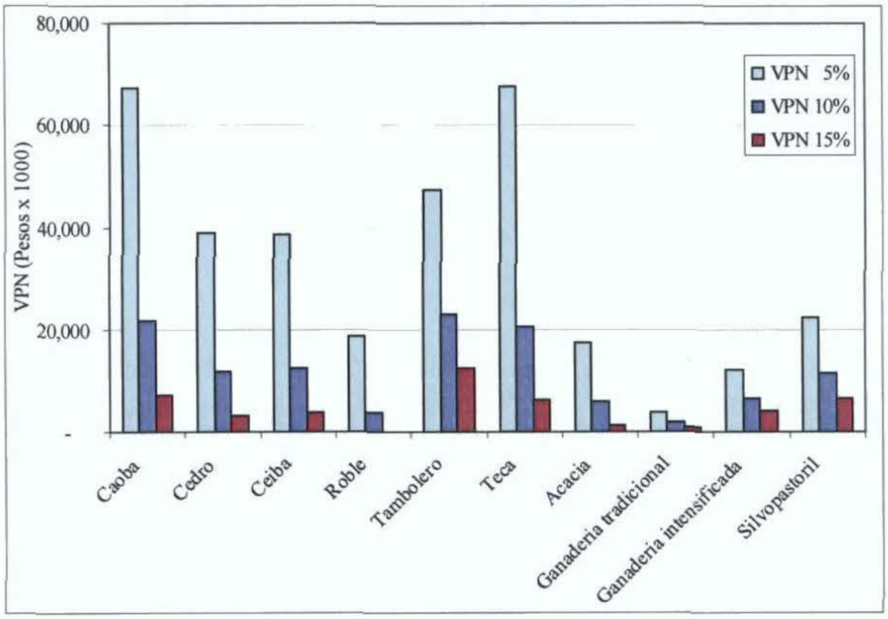

Figure 5. Net present value (VNP) of plantations, traditional and intensive cattle production systems (ganadería) and the silvopastoral (silvopastoril) system without external backing (CER or CIF).

In contrast, Table 5 shows annual returns of the forestry systems. Teca and Caoba have the best average and maximum (in the final year) annual return. Acacia, which is a plantation of 2200 seedlings/ha needs more investment in inputs and labor. Therefore Acacia shows lower return in its first year

Table 5. Mean, maximum and minimum annual return without discount.

	Caoba	Cedro	Ceiba	Roble	Tambolero	Teca	Acacia
Mean	8,184	5,058	4,699	2,786	4,126	8,463	1,867
Maximum	191,344	120,114	103,482	70,025	31,618	198,533	22,345
Minimum	-1,547	-1,460	-1,542	-1,631	-1,678	-1,792	-2,914

Financial support affects the financial performance of forestry plantations. Table 6 and Figure 5 give summaries of the economic benefits if CIFs and CERs are not available: profitability of all plantations is reduced. The returns of Roble become negative under the assumption of a discount rate of 15%. Moreover, with 15%, intensive cattle production and the silvopastoral system are more profitable than Cedro, Ceiba, Roble and acacia. With a discount rate of 10%, intensive cattle production gives better returns than either Cedro, Roble and Acacia. The silvopastoral system is better than Teca with a discount rate of 15%. At almost all discount rates, traditional cattle raising provides the lowest cash return.

Table 6. Summary of financial indicators of plantations, catlle production and silvopastoral systems without CIFs and CERs (,000 Colombian pesos).

Financial results	Caoba	Cedro	Ceiba	Roble	Tambo-lero	Teca	Acacia	Traditional cattle	Intensified cattle	Silvo-pastoral
NPV 5%	67,281	39,017	38,462	18,536	47,431	67,572	17,360	3,619	12,051	22,316
NPV10%	21,650	1,683	12,426	3,612	23,002	20,464	5,924	1,818	6,635	11,515
NPV15%	7,311	3,199	3,863	-753	12,482	6,260	1,265	977	4,075	6,531
IRR	24.0%	20.1%	21.3%	13.6%	47.0%	23.0%	17.5%	33.6%	64.4%	47.1%
CBR	12.2	7.7	7.3	4.6	4.4	12.6	2.4	1.6	2.5	4.7

The financial support of CIFs and CERs add between 2% and 98% more to the returns of forest products, with the CERs providing more benefits to the investor for all plantations. CIFs provide more support only for acacia under the assumption of a discount rate of 15% because CIF's are a benefit that is obtained at the start of the investment, and are not discounted like the CERs, which are obtained at the end of the time horizon.

CERs make up between 0.5% (Teca, NPV with 5%) to 81% (Roble, NPV with 15%) of total returns of plantations (Figure 6). The first example, Teca, shows that the value of wood dominates the returns. In contrast, Roble wood does not have much value because of its slow growth and its low price in the local market. In this case, returns depend on the CERs, but they should consider international markets such as North America. Tropical timbers of the genus *Tabebuia* have considerable hold in today's markets and can compensate for the effect of the local market.

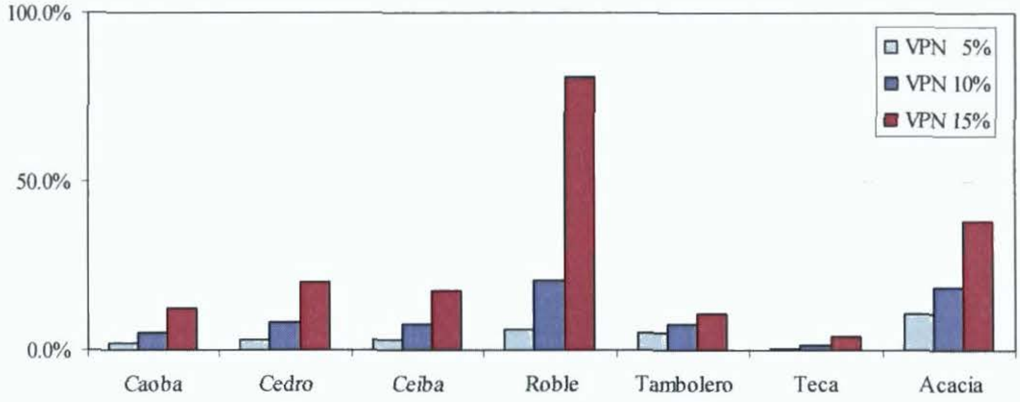

Figure 6. Contribution of Certified Emmission Reductions (CER) to the net present value of (VPN) of the forest species.

CIF's provide benefits to the investor who depends on the species and the assumptions of the discount rates (*Figure* 7). Owing to its slow growth and low returns from the sale of wood, Roble receives the major part of its return (65%) from CIFs. Moreover, because it is a native species, it has greater support (of the CIF). The returns of tambolero depend little on CIFs because it is a fast-growing species that produces high-value timber.

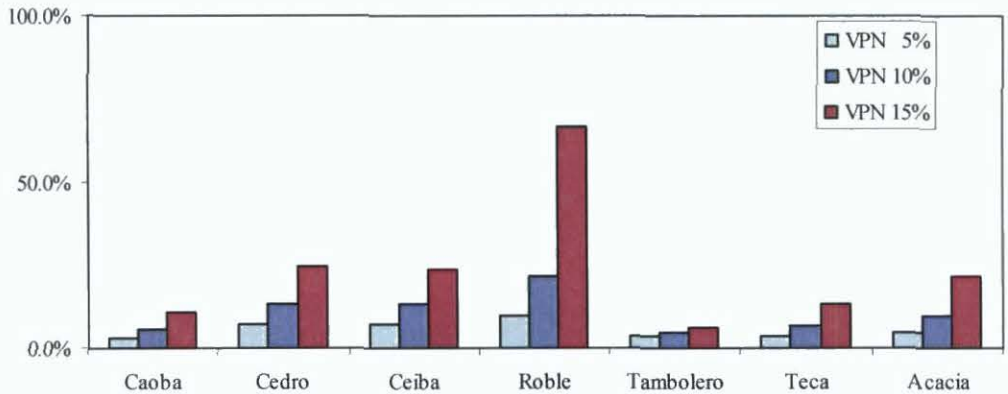

Figure 7. Contribution of Forestry Incentive Certificates (CIF) to the net present value of (VPN) of the forest species.

In summary, the selection of a species for plantations or other land-uses depends on the preferences of the investor. In addition to financial factors, other non-financial factors must be taken into account, such as the promotion of environmental and/or social benefits. Nevertheless, the financial analysis gives an information base to forecast returns. The analysis also shows the effects of government policies such as CIFs and the potential of environmental markets such as that for carbon (CERs) to influence land-use.

In the silvopastoral production system, the sale of products (milk and meat) provides 98% of the system's returns. The average net annual income is \$2,268,878/ha/year. When the value of the CERs is included, the system gives a mean profit of \$2,321,965. The benefits of silvopastoral systems tally with others such as that of CIPAV (Murgueito 2002).

Conclusions

A forestry context includes topics of public and private incentives. This study's analysis shows the economic benefits of forest plantations. The majority of the species can provide profits without the support of the public sector (CIFs) or of the carbon market (CERs). Nevertheless the decisions to reforest bring more than economic benefits.

The market for environmental services offers a powerful incentive for the conservation and restoration of tropical forests and new income opportunities for rural people. Nevertheless, it is still not clear which producers, consumers and types of forest resources will be the real beneficiaries of these markets. Nor is it clear what are the most effective conditions for the creation of markets for environmental services to achieve the objectives of forest policy. The majority of the markets are still incipient and their development demands concerted action of governments. The implications for the future of decisions that will be taken in the next years require a good review of the impacts of the efficacy, efficiency and equity of the markets.

The Colombian forest sector is characterized by a confluence of production from natural forests and forest plantations, a diversity of species with great potential, but scarcely developed. The Colombian balance of trade of wood and manufactured timber products is increasing exports. Colombia is taking advantage of the immense opportunities that international commerce of forest products offers. Because of its closeness to the sea and maritime ports, Cordoba can have good access to the demand for forest products concentrated in developed countries (Martínez y González 2005). Moreover, the warm humid environments of Cordoba provide the possibility to produce trees and timber rapidly and profitably.

Plantations can also be used in silvopastoral systems. A topic worthy of further research is the identification ofsynergies instead of competition between the production of trees and pastures (Andrade *et al.* 1999). Reforestation in given circumstances can be a good business, viable not only for companies that have considerable resources but for smallholders wishing to reforest their lands.

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Impacts and indicators of impact of fair trade, fair trade organic, specialty coffee

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Introduction

The intent of the research reported in this paper is perhaps best explained by a recent email from Michael Dupee, Vice President, Corporate Social Responsibility, Green Mountain Coffee Roasters (GMCR):

> "For many years, Green Mountain Coffee Roasters has supported a variety of collaboratively developed environmental, economic, and social initiatives in communities where we purchase coffee. Our goal has been to do good in the world, and while we believe that this has been the case, we have been challenged to measure the effectiveness and impact of these programs. We have often asked ourselves questions like, "Have these programs had the intended impact, and if so, how do we know?" "Can these programs be more effective, and if so how?" "What does success look like, and how do we measure it?"
>
> "In 2005, we decided to focus our efforts on four bottom line goals: reducing poverty, hunger, and waste, and increasing responsible energy usage in the communities we touch. Over the past few months, Green Mountain Coffee Roasters, the Sustainable Food Lab, CIAT (International Center for Agricultural Research), ForesTrade and other stakeholders, have undertaken a study and fieldwork focused on developing Key Performance Indicators (KPI's) related to poverty and hunger in coffee-growing communities. Our hope is that these indicators will ultimately enable Green Mountain Coffee Roasters to be a better partner to these communities by being able to jointly develop goals for, and measure the impact of, the social programs and business practices we have developed with our partners throughout all of our supply chains. We also hope that these results may be of value to others in the specialty coffee industry, and beyond" (Dupee 2006, personal communication)

There are several approaches to indicators of poverty, ranging from single criteria to long lists of welfare variables to criteria elicited from the poor themselves.

The World Bank has used single indicators (e.g., income of less than US$2.00 a day) based on census estimates to establish baselines and to measure change for large numbers of people. Although widely criticized, the approach has served as a litmus characterization at the district, national, and regional level. Other single specific measures include our use of childhood stunting as *the* poverty measure for our global work on both crop biofortification and development of drought tolerant cultivars (Hyman, Fujisaka, Jones 2006).

Large researcher-determined lists of indicators have been used to measure impact. Data elicited through large sample surveys include income sources and amounts, self-employment, seasonal and occasional labor, land and livestock holdings, costs of farm/enterprise inputs including family labor, housing and housing construction materials, holdings and value of different assets from radios to domestic appliances and motorcycles, levels of education, literacy, health measures, debt and savings, and access to water, power, health care, education, roads, and markets. Such data can be subjected to econometric analysis with results that are not always convincing but they are almost always expensive to come by.

A somewhat more recent approach has been to measure changes in terms of human, social, physical, financial, and natural capital. One such approach is the Department for International Development (DfID)

Sustainable Livelihoods Framework[1]. The approach is attractive in that gains and losses are estimated for the different capitals and that the capitals are recognized as convertible from one form to another (e.g., trees [natural capital] are cut down to provide funding [financial capital] for schooling [human capital]), which in turn can lead to better jobs [more financial capital] and to better housing [physical capital]). The difficulty of this and the long-list approach is in monetizing or standardizing values across indicators.

More technical work on crop improvement or innovations in management can be analyzed in terms of changes in enterprise budgets and benefit-cost ratios. Such analysis is quantitative and focused, but deals neither with whole farm budgets nor necessarily directly with poverty. On the other hand, for farm families largely reliant on a single crop (e.g., coffee, rice), simple enterprise budget analysis may provide a good portrait of welfare improvement.

In reaction against measures thought to be locally inappropriate, researchers have used different forms of indicators elicited from the poor themselves. One approach asks people about their classificatory systems regarding poverty and wealth. Once categories are defined, definitions of each category are elicited; and these latter serve as locally-appropriate indicators of poverty. In village x, for example, housing material may be irrelevant to local definitions of either poor or rich; and the number of educated sons may be all important. The recommendation would be to use the locally agreed-upon indicators.

The approach used in this study is similar to the one described above. Key to the work was the eliciting of livelihood circumstances in good compared with bad years and of the use or allocation of good-year resources. As shown below, the approach generated a set of indicators relevant to coffee growers; albeit given the heterogeneity of groups, each is not necessarily applicable to all groups.

Methods

Coffee producers were interviewed in three areas of Guatemala (Huehuetenango, Coban, and Barbarena) and in two areas of Mexico (Jatelnango in Chiapas and Huatusco in Veracruz). Three to five communities were visited in each area, with fieldwork facilitated by representatives of respective local organizations selling coffee to GMCR. The research team included Fujisaka, Oberthür, Rosales and Usma in Guatemala; and Fujisaka, Rosales, and Escobar in Mexico.

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[1] The word `livelihood' can be used in many different ways. The following definition captures the broad notion of livelihoods: 'A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future, while not undermining the natural resource base.' (Adapted from Chambers and Conway 1992) DfID stresses the importance to livelihoods of capital assets and distinguishes five categories of such assets: natural, social, physical, human and financial. It also stresses the need to maintain an 'outcome focus', thinking about how development activity impacts upon people's livelihoods, not only about immediate project outputs. DfID is operationalizing livelihoods approaches in many different contexts. Broadly speaking one can aim to promote sustainable livelihoods through direct support to assets (providing people with better access to the assets) or contribute to the more effective functioning of the structures and processes (policies, markets, social relations, etc.) that influences not only access to assets, but also determines which livelihood strategies are open to poor people. The idea is that if people have better access to assets they will have more ability to influence structures and processes so that these become more responsive to their needs. At a higher organizational level, DfID has identified three types of activity that can contribute to poverty elimination: (a) enabling actions to support the policies and the context for poverty reduction, (b) inclusive actions that broadly improve opportunities and services generally, and (c) focused actions that are targeted directly at the needs of poor people.

Groups of small-holder coffee producers were interviewed using participatory methods in all communities except Barbarena, Guatemala (where three large-holders were interviewed). Elicited and prioritized in the group interviews were:

- *Livelihood activities or resources used in good and bad years*, with "good" and "bad" defined in terms of coffee production and price. The elicited responses identified the different enterprises, activities, and income sources that producers relied upon and their relative importance in both good and bad years. As a set of potential impact indicators, projects or programs such as fair trade payments and organic certification and premiums would strive to reduce "bad" year outcomes and to increase years approximating what farmers described as "good" years.
- *Allocation of resources gained in "good" years.* Farmers' real or desired investments in good years provide insights into desired outcomes that, if and when met, can serve as indicators of impact.
- *Coffee production and coffee-related problems.* Solution of prioritized problems related to coffee production, processing, and marketing would have clear, positive impacts on the lives of farmers. Work on increasing benefit-cost ratios via problem solution and improvement of returns to factors of production within the coffee enterprise could be achieved through technical programs (not encountered in the course of the research).
- *Rough estimation of costs-benefits.* Farmer provided very rough estimates of yield, production costs, prices paid for conventional specialty vs. organic/fair trade specialty coffee. Detailed enterprise budgets would have been desirable but were not possible to elicit given the limited time in the field and the number of researchers.
- *Community problems.* Groups identified and prioritized community level problems. Programs seeking to ensure that price premiums benefit local producers could easily invest in community rather than individual needs.

In each of the above areas, except for the estimates of cost-benefits, respondents quantitatively prioritized the elicited items by distributing counters (100 beans or kernels of maize) relative to perceived importance.

Interviews, conducted by the researchers working in pairs, required up to 2-1/2 hours; were preceded by an explanation of objectives and methods, possible outcomes, and a request to continue. Interviews ended with questions and concerns of the respondents. Group participation was universally lively and enthusiastic. Where strong, people would conduct heated discussions in their indigenous languages before turning back to provide decisions in Spanish. Both males and females participated. Each and every one was encouraged to participate. The participatory work sessions were usually liberally sprinkled with humorous banter and jokes. Travel time was generally long and uncomfortable, albeit with incredible scenery.

The team interviewed and visited the farms of three wealthy large-holder coffee producers in the area around Barbarena, Guatemala.

Findings

Livelihood activities and resources used in good and bad years

As expected, coffee production was the most important livelihood source, followed by hiring out as farm laborers (Table 1a). Other important sources of livelihoods were encountered in some, but not all communities: remittances (important in 10 of 14 communities), production of maize and beans (11 of 14 communities), and use of forest products (10 of 14 communities). Other sources were sales of home products (foods, crafts, other in 6 communities); chickens and pigs in five communities; government or aid assistance in three communities; cardamom production in the three communities in Coban, Guatemala; coffee seedling or flower nurseries in three of the five Huatusco communities; and cattle in one community.

Other crops such as sugar cane, fruit, nuts, and vegetables also contributed to livelihoods in several communities.

The good year-bad year contrast for livelihood activities or sources was strong (Tables 1a, 1b). Overall, in response to bad years, *farmers relied less on coffee; had to hire out* (work off-farm) more; relied more on remittances; and were able to hire less labor to work on their own farms (as is shown in the next section). Working as migrant laborers meant neglecting coffee plantations, parcels of maize and beans, and cardamom production (in the one Coban community in which respondents greatly increased hiring out in bad years). Producers also tended to rely somewhat more on forest products and on small livestock (chicken and pigs) in bad years.

Table 1a. Livelihood activities in good (G) and bad (B) coffee years.

	Huehuetanago						Coban						Jatelnango						Huatusco									
	Buenos Aires Huixol		Chilin-San Martin		Chichimes-san Pedro Necta		Santa Teresa		Nueva Esperanza		Monte Blanco		Laguna del Cofre		Nueva Independencia		Nueva Colombia		Ocote		Potrerillo		Carrizal		Xuchilt		Capulapa	
Livelihood	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B	G	B
Coffee	55	20	50	20	37	20	36	9	35	13	50	27	36	8	53	9	34	16	46	6	45	9	37	8	24	14	27	11
Laborer	12	23	18	27	42	13	3	37	2	8	5	9	27	26	15	34	5	26	14	35	22	39	14	21	21	19	8	21
Maize-beans	22	18	12	4	11	17	13	8	5	19	3	10	6	5	0	0	17	6	5	5	5	0	0	0	0	0	4	4
Remittances	3	21	8	15	10	50	0	0	0	0	0	0	8	29	5	11	7	15	0	0	13	46	15	56	16	33	33	29
Forest prod	0	0	0	0	0	0	14	21	12	4	4	9	4	6	4	6	0	0	2	3	4	0	10	15	10	15	2	5
Home prod	0	0	0	0	0	0	3	2	4	7	0	0	0	0	6	13	8	6	6	15	0	0	0	0	0	0	1	7
Chick/pigs	0	0	0	0	0	0	4	8	2	14	0	0	0	0	10	12	8	6	0	0	0	0	4	0	0	0	0	0
Assistance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	15	0	0	6	6	0	0	0	0	6	8
Cardamom	0	0	0	0	0	0	23	9	19	19	34	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nurseries	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	14	0	0	0	0	21	10	3	5
Cattle	0	0	0	0	0	0	0	0	0	0	0	0	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other	8	18	15	26	0	0	4	6	21	16	4	9	14	20	7	15	6	10	20	22	5	0	20	0	8	9	16	10
Others	Beans		Vegetables Beans						Fruit Nuts Bananas Vegetables Cacao				Fruit Vegetables Chili		Vegetables		Sugar cane Fruit Nuts		Sugar cane Fruit Nuts				Sugar cane Fruit Vegetables				Sugar cane Fruit Nuts Vegetables	

Table 1b. Means, good and bad coffee year livelihoods

	Good	Bad
Coffee	40	14
Laborer (hire out)	15	24
Remittances	8	22
Maize-beans	7	7
Forest products	5	6
Home products	2	4
Chickens/pigs	2	3
Assistance	2	2
Cardamom	5	5
Nurseries	2	2
Cattle	0	0
Other	11	12

Impact indicators would have to include:

- Contribution of coffee to family livelihoods[2];
- Need to work as laborers off-farm;
- Ability to remain on-farm to care for different whole farm enterprises; and
- Need to rely upon remittances.

Use/allocation of "good year" resources

Respondents' major priorities for the allocation of good-year resources were investment in the coffee plantation, improved diet and food intake, housing improvement or expansion, and health or medicine. Slightly more secondary priorities were clothing, school goods, increased hiring in, savings and/or debt payment, and less hiring out (Table 2).

[2] It is important here to note that most of the business models employed in the source communities had most of the elements of a typical commodity model. The contribution of coffee to livelihoods may become more important if different "specialty coffee" business models such as direct relationship models are models that transparently transmit information and benefits between supply chain actors. A full supply chain analyses would be required in order to obtain the necessary insights into the workings of the currently used business models.

Table 2. Use/investment of "good year" resources

	Huehue		Coban			Chiapas			Huatusco					
Use	Tojkian-San Martin	Chilin-San Martin	Santa Teresa	Nueva Esperanza	Monte Blanco	Laguna del Cofre	Nueva Independencia	Nueva Colombia	Ocote	Potrerillo	Carrizal	Xulchit	Cupulapa	Mean
Plantation	9	0	5	18	0	0	0	32	38	20	20	26	42	16
Food	0	25	29	10	16	12	16	18	12	12	16	0	18	14
Housing	16	0	7	19	17	25	10	13	16	12	19	9	6	13
Health	28	25	4	4	13	9	14	0	5	8	11	13	16	12
Clothing	0	25	17	13	7	8	7	15	5	10	8	17	4	10
Education	24	25	0	8	0	-	11	8	8	9	6	10	0	8
More hire in	0	0	0	10	14	23	25	0	0	0	0	15	0	7
Save/pay debt	2	0	0	7	26	0	0	4	11	0	9	6	7	6
Less hire out	0	0	20	0	6	6	15	0	0	22	0	0	0	5
Land	14	0	7	0	0	0	0	3	4	0	3	0	2	3
Mules	7	0	0	3	0	15	0	0	0	0	8	0	0	3
Vehicle	0	0	0	0	0	0	0	0	0	0	0	4	2	0
Other	0	0	11	8	1	2	2	7	1	7	0	0	13	4

Variability by location of the responses was important in terms of indicator development. Communities varied considerably in what they did with resources in good years. Not one of the categories was elicited across all communities visited; and what was a highest priority in one community might not be mentioned by another. For example:

- Although plantation improvement was the highest priority in five communities, it was not even mentioned in four others.
- Although health and education were highest priorities in two Huehuetenago, Guatemala, communities, these were low priorities in two of the Coban, Guatemala, communities. Health was not mentioned at all by respondents in Nueva Colombia, Chiapas, Mexico.
- In the two Guatemalan communities in which health and education were highest priorities, one also prioritized food and clothing, items not mentioned by the other set of respondents.
- The ability to hire out less in good years was a strong priority in some communities, but was not mentioned at all in others.
- Some communities were land-scarce; others were land-rich. People with plantations on steep slopes with poor access needed mules, while others with easy access did not.
- Only respondents in two of the Huatusco, Mexico, and communities saved for buying a pick-up truck, a priority not mentioned in any of the other areas.

The key lesson is that, to be useful and appropriate, impact indicators will need to vary according to (very) local circumstances. Baselines and change, however, can be measured in terms of the set of priorities elicited: those shown in Table 2 also indicate that the category "other" had relatively few entries across the board.

Problems related to coffee

Price received was the major problem in 11 of the 15 communities (Table 3) and the greatest problem overall (albeit two communities did not mention prices). Pests and diseases, cost and timely availability of hired labor, and cost of transport followed as problems. Other problems were excess rain, cost of fertilizers, lack of a local collection and storage facility, and lack of means for wet processing. Drought was a problem in three communities; hurricanes in the three communities in Chiapas. Lack of capital, poor harvest logistics, and the need to rehabilitate older plantations were also seen as problems in several cases. Again, for each category elicited, some groups of respondents failed to mention it. The two communities that did not mention the selling price for coffee were among the three in Coban, Guatemala, who also relied on the (lucrative) production and sale of cardamom.

Table 3. Coffee problems

	Huehuetenango				Coban			Chiapas			Huatusco					
Problem	Buenos Aires Huixol	Tojkian-San Martin	Chilin-San Martin	Chichimes San Pedro	Santa Teresa	Nueva Esperanza	Monte Blanco	Laguna del Cofre	Nueva Independencia	Nueva Colombia	Ocote	Potrerillo	Carrizal	Xulchit	Cupulapa	Mean
Price	23	34	50	30	0	22	0	17	19	24	52	38	24	32	47	27
Pests/diseases	11	22	16	-	20	15	25	5	0	10	8	0	6	11	13	11
Hired labor	31	0	0	10	0	0	25	6	16	13	7	0	4	12	13	9
Transport cost	0	0	18	6	0	0	25	14	14	14	3	25	15	0	4	9
Excess rain	0	26	0	0	0	0	0	20	19	-	8	0	5	25	8	7
Fertilizer cost	14	0	16	24	0	0	0	0	0	0	9	0	0	0	6	5
Collection point	0	0	0	0	0	0	25	8	0	7	7	0	15	0	8	5
Wet processing	0	18	0	30	4	0	0	4	0	14	0	0	0	0	0	5
Drought	15	0	0	0	0	0	0	0	0	0	0	0	0	6	0	1
Others	6	0	0	0	76 [1]	63 [2]	0	26 [3]	22 [4]	18 [5]	6	37 [6]	31 [7]	14 [8]	1	21

[1] Lack of capital, harvest logistics.
[2] Poor soils, certification difficulties, low temperatures.
[3] Hurricanes
[4] Hurricanes
[5] Hurricanes
[6] Need to rehabilitate old coffee plantations
[7] Need to rehabilitate old coffee plantations, lack of capital
[8] Lack of capital

- Price received by farmers is a strong and obvious indicator. In the present study, however, many of those interviewed were producing conventional coffees; and others were in transition to organic certification.

- Technical assistance to address pest and disease problems is needed in several areas. Benefits to producers could be channeled through locally adapted integrated pest management programs. Losses to pests and diseases would have to be monitored starting as a baseline activity.[3]
- Other indicators can include: Is coffee the only cash crop? If so, is coffee more important compared to the others? If not, or if coffee is more important than other cash crops, what are the marketing channels available? Are niche-marketing channels generating substantially more income than other channels?

Community level problems

Groups complained about the lack of, or distance to, elementary schools and/or the costs involved in sending students to secondary schools in 13 of 15 communities (Table 4). "Schools" represented the most pressing problem among those named in 8 communities. "Health" (i.e., lack of a health post, presence of a health post but lack of doctors, and/or presence of health post and doctors but lack of medicines) was also a problem in all but one community and was the highest priority in three. Six groups were concerned about the lack of potable water or the poor state of delivery systems. The lack of or poor conditions of access roads were problems for seven communities. Roads were good and travel times short in the areas visited in Huatusco; and none of the groups visited there mentioned roads as a problem. Long travel times and poorer roads in parts of Coban, Guatemala, and Chiapas, Mexico, were reflected in groups from these areas identifying roads as a problem. People in five communities wanted a community meeting center. Lack of latrines was a problem in four communities. Lack of or faulty electrification was a major problem in all three communities in Chiapas, a problem not mentioned elsewhere. Poor or inadequate nutrition was a problem in two communities in Guatemala. Petty crime was a problem in one community in Chiapas. Most common among the category "other" was the lack of a recreational area, that is, a football field.

[3] A functioning extension system was only found in the Sierra de las Minas region where Forestrade is providing outstanding business and agronomic support services to the producers. Unfortunately the small difference between organic-fairtrade coffees and the currently strong market price for conventional coffees place this business model under pressures. Coincidentally the Sierras de las Minas region provides ample opportunity to develop business models that are based on a number of symbolic product qualities such as environmental service provision, not just certification schemes.

Table 4. Community problems

	Huehuetenango				Coban			Chiapas			Huatusco					
Problem	Buenos Aires Huixol	Tojkian-San Martin	Chilin-San Martin	Chichimes San Pedro	Santa Teresa	Nueva Esperanza	Monte Blanco	Laguna del Cofre	Nueva Independencia	Nueva Colombia	Ocote	Potrerillo	Carrizal	Xulchit	Cupulapa	Mean
Schools	23	20	45	22	50	22	11	38	0	11	100	36	12	0	25	28
Health	17	7	24	24	50	20	24	17	34	14	0	25	18	100	15	26
Water	54	15	0	0	0	6	0	0	17	16	0	36	0	0	0	10
Roads	6	16	0	10	0	18	24	16	0	23	0	0	0	0	0	8
Com center	0	19	17	0	0	0	27	0	0	5	0	0	36	0	0	7
Latrines	0	15	0	19	0	19	0	0	0	5	0	0	0	0	0	4
Electricity	0	0	0	0	0	0	0	20	22	13	0	0	0	0	0	4
Nutrition	0	0	0	25	0	0	14	0	0	0	0	0	0	0	0	3
Crime	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0
Other	0	8	14 [1]	0	0	15 [2]	0	9	20 [3]	13 [4]	0	3	34 [5]	0	60 [6]	12

[1] Recreational areas (14)
[2] Transport (10), access to improved varieties (3), wet processing (2)
[3] Flooding from adjacent river (20)
[4] Recreational areas (6), wet processing (7)
[5] Recreational areas (17), ecotourism center (17)
[6] Unemployment and migration of women (38), lack of technical assistance (14), pollution (8)

Communities face different mixes of problems, usually some combination of schools, health, water, roads, community center, latrines, and electrification. Clearly, more prosperous and accessible communities (e.g., those in the Huatusco area) had to think a bit harder in order to come up with problems. Programs directing benefits to communities rather than individuals may do well to address problems related to schooling, health, and domestic water systems *in selected communities* where these are serious problems. Indicators would simply be measures of the direct changes in such infrastructure.

Large-holder coffee producers

We visited three large coffee plantations and conducted informal interviews with their wealthy owners. All three lived in Guatemala City (about an hour away by car) and relied more on other sources of income. One was a recent MBA from a US university; one was more interested in horse breeding; and the last was a city businessman. Two of the three had processing plants and long family histories in the regional production of coffee. All three relied on large numbers of seasonal labor (up to 2000 in one case). Attitudes regarding the welfare of the labor force ranged from enlightened benevolent paternalism to expressed indifference. Interest in welfare benefits and to poverty alleviation must, in the case of the large plantations, be directed at the seasonal labor force.

- Findings ways to benefit the seasonal labor force on large plantations should be an objective of programs designed to benefit the poor in the coffee-producing areas.

- The Farm-ID program generated clear benefits to only one large-scale producer. An indicator would be the redistribution of premiums to contracted farm labor.

Cultural differences

Groups visited differed in terms of what perhaps might be called "cultural integrity". The *Mam* speakers of Huehuetenango were proud of their culture and language, have been largely independent of *mestizo* culture, and have adapted to present-day conditions by learning Spanish, while maintaining *Mam,* allowing them to work in Mexico or the US with relatively little difficulty. Although relatively poor, many had cell phones. By contrast, the ex-hacienda *peones* in the Coban area, while financially better-off due to cardamom + coffee production and land abundance, were more reticent with outsiders, perhaps more conservative in outlook. They learned far less Spanish and were less able to benefit from remittances sent from both other countries and even other areas of Guatemala. In the sense of livelihood assets, the *Mam* speakers are rich in human and social capital but poor in natural, physical, and financial capital. The Coban groups are wealthier in term of financial and natural capital, but poorer in terms of social and human capital.

Returning to the bigger concerns

Don Seville of the Sustainability Institute kindly supplied feedback to the first draft of this report. His queries are addressed in this section.

What was the current status of poverty and hunger?

Coffee producers in Guatemala and Mexico are not the poorest of the poor. Childhood malnutrition and stunting were rarely observed. As pointed out above, the relatively financially-well-off coffee-cardamom producers in Coban[4] did not appear to be so; while the poorer (financially, in terms of land) Huehuetenango producers appeared to be in good shape because of cultural integrity and high social capital. The poorest of those associated with coffee production are the migrant workers; and this group includes those interviewed who work as laborers in bad years.

How will we measure reductions in poverty over time? Our research suggests a simple approach. Baselines can be established[5] and then monitored for:

- Coffee producers in terms of comparative benefit-cost ratios (compared to conventional specialty coffee) and their hiring out as low-skilled migratory labor; and
- For migrant labor in terms of provision of shelter, wages, food and nutrition, and medical care.

[4] Interestingly these producers did not perceive an apparent link between the organic-fairtrade business model they were part of and their livelihood situation. If there is dependence, then the lack of perception may jeopardize the sustainability of this production and business model.

[5] It is important to note here that there is baseline information being collected in Guatemala by various institutions. This information would be useful if GMCR decides to establish a monitoring system in order to track livelihood changes through time.

Were returns to coffee sufficient?

We previously conducted an *ex ante* impact study in Chiapas (in exactly the same area) of biofortified maize and beans. Maize and bean farmers without coffee are the area's poorest-of-the-poor. Being a coffee farmer implies a relative degree of success[6]. On the other hand, the relatively poor economic benefits vis-à-vis conventional production supports that target benefits are not necessarily sufficient. The benefits of low or no-cost credit and of timely payment cannot be underestimated as a financial incentive, however.

How do we interpret the relative importance ratings of coffee prices and use of investments in good years to assess whether poverty was increasing or decreasing in those communities?

On the one hand, change could not be measured given lack of baseline data. On the other, farmers described cyclical poverty, as expressed by good years-bad years. Although establishment of consumer-financed high floor prices might appear attractive, the approach would be economically dangerous: production efficiency would decrease and certification costs (including higher risk and cost of corrupting the process) would increase.

Are the supply chains contributing to lifting people out of poverty? How much?

True decreases in absolute poverty should probably be measured for the non-coffee producers and landless who work as seasonal labor. Certainly their welfare has improved with the overall increased demand for specialty coffees in developed countries. We do not know by how much. A possible limiting factor to increased benefits to workers is that all such workers are contracted by middlemen.

Were there any other specific observations about those supply chains that suggest problems that need to be fixed in the way the chain is structured or important models to be learned from?

Purchases from large holders should probably be made contingent upon their treatment of their respective labor forces. Some sort of additional certification would be required.

Furthermore, it is important for GMCR to understand, through a supply chain analyses, whether the small amount of income obtained by growers through premiums for certified coffee is related to supply chain governance and the distribution associated benefits within the chain or simply to the fact that no fair price is being paid.

Innovative business models such as those developed in the Sierras de las Minas region by Forestrade may merit closer consideration. Such business models may serve as pilot projects to explore the feasibility, and then implement and market product differentiation based on symbolic product qualities that do not exclusively rely on organic and/or fair-trade certification. Other symbolic product qualities may be built and marketed on environmental (such as biodiversity or hydrologic) services.

Finally, examination of poverty in terms of natural, financial, physical, social, and human capital appears especially appropriate for the coffee producers. GMCR may want to address increases or maintenance of the non-financial capitals in the quest to reduce poverty.

[6] Please note that the surveys took place during an upswing phase in the international coffee markets. Coffee producers supplying under the commodity coffee model have to generate sufficient resources in the boom phases of the commodity treadmill cycles in order to remain afloat during the bust phases. That this is usually not possible is sadly illustrated by thousands of farms in Central America abandoned during the last crisis or by those farms where productivity dropped to a level that cannot sustain farm families or the employment of migrant laborers. We even observed this in the large-holder farms.

Reference

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THEME 4:

ESTIMATING THE MAGNITUDE AND DISTRIBUTION OF SOCIO-ECONOMIC AND ENVIRONMENTAL IMPACTS OF AGRICULTURAL R&D ON POVERTY AND VULNERABILITY IN RURAL COMMUNITIES

Strategic approaches to targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production

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Summary

The world's poorest and most vulnerable farmers have for the most part not benefited from international agricultural research and development. Past efforts tried to increase countries' production in more favorable environments; farmers with relatively higher potentials for improvement benefited most from these advances. This study prioritizes areas of high poverty, the key problem of high drought risk and the crops grown and consumed in these areas. We used global spatial data on crop production, climate and poverty (as proxied by child stunting) to identify geographic areas of high priority for crop improvement. Spatial overlay, drought modeling and descriptive statistics were used to identify regions to which technology generation might best be targeted to achieve its intended human welfare goals. Analysis showed that drought coincides with high levels of poverty in 15 major farming systems, especially in South Asia, the Sahel, and eastern and southern Africa, and also showed that the environments in these systems are characterized by high diversity in the frequency of drought. Twelve crops make up the bulk of food production in these areas. A database was developed for use in agricultural research and development targeting and priority setting.

Introduction

Progress over the last half-century in reducing poverty and malnutrition has been mixed (World Bank 2004, FAO 2005). A reduction in the proportion of the poor and undernourished has been achieved in most regions of the world. But the absolute numbers of poor people continues to grow across sub-Saharan Africa (SSA) and, between 1991 and 2002, the number of hungry has grown by over 40m people in Central and Eastern Africa and South Asia. These negative trends exacerbate a situation in which many regions are already projected to fall short of international poverty and hunger goals (UNDP 2006). Given the importance of agriculture in the food security and livelihoods of the poor, any strategy to address poverty in such regions must pay particular attention to raising the productivity, profitability, and sustainability of agricultural enterprises (Dixon *et al.* 2001, Gryseels 1992).

Unfortunately, most farmers in marginal environments have obtained few benefits from agricultural research and development (CGIAR 2000, Evenson and Gollin 2003, Freebairn 1995). The dominant humanitarian goal of early international research and development efforts, including that of the Consultative Group on International Agricultural Research (CGIAR), was to "increase the pile of rice" in poor and famine-prone countries (Shah and Strong 1999). But, while the new "Green Revolution" technologies succeeded in raising overall levels of food security, they were primarily adopted by relatively well-off farmers with access to resources and capital. There is now a growing commitment to the notion that accelerating progress in reducing poverty and hunger requires an urgent re-focusing of development efforts on resource-poor farmers in marginal environments.

In the past it has proved difficult to respond to this challenge because the necessary layers of information, and the tools to analyze them in an integrated fashion, were not available. In this study we bring together a unique combination of new spatial data and analyses that allow research investors and scientists to take a broad, strategic perspective of the most important geographical regions, farming systems and crops for which development of drought tolerant traits would likely bring major benefits to the poorest people.

Specifically, this study identified the coincidence of poor populations in developing countries, the production of key food staple crops on which the poor depend, and drought-prone production environments. Farming systems were used as our geographic units of analysis (Figure 1; Dixon et al., 2001). Our study used malnutrition, identified by childhood stunting, as a proxy for poverty (FAO, 2003). A model was developed to appraise the susceptibility of regions more and less prone to drought. We assessed the relative importance of different crops in the farming systems using a global database of harvested area and production for the main food staples (You and Wood, 2006).

Fifteen farming systems have between 2.5 and 28 million stunted children each, combining for over 70 percent of the world's stunted children. High average crop production losses from drought are found in these systems. They have evolved largely to support the production of 12 food staple crops, with at least five percent of the global harvested area of the dominant food staples in each system. They include a large area in Mesoamerica, the African Sahel, parts of eastern and southern Africa and large areas of South Asia, Southeast Asia and East Asia. Our study ranks the farming systems according to the total scale of poverty, the average drought frequency, and the total area of food staple crops. The derived information base is intended to support priority-setting for research and development on raising the productivity of food staple cropping systems targeted to addressing the needs poor people in marginal environments.

Materials and Methods

Population, poverty and crop production

A spatial database was developed to support assessments of poverty and crop production. Global data sets were acquired with estimates for grid cells of 1 km^2 to 400 km^2 spatial resolution. The database includes population information the Gridded Population of the World (GPW) Version 3 project (CIESIN *et al.* 2004). We used infant mortality rates, and the prevalence and absolute number of underweight and stunted children as measures of poverty (CIESIN 2005, CIESIN 2006, FAO 2003). The underweight and stunted children data sets are based on health surveys such as the Demographic and Health Survey (Balk *et al.* 2005, FAO 2003). The data reports the percentage and absolute number of children under 5 years of age that are two standard deviations below the global average of weight for age (underweight) and the global average of height for age (stunting). Tabular data for administrative units were linked to maps in a geographic information system (GIS).

We chose to use stunting as our principle poverty indicator for the following reasons (Table 1):

- Stunting occurs in households that cannot provide sufficient food or income for healthy nutrition; and because
- Poor families first try to improve their food and nutrition with greater income or crop production.
- Income or wealth as indicators are difficult to elicit or standardize in a way that allow comparison, and are highly variable as a contributing factor to well being.
- Only 20-30 countries of in the world have detailed mapping of income or consumption that is sufficiently reliable and of significant resolution; while
- Stunted children have received inadequate nutrition over a longer time period than is usually the case for underweight children.
- The measurement of stunting is straightforward and comparable globally.

Estimates of the spatial distribution and productivity of crops were derived for 10 km grids using a novel allocation approach involving the fusion of sub-national crop production statistics. This was combined with an array of digitally-mapped data on the distribution of rainfed and irrigated cropland, the potential biophysical yield of each crop, and population density. Sub-national crop production data were derived from agricultural censuses and surveys, and all values were scaled so as to obtain national production estimates that were compatible with the annual average FAO national crop statistics for 1999-2001 (You and Wood, 2006)[1]. The following digital crop maps in GIS formats were used in our analysis:

- Barley
- Bean
- Cassava
- Groundnut
- Maize
- Millet
- *Musa*
- Other pulses
- Potato
- Rice
- Sorghum
- Soybean
- Sweet potato
- Wheat

Three of the crop maps in the list above are combined categories. "Other pulses" include cowpea, chickpea, pigeon pea and lentils. *Musa* includes banana and plantain. Millet includes pearl millet and finger millet. These three maps combined crops because of difficulties in reporting these crops separately at the global scale. Accounting for the combined categories, the list above includes 18 crops.

Irrigated areas are obviously less susceptible to weather variability and drought (albeit lower than normal rainfall may reduce ground and surface water needed for irrigation). A focus on poor farmers in marginal environments largely excludes targeting of irrigated areas. Our analysis excluded irrigated areas based on estimates from the global digital crop maps (You and Wood, 2006)[1].

Farming systems

We used the farming system region (Figure 1) as the geographical unit of analysis. Dixon *et al.* (2001) mapped 72 farming systems in the developing countries. The map includes Latin America and the Caribbean, Sub Saharan Africa, the Middle East and North Africa, South Asia, East Asia and the Pacific, Eastern Europe and Central Asia. The map was based on the knowledge of agricultural experts of these regions at local, regional and global scales. The regions were defined based on the dominant pattern of the natural resources base, farm activities and household livelihoods. Factors such as climate, water availability, land cover, tenure and organization, farm size, dominant crop types, off-farm activities, technologies that determine production intensity and integration of crops, livestock and other activities were used in drawing the boundaries of the farming systems.

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[1] The prototype crop distribution database used in this study is available upon request from the authors, but is currently being regenerated using newer and additional data sources (including revisions based on expert validation), and an enhanced allocation algorithm. A large share of the sub-national crop production can be downloaded directly from FAO's (2006) Agromaps site (http://www.fao.org/landandwater/agll/agromaps/interactive/index.jsp).

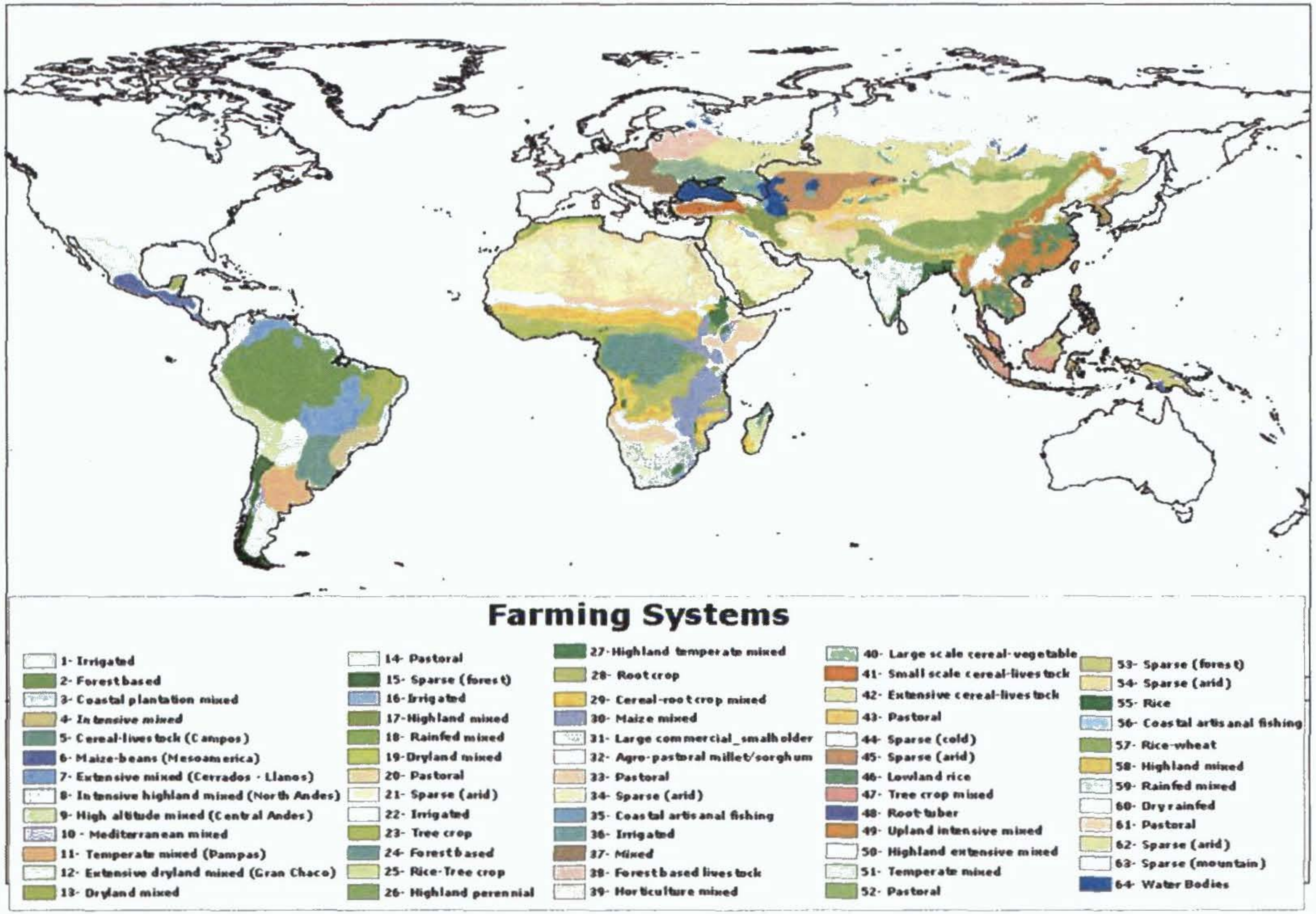

Figure 1. Sixty-three farming systems (from Dixon *et al.*, 2001)

Using these factors as criteria, eight broad categories were identified based on the above criteria:

- Irrigated farming systems;
- Wetland rice-based farming systems;
- Rainfed farming systems in humid areas of high resource potential;
- Rainfed farming systems in steep and highland areas;
- Rainfed farming systems in dry or cold areas of low potential areas;
- Dualistic (mixed large commercial and small holder) farming systems;
- Coastal artisanal fishing; and
- Urban-based farming systems

Urban-based farming systems are excluded from the global map due to their relatively small size, leaving 63 systems, which had average agricultural populations of 40 million, ranging from less than one million to several hundred million people.

Our analysis relies on comparing the 63 farming systems according to their levels of poverty, crop production and drought. All the data were converted to grid cells with 10 km spatial resolution within the 63 farming systems shown in Figure 1. We then used *zonalstats* in ArcInfo to calculate population, poverty and crop production statistics for each agricultural region. The algorithm considers each 10 km grid cell falling within an agricultural region. The method can calculate the mean, median, maximum, minimum, standard deviation, sum and other statistics for each region.

Assessing the frequency of drought by farming system

In order to map drought risk, we estimated the probability of a failed growing season. At a conceptual level, a failed season is one in which the harvest was not worth costs of producing the crop, one in which less food has been harvested than the human effort expended. What we need here is a simple surrogate measurement for this concept that might apply across a number of crops. There is no hard-and-fast rule for these assumptions, so we have designated a failed season as that which has rainfall at the start sufficient for germination and establishment, less than 50 growing days and a clearly defined end. This definition is clearly generic and does not apply to any specific crop. Thus the failed-season approach depends upon the use of a reliable means to assess the water- and temperature-constrained length of growing period in each locale.

Rainfed crops rely on soil water available to their roots to support growth and yield formation. The amount of water available depends upon rainfall, the water holding capacity of the soil profile, the rooting depth of the crop, and the potential and actual rates at which a crop can consume soil water during its growth cycle. Although there are reasonable soil maps for most of the world, it is difficult to determine the actual soil water holding capacity of any given square meter of soil. Our analysis assumed that all soils were capable of storing 100 mm of available soil water - a value that holds true for most of the agricultural areas in the drought-prone regions of the tropics. Where the storage capacity is larger, this assumption will lead to the under prediction of growing season lengths. For example, Fluvisols ,flood plain soils are likely to have, by definition, extra soil water resources within rooting depth that this analysis cannot account for.

The actual rate at which a crop consumes water (actual evapotranspiration, Ea) can often be less than the potential rate at which the crop could consume water if it was in abundant supply (potential evapotranspiration, Et). This happens, for example, when soil water content is low and it becomes more difficult for the roots to extract water. Thus the ratio Ea/Et is a well-established index of the water stress a plant experiences during its growth. Ea/Et ratios of between 0.8 and 1.0 imply little or no yield-reducing water stress. An Ea/Et ratio of less than 0.4 is, for most crops, an indication that severe drought stress is being experienced and that the ability of the crop to deliver an economic level of yield is severely compromised. WATBAL (see below) uses the ratio internally to determine the dynamics of the water balance and the extent of drought stress on a daily basis.

Our method establishes rules for defining a growing season. To have a reasonable chance of seed germination, certain minimum level of soil water and temperature must prevail. Thus we stipulate that a growing season cannot start until at least 5 days have occurred with Ea/Et greater than 0.8, and that the mean temperature during those days is above 8°C. Conversely, we define the end of a growing season for annual crops such as maize or beans to occur following 12 consecutive days with Ea/Et less than 0.4 (stress days) or any sequence of 12 consecutive days with temperatures less than 4°C. Crop physiologists will differ on the meaning of water stress for relevant crops; but we used these rules to enable us to define a generic growing season. Some crops such as cassava would easily tolerate this stress, where beans would be deeply stressed--folding their leaves and closing their stomata thus shutting down photosynthesis. The temperature criteria are aimed at tropical and subtropical crops. They do not represent truly temperate crops and will not reflect the correct situation for cold-adapted, temperate cereals.

To implement the length of growing period analysis we used the soil water accounting model WATBAL (Kieg and McAlpine, 1974) that directly assesses available soil moisture in each time period based on the factors highlighted above. WATBAL assumes that the Ea/Et ratio is proportional to the ground cover, thus a wet soil surface and/or a complete cover of an unstressed growing crop have a value of 1.0, a completely dry soil open surface will have a ratio close to 0. This is termed the CROP FACTOR. For simplicity we have assumed a value of 0.8 during a crop cycle.

We simulated 100 years of daily rainfall, temperature and radiation data for 30 arc-second pixels within the study area using MarkSim (Jones and Thornton 2000, Jones *et al.* 2002). Potential evapotranspiration was calculated using Linacre's (1977) method. Daily water balance was calculated using WATBAL (originally Keig and McAlpine: 1974; here applied as a FORTRAN subroutine in Jones (1987).

The failed seasons model can be used as a standardized index of the agricultural reliability. The model is not calibrated to specific crops; for example a failed season may apply more to a long- rather than short-season maize. It would be more accurate if we knew which soils the crops were grown on, but in most areas this is dependent on local variability that we cannot determine from the FAO soils map.

Secondary growing seasons occur sporadically in wide geographic areas. They often do not occur with a frequency that can be reasonably planned for and can be exploited. Analysis excluded the secondary or shortest growing season because global crop production and area data is not linked a particular growing season[2]. Thus, drought assessment is based on the longest growing season of the year.

Images are speckled, particularly in marginal areas, due to the stochastic process generating the climate data (Figure 2). The effect highlights the true environmental variability in these areas.

[2] These can be either the first or the second season in any one place or year so it is not correct to label them first and second.

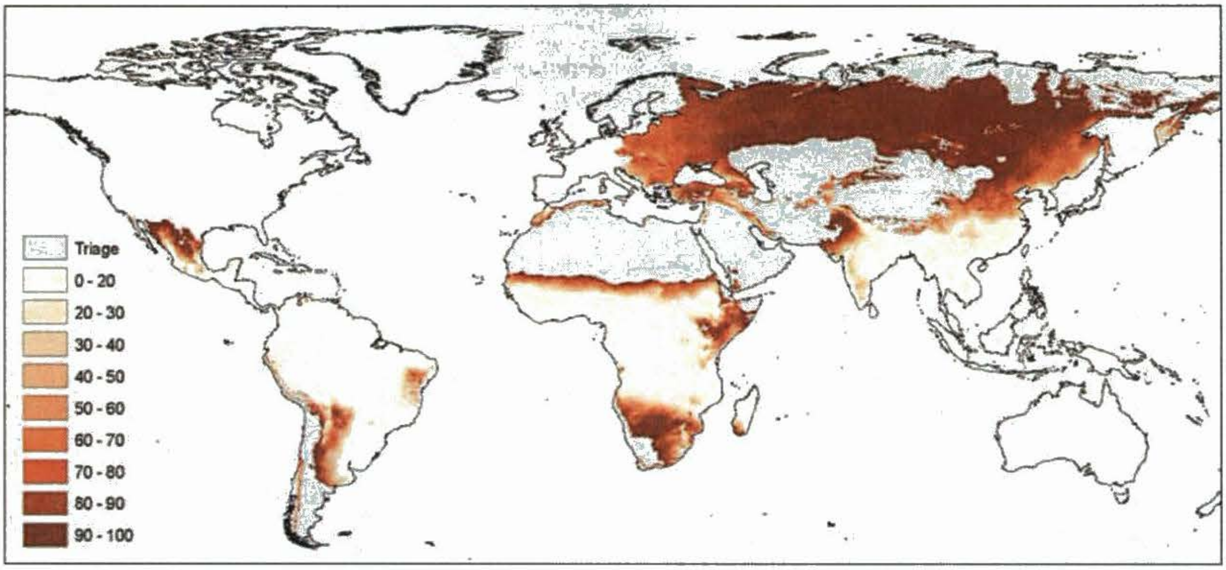

Figure 2. Global failed seasons drought model.

Two drought indicators were developed using data on the harvested crop area and the failed seasons model. Table 1 lists the farming systems and the respective drought indicators. Our principle drought indicator, labeled "Potential Drought Impact Index" in the table, is a reflection of expected loss of production due to drought. This indicator is derived by multiplying the area of rainfed food staple crops by the probability of a failed season. An example of two hypothetical grid cells illustrate how it was calculated:

	Rainfed Staple Crop Area (ha)	Mean Probability of a Failed Season (%)	Potential Drought Impact Index
Grid cell #1	1000	60	600
Grid cell #2	3000	40	1200

Table 1. Rankings of farming systems according to failed seasons drought model. The "Avg Fail" indicator is the mean probability of a failed season in the farming system. The "Potential Drought Impact" index takes account of staple crop area and the frequency of drought.. Shaded systems represent the 14 farming systems with over 2.5 million stunted children.

Farming Systems	Region	Stunted Children	Stunting Prevalence	Potential Drought Impact Index	Avg Fail	Global Rank	Regional Rank
Rainfed mixed	SA	24,546,900	63	8,176,456	16	1	1
Lowland rice	EAP	13,367,800	34	7,963,917	15	2	1
Cereal-root crop mixed	SSA	6,318,680	43	5,331,317	17	3	1
Rice-wheat	SA	28,310,301	52	4,050,261	42	4	2
Upland intensive mixed	EAP	15,434,700	35	3,725,591	28	5	2
Agro-pastoral millet/sorghum	SSA	3,135,510	37	2,633,259	52	6	2
Rice	SA	11,664,100	51	2,632,872	5	7	3
Maize mixed	SSA	6,318,490	43	2,535,536	23	8	3
Coastal plantation mixed	LAC	1,692,180	19	1,841,622	7	9	1
Root crop	SSA	4,988,630	40	1,802,876	8	10	4
Intensive mixed	LAC	309,548	5	1,500,188	7	11	2
Temperate mixed (Pampas)	LAC	209,061	13	1,446,738	54	12	3
Tree crop	SSA	2,290,560	32	1,355,889	4	13	5
Dry rainfed	SA	3,609,880	65	1,227,981	31	14	4
Maize-beans (Mesoamerica)	LAC	2,837,030	37	1,218,125	15	15	4
Cereal-livestock (Campos)	LAC	220,634	9	1,179,115	13	16	5
Mixed	EECA	92,593	7	1,142,759	70	17	1
Forest based	SSA	3,242,720	37	1,029,787	3	18	6
Extensive mixed (Cerrados_Llanos)	LAC	225,201	11	1,020,812	7	19	6
Horticulture mixed	EECA	736,312	15	914,768	61	20	2
Highland temperate mixed	SSA	2,760,640	50	909,683	18	21	7
Dryland mixed	LAC	684,261	19	897,951	27	22	7
Temperate mixed	EAP	2,595,720	26	849,686	77	23	3
Highland mixed	SA	5,161,720	48	827,142	18	24	5
Tree crop mixed	EAP	3,105,960	39	777,050	0	25	4
Highland perennial	SSA	2,625,490	50	715,601	12	26	8
Pastoral	SSA	3,229,600	38	711,772	79	27	9
Highland extensive mixed	EAP	2,536,590	44	682,635	12	28	5
Large scale cereal-vegetable	EECA	319,264	16	623,956	76	29	3
Rainfed mixed	MENA	499,124	17	592,646	38	30	1
Forest based	LAC	464,514	18	585,286	1	31	8
Irrigated	SSA	476,825	38	521,208	51	32	10
Large commercial_smalholder	SSA	906,810	23	520,323	76	33	11
Dryland mixed	MENA	749,673	19	413,712	54	34	2
Coastal artisanal fishing	SSA	1,290,450	43	406,598	9	35	12
Sparse (forest)	EAP	4,359,630	36	314,216	29	36	6
Intensive highland mixed (North Andes)	LAC	380,454	16	281,978	7	37	9
Irrigated	LAC	809,235	19	278,918	74	38	10
Coastal artisanal fishing	SA	1,146,450	55	242,045	5	39	6
Small scale cereal-livestock	EECA	382,117	20	205,774	81	40	4
Pastoral	EAP	2,420,440	31	147,376	85	41	7
High altitude mixed (Central Andes)	LAC	599,614	30	131,325	50	42	11
Rice-Tree crop	SSA	962,130	49	126,952	6	43	13
Extensive dryland mixed (Gran Chaco)	LAC	66,178	16	106,230	63	44	12
Pastoral	SA	2,366,160	58	104,446	75	45	7
Highland mixed	MENA	1,573,990	21	95,782	74	46	3

The index accounts for the scale of staple food crop production weighted by the probability of a failed season. Some form of drought can occur in all farming systems. In systems where the probability of drought is low, the index may still be high if the cultivated area is large. For example, the lowland rice system in South Asia covers relatively well-watered areas of South Asia that are less prone to drought. But since the cultivated area of this system is so large, the potential impacts of droughts when they do occur can be very large.

The mean probability of a failed season within the farming system region is a second drought indicator, labeled "Avg Fail" in Table 1. The value was derived by averaging the probability of a failed season (Figure 2) over all the pixels in each of the 63 farming systems (Figure 1). Within some systems, some areas are very dry or experience temperature extremes that render those areas unsuitable for crop growth. Those pixels falling into this category were excluded from the calculation of the mean probability of a failed season. This indicator locates the most drought-prone and marginal environments. As might be expected, many of the systems with high values have very little cultivated area.

Our study also assessed the distribution of drought frequencies within the farming systems to understand better how heterogeneous were drought conditions across those regions, and where the mean probability of failed seasons could be biased by a few large or small drought frequency values. The assessment also allowed us to identify the mix of crops under different drought frequency conditions across the farming systems. We developed cumulative frequency curves that show the extent of areas under all probabilities of failed seasons. The curves are discussed below in the results section of the paper.

Results

Population and stunted children by farming system

The study area includes five billion of the planet's six billion people[3] (Figure 1). Of these five billion people, about 3 billion (60%) live in rural areas and 2 billion (40%) live in urban areas. The total number of stunted children is 184.3 million, a figure that corresponds well with the World Health Organization's estimate of 181.9 million stunted children in developing countries in the year 2000 (WHO, 2000).

Table 1 shows average prevalence of stunting within the farming systems. Since this figure combines all the sub national administrative districts in a farming system, high prevalence values reflect serious malnutrition throughout the region. Of the top 20 systems in terms of the absolute number of stunted children, only one has a stunting prevalence below 34 percent (i.e., the mixed temperate system of East Asia, 26%).

Rural population data also indicates that the systems with high numbers of stunted children also have high rural populations[1]. Unfortunately, no global data set distinguishes between urban and rural stunting, potentially biasing our results towards farming systems that include large cities.

The total number and the prevalence (or percentage) of stunted children agree reasonably well. High stunting prevalence coincides with high absolute numbers of stunted children. Farming systems with high prevalence of stunting, however, have a wide range of absolute figures. Of the top 10 farming systems according to absolute numbers of stunted children, four systems are in South Asia; and three each are in Sub Saharan Africa and East Asia. In terms of stunting prevalence, eight of the top 10 systems are in South Asia, with the remaining two in Sub Saharan Africa.

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[3] A complete table organized by farming system showing urban, rural and total population, and showing absolute and proportional numbers of stunted children can be found at http://gisweb.ciat.cgiar.org/drought/poptable.htm

Drought

The ten systems in which the potential impact of drought on the production of staple crops are the largest are found in South Asia (3), Sub Saharan Africa (4), East Asia (2) and Latin America (1) (Table 1). The next group of ten systems is dominated by five Latin American systems, added to four other systems from the three regions in the first group, and an additional system in Eastern Europe and Central Asia. The remaining 44 systems in the ranking are varied in their regional composition. Systems in the Middle East and North Africa tend to be found in the lower half of the ranking, reflecting the smaller cultivated area in these regions. The bottom third of the list is made up of systems that are marginal for cropping. Although these areas are drought-prone, they have insufficient cultivated area to rank high on the list. In other words, people usually cultivate very little where drought is a frequent problem; because of this we emphasized target areas where many people can and do grow crops and where drought is a major problem affecting food security.

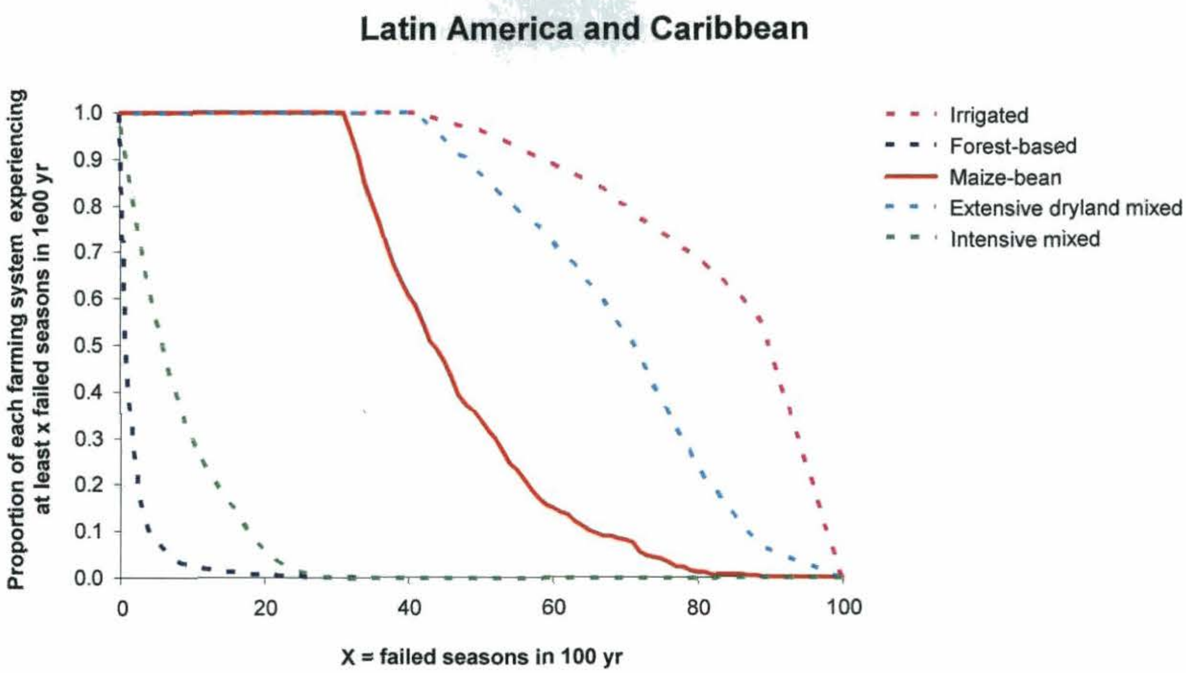
The values for mean probability of a failed season show a wide distribution throughout the list of 63 systems. The top third of Table 1, sorted by the potential drought impact index, includes a wide range of values. Some systems in that top third with relatively low mean values of the probability of a failed season, For example, the root crop system in Sub Saharan Africa has a high potential drought impact index, indicating large areas susceptible to drought, but a relatively low drought intensity value (mean failure) of eight. The middle and bottom thirds of the table have higher probability of failed seasons, including a few farming systems with very high values. The highest values in these two groups are associated with arid farming systems with a small aggregate of cultivated areas. For example the sparse arid system in Sub Saharan Africa has a 94 percent probability of failed seasons. This system occurs in the Kalahari Desert and has very little area under cultivation.

The spatial variability of drought frequencies within farming systems

The incidence and frequency of drought varies within individual farming systems, ranging from completely absent to always present[4]. The driest systems have large areas where the probability of a failed season is high. Well-watered systems have small areas with a high probability of a failed season. At these two extremes, the farming systems rely on fewer crops. Not surprising, high value and perennial systems are all found in well-watered areas, while pastoral systems are found in the drier areas. Farming systems that have values with a wide range of failed seasons rely on a greater number of crops. These high poverty, priority systems all show moderate to severe drought risk in between the extremes.

Figure 3 shows the cumulative frequencies of failed seasons of selected highest-poverty farming systems in the context of their respective regions. With the exception of the South Asian rice system, all show a wide range of drought frequency as evidenced by the gently sloping curves. The curves closer to 45 degrees show more varied environments. Farmers in these high-poverty systems are therefore attempting to cope with a range of drought regimes; and this is probably the reason for the diversity of cropping in these systems.

[4] Figure 3 shows the distribution of drought in 4 important regions of the developing world. Cumulative frequency curves for each of the 63 farming systems in the entire developing world are found at http://gisweb.ciat.cgiar.org/drought/freqcurves.htm.



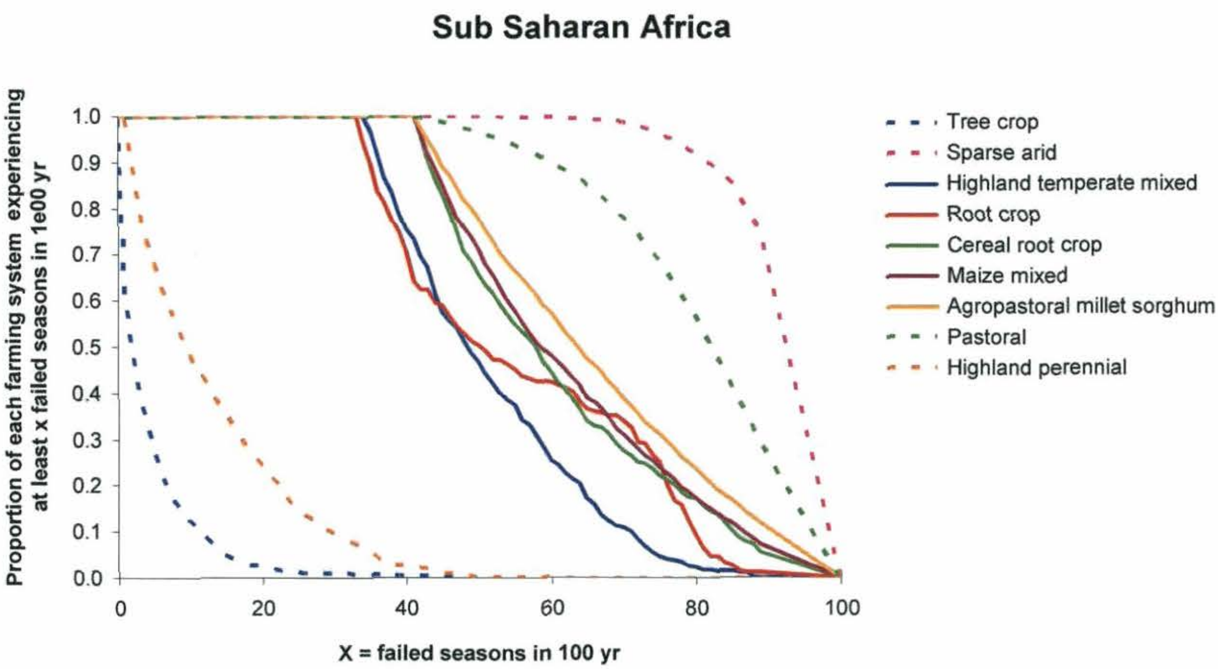
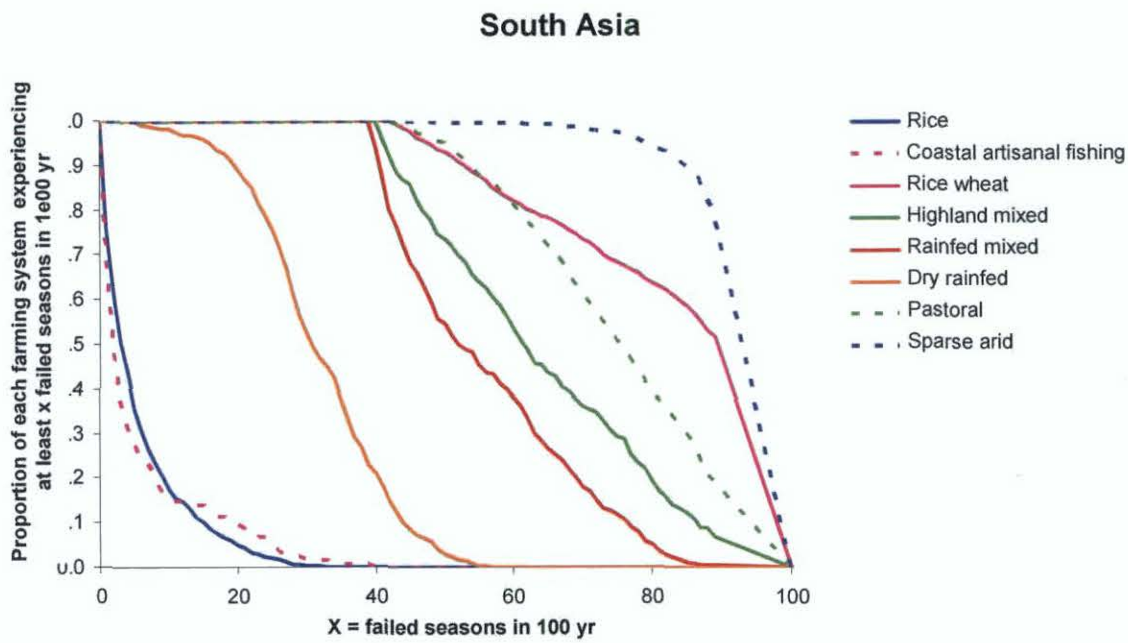


Figure 3A. The proportion of area within each farming system experiencing at least a given number of failed seasons in a 100 year period. Systems represented by solid lines are among the 15 systems of the world with more than 2.5 million stunted children.



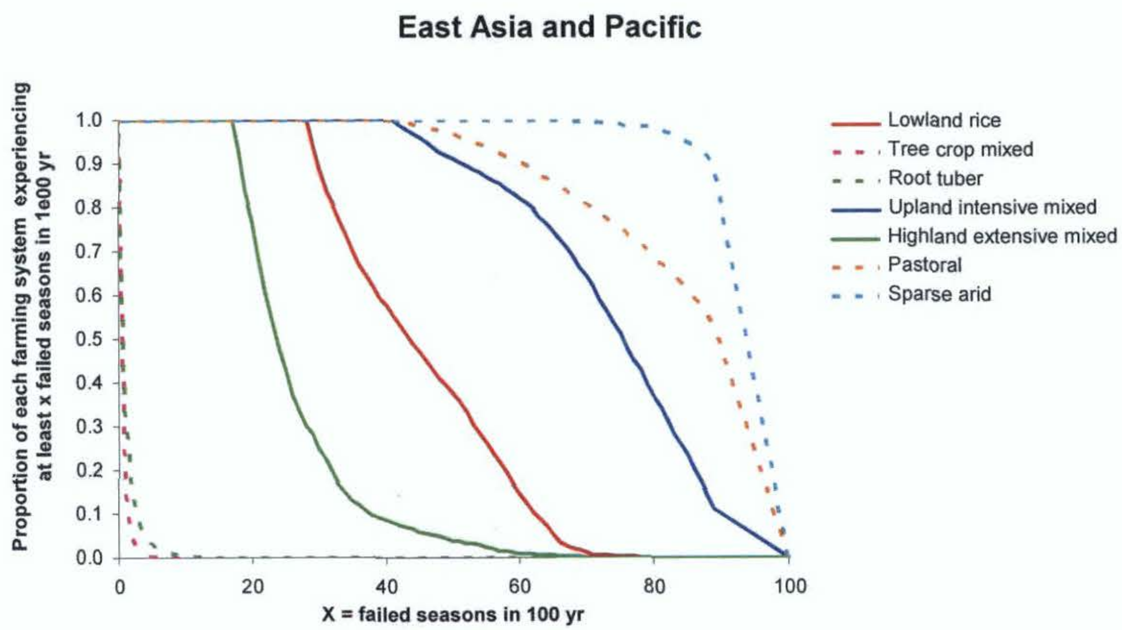


Figure 3B. The proportion of area within each farming system experiencing at least a given number of failed seasons in a 100 year period. Systems represented by solid lines are among the 14 systems of the world with more than 2.5 million stunted children.

Combination of poverty, crops and drought indicators

Poverty and drought are a combined problem in Latin America and the Caribbean, Sub Saharan Africa, South Asia and East Asia (Table 1). These regions are discussed in greater detail below. Farming systems in Eastern Europe and Central Asia, and in the Middle East and North Africa generally have fewer poor and less cultivated areas susceptible to drought. While these regions do suffer from drought combined with poverty, they are relatively less important in the context both of population and cultivated area.

Poverty and drought in the farming systems of the Latin America and Caribbean region are shown in Table 2. The maize-beans system in Mexico and Central America stands out, with 2.8 million stunted children and global and regional drought rankings of 14 and 4, respectively. The second system in the ranking is coastal plantation mixed, a system that follows much of the coast of northern South America, Central America and Mexico. This system has high numbers of urban population related to the port cities on the coast. The third system in the list is the irrigated system, found in northern Mexico and along the Peruvian coast. This system also has high urban population, including one of the region's largest cities, Lima, Peru. The fourth system in the list, dryland mixed, is often considered to be particularly drought prone, but it ranks in the middle third of the global ranking of farming systems according to drought. The remaining systems in Latin America have less than 600,000 stunted children and global drought rankings greater than 24. Overall Latin America and the Caribbean conform to the accepted view that the region is less poor than Africa and Asia and suffers less from drought.

Table 2. Top 10 systems in Latin America by stunted children and both regional and global failed seasons rankings.

Farming system	Region	Millions	Failed	Failed
Maize-beans	CA	2.8	15	4
Plantation mixed	Coastal	1.7	9	1
Irrigated	LAC	0.8	38	10
Dryland mixed	LAC	0.7	22	7
High altitude mixed	Central Andes	0.6	42	11
Forest based	LAC	0.5	31	8
Intensive highland mixed	N Andes	0.4	37	9
Intensive mixed	LAC	0.3	11	2
Extensive mixed	Cerrados-llanos	0.2	19	6
Cereal-livestock	Campos	0.2	16	5

Sub Saharan Africa and the Middle East and North Africa suffer more from poverty and drought: each of the poorest top 10 systems has more than 2 million stunted children (Table 3). Four of these systems are in the top 10 globally in the crop drought rankings. The cereal root crop and maize mixed systems both have 6.3 million stunted children. These two systems, spanning the southern portion of the Sahel and a large part of East Africa, have high rural populations. The root crop system has a high number of stunted children (5 million), even though drought intensity is relatively low. The other notable system in this region is agro-pastoral millet sorghum, a Sahel system with more than three million stunted children and high drought intensity.

Table 3. Top 10 systems in Sub Saharan Africa and the Middle East and North Africa, by stunted children and both regional and global

Farming system	Region	Millions stunted	Failed global	Failed regional
Cereal root crop	SS Africa	6.3	3	1
Maize mixed	SS Africa	6.3	8	3
Root crop	SS Africa	5.0	10	4
Forest based	SS Africa	3.2	18	6
Pastoral	SS Africa	3.2	27	9
Agro-pastoral millet-sorghum	SS Africa	3.1	6	2
Highland temperate mixed	SS Africa	2.8	21	7
Highland perennial	SS Africa	2.6	26	8
Sparse arid	ME & NA	2.4	56	5
Tree crop	SS Africa	2.3	13	5

Areas of high drought risk in Asia have even higher numbers of stunted children (Table 4). Five of these systems each have more than 10 million stunted children. Five of the top six drought systems are also the top five systems with stunted children. The rainfed mixed system in South Asia stands out, with the second highest stunting value and the highest global drought ranking. The rice-wheat system in South Asia has the highest number of stunted children and the fourth highest drought ranking. The lowland rice system in East Asia has the second highest drought index, but less than half as many stunted children compared to the South Asian rice-wheat system. These three Asian systems are marked by large populations with large cultivated areas. The upland intensive mixed system of East Asia has somewhat lower poverty and drought figures compared to the top two South Asian systems, but these are still among the top rankings of the 63 systems. Fifth in the list in Table 4, the rice system in South Asia has a high number of stunted children (fifth largest), with a drought ranking of 7 out of 63 systems. The highland mixed and dry rainfed systems have less than 10 million stunted children, with drought rankings of 24 and 14 respectively. The Asian systems rank very high for poverty and drought throughout their top 10.

Table 4. Top 10 systems in Asia by stunted children and both regional and global failed seasons rankings.

Farming system	Region	Millions stunted	Failed global	Failed regional
Rice-wheat	South Asia	28.3	4	2
Rainfed mixed	South Asia	24.5	1	1
Upland intensive mixed	E Asia & Pacific	15.4	5	2
Lowland rice	E Asia & Pacific	13.4	2	1
Rice	South Asia	11.7	7	3
Highland mixed	South Asia	5.2	24	5
Sparse (forest)	E Asia & Pacific	4.4	36	6
Dry rainfed	South Asia	3.6	14	4
Tree crop mixed	E Asia & Pacific	3.1	25	4
Temperate mixed	E Asia & Pacific	2.6	23	3

Poverty and drought are more severe in the farming systems of Asia and Africa, with notably less severity in Latin America. Table 5 shows the top 15 farming systems ranked by the absolute number of stunted children. These systems each have more than 2.5 million stunted children. We chose 2.5 million as a threshold for inclusion in this table because these systems rely more heavily on staple crops. The values just below 2.5 million in Table 1 are mostly livestock-based systems. Below these, the number of stunted children begins to decrease substantially.

Table 5. Fifteen farming systems with over 2.5 million stunted children, with global (fsg) and regional (fsr) farming systems rankings according to potential drought impact index. Crops appearing first time in the list are highlighted and in italics.

System	Stunting	Crops	fsg	fsr
SA rice wheat	28.3	*rice, pulses (chickpea) millet, wheat, maize, bean*	4	2
SA rainfed mixed	24.5	rice, millet, *sorghum*, chickpea, bean, *groundnut*, maize, wheat	1	1
EA upland intensive mixed	15.4	Maize, rice, wheat, *sweet potato, potato*, bean	5	2
EA lowland rice	13.4	rice, maize, wheat, sweet potato, groundnut	2	1
SA rice	11.7	rice, pulses (chickpea)	7	3
SSA cereal-root	6.3	sorghum, millet, *pulses (cowpea)*, maize, groundnut, *cassava*	3	1
SSA maize mixed	6.3	maize, cassava, sorghum, pulses, groundnut, millet, bean, sweet potato	8	3
SA highland mixed	5.2	rice, maize, wheat, potato , groundnut, pulses (chickpea)	24	5
SSA root	5.0	maize, cassava, rice, sweet potato, cowpea, sorghum, groundnut, bean	10	4
SA dry rainfed	3.6	Sorghum, millet, chickpea, groundnut, bean	14	4
SSA agro-pastoral millet sorghum	3.1	millet, sorghum, pulses groundnut, maize	6	2
LA maize beans	2.8	maize, bean, sorghum	15	4
SSA high temperate mixed	2.8	maize, wheat, sorghum, *barley*, millet, pulses	21	7
EA temperate mixed	2.6	maize, wheat, potato, groundnut, millet	23	3
EA highland extensive mixed	2.5	rice, maize, wheat, potato, groundnut, pulses	28	5

The main crops of the farming systems with high levels of poverty and drought are also shown in Table 5. Each of these crops covers at least 5 percent of the total cultivated area in each respective farming system (Table 6). This list suggests that poor farmers in drought-prone areas rely largely on 12 crops:

- Rice
- Wheat
- Chickpea
- Maize
- Millet
- Sorghum
- Groundnut
- Cowpea
- Cassava
- Sweet potato
- Bean
- Barley

The drought ranking of the 15 systems shown in Table 5 are all within or near the top third of the 63 farming systems globally. Nine of these 15 systems are in the top ten in terms of their drought ranking. Only the East Asia temperate mixed system (drought rank=23) and the East Asia highland extensive mixed system (drought rank=28) did not fall into the top third of the 63 systems.

Table 6. The proportional area of each crop in the agricultural systems with more than 2.5 million stunted children. Areas shaded in gray have more than 5% of the area in their respective system. BANP is the combined category of bananas and plantain. OPUL is the combined category of cowpea, chickpea, lentils and other pulses

Farming Systems	Region	BANP%	BARL%	BEAN%	CASS%	GROU%	MAIZ%	MILL%	OPUL%	POTA%	RICE%	SORG%	SWPY%	WHEA%
Maize-beans (Mesoamerica)	LAC	0.017	0.008	0.161	0.002	0.007	0.668	0.000	0.009	0.005	0.009	0.098	0.000	0.016
Cereal-root crop mixed	SSA	0.007	0.001	0.032	0.052	0.093	0.125	0.224	0.126	0.004	0.045	0.255	0.033	0.002
Maize mixed	SSA	0.000	0.004	0.057	0.091	0.063	0.461	0.059	0.073	0.023	0.024	0.075	0.056	0.016
Root crop	SSA	0.004	0.000	0.060	0.222	0.074	0.275	0.030	0.027	0.002	0.117	0.074	0.117	0.000
Agro-pastoral millet/sorghum	SSA	0.003	0.002	0.010	0.018	0.125	0.065	0.377	0.146	0.001	0.009	0.238	0.006	0.001
Highland temperate mixed	SSA	0.000	0.166	0.040	0.009	0.008	0.251	0.062	0.051	0.008	0.003	0.168	0.016	0.218
Rice-wheat	SA	0.002	0.009	0.053	0.000	0.011	0.101	0.109	0.118	0.023	0.428	0.038	0.001	0.106
Rainfed mixed	SA	0.002	0.002	0.109	0.001	0.071	0.066	0.170	0.150	0.001	0.205	0.166	0.001	0.056
Rice	SA	0.015	0.001	0.011	0.011	0.020	0.009	0.038	0.100	0.021	0.722	0.023	0.003	0.026
Highland mixed	SA	0.009	0.023	0.026	0.007	0.007	0.196	0.081	0.117	0.021	0.281	0.013	0.002	0.217
Dry rainfed	SA	0.001	0.000	0.053	0.000	0.064	0.021	0.327	0.132	0.001	0.020	0.358	0.000	0.023
Upland intensive mixed	EAP	0.012	0.009	0.060	0.035	0.045	0.267	0.017	0.021	0.062	0.249	0.005	0.080	0.137
Lowland rice	EAP	0.012	0.012	0.043	0.041	0.060	0.166	0.004	0.009	0.026	0.379	0.004	0.097	0.148
Temperate mixed	EAP	0.000	0.010	0.037	0.005	0.070	0.532	0.057	0.026	0.080	0.002	0.041	0.049	0.093
Highland extensive mixed	EAP	0.004	0.008	0.041	0.012	0.056	0.144	0.022	0.055	0.094	0.427	0.002	0.015	0.119

Conclusion

This assessment of poverty, crops and drought suggests that 15 farming systems should be given high priority for agricultural research and development (Table 5 and Figure 4). These systems account for substantial populations of the poor, including over 70 percent of stunted children in the world. The 14 systems have large areas of cultivated lands susceptible to drought. Land use and the agricultural economy in these 14 systems rely largely on just 12 crops.

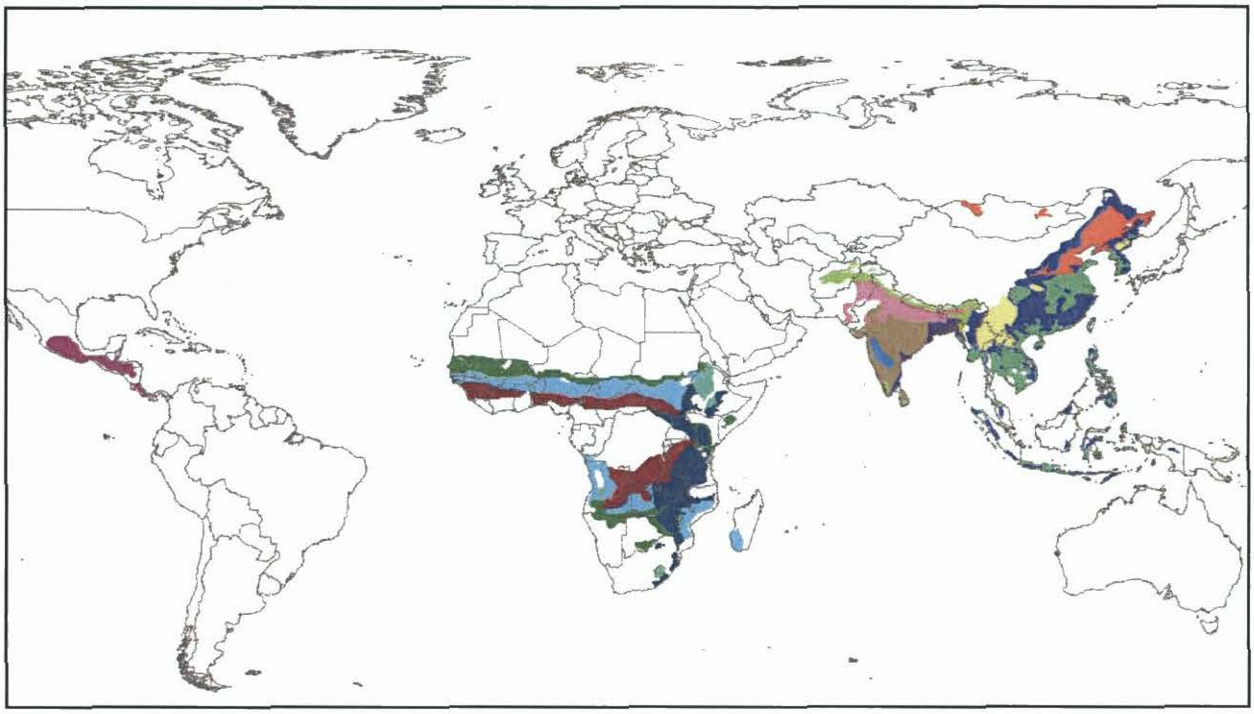


Figure 4. Priority systems, with over 70 percent of all stunted children and substantial drought.

With few exceptions, the poorest, most drought susceptible systems have diverse environments and farmers have developed effective mechanisms to cope with risk. These farmers cope through diversity of livelihoods, including livestock. Judicious employment of improved crops may well be successful if the varieties can fit into such diverse and risky systems.

The databases used and developed in this study have great potential for research and priority-setting for developing country agriculture. Our assessment used criteria that would help us focus on a reasonable number of regions and crops that could be given priority for investment in agricultural research and development. These criteria could be easily modified to reflect other priorities than those developed in the study to date.

The results of this study are limited by the aggregate scale of the analysis. Future work could include other poverty indicators and poverty analysis at finer geographic resolutions within the farming systems. In addition, further work should develop crop-specific drought models in order to provide more detailed information to crop improvement programs. This analysis excluded assessment of factors within farming systems such as variety adoption and the potential to use agricultural technology. Nor did we make economic assessments to estimate the potential impact of focusing on the priority crops and systems identified in the study. While further research could complement the results obtained here, this study provides an initial assessment of the previously by-passed poor that face high drought risk, and the principal crops on which they depend.

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How cost-effective is biofortification in combating micronutrient malnutrition? An ex-ante assessment

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Micronutrient malnutrition and the potential of biofortification

The magnitude of micronutrient malnutrition is increasingly taking centre stage in policy discussions relating to food and nutrition security. It is recognized that food security needs to refer not merely to adequate energy intakes, but also to ensure sufficient intakes of essential micronutrients. Estimates of the number of people affected by micronutrient malnutrition are high, with up to 5 billion people suffering from iron deficiency and about a quarter of all pre-school children (about 140 million) from vitamin A deficiency (United Nations 2005; pp. 14 and 19). Estimates of those at risk of inadequate zinc intakes are put at between a quarter and a third of the developing country population (Hotz and Brown 2004).

Public health interventions to address this problem include fortification (of flour with iron, for example) and supplementation (twice-yearly vitamin A capsules for pre-school children). Yet few governments have the resources to fund such programs on a permanent basis. Biofortification, which uses plant breeding techniques to enhance the micronutrient content of staple foods, is a new, complementary, approach.

The premise of biofortification is that diets of undernourished people are based primarily on a staple, as poor people lack the purchasing power for a more diverse diet containing sufficient quantities of micronutrient-rich foods. The objective of biofortification is to enhance the micronutrient content of these staple food crops, through plant breeding techniques, thus resulting in higher micronutrient intakes by vulnerable people. Unlike commercial fortification, which necessitates the purchase of the fortified food, biofortification particularly targets rural areas where produced food stays within the community and is consumed either on-farm, or locally. Further, repeat purchases or treatments are not necessary; for most crops, a one-time investment of disseminating varieties with the nutrient-dense trait becomes self-sustaining. Research has shown that it is feasible to breed at least some staple food crops to have higher micronutrient levels (Bouis 2000).

The proof of concept that biofortified crops can have an impact on public health is starting to emerge from efficacy studies where trials are conducted with human subjects under a controlled setting. For example, there is evidence from a 9-month feeding trial in the Philippines, that regular consumption of rice containing an additional 2.6 ppm of iron was efficacious in improving body iron stores among women with iron-poor diets (Haas *et al.* 2005). Similarly, a feeding trial of school children in South Africa indicates that consumption of orange-fleshed sweetpotato, high in beta-carotene, led to improvements in their vitamin A status (van Jaarsveld *et al.* 2005).

Given this, the question becomes whether it is also economically efficient, and it is this question that this paper attempts to answer. Biofortification is a long-term strategy requiring a significant up-front investment in agricultural research and development. Its success will also depend on the current diets of the target populations, how much of the staples they eat, in what forms and with what other foods. Thus, its economics are quite different from those of interventions such as fortification of flour or sugar, or the distribution of vitamin capsules. Recognizing this, in this study we estimate the cost effectiveness of biofortification for a sample of crops and countries throughout the developing world. Because biofortified crops are still being developed, the analysis is *ex ante* in nature.

In determining cost-effectiveness, we use the disability-adjusted life years (DALYs) framework, which captures both morbidity and mortality outcomes in a single measure (see below). Relatively underutilized in the economics literature as a metric for welfare, the use of DALYs obviates the need for the monetization of health benefits, a contentious issue that has been the subject of long debate with little satisfactory resolution. Instead, benefits can be quantified directly using DALYs saved, and costs per DALY saved offer a consistent way of ranking a range of alternative health interventions—be they water and sanitation projects, or biofortification, the case considered here.

In particular, this paper presents a synthesis of the evidence from several countries and crops that are targeted under HarvestPlus, a program that is engaged in biofortification research. The target nutrients are: provitamin A[1] in cassava, maize and sweetpotato; and iron and zinc in beans, rice, and wheat. The choice of target countries (eleven in all) is based on a number of factors, including the magnitude of micronutrient deficiencies, the importance of the target crop in the diet, and the availability of reliable data. To understand how sensitive results may be to the specifics of cropping patterns and diets, we include two East African, one Central African and one West African country. Similarly three South Asia and one Southeast Asian country are featured in the analysis, as are three Latin American countries.[2] This is thus the first paper to provide a comprehensive overview of the evidence to support biofortification, one that spans across crops, countries and micronutrients. The results provide evidence on whether biofortification can be a useful approach to combating micronutrient malnutrition, as well as identify the conditions under which is it most likely to be successful. The basic reports on which this synthesis has been generated are listed in the references.

Given that the analysis is *ex ante* in nature for many crops, we consider both pessimistic and optimistic scenarios, which also enables a check on the robustness of the results to changes in assumptions.

Quantifying micronutrient malnutrition

The disability-adjusted life years (DALYs) framework

The first step in assessing the cost-effectiveness of any intervention, including biofortification, is to determine the magnitude of the problem that the intervention is trying to address. One strand of literature has focused on the productivity losses that occur as a consequence of malnutrition (see for example, see Horton 1999 and Horton and Ross 2003). Other studies have examined the impact of malnutrition individually on mortality outcomes, cognitive development or child growth (for example, Gillespie 1998; a good review of the issues is contained in Alderman *et al.* 2004).

An increasingly popular measure for quantifying the magnitude of ill health is the disability-adjusted life year or DALY, first detailed in the seminal contribution by Murray and Lopez (1996). It is also important to mention the contribution of Zimmerman and Qaim (2004) who first used this framework in the context of biofortification. DALYs lost enable the addition of morbidity and mortality outcomes and are an *annual* measure of the burden of disease. Also, they provide a way to "add up" the burden of temporary illness (such as diarrhea) with more permanent ones (such as blindness) to give a single index. Thus, DALYs lost are the sum of years of life lost (YLL) and the years lived with disability (YLD). YLL represents the number of years lost because of the preventable death of an individual; while the YLD represents the number of years spent in ill-health because of a preventable disease or condition:

$$\text{DALYs Lost} = \text{YLL} + \text{YLD}$$

[1] There is a distinction between provitamin A and vitamin A: plants contain *provitamins* A, such as beta carotene, which are precursors to the *vitamin* A that is formed in the liver.

[2] In the case of Brazil, the estimates refer not to the entire country, but only to one region—the northeast—where poverty and undernutrition levels are high.

A public health intervention is expected to reduce the number of DALYs lost, and this difference is a measure of its benefit. Thus YLL saved represents the years of life saved because a death has been prevented and YLD saved or averted refers to the years of life spent in perfect health, because a non-fatal outcome or disability has been cured or prevented.

The DALYs saved are then a direct metric for analyzing benefits of an intervention, and do not necessarily have to be monetized to ensure comparability across interventions. Unlike most agricultural technologies, biofortification does not lead to a shift of the supply function; hence changes in economic surplus are not relevant. Instead, it is the supply of dietary sources of iron that is increased, and it is the impact of this shift on public health that is captured here. DALYs saved also have the appeal of being consistent with "specific egalitarianism" whereby everyone—irrespective of income—is presumed entitled to be free of ill-health. For this reason, cost-effectiveness measures expressed in terms of DALYs saved are increasingly being used by agencies such as the World Bank and the WHO in priority ranking exercises (World Bank 1993).

The use of disability weights, ranging from zero to unity, enables the incorporation of the severity of the disability, with higher weights implying greater disability (and 1 representing death). Further, since some outcomes affect only certain target groups (young children, or pregnant women for example), disaggregation by gender and age-specific target groups is needed. Finally, since many of the adverse outcomes are permanent and may last the rest of an affected individual's life span, a conversion to an annualized measure is necessary. Thus, more formally, the DALY burden may be written as:

$$DALYs_{lost} = \sum_j T_j M_j \left(\frac{1 - e^{-rL_j}}{r} \right) + \sum_i \sum_j T_j I_{ij} D_{ij} \left(\frac{1 - e^{-rd_{ij}}}{r} \right)$$

where T_j is the total number of people in target group j,

M_j is the mortality rate associated with the given disease,

L_j is the average remaining life expectancy,

I_{ij} is the incidence rate of temporary disease i that is of interest,

D_{ij} is the corresponding disability weight,

d_{ij} is the duration of the disease. (For permanent disabilities d_{ij} equals the remaining life expectancy L_j.), and

r represents the discount rate that captures time preferences. That is, the use of the discount rate implies that health gains today count more than health gains in the future.

In adapting this framework to the present exercise, we made a few modifications to the original model. The first is that we exclude the age-weighting term that assigns a higher weight to the disabilities of the young than for those who are older. This is because a form of age-weighting is implicit above, as permanent outcomes that affect young children add up to more DALYs lost than those that affect adults. Also, unlike the original exercise, where the estimated life expectancy is interpreted as the maximum possible in a biological sense, here, we use a country-specific figure. We justify this on the grounds that the amelioration of a given micronutrient deficiency alone is not expected to change the average life expectancy in a country.

Of greater importance, perhaps, is that the adaptation of this approach to the specific context of micronutrient malnutrition necessitated some additional modifications in terms of the level of disaggregation incorporated in determining the functional consequences of vitamin A, iron and zinc deficiencies. Nutritionists gave expert opinionon the detail of specific outcomes that may be attributed to each of these deficiencies. In doing so, the approach was conservative, for example, adverse functional outcomes are proven only for clinical manifestations[3] of vitamin A deficiency (VAD), and these are all that are incorporated. We considered moderate and severe, but not mild, anemia in calculating the burden of iron deficiency, moreover anemia has multiple causes, of which iron-deficiency is only one. Similarly, we included only those outcomes for which there is evidence from meta-analyses. Where only an association is noted, (as, for example in the case of vitamin A where studies suggest that its deficiency is associated with diarrhea, acute respiratory infection, stunting and maternal mortality) these are excluded from the analysis. The estimated used here may be construed as a lower bound in attributing disease and adverse functional outcomes to micronutrient deficiencies. Stein *et al.* (2005) give a more detailed description of this topic.

Burden of vitamin A deficiency

Vitamin A deficiency leads to vision impairment, including night blindness, corneal scarring, and in the most severe cases, blindness. In addition, it also causes increased mortality for children under the age of six, and in the incidence and poor recovery from measles. An estimated 3% of the mortality rate of young children is attributed to vitamin A deficiency. One-fifth of the incidence of corneal scarring and measles is due to VAD; and all of night blindness (both among children and pregnant and lactating women) is due to insufficient intakes of vitamin A. While Stein *et al.* (2005) provides additional details, these form the basis of the calculation of DALYs lost due to VAD (Table 1).

Table 1. Burden of vitamin A deficiency, by country.

Country	Total DALYs lost (millions)	YLL as percent of DALYs lost	DALYs as percent of population
Ethiopia	0.39	73	0.5
Kenya	0.12	71	0.4
Uganda	0.16	73	0.6
D.R. Congo	0.39	98	0.8
Nigeria	0.80	98	0.6
Northeast Brazil	0.05	90	0.1

Virtually all of the DALYs lost above—lost either due to mortality or morbidity—are accounted for by children under six, underscoring the disproportionate impact of the burden of vitamin A deficiency on young children.

The DALYs lost from VAD are high in Africa, corresponding to between 0.4 and 0.8 percent of the population in these countries. Thus, annually, 121 thousand DALYs are lost to VAD in Kenya each year, while in Nigeria, the figure is nearly 800 thousand DALYs lost. Put another way, between 0.5 and 1 percent of the national product is lost due to VAD each year in these countries.[4] In contrast, the magnitude of VAD is not as high in Latin America as it is in most regions of Africa. However, there are pockets with high levels of deprivation as is found in the northeastern regions of Brazil. In this part of Brazil, VAD leads to the loss of the equivalent of 0.1 percent of the national income each year. Note once again that these are conservative estimates of the loss due to VAD, largely because these take into account only clinical

[3] Clinical manifestations include corneal scarring, and problems with vision. Subclinical vitamin A deficiency is far more prevalent and insidious as it is not a disease in itself and is in some sense asymptomatic, but renders an individual more susceptible to infections.

[4] That is, had this proportion of the population been healthy, they would have been able to contribute to the national income, and the average gross national product provides an approximation of this loss to the economy.

manifestations of VAD, and only for those outcomes for which definitive causality has been shown in the literature.

The bulk—over 70%—of all DALYs lost are due to years of life lost due to premature mortality. This explains why, for instance, the burden of VAD is higher in Uganda than in Kenya, countries with approximately similar population sizes. The number of deaths of children under 6 (per 1000 live births) in Uganda (152) is higher than in Kenya (114), while life expectancies are approximately the same.

Burden of iron deficiency

Iron deficiency leads to impaired physical activity for all age groups and impaired mental development for children under the age of six. In addition, it is estimated that 5% of all maternal mortality is caused by iron deficiency. A mother's death, in turn, implies still-born children, and other child deaths due to the absence of breast-feeding and care that she would have provided had she lived (for complete references see Stein *et al.* 2005). To estimate the DALY burden, we use published data on the prevalence of anemia. However, since not all anemia is due to iron deficiency, we assume that approximately 50% of it is due to insufficient dietary intakes of iron (this percentage can vary by country). This percentage was determined based on expert opinion from nutritionists. These form the basis for the figures detailed in Table 2.

Table 2. Burden of iron deficiency, by country.

Country	Total DALYs lost (millions)	Percent share of YLDs of children under 5 to total DALYs	DALYs as percent of population
Bangladesh	0.49	66	0.4
India	4.00	66	0.4
Pakistan	0.52	53	0.3
Philippines	0.07	35	0.1
Northeast Brazil	0.20	66	0.4
Honduras	0.02	41	0.3
Nicaragua	0.03	53	0.5

In quantitative terms, the burden is, as expected, the highest in the populous countries of India, Bangladesh and Brazil. Normalized for population size, the burden of iron deficiency ranges between 0.1 percent of the total population in the Philippines to 0.5 percent in Nicaragua. Much of this burden arises from disability—especially among children aged five and under—with a share between 35 to 66 percent.

These figures also illustrate the advantage of using the DALY methodology over methods that, for example, are based on the number of deaths caused. The use of the DALY method, which can "add" mortality and disability outcomes, indicates for example that in northeast Brazil, the burden of iron deficiency is higher than that of vitamin A deficiency—whereas the use of the 'number of deaths caused' criterion would indicate VAD to be a far greater problem than iron deficiency.

Burden of zinc deficiency

There is evidence from meta-analyses to show that zinc deficiency is implicated in adverse functional outcomes associated with diarrhea, pneumonia and stunting among children. Further, some diarrhea and pneumonia cases can also be fatal. Thus nearly one-fifth of diarrhea incidence, nearly two-fifths of pneumonia and 4% of mortality of children under 5 can be attributed to zinc deficiency. The evidence in Table 3 suggests that 0.1% of the population in the Philippines, and 0.3 to 0.4 % of the population in South Asia suffer the consequences of zinc deficiency on an annual basis. The bulk of the burden is contributed by infants under the age of one; further, it is the mortality component of the DALYs lost that drives these results.

Table 3. Burden of zinc deficiency, by country.

Country	Total DALYs lost (millions)	Percent share of DALYs of children under 1 in total DALYs	DALYs as percent of population
Bangladesh	0.44	71	0.4
India	2.83	70	0.3
Pakistan	0.64	77	0.4
Philippines	0.08	71	0.1
Northeast Brazil	0.10	66	0.2
Honduras	0.01	70	0.2
Nicaragua	0.01	74	0.2

Thus the burden of micronutrient deficiencies, both in terms of the numbers of people affected, and its economic cost (even when valued at national GDPs), is extremely high.[5] The next section examines whether biofortification can lead to a substantial reduction in the burden of micronutrient malnutrition.

Analyzing the reduction in burden of micronutrient deficiencies

The extent to which a food-based intervention such as biofortification can help ameliorate micronutrient deficiencies depends on a number of factors; several steps are involved in achieving impact on health. First, once plant breeders have developed biofortified varieties, these have to be adopted by farmers. Conditional on adoption, once biofortified crops are produced, these have to be consumed by target groups in a form that minimizes processing losses of nutrients. Finally, enhanced micronutrient intakes have to translated into improved health outcomes and result in a reduced DALY burden.

As with any new technology or public health intervention, at each of these steps, outcomes are uncertain. One way to account for these uncertainties is to specify probability distributions and compute the expected value of benefits. However, for many of the outcomes discussed here, such probabilities are difficult to assign. Instead, we used a scenario analysis where a range of plausible outcomes may be specified at each step, and benefits computed under the collective best and worst case scenarios. These assumptions are elaborated below.

Likely coverage rates, by region

The coverage rate, or the share of biofortified staples in production and consumption, is a key determinant of the magnitude of impact. The more farmers produce, and thereby the more that target households consume biofortified staples, the greater the reduction in the prevalence of insufficient intakes. The biofortification strategy is to have micronutrient-dense trait in a mainstream staple foodstuff so that there will be a multiplicity of biofortified varieties available for each crop.

[5] A direct comparison with WHO estimates of the DALY burden of micronutrient deficiencies is not feasible because of differences in methodology; however, the order of magnitude of their estimates is similar to those presented here (WHO 2006).

In this paper, we make assumptions on likely coverage, from both producer and consumer perspective, based on experience with the spread and diffusion of other modern varieties in these countries.[6] For crops where the micronutrient trait is visible, such as with provitamin A, consumer acceptance also needs to be factored in. For this reason, we assume lower coverage rates for maize, sweetpotato and cassava than for high mineral rice and wheat. Experience suggests that farmer adoption with cereals in Asia, which has well-developed seed systems in place, coverage rates are likely to be high. As a conservative estimate, we assume a 30% coverage under a pessimistic scenario, and a 60% coverage in the optimistic scenario. In Africa, which does not have such well-developed seed systems, we use much lower coverage rates, with a pessimistic assumption of 20% and an optimistic assumption of 40% for all crops. In Latin America, coverage rates are assumed to range between 25 and 30%; in northeast Brazil, however, where coverage of new varieties of cassava has always been low, we assume 10-25% coverage for this crop (see Evenson and Gollin 2003 for summary of adoption data for maize, cassava and beans). Farmers in this region typically cultivate traditional varieties and do not receive much government support for agriculture (Gonzalez *et al.* 2005).

Consumption of staples by target populations, and processing losses

Clearly, the higher the level of consumption of a given staple food (including how many people consume the staple and how frequently), the greater the impact of a given increment in micronutrient intake will be. Thus, with a 400 gram daily intake of a given food, a 10 ppm increase in micronutrient content will translate into a 4 mg increase in micronutrient intake, whereas a 200 gram intake will translate only into half this amount.

Obtaining data on food consumption and micronutrient intakes is difficult. For example, information on food intakes by crop for each age and gender-specific target group is scanty. Ideally, such consumption estimates should be based on individual-level dietary recall data, but unfortunately such data sets are rarely, if ever, nationally-representative. Where food composition tables and unit record data are available from dietary recall surveys, these have been used to derive micronutrient intakes. Where nationally-representative data sets are available, these tend to report food consumption at the household level, and not the individual level. When such data were available, as for example with Bangladesh and India, we used consumer equivalent units to derive food consumption at the individual level. In Latin America, we used regression techniques to identify consumer equivalence. For many countries in Africa, food consumption surveys are dated, and are based on smaller sample sizes. Therefore in these cases, we have used the most recent information available, and validated these figures through qualitative surveys. Additional details are contained in the individual reports listed in the references.

Table 4 details the consumption figures used in each case (for ease of presentation the table reports data for only one target group: children under 6 years of age, but the calculations include all other relevant target groups). These range from approximately 100 grams of sweetpotato in Uganda, to about 225 grams of cassava (fresh roots) in the DR of Congo. For maize in East Africa, consumption levels are lower—they range from 70 grams in Ethiopia to 120 grams in Kenya.

[6] For simplicity, we do not take into account any trade effects, or of the possibility of biofortified food aid

Table 4. Average staple crop intakes by children under 6, and assumptions on processing losses, by nutrient and country.

Nutrient/*Crop*/Country	Consumption among children <6 years (grams/day)	Processing losses Pessimistic (%)	Processing losses Optimistic (%)
Provitamin A			
Cassava (fresh weight)			
DR of Congo	225	90	70
Nigeria	176	90	70
Northeast Brazil	122	64	54
Maize			
Ethiopia	71	90	50
Kenya	120	50	40
Sweetpotato			
Uganda	96	25	18
Iron and Zinc			
Beans			
Honduras	56	5	0
Nicaragua	45	5	0
Northeast Brazil	57	5	0
Rice			
Bangladesh	140	0	0
India	118	0	0
Philippines	121	0	0
Wheat			
India	87	20	10
Pakistan	94	20	10

For beans, consumption levels are much lower, approximately 45-55 grams per day for children under six in Latin America. Consumption levels of rice among children, the staple food in much of Asia, are higher, and are between 120 and 140 grams per day. The corresponding consumption levels for adults are about 2-3 times as much. Finally, wheat consumption among young children is about 90 grams per day.

Related to the level of consumption are processing losses between the harvest and the plate. This is particularly important in the case of provitamin A. For example, sweetpotato and cassava are commonly sundried, which can result in the complete degradation of provitamin A. Other processes such as fermentation (to make *gari* in Nigeria or *injera* in Ethiopia, for example) can also reduce provitamin A content. Table 5 outlines the key parameters used for processing losses.

Table 5. Micronutrient content of biofortified crops under pessimistic and optimistic scenarios (parts per million).

Crop/Scenario	Vitamin A	Iron	Zinc
*Cassava**			
Pessimistic	10		
Optimistic	20		
*Maize**			
Pessimistic	10		
Optimistic	20		
*Sweetpotato**	32		
Beans			
Baseline		40	30
Pessimistic		80	40
Optimistic		100	50
Rice			
Baseline		3	13
Pessimistic		6	24
Optimistic		8	35
Wheat			
Baseline		38	31
Pessimistic		46	37
Optimistic		61	55

* Note: These crops currently have no betacarotene, the baseline is thus zero.

Source: HarvestPlus crop leaders and plant breeding coordinator.

On the basis of qualitative surveys, it appears that processing losses are greatest in cassava in Africa, where between 70 and 90% of provitamin A may be lost in cooking (Manyong *et al.* 2005). In northeast Brazil, processing cassava into farinha (flour) gives losses between 54 and 64%. Maize-based foods are prepared by different methods so that processing losses differ on a country by country basis. In Ethiopia cooking maize to make *injera* (pancake-like bread) may lose as much as 90%, while in Kenya making *ugali* (a porridge) loses less, about 50%. Sweetpotato is usually boiled in cooking so that post-harvest losses of beta-carotene are relatively low, 18-25%. Note that there are no processing losses for rice, which is consumed in boiled form. Micronutrient content is expressed in milled form, thus milling losses are not relevant.

Expected increases in micronutrient content

Relatively low levels of consumption or high processing losses may be offset by a high micronutrient concentration in the biofortified crops. Since biofortification is still in the research phase for most crops, target micronutrient concentrations are based on the best-estimates from plant breeders, based on data from germplasm screening. These are typically (but not always) higher than the minimum incremental breeding targets that have been determined by nutritionists as being necessary for demonstrating health (biochemical) impact.

Current levels of beta-carotene in the widely-consumed varieties of bean, maize and sweetpotato ar currently nil. For cassava and maize, breeders hope that under a pessimistic scenario, it will be possible to breed varieties containing 10 ppm; and under an optimistic scenario this could be as high as 20 ppm (Table 5). The case of sweetpotato is different. Breeders have already identified varieties that are high in beta-carotene content, and these are being disseminated in east and southern Africa on a pilot basis. The average beta-carotene content of these orange-fleshed sweetpotato varieties is approximately 32 ppm. Thus unlike the case with cassava and maize, where varieties high in beta-carotene have yet to be developed, there is more certainty about the technical parameters that underlie the DALY analysis for sweetpotato.

The expected increase in iron concentration ranges between 3 and 5 ppm for milled rice, 8 and 23 ppm for wheat and 40 and 60 ppm for beans. The increase in zinc concentrations is likely to range between 11 and 22 ppm for rice, 6 and 24 ppm for wheat and 10 and 20 ppm for beans. It is important to note that these increases are all expected to be achieved using conventional breeding techniques; none of the scenarios pertain to what might be achieved using transgenic methods. For example, conventional breeding methods cannot enhance the provitamin A of rice because there is no known naturally-occurring genetic variation for this trait that breeders could exploit. We did not consider the transgenic provitamin-A-dense "golden" rice in this study.

Dose response

The impact of any food-based intervention depends on the dose-response to increased nutrient intakes. Ideally, this entails determining a biologically-based relationship between enhanced micronutrient intakes and nutritional outcomes. Many such relationships are based on step functions, where the response is measured to a nutritional supplement, which usually translates into intakes above the recommended dietary allowance (RDA). Theoretically, however, the relationship is a continuous one. Here we use an inverse hyperbolic function to capture this continuum, as proposed originally by Zimmerman and Qaim (2004) (Figure 1) and elaborated by Stein *et al.* (2005).

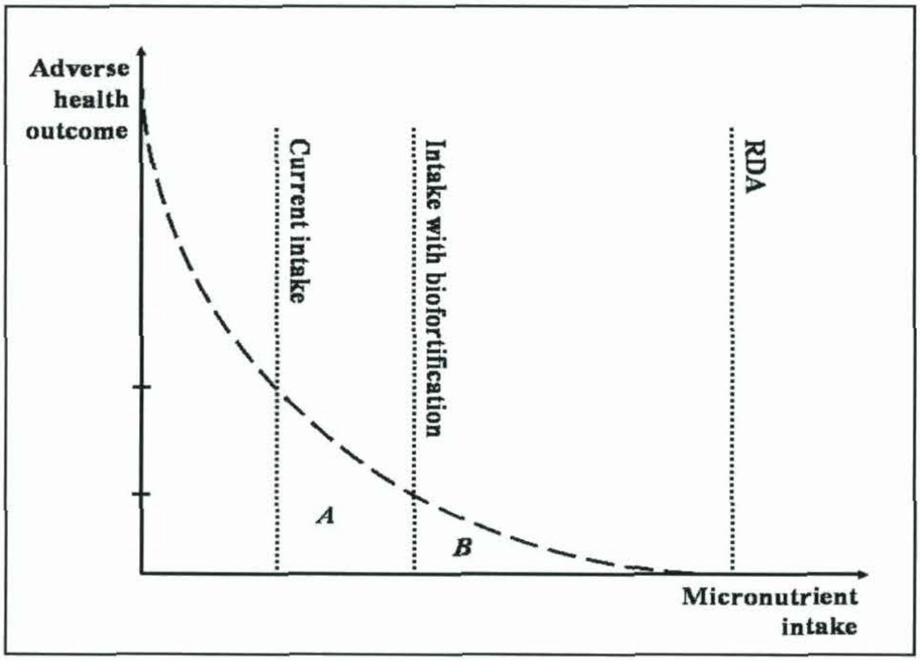

Figure 1. Modeling the impact of increased intakes on health outcomes. Source: Zimmerman and Qaim (2004).

An increase in intakes from biofortification results in a reduction in the burden of deficiency of a magnitude given by the ratio of the areas A and A+B. A hyperbola that intersects the horizontal axis at the RDA fixes this functional form as *1/x – 1/RDA.*[7]

Note that the use of this function implies that the greater the distance between current intakes and the RDA, the greater the impact of a given increment in dietary intakes. This is in line with well-established principles in nutrition, which suggest that individuals with poor initial nutritional status have a higher biological response to an intervention than those with better initial nutritional status.

The bioavailability and absorption of the additional micronutrients that are available through the consumption of biofortified staples is also important. For the purposes of this paper, we assume that the diets of target populations are characterized by low bioavailability of the relevant micronutrient, and that this situation will prevail, as diets continue to be based on cereal/root crops. Thus, in computing the deficit in intakes we use the RDAs corresponding to low bioavailability for iron and zinc. Also, to ensure general comparability for all cases we consider in this paper, we use the same RDA for all countries.[8]

These ranges in assumptions and parameters are used to derive the impact of biofortification in reducing the DALY burden of vitamin A, iron and zinc deficiencies under both pessimistic and optimistic scenarios. A summary of data sources used in making these computations is listed in Appendix Table 1.

Impact on VAD

The percentage reduction in the burden of VAD ranges between 3 and 30% in the case of cassava, and between 1 and 32% in the case of maize (Table 6). In the case of sweetpotato, between two-fifths and two-thirds of the burden of VAD may be eliminated through the successful dissemination of orange-fleshed varieties. The reason for the much greater impact of orange-fleshed varieties of sweetpotato is not difficult to discern. A child consuming 100 grams of OFSP with 32 ppm beta-carotene would obtain nearly half the recommended dietary intake of 440 RE (assuming 18% losses, and bio-conversion factor of 1:12) from this one food alone. In contrast, a child consuming a much higher 200 grams of cassava with 10 ppm beta-carotene, with 90% losses from processing, would obtain less than 4% of the recommended dietary intake of vitamin A. Similarly, a child consuming 120 grams of maize with 10 ppm beta-carotene, with 50% retention of the nutrient, would obtain slightly more than 10% of the RDA.

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[7] Ideally the point of intersection with the horizontal axis should be a value greater than the RDA, as the RDA represents the level at which the requirements of most—but not all—individuals in the population are met. However, since the requirements of 97.5% of healthy individuals would be met at the RDA, and because a higher number can be determined only somewhat arbitrarily, we use the RDA. Note further that the use of the estimated average requirement is not appropriate here, as the focus is *not* on determining prevalence rates of inadequate micronutrient intakes.

[8] For example, for countries such as the Philippines, where diets contain more meat products than the other countries considered in this study, a higher bioavailability figure may be more appropriate; indeed, the RDA figures commonly used in the Philippines are lower than those used here.

Table 6. Reduction (percent) in DALY burden of micronutrient deficiency through biofortification under pessimistic and optimistic scenarios, by nutrient crop and country.

Nutrient/Crop/Country	Pessimistic	Optimistic
Vitamin A		
Cassava		
DR Congo	3	32
Nigeria	3	28
Northeast Brazil	4	19
Maize		
Ethiopia	1	17
Kenya	8	32
Sweetpotato		
Uganda	28	64
Iron		
Beans		
Honduras	4	22
Nicaragua	3	16
Northeast Brazil	9	36
Rice		
Bangladesh	8	21
India	5	15
Philippines	4	11
Wheat		
India	7	39
Pakistan	6	28 [1]
Zinc		
Beans		
Honduras	3	15
Nicaragua	2	11
Northeast Brazil	5	20
Rice		
Bangladesh	15	46
India	20	56
Philippines	11	39
Wheat		
India	9	48
Pakistan	5	33

[1] In Pakistan, average iron intakes for young children are believed to be sufficient; hence the DALY calculations refer to the impact only of improved intakes among older children and adults.

The percentage reduction in DALYs lost is lower in Ethiopia than in neighboring Kenya because of much higher processing losses of beta-carotene (particularly under the pessimistic scenario) and the lower consumption levels of maize in Ethiopia. Indeed, under the pessimistic scenario, there would only be a 1% reduction in the burden of VAD in Ethiopia. In northeast Brazil, up to one-fifth of the burden of VAD is eliminated by biofortified cassava in the optimistic scenario.

Impact on iron deficiency

Even though consumption levels of beans is low (50-60 grams/day), the influence of the incremental iron content is high, higher than for the other crops. The expected decrease in the burden of iron deficiency ranges from 3-22 percent in Central America and between 9-33 percent in northeast Brazil.

For rice, the reduction in the DALY burden of iron deficiency is 4-8 percent in the pessimistic scenario and 11-21 percent in the optimistic scenario. Even though the expected increments are more modest (certainly as compared to beans), consumption is twice or more that of beans. Furthermore, anemia is more prevalent in South Asia is higher than in Central America.[9]

Impact on zinc deficiency

The reduction in the DALY burden of zinc deficiency from biofortified beans is 3-20 percent in Latin America. Biofortification of rice in Banglasesh reduces the burden 15-46% of wheat in Pakistan by 5-33%. This is not surprising, given that the incremental zinc density as well consumption is much higher for wheat and rice than for beans.

Cost-effectiveness of biofortification

The figures discussed above suggest that biofortification can lead to reductions in the burdens of micronutrient deficiencies, even though the reductions are modest in some cases of the pessimistic scenario. The next question is what are the costs of achieving these reductions,and how do they compare with the cost of other interventions. As noted earlier, costs per DALY saved provide a consistent way of ranking alternative interventions.

The costs of biofortifcation involve research and development, adaptive breeding and dissemination and maintenance. Investment in basic research and development is incurred in the initial years of any planned intervention. Once promising parent lines are identified, there is a phase of adaptive breeding, where these traits are bred into popular varieties that are cultivated in target countries, a process that can take up to five years. Once dissemination takes place, some costs are incurred to maintain the trait over time. Thus, the bulk of the investment is upfront. The key components of the costs estimated in this exercise are summarized in Table 7.

[9] Note that the figures for India cited in another paper (Stein *et al.*, forthcoming) are somewhat different; this is because a different methodology, one that utilizes unit record data to compute a distribution of intakes, has been used in computing the reduction in DALY burden.

Table 7. Key costs, by category, nutrient and country (US $ per year).

Nutrient/*Crop*/Country	R&D costs (years 1-4)	R&D costs (years 5-10)	Adaptive breeding costs	Dissemination and maintenance costs (high assumption)
Provitamin A				
Cassava				
DR Congo	120,000	36,000	400,000	200,000
Nigeria	240,000	72,000	600,000	185,000
Northeast Brazil	677,000	206,000	500,000	100,000
Maize				
Ethiopia	145,000	57,000	300,000	100,000
Kenya	145,000	57,000	300,000	60,000
Sweetpotato				
Uganda	778,000	243,000	368,000	147,000
Iron and zinc				
Beans				
Honduras	35,000	14,000	70,000	20,000
Nicaragua	70,000	28,000	70,000	20,000
Northeast Brazil	448,000	181,000	700,000	200,000
Rice				
Bangladesh	320,000	110,000	100,000	100,000
India	1,600,000	552,000	800,000	200,000
Philippines	320,000	110,000	50,000	200,000
Wheat				
India	1,400,000	600,000	800,000	200,000
Pakistan	600,000	300,000	600,000	200,000

Source: HavestPlus budgets and country-specific expert opinion.

The research and development costs used for this exercise are derived from HarvestPlus budgets, apportioned to countries taking into account both plant breeders' estimates of geographical allocations as well as production shares. For example, breeding efforts for cassava are focused on countries both in Africa and Latin America, with equal emphasis on both; thus half the research and development costs are allocated to each region. Within a region, approximate production shares are used to allocate costs, so that northeast Brazil accounts for two-thirds the costs for Latin America.

With regard to iron and zinc in Asia, we attribute all of the research and development costs to India but add to this 20% for Bangladesh and 20% for the Philippines. While this accounts for 140% of total costs in these three countries, the error is on the side of overstated costs. Further, we do not attempt to disaggregate research development costs for iron and zinc and use the entire crop budget in each case. Again, while this may be double-counting, there is no natural way to separate these cost, apart from assuming a 50% share to each mineral, as screening and breeding for both nutrients occur simultaneously.

We estimated costs of adaptive breeding for each country using the opinions of experts within each so that they are country-specific. The estimates show that adaptive breeding can cost up $400,000 to $600,000 per year for about 5 years for cassava and $800,000 and $100,000 per year for rice in India and Bangladesh respectively. Similarly, we used expert opinion and current budget levels in each country to estimate country-specific costs of dissemination and maintenance breeding. For the last category of costs we use pessimistic and optimistic scenarios to capture possible differences in the ease of dissemination of biofortified foods.

In all cases we estimatedd *incremental* costs of incorporating nutrient-dense traits into plant varieties that are currently under development. Moreover, the estimates are for using conventional breeding techniques, so that regulatory costs associated with transgenic crops do not apply here. Costs and benefits are discounted at 3%, a figure commonly used in the health economics literature. All calculations assume a 30-year time horizon, with dissemination starting in year 10, and ceiling adoption levels (be they under the pessimistic or optimistic scenarios) achieved in year 20.

The resulting cost per DALY saved estimates are presented in Table 8. The World Development Report for 1993 (World Bank 1993), which reviews many public health interventions, suggests that those costing less than US $150 ($196 in 2004 dollars) per DALY saved are highly cost-effective.[10]

[10] To cite the report: "Governments need to ... move forward with ... promising public health initiatives. Several activities stand out because they are highly cost-effective: the cost of gaining one DALY can be remarkably low—sometimes less than $25 and often between $50 and $150" (World Bank 1993, p. 8).

Table 8. Cost per DALY saved with biofortificaiton under pessimistic and optimistic scenarios, by nutrient, crop and country

Nutrient/*Crop*/Country	Cost per DALY saved (US$)	
	Optimistic	Pessimistic
Vitamin A		
Cassava		
DR Congo	3.70	45.80
Nigeria	3.00	35.40
NE Brazil	84.00	433.60
Maize		
Ethiopia	5.00	98.00
Kenya	9.50	44.10
Sweetpotato		
Uganda	4.20	9.70
Iron		
Beans		
Honduras	19.80	113.60
Nicaragua	23.30	139.00
Northeast Brazil	12.50	56.30
Rice		
Bangladesh	3.40	10.50
India	2.90	9.60
Philippines	49.60	197.30
Wheat		
India	1.10	6.60
Pakistan	6.50	33.30
Zinc		
Beans		
Honduras	48.50	422.80
Nicaragua	208.40	1880.30
Northeast Brazil	95.10	799.00
Rice		
Bangladesh	1.70	6.10
India	1.10	3.30
Philippines	7.00	46.30
Wheat		
India	1.20	7.10
Pakistan	4.50	33.90

Provitamin A-dense cassava, maize and sweetpotato

In the optimistic scenario, the costs per DALY saved for provitamin A-dense staples are all less than $10 per DALY saved for all crops and countries with the exception of northeast Brazil. In the pessimistic scenario, costs per DALY saved are still less than $10 for sweetpotato. For cassava, they are between $35 and $46 per DALY saved in Africa, and greater than $400 in northeast Brazil. With maize, biofortification costs $44 per DALY saved in Kenya and $98 in Ethiopia (recall that this latter figure assumes only a 10% retention of betacarotene). Nevertheless, even in the pessimistic scenario, all but the northeast Brazil figures correspond to a highly cost-effective intervention.

An important question is how the costs per DALY saved with biofortification compare with those associated with other vitamin A interventions, by fortification and supplementation. The literature in this area is limited; we use the figures cited in the influential 1994 World Bank report, which were in turn drawn from Levin *et al.* (1993). They report that supplementation costs approximately US $ 9.3 per DALY saved (in 1994 dollars, corresponding to about $12 in 2004 terms) and fortification costs are about $29 per DALY saved, equal to almost $37 dollars in 2004 terms.

These figures are not directly comparable with costs per DALY saved computed here for biofortification, primarily on account of the differences in the assumed rate of coverage. The calculations for supplementation and fortification assume a 75% coverage rate, whereas with biofortification, coverage rates even under an optimistic scenario are assumed to be more conservative (50% in Africa). Despite these differences, costs of biofortification are much lower than those of fortification and supplementation in the optimistic case, the only exception is the northeast Brazil. Even in the pessimistic scenario, biofortification is relatively more cost-effective than the other two vitamin A interventions in the case of sweetpotato.

We also ran a separate exercise, retaining all the other 'pessimistic' assumptions on increase in micronutrient content and processing losses, but enhancing coverage rates to 75%. With these higher coverage rates, biofortification costs are lower than those of fortification in all cases except in northeast Brazil, and comparable or lower than those of supplementation in the DR Congo, Nigeria and Kenya. However, we do not report these results in Table 8, as we believe that the 75% coverage assumption is unrealistically high (even for the alternative interventions).

Iron-dense beans, rice and wheat

With iron, as well, costs per DALY saved fall under the "highly" cost-effective category in the optimistic scenario. For rice in South Asia, they are particularly low at approximately $3 per DALY saved, and are somewhat higher in the Philippines at about $50 per DALY saved. Even in the pessimistic scenario, the costs for rice are about $10 per DALY saved in South Asia. Costs of iron biofortification are similarly extremely low for wheat in South Asia, as little as $1 per DALY saved. With high-iron beans in Latin America, costs are between $12 and $23 per DALY gained in the optimistic scenario, and go up to $139 per DALY saved in the pessimistic scenario.

Compared with iron supplementation, which is reported to cost about $17 per DALY saved, biofortification enjoys an advantage in the optimistic scenario in all regions and with all crops. Even in the pessimistic scenario, biofortification costs are lower in South Asia with wheat and rice, and are comparable in Latin America. As above, the fortification calculations assume a 75% coverage. To examine the impact of coverage rates, we re-computed the costs in the pessimistic scenario, assuming a higher 75% coverage, but retaining the pessimistic increment in iron content for the three crops. The results of this exercise suggest that the costs of biofortification would be comparable or lower than those of other forms of supplementation in all regions and with all crops.

Similarly, costs of iron fortification have been estimated at about $6 per DALY saved[11] Biofortification enjoys a relative advantage even here in South Asia certainly in the optimistic scenario, and even in the pessimistic scenario if the higher 75% coverage rates are assumed. Only with high-iron beans in Latin America does fortification appear more attractive than biofortification. Once again, we do not report these numbers in Table 8, as the 75% coverage rates appear somewhat unrealistic.

In making these comparisons it is important to note other differences in methodology as well. For example, Levin *et al.* (1993) use a $0.50 per capita cost for supplementation, and $0.20 per capita cost for

[11] These figures are in 2004 dollars, and are converted from the $12.80 per DALY saved for supplementation and $4.40 per DALY saved for fortification reported by Levin *et al.* (1993).

fortification to derive the costs per DALY gained. At least in the context of provitamin A, these costs have been questioned by some as being too low (Fiedler *et al.* 2000).

Zinc-dense beans, rice and wheat

Once again, in South Asia, biofortification is extremely cost-effective, with cost per DALY saved lower than $10 even in the pessimistic scenario for both wheat and rice. Costs per DALY saved with beans in Latin America are higher, but still cost-effective in the optimistic scenario. It is only in the pessimistic scenario that costs per DALY saved exceed $196 by a wide margin.

A comparison of the zinc biofortification numbers with that of other zinc-based interventions is difficult as these are primarily used therapeutically (as for example administration of zinc supplements). [12]

Discussion and Conclusions

This paper presents, for the first time, evidence from a large number of countries and crops that biofortification can have important impacts on the burden of micronutrient malnutrition. Moreover, it does so in a cost-effective manner, with most costs per DALY saved falling in the "highly" cost-effective category. Also, in all cases but one, benefit-cost ratios of biofortification exceed one, that is, benefits far outweigh costs. These results are encouraging for biofortification, especially since the underlying cost assumptions are often estimated on the high side, as for example, with the 'double counting' of costs for increasing the concentration of two minerals in the same crop.

Depending on the context and the scenario, and subject to the caveats noted in the text above, biofortification also appears to be more cost-effective than supplementation or fortification. In South Asia, biofortification enjoys a clear advantage, given that the high proportion of the rural populations in these countries, and the relatively well-functioning seed systems there. Similarly, in Africa, biofortification enjoys an advantage over supplementation in many cases, both in the optimistic scenario, as well in the pessimistic scenario when higher coverage rates are assumed. Relative to other interventions, the only instances where biofortification may not enjoy an advantage are in Latin America, with cassava in northeast Brazil, or with zinc in Latin America especially in the pessimistic scenario.

In interpreting these results, it is important to bear in mind that these figures are based on national averages, because this is the way the data of prevalence of deficiencies are reported. However, we caution that data of national averages can mask considerable variation within any one country, especially where consumption data are concerned. Because of this the impact of biofortification in areas of high staple consumption and micronutrient deficiency can be greater than implied by considering national data.

The analysis here considers the impact of the consumption of a single biofortified staple. In actuality, diets often consist of more than one staple (cassava and beans, rice and wheat, or maize and beans, for example). In these situations, the consumption of more than one biofortified staple is likely to have an enhanced impact (for example, if vitamin A improves iron absorption). Capturing the impact of an intervention with multiple micronutrients by taking into account their interactions is an area for further research.

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[12] As an additional exercise, we also compute benefit-cost ratios, as these are commonly reported. Ratios that exceed unity are indicative of a worthwhile investment. These require benefits to be monetized; that is, a dollar value needs to be assigned to the DALYs saved. Needless to say this valuation is problematic: if GDP per capita is used to value benefits, this tends to favor high-income countries. We use a somewhat-arbitrary US$1000 per DALY saved for all countries. The results in Appendix A suggest that benefit cost ratios are all high, and well exceed unity in all cases. The only exception is the case with zinc in Nicaragua in the pessimistic scenario, where the value of the benefits appears too low to justify costs. The use of an alternative figure, say of US $500 per DALY saved, does not alter the substance of the results: biofortification continues to be cost-effective, except that with this lower valuation of benefits, biofortification of beans with zinc in Latin America is also no longer feasible.

The challenges to implementing biofortification should not be underestimated. Attention will need to be paid to community awareness, dissemination, and behavior change interventions, many of which are commonly used in health and nutrition programs but are foreign to agriculture. This will be especially true when the micronutrient trait is visible, for example, in the case of the color change due to increased provitamin A content. The results of this analysis suggest that the pay offs from linking both agriculture and public health approaches, which often function independently, can be very high. In sum, the analysis above suggests that biofortification is a viable strategy, and an important complement to the existing set of interventions to combat micronutrient malnutrition.

Appendix

Table 1. Benefit-cost ratios of biofortification under pessimistic and optimistic scenarios, by nutrient and country.

Nutrient/*Crop*/Country	Benefit-cost ratios	
	Optimistic	Pessimistic
Vitamin A		
Cassava		
DR Congo	271	22
Nigeria	331	28
NE Brazil	12	2
Maize		
Ethiopia	198	10
Kenya	105	23
Sweetpotato		
Uganda	239	103
Iron		
Beans		
Honduras	39	9
Nicaragua	43	7
Northeast Brazil	63	18
Rice		
Bangladesh	296	95
India	347	104
Philippines	20	5
Wheat		
India	931	153
Pakistan	153	30
Zinc		
Beans		
Honduras	16	2
Nicaragua	4	<1
Northeast Brazil	8	1
Rice		
Bangladesh	590	163
India	894	308
Philippines	144	22
Wheat		
India	807	141
Pakistan	222	29

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Spatial trade-off analyses for site-sensitive development interventions in upland systems of Southeast Asia[1]

Annual Progress Report: CIAT Laos February 2007

General Information

Project Title	Spatial trade-off analyses for site-sensitive development interventions in upland systems of Southeast Asia
Start Date	December 2004
End Date	December 2007
Budget	€117,000 (US$141,000) for 2006
CGIAR Centre	CIAT (Centro Internacional de Agricultura Tropical)
Project Leader	Douglas White
Partner: BOKU	Department of Sustainable Agricultural Systems Department of Economics and Social Sciences Department of Landscape, Spatial and Infrastructure Sciences Research for Development Forum
Project Leader	Michael Hauser
Other Partners	• National University of Laos (NUoL) • National Agriculture and Forestry Research Institute (NAFRI) • Oudomxay Community Initiative Support Project (OCISP) • International Fund for Agricultural Development (IFAD) • CIAT-Asia Regional Office

Narrative Summary

Background

The project has completed its second year with significant advances with respect to the three research-for-development (R4D) themes of: (1) spatial analysis of changing natural resource endowments, (2) participatory market chain analysis, and (3) collaborative livelihood analysis and opportunity identification support. Links to other projects and development organizations, both government and non-government, continue to deepen and broaden.

Project goals

To contribute to equitable and sustainable improvement of livelihoods of rural communities in northern Laos with site-specific identification and implementation of intervention strategies, and ultimately in similar upland systems elsewhere that rely on shifting cultivation.

[1] This article is essentially the report submitted to the donor, the Austrian Government but without the budget details.

Development objectives

- To identify, design, share, adapt, and implement intervention strategies with local communities and rural development partners that are sensitive to site and market conditions in order to optimize social, economic and ecologic benefits.

Scientific objectives

- To develop and apply a robust and cost-effective method that identifies and quantifies agronomic production risks that arise from the spatially-variable suitability of land resources to intensification and diversification.
- To analyze product supply chains for their ability to provide equitable distribution of economic benefits.
- To develop and implement effective methods to co-identify livelihood strategies with households and communities.

Previous achievements (2005)

- Collaborative research plan refined with a major IFAD development project in the province: the Oudomxay Community Initiative Support Project (OCISP), an eight-year integrated rural development project.[2]
- Spatial analyses of income generation by NTFP products commenced to discern patterns and their causes. Data provided by IFAD.
- Links formalized with the East-West Center and National University of Laos (NUoL) project: *Understanding Dynamic Resource Management Systems and Land Cover Transitions in Montane Southeast Asia.*[3] A small financial grant from USAID (US$ $16,000) enabled a comparison with a similar R4D effort in the neighboring Luang Namtha province.
- Research activities conducted with the *Smallscale Agro-enterprise Development for the Uplands of Vietnam and Laos Project - SADU* (funded by the Swiss Agency for Development Cooperation - SDC).

Achievements (2006)

- Collaborative Livelihood Analysis and Opportunity-identification Support (C-Laos) approach developed, refined and implemented with 4 communities, 12 OCSIP extension staff, and 3 scientists from the National Agriculture and Forestry Research Institute (NAFRI).
- Market supply chain of paper mulberry, an important non-timber forest product (NTFP), co-analyzed with 42 diverse participants (farmers, traders, government staff, manufacturers, exporters, and development organization staff).
- Village and local trader action plans developed.
- Implementation of action plans started.
- Identification of the pattern and magnitude of spatial and temporal land cover changes in Oudomxay province using spatial analysis from time series of Landsat 7 ETM+ images and ground reference data from field work. Predominant land cover classes include permanent agriculture, fallow and forest.

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[2] The OCISP project is financed from three different sources: an IFAD loan project of 10.8 million SDR (~US$15m), a grant of €1.7 million from the Luxembourg government, US$1.7 million grant from the World Food Program. The Austria-funded project contributes to the 5th component of OCISP effort by improve farming systems and natural resources management for increased farm production and income.

[3] http://www.eastwestcenter.org/res-pr-detail.asp?resproj_ID=196

- Research support from 4 BOKU students (1 PhD, 3 MSc).
  - Maria Miguel Ribeiro: *Supply chains of non-timber forest products and Learning alliances in Oudomxay, Northern Laos*
  - Kendra Leek: *Natural resources and rural livelihood strategies in Oudomxay*
  - Antonia Fay Forster: *Classifying fallow period lengths using Normalized Difference Vegetation Index (NDVI)*
  - Kathrin Leitner: *Women's views on paper mulberry in Lao PDR: Local knowledge, perceived potentials*
- Poster presentation at an IDRC (Canada)-NUoL workshop in Vientiane, Laos: Community-based Natural Resource Management Research and Capacity Building.

Planned activities (2007)

The third year of the project will conclude field research activities at mid-year. Emphasis will shift to consolidate, interpret, and synthesize results. Concerted efforts are planned to discuss, share and publish results with other CIAT project efforts and similar R4D projects in Laos. Details of planned activities are in the section on Project implementation below.

Management issues

No personnel issues affected the project and financial resources are ample. A portion of unspent funds is being used to cover researcher salaries given that core fund availability has markedly decreased since project inception. Research site is in Oudomxay and CIAT-Asia office (in Vientiane) provides management support.

Research process

Main results and milestones are outlined below in project implementation.

Project advances in Laos have influenced curricula at BOKU (Department of Sustainable Agricultural Systems) and fostered discussion with another CIAT-BOKU project in Africa. The follow aspects of the project addresses the ADA goals:

1) *Sustainable increase in agricultural productivity*:
   - NTFPs for household food and economic security
   - Livelihoods analysis of resources and opportunities
2) *Conservation and efficient use of natural resources and biodiversity*:
   - Sustainable management strategies for NTFPs
   - Spatial analysis of the productive capacities of natural resources
3) *Development of sustainable production and marketing systems*:
   - NTFPs production potential and alternative options
   - Market chain analysis for equitable distribution of benefits
   - Learning alliances for market identification and innovation
4) *Strengthening institutions and improving policy development*:
   - Learning alliances for institutional analysis, public-private partnerships and empowerment.
   - Collaboration with IFAD project and government ministries for project short and long term impacts.

Capacity-building and training achievements:

- With the Learning alliance workshops, interaction and communication between stakeholders of the supply chain of paper mulberry bark resulted in:
  - Diffusion of tacit knowledge along market chain
  - Development of an action plan made by participants
  - Experimentation with new knowledge on production, post-harvest and market requirements.
- Farmer and government extension training in:
  - Paper mulberry bark harvest and post-harvest techniques.
    - 42 participants: farmers, traders, government staff, manufacturers, exporters, and development organization staff
  - Livelihood analysis and opportunity identification.
    - 12 OCSIP extension staff
    - 3 NAFRI scientists

Problems encountered and lessons learned related to capacity building:

- Although farmers are interested in producing other crops, farmers prioritize the staple crop rice. Consequently, participation in the training on paper mulberry bark production and post-harvest techniques was lower than expected. *Lesson:* For many rural Lao, identifying livelihood options is new. Diversifying from rice cultivation, a centuries-old tradition, requires process of review and analysis with farmers.
- Lack of leadership in one of the villages has led to lower farmer participation in training and other type of events. *Lesson:* Leaders, or champions, play an important role in fostering village interest and participation. Again, facilitating livelihood change is a process that may time extra time and effort.
- Training local stakeholders may not benefit women farmers if government extension staff cannot communicate in Khamu language. *Lesson:* Extra effort is required to facilitate equitable benefits. Village men can help translate Lao to Khamu.
- Provincial and district extension staff are accustomed to using standard questionnaire formats. *Lesson:* Training sessions required discussion of development processes and the dual role of extensionists (solution providers and opportunity identifiers/facilitators). For survey instruments, the C-Laos approach concentrated on developing ways to foster mutual learning instead of extractive data gathering. The perspective of having conversations instead of conducting interviews addressed the process and content of extensionist-farmer interactions.
- Efforts to encourage conversational interactions, a review of farmer responses, and critical thought require extra time and discussion with extension staff. *Lesson:* Despite a difference in culture and educational backgrounds, extensionists appreciated learning different ways to interact with farmers. A new training technique to the extensionists, role plays as farmers, village leaders and extensionists, was effective in encouraging participation, discussion and debate.

Dissemination of outputs

- Development of project websites: http://gisweb.ciat.cgiar.org/Austria-Laos and http://www.wiso.boku.ac.at/laos.html
- Two posters presentations at the KEF Commission for Development Studies MDG+5 workshop: *A critical look at the role of research in achieving the MDGs* (November 2005).
- Market-led options to improve farmer livelihoods in Oudomxay, Laos
- Building a learning alliance in Lao PDR
- The project presented one poster at the IDRC workshop: *Community-based Natural Resource Management Research and Capacity Building* (March 2006)
- Fostering site-specific market options to improve rural livelihoods and land management in Laos
- Project results summarized in CIAT annual reports.
- Project brochure (4 pages) developed to disseminate at meetings and discussions.

Project implementation

The effects of language, weather, and the agricultural calendar had the most impact on project implementation. Discussions and interviews with farmers often require a double translation (Khamu-Lao-English). Subtle and abstract concepts need careful explanation. In order to avoid leading a dialogue and question process, the use of analogies and personal experience needs to be employed carefully. Field activities are difficult to realize during the rainy season. Roads to villages become dangerously slick when wet. All fieldwork needs to be coordinated to avoid busy periods of the agricultural cycle (e.g. planting, harvest).

- Livelihood analysis: Livelihood transitions in the uplands of Lao PDR are rapid and wide ranging. The aim of this research is to: (1) explore livelihoods transitions in different bio-physical, economic and social contexts, (2) examine the potential for extensionists to facilitate community discussion about tradeoffs associated with livelihood transitions.
    - Tradeoffs include changes to:
        - Household food and economic security,
        - Resource impacts (soil, forest, water), and
        - Cultural traditions at the household (e.g. gender) and community level (e.g. social equity).
    - The C-Laos approach at the household level is an adaptation of the community-level work of 2006. Extension staff will implement the dialogues with households (n= 54) in four communities. Steps include:
    - Recognising livelihoods strengths (goal instead of problem-oriented approach)
        - Envisioning future livelihood goals
        - Designing livelihood development strategies
        - Drawing and implementing livelihood actions plans
        - Conducting participatory monitoring and evaluation
    - A fourth MSc student will conduct research activities in Oudomxay to:
        - Determine the likely effects of new livelihood strategies on household and community institutions/traditions.
        - Identify development policies that foster equitable outcomes.
        - Adapt research with NUoL and NAFRI experience and build capacity.
    - A synthesis will be conducted of 36 enterprise budgets compiled by IFAD/OCSIP of predominant agriculture and livestock systems.
    - Tradeoff (economic-social-environmental impacts) and scenario analysis of livelihood options coordinated with results of spatial analysis (June).

- Market analysis
    - Refinement of paper mulberry supply chain analysis.
    - Implementation of action plans for villages and local traders.
    - Conceptualization and participation in Southeast Asia NTFP workshop (SNV, FAO) in Vientiane (April).
    - Co-development of summary NTFP information (with SNV, NAFRI) for development workers and policymakers regarding optimal conditions and requirements of
        - Agro-environments
        - Management
        - Post-harvest and marketing
- Spatial analysis
    - Detailed map of land cover changes from study years 2001 to 2003.
    - Summary maps of human pressure on land use created.
    - Trends of human pressure on land use estimated.
    - Results discussed with villages and development projects (IFAD).
    - Conference poster presentation *Analysis of Time Series of Image Data*. Bozen, Italy June 2007) http://las.physik.uni-oldenburg.de/timeseries-workshop/
- Synthesis of project results and implications discussed with project partners.
- Co-organization, participation, and publication of synthesis and lessons-learned workshops at two scales:
    - CIAT projects in Southeast Asia.
    - Other major research-for-development projects in Laos (NAFRI, SDC, SNV, SIDA, IDRC, IFAD, etc).

Assessing the potential impact of the consortium for improved agriculture-based livelihoods in Central Africa (CIALCA): Spatial targeting of research activities

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Introduction

Consortium for improved agriculture-based livelihoods in Central Africa

In 2005, the Directorate General for Development Cooperation (DGDC - Belgium) approved three proposals for projects working with the national agricultural research systems of Rwanda, Burundi, and the Democratic Republic of the Congo (DRC) and in similar geographic regions. The three projects are led by IITA, Bioversity-INIBAP, and TSBF-CIAT, focussing on banana-based systems in the first two cases and on sustainable natural resource management and marketing, coupled with resilient legume germplasm in the third project.

In order to exploit these similarities in project objectives, structure and sites, the three CGIAR institutes and their NARS partners proposed to operate as a consortium. Using the different capacities of the participating institutes, the consortium aims to enhance research synergies, while avoiding needless duplication of research activities. The setup of the Consortium for Improved Agriculture-based Livelihoods in Central Africa (CIALCA) was endorsed by the Director-Generals of INERA, ISAR, ISABU, IRAZ[1] in Kigali, on 15-16 September 2005.

CIALCA mandate areas

CIALCA has chosen to work in ten geographical areas in Burundi, DRC and Rwanda. These ten 'Mandate Areas' (Figure 1) have been chosen to represent the diversity in agro-ecological characteristics, in demographic profile and in access to markets that are encountered in the three countries (Table 1). The mandate areas chosen also reflect the areas where bananas and legumes are an integral part of the farming system (Figure 2).

[1] l'Institut de l'Environnement et de Recherches Agricoles (INERA- DRC), Institut des Sciences Agronomiques du Rwanda (ISAR), l'Institut des Sciences Agronomiques du Burundi (ISABU), Institut de Recherche Agronomique et Zootechnique (IRAZ) – regional mandate based in Burundi.

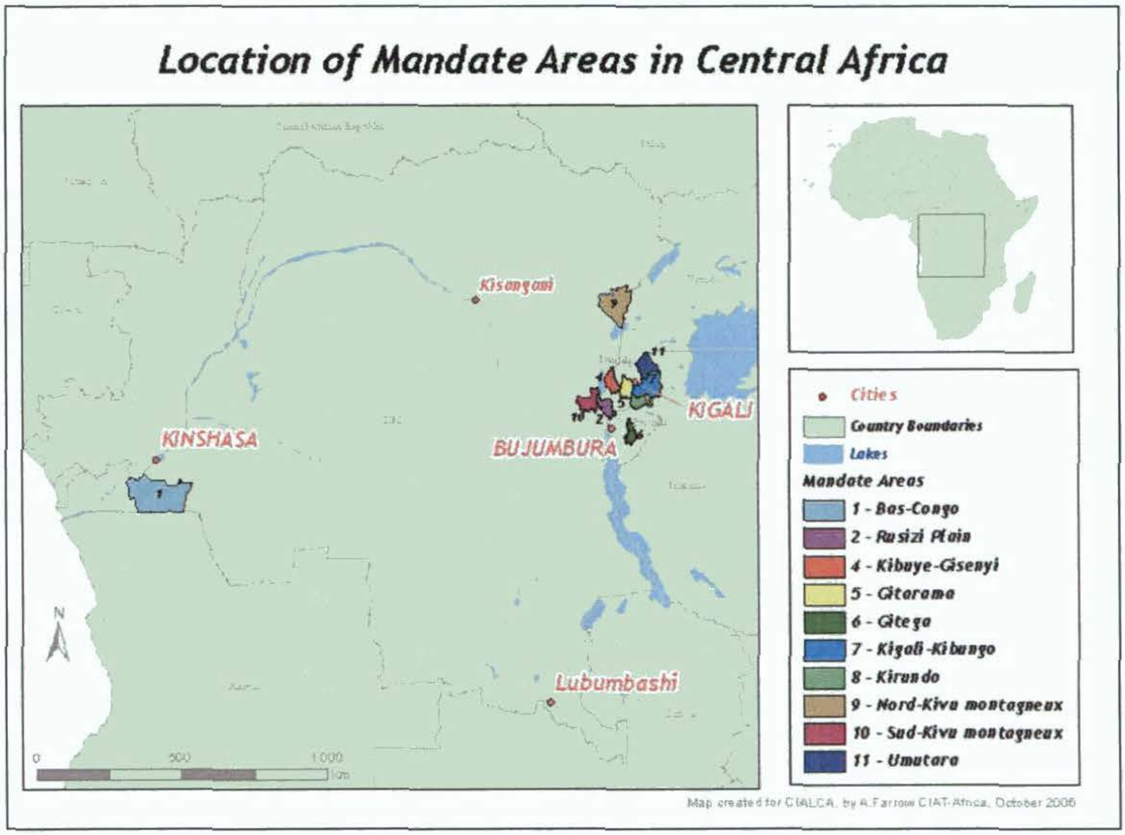

Figure 1. Mandate areas in Central Africa

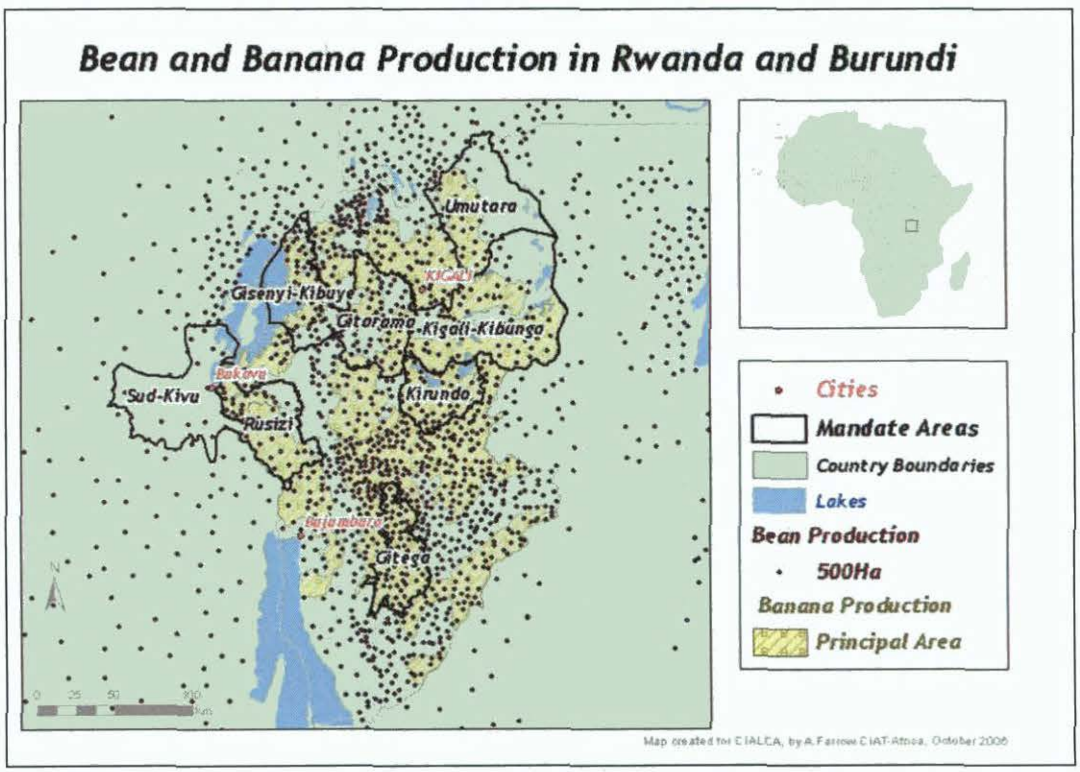

Figure 2. Bean and Banana production in Rwanda and Burundi (data unavailable for banana production in DRC).

Table 1. Characteristics of the 10 mandate areas.

Name	Country	Approximate political boundaries	Biophysical characteristics	Description/reason for interest	Main markets
Bas-Congo	DRC	Cataractes, Lukaya district	Lowlands	Lowlands, close to Kinshasa	Kinshasa, Mbanza-Ngungu
Ruzizi plain	Burundi / Rwanda	Cibitoke province/district	Ruzizi plain	Banana good access to Bujumbura, lowlands (800m)	Bujumbura
Gisenyi-Kibuye	Rwanda	Gisenyi, kibuye provinces	Highlands, high ppt, relatively young soils	Bananas, beans with good growth potential	Kigali, Gisenyi, Goma, Ruhengeri, Kibuye
Gitarama	Rwanda	Gitarama province	Granite plateau, poor soils	High population density good market access, poor soils on granitic plateau	Kigali, Gitarama, Ruhango
Gitega	Burundi	Gitega province	Poor acidic soils, central plateau,	Banana, representative of central area, high population density, with input use common	Gitega, Bujumbura
Kigali-Kibungu	Rwanda	Kigali, kibungu provinces	900-1200mm, 900 – 1700m mid-altitude, old weathered soils on schist	Bananas, beans, potentially good access to Kigali	Kigali
Kirundo	Burundi	Kirundo province	900-1200mm, 900 – 1700m mid-altitude, old weathered soils on schist	Banana area, similar to Kibungu, international NGOs are there	Kirundo, potentially to Kigali
Kivu montagneux*	DRC	Ngweshe, Kabare, Masisi, Butembo, Kamanyola (territoires)	Highlands	Banana-bean area, high population, high rainfall, potential good access to urban centres	Beni, Butembo, Kasindi, Kampala, Bukavu, Goma, Kigali, Cyangugu, Gisenyi
Umutara	Rwanda	Umutara province	800-1000mm with drought stress, potentially good NRM base	Recently settled, potentially good access to Kigali	Kigali

* Kivu montagneux has been split into Sud-Kivu montagneux and Nord-Kivu montagneux.

Representativity and scaling-out

A number of locations have been chosen as candidates for action sites. At each location a participatory rural assessment (PRA) was carried out to determine the important characteristics of the communities, such as the major farming systems, their engagement with markets, and to gauge the presence and strength of local organisations. As part of the characterization of mandate areas we have also analyzed the representativity of each PRA site within the mandate site as a whole in terms of the major variables described above. In addition an exploratory scaling-out exercise has been carried out for each PRA site in order to judge potential diffusion areas and beneficiaries of the technologies developed by the CIALCA projects.

Methods and Materials

Data

Each mandate area was characterized in terms of certain key variables, these included the agro-climatology of the area, the population density of the area, and the access to markets. Population density was provided by the Global Rural Urban mapping project (GRUMP 2005) datasets for Africa. This dataset was chosen to ensure consistency across the three countries. GRUMP is inferior to some publicly-available data for Rwanda (the GRUMP data are older and the spatial resolution is poorer) but it is the only reliable source of data for DRC.

Different markets were chosen for characterizing the mandate areas (Table 1); these were based on local knowledge of current trade flows as well as for the identification of potentially new markets. Accessibility was then calculated to all of these markets. The access is modelled in a geographical information system (GIS) using a set of rules and data, which results in a value in minutes to a pre-determined market (Farrow and Nelson 2001). The model takes into account road location and quality as well as barriers such as international borders and constraints to movement, like slope. The values generated were validated by the project team coordinators in Rwanda, Burundi and DRC. Each market was modelled individually, assuming a transport mode of medium-sized trucks able to carry agricultural goods (both input and output) in bulk[2]. This links with CIALCA's research on collective action for marketing outputs and bargaining power for the purchase of inputs.

Due to lack of digital soils data, the characterisation of the agro-climatology was limited to the annual precipitation (Hijmans *et al.* 2005) and a calculation of the length of growing season (Thornton *et al.* 2006). An indication of the soils can be derived by the underlying geology. For Rwanda geological maps are available in scanned format (Selvaradjou *et al.* 2005) and can be used for those mandate areas located in that country. No data were available for Burundi or DRC.

The results of characterising the mandate areas were combined to form development domains similar to those used for priority setting by the Association for Strengthening Agricultural Research in East and Central Africa (ASARECA). The agro-ecological potential layer was the same as that used by IFPRI-ASARECA. Slight modifications were made to the ASARECA development domains, especially in the choice of markets and in the threshold values used.

Assessing representativity of PRA sites

While it will be the results from the PRA that decide which sites will be chosen as the locations for interventions[3], it was deemed important by CIALCA that the PRA sites themselves are broadly representative of the mandate area. This has slightly different connotations in each mandate area but in general the researchers were keen to avoid outliers in terms of the major biophysical and socioeconomic

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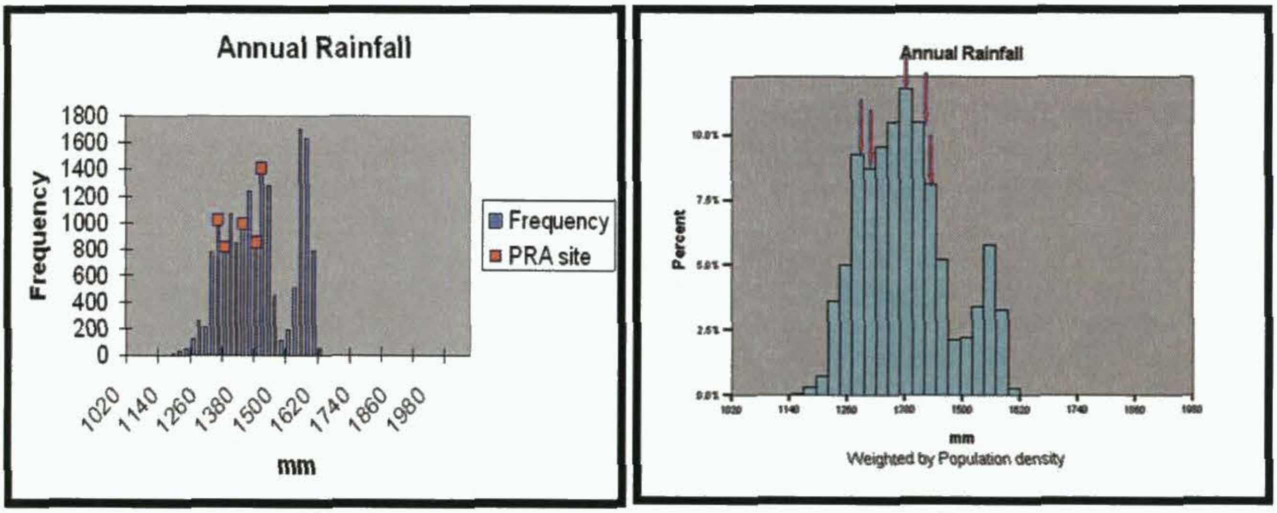
[2] Where no roads or tracks are mapped, the model uses values for walking.

[3] Half of the PRA sites in each mandate area will be chosen as action sites depending on a number of factors including the strength of community organisations, and current engagement with markets.

variables used to characterise the mandate areas. A sampling framework is traditionally devised to ensure representativity and to enable inferences to be drawn about the population at large. However given the small number of intervention sites, our analysis of representativity is visual and intuitive rather than statistically rigorous.

We compare the values of the characteristics at the location of the village where the PRA was undertaken with the values of the mandate areas as a whole. All of the PRA sites are plotted on the histogram of observations. A histogram can be produced for each variable where each observation refers to a $1km^2$ cell. The interpretation of the annotated histogram is improved[4] when the variable is weighted according to the population density as shown below (Figure 3).



(a) (b)

Figure 3. Histograms of annual rainfall in Bas-Congo mandate area; (a) unweighted, and; (b) weighted by population density.

Scaling-out as a guide to potential impact

The interventions that will be carried out as part of the CIALCA projects in the action sites will be analyzed and the best practices will be scaled-up via development partners and the national agricultural research and extension systems. Another aspect of "going to scale" is the horizontal replication across the three countries and beyond (Cook and Fujisaka 2004). The potential areas of this scaling-out are determined in part by the interventions themselves, which are constrained by various external factors, notably the edapho-climatic conditions, the receptiveness of the livelihood systems and access to input and output markets.

We have used two methods of assessing the potential for the scaling-out of interventions in the action sites. The first and most fully developed is the use of the Homologue software (CIAT 2004) to search for environments similar to those encountered in each mandate area. The second method has resulted in the creation of development domains based on key variables related to agricultural livelihoods (e.g., Pender *et al.* 2004).

[4] The PRA site should be representative of the population of the mandate area rather than the area *per se*.

Homologue

Homologue produces raster grids of the probability of encountering an environment similar to the input location. For each mandate area we chose the position of each PRA as the input location. These individual grids were then merged to form a probability cloud, whose values varied between 1 (100% chance of encountering a similar edapho-climatic environment) and 0.

The probability 'cloud' was then used to give the population in the probability band between 50% and 100%. No account was taken of the actual diffusion mechanism, that is whether the diffusion was a natural process or was aided by NARS and NGOs.

ASARECA Development Domains

For scaling-out purposes we have decided to use the development domains developed for ASARECA (2005). These domains have been created using many more markets than those used in the characterization of the CIALCA mandate areas. The domains have been produced for eastern and central Africa, so the results are only comparable for a selection of countries. Each PRA in the mandate area is located in a particular domain, and each domain has a total population in eastern Africa. Therefore for each mandate area the scaling-out population is the total population of all the domains represented by the PRA sites.

Results

Assessing representativity of PRA sites

The PRA sites in Bas-Congo represent well the mandate area in all of the variables although they tend to be located in the lower and drier parts of the region. Differences between the weighted and un-weighted distributions are obvious for elevations above 800m and for annual rainfall totals above 1500mm. These sparsely-populated, higher and wetter areas in Madimba *territoire* tend to have poorer access to Kinshasa and to Mbanza-Ngungu. All except two of the PRA sites are within 8 hours of the capital Kinshasa. In Gitarama the single PRA site is broadly representative of the mandate area although a location a little higher and wetter would have been more typical. More importantly the PRA site is located on the granitic plateau that characterises the south-central part of the Mandate area and for which reason the mandate area was chosen.

The focus of research in the Gitega mandate area is banana-based systems; as such, the higher elevation parts of the district were not sampled. The differences between the weighted and un-weighted histograms are small in this mandate are due to the lack of variability in the distribution of the (high) rural population. Also in Burundi, the PRA sites in Kirundo represent the mandate area well. The sites offer sufficient variation to capture differences in key biophysical and demographic variables, although the driest areas were not captured.

In the Kibuye-Gisenyi mandate area the two PRA sites are in the lower and drier locations close to Lake Kivu; this is where the urban population is located and where market access is good. Nevertheless the PRA sites do not represent well the whole mandate area as a whole, this is perhaps because the emphasis in this mandate area is bananas, which are not well suited to the higher areas of the mandate area. In terms of geology the PRA sites are located on the granitic/volcanic-derived soils in the north and on schist-derived soils in the south, representing well the mandate area. In contrast the PRA sites in Kigali-Kibungo represent the mandate area well. Despite similar altitudes they are well spread in each of the other variables and are located on the granite-derived soils in Bugasera and on schist-derived soils in Kibungo, representing well the range of the underlying geology in the mandate area.

The PRA sites in the Rusizi plain and Nord-Kivu montagneux mandate area represent well the mandate areas in all of the variables, although in the latter case they tend to be located in the lower and drier parts of the region, which is not surprising given the mountainous terrain. The PRA sites in sud-kivu montagneux represent well the mandate area, especially when the western portion of the area (which is included for administrative rather than biophysical reasons) is ignored. Finally in Umutara the four PRA sites represent well the granite-derived soils in the north and the schist-derived soils in the west and south, representing well the mandate area. There is perhaps a gap in the coverage for the lower elevations, which are areas with longer growing seasons and higher precipitation. These areas are, however, almost mutually exclusive with the lower elevations in the east of the mandate area associated with lower rainfall and shorter growing seasons.

We have shown that access to markets in Burundi and Rwanda appears to be more widespread than in DRC, due to the number and quality of the feeder roads in these two small countries. The quality of the digital data is also probably a factor with very good datasets available for both Burundi and Rwanda.

Potential impact of CIALCA interventions

We summed the total populations that inhabit those areas in Africa that have similar biophysical conditions to those encountered in each of the CIALCA mandate areas (Table 2). The population in this table could be considered the potential population that could be positively impacted by the interventions proposed in the three CIALCA projects. The results show that the Bas-Congo mandate area and the Gitega mandate areas have homologue environments with large populations; in the latter case this includes almost half of Burundi as well as the higher density areas of eastern DRC. Despite the fact that there are eight PRA sites in the Sud-Kivu montagneux mandate area, the population in similar environments is quite small.

Table 2. Population in homologue environments for each CIALCA mandate area.

Name	Bas-Congo	Rusizi	Gisenyi	Gitega	Gitarama	Kigali	Kirundo	Nord-Kivu	Sud-Kivu	Umutara
Algeria	0	0	0	0	0	0	0	0	0	0
Angola	1519540	0	0	1723620	0	0	0	0	0	0
Burundi	668126	1153700	59911	4972120	1120200	915970	2104300	28645	249612	158455
Cameroon	35876	0	0	0	0	0	0	256198	0	0
CAR	8432	0	0	0	0	0	0	22128	0	0
Comoros	41583	0	0	0	0	0	0	0	0	0
Congo	1750460	0	0	0	0	0	0	32048	0	0
DRC	12983800	1244920	3021390	1331850	116444	4001	1276570	6928020	1642020	0
Ethiopia	0	731651	43134	5154090	680552	1481410	867383	295808	295540	274822
Gabon	150812	0	0	0	0	0	0	0	0	0
Ghana	502816	0	0	0	0	0	0	0	0	0
Ivory	107498	0	0	0	0	0	0	0	0	0
Kenya	0	51924	421689	0	42866	43724	36865	2299330	0	55196
Madagascar	0	5095160	332220	435472	0	0	0	116420	1350000	0
Malawi	2206	95508	0	262678	0	0	0	45987	0	0
Mozambique	0	484495	0	293501	0	19979	13322	53368	0	0
Nigeria	5759550	0	0	0	0	0	0	0	0	0
Zimbabwe	0	98373	0	2678680	0	0	0	0	0	0
Rwanda	0	2703150	2904360	1226640	4583970	3571420	4687340	3377510	660407	2509720
South Afri	0	631952	0	4387470	640283	1215580	1158240	0	43449	240925
Sudan	0	121	0	10	0	0	0	0	0	0
Swaziland	0	119135	0	595835	0	88446	87171	0	0	0
Tanzania	1445380	866905	665303	1157340	1207100	1709000	1794390	453330	0	815034
Togo	55291	0	0	0	0	0	0	0	0	0
Uganda	0	213048	531940	3991	54832	156219	151654	3571960	7214	195280
Zambia	0	17499	0	235754	0	0	0	0	0	0
Total	25,031,370	13,507,541	7,979,947	24,459,051	8,446,247	9,205,749	12,177,235	17,480,752	4,248,242	4,249,432

An alternative strategy for gauging the potential population who might benefit from the technologies tested in the CIALCA projects is to analyze the development domains in which each PRA site is located, and extrapolate to the population of the same domains in the countries of eastern and southern Africa. The result of this extrapolation (Table 3) gives a far larger potential population than the results of the analysis of homologue environments. This is most evident in the Sud-Kivu Montagneux mandate area, which in this case has the largest potential scaling-out population.

Table 3. Population in development domains of the PRA sites in each mandate area.

Name	Bas-Congo	Rusizi	Gisenyi	Gitega	Gitarama	Kigali	Kirundo	Nord-Kivu	Sud-Kivu	Umutara
Burundi	3652910	2173050	5089160	4848160	1784100	4101446		152990	2284940	454968
Ethiopia	25817000	25075460	15487910	33077400	2479110	35077720	15487910	12494807	27782117	14869530
Kenya	11901490	10949010	16374860	15138510	6218460	16517975	16374860	4939037	12902587	2701355
Madagascar	8859280	12011990	3156820	2652740	1671280	10745486	3156820	5197738	14242758	8658940
Rwanda	2487108	4763287	7005370	3093455	4640750	3169464	7005370	129219	4892457	233870
Sudan	10715580	22918420	7645530	2323631	5874270	14342136	7645530	14965450	29784040	12025820
Tanzania	15864820	14127053	7194633	9543220	891803	21259736	7194633	10519240	20973033	14123440
Uganda	14017360	5889020	13207940	15767220	2300640	15713171	13207940	1928310	7339010	4296850
Zaire	31592510	37912270	12607700	11946190	6151890	37683040	12607700	12058610	43347200	29336850
Eritrea	747565	2779658	1257985	269180	989499	986556	1257985	2378141	3846719	707079
Total	125,655,623	138,599,218	89,027,908	98,659,706	33,001,802	159,596,730	83,938,748	64,763,542	167,394,861	87,408,702

Conclusions and Discussion

The case of Umutara highlights the difficulty of assuring representativity in multivariate space, especially when limited to at most eight sites across areas of up to 20,000 km^2. One solution is to reduce the dimensions of this multivariate space by classifying and merging the variables to create domains that reflect the objectives or research questions tackled by the project, program or organization. The CIALCA mandate areas have been assessed in terms of the development domains, which are based on access to markets, agro ecological potential and population density. The markets used in the creation of these domains are specific to the particular mandate areas. This makes it difficult to use the same development domains for scaling-out purposes and a more general set of domains, such as those used by ASARECA was necessary.

The analysis of spatially-variable characteristics has been used in combination with the participatory rural assessments which were carried out in each mandate area. A criticism of the methodology used by CIALCA could be that the characterisation should precede the choice of sites for the PRAs. There are, however, practical reasons why this approach was chosen, not least because the characterization consumes time, which is itself a limited resource in research projects like CIALCA. Nevertheless the characterization process has confirmed the soundness of the sites chosen for PRAs and ultimately for action sites and interventions.

The assessment of areas for the scaling-out of interventions might normally be confined to an *ex ante* economic analysis. We feel that a combination of economic impact assessment and spatial analysis can deliver a realistic range of impacts. Both the strategies of assessing the potential scaling-out populations have flaws. The use of homologue environments ignores the socio-economic conditions that ensure the success of the intervention, while the development domains are too broad for anything other than policy recommendations. Neither of these considers the precise mechanisms for scaling-out and neither considers the effects of distance, for instance some homologue environments occur in southern Africa). The scaling-out assessments undertaken in this study can also be improved by the consideration of the welfare or nutritional levels of the potential beneficiaries (see, for example, the section *Strategic approaches to* *targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production* by Hyman *et al.* in this Report).

A response to this evaluation would be the further development of the CaNaSTA (Crop Niche Selection in Tropical Agriculture) tool (O'Brien, 2004) for a range of technologies allied with research on socio-ecological niches (Ojiem 2006) and impact pathways (Douthwaite *et al.* 2003).

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THEME 5:

OBTAINING, DEVELOPING, AND MANAGING DATA AND INFORMATION

An evaluation of void-filling interpolation methods for SRTM data

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Abstract

The Digital Elevation Model that has been derived from the February 2000 Shuttle Radar Topography Mission (SRTM) has been one of the most important publicly-available new spatial datasets in recent years. However, the 'finished' grade version of the data (also referred to as Version 2) still contains data voids (some 836,000 km^2) – and other anomalies – that prevent immediate use in many applications. These voids can be filled using a range of interpolation algorithms in conjunction with other sources of elevation data, but there is little guidance on the most appropriate void filling method. This paper describes: (i) a method to fill voids using a variety of interpolators, (ii) a method to determine the most appropriate void-filling algorithms using a classification of the voids based on their size and a typology of their surrounding terrain; and (iii) the classification of the most appropriate algorithm for each of the 3,339,913 voids in the SRTM data. Based on a sample of 1,304 artificial but realistic voids across six terrain types and eight void-size classes, we found that the choice of void-filling algorithm is dependent on both the size and terrain type of the void. Contrary to some previous findings, the best methods can be generalised as: Kriging or Inverse Distance Weighting interpolation for small- and medium-size voids in relatively flat low-lying areas; Spline interpolation for small and medium sized voids in high altitude and dissected terrain; Triangular Irregular Network or Inverse Distance Weighting interpolation for large voids in very flat areas, and an advanced Spline Method (ANUDEM) for large voids in other terrains.

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Key words: DEM, interpolation methods, void filling, DEM fusion

Introduction

A digital elevation model (DEM, or more correctly a land surface model - LSM) is one of the most useful sources of information for spatial modelling and monitoring, with applications as diverse as: environment and earth science, e.g. catchment dynamics and the prediction of soil properties; engineering, e.g. highway construction and wind turbine location optimisation; military, e.g. land surface visualisation, and entertainment, e.g. landscape simulation in computer games (Hengl and Evans 2007). The extraction of land surface parameters – whether they are based on 'bare earth' models such as DEMs derived from contour lines and spot heights, or 'surface cover' models derived from remote sensing sources that include tree top canopies and buildings for example – is becoming more common and more attractive due to the increasing availability of high quality and high resolution DEM data (Gamache 2004). One of the most widely used DEM data sources is the elevation information provided by the shuttle radar topography mission (SRTM) (Coltelli *et al.* 1996, Farr and Kobrick 2000, Gamache 2004), but as with most other DEM sources, the SRTM data requires significant levels of pre-processing to ensure that there are no spurious artefacts in the data that would cause problems in later analysis such as pits, spikes and patches of no data (Dowding *et al.* 2004, Gamache 2004, Chaplot *et al.* 2006, Fisher and Tate 2006). In the case of the SRTM data, these patches of no data are pervasive (USGS 2006*b*) and must be filled or interpolated, preferably with auxiliary sources of DEM data. This paper describes a procedure to determine the most appropriate interpolation methods (with and without auxiliary DEM data) for no data patches of different sizes and in different terrain types. The rationale for this paper stems from a statement by Fisher and Tate (2006) that no single interpolation method exists for the most accurate interpolation of terrain data. Such a procedure is necessary for developing a high quality global DEM derived from the SRTM data where all no data areas have been filled using the best performing interpolation algorithm available.

The shuttle radar topography mission (SRTM)

The 11 day SRTM flew in February 2000, and has provided publicly-available elevation surface data for approximately 80% of the world's land surface area (from 60°N to 56°S), with a post spacing of 1 arc second (often quoted as 30 metres resolution) in the USA, and a degraded 3 arc second (often quoted as 90 metres resolution) product for the rest of the world. It is a snapshoot of the reflective surface of the earth during the time period of the mission, and is about 100 times more detailed than other existing freely-available global elevation data, such as GTOPO30 (USGS 1996) and GLOBE (Hastings and Dunbar 1998). The SRTM elevation data is derived from X-band and C-band interferometric synthetic aperture radar (InSAR) (Werner 2001, USGS 2006b). This paper deals with the better-known and widely-available C-band product, which we shall refer to as SRTM elevation data. As with all DEMs derived from remote sensing sources, the SRTM elevation data include trees, buildings and other objects on the earth surface and therefore the dataset is a surface elevation model (Rodriguez *et al.* 2005, 2006).

Several products have been derived from the SRTM data. Firstly, the raw data were processed by a suite of programs at JPL (Farr and Kobrick, 2000), and was made available primarily for research purposes. This was termed "unfinished" data. Further processing generated DEMs in full DTED compliance level, and these were termed "finished" data (Slater *et al.* 2006). For both datasets: elevations outside the USA are degraded either by (i) averaging or (ii) by thinning (i.e. taking one sample out of the nine available posts). The horizontal datum of the SRTM data is WGS84, whilst the vertical datum is EGM96 which has implications for certain applications.

The C-band product has significant areas of missing data due to the nature of radar data and the interferometric process used to create the DEM (Figure 1). The reasons for the missing data are geometric artefacts, specular reflection of water, phase unwrapping artefacts and voids due to complex dielectric constant (see Kervyn 2001 for further information). For example, the InSAR instrument used to generate the SRTM elevation data had an incidence angle of between 30° and 60°, making it difficult to generate images for terrain slopes corresponding to that range of angles (Gamache 2004, Eineder 2005).

For the purpose of this paper, we define any areas of missing data that exist in the SRTM data as voids. The number of remaining voids with different sizes in the SRTM data are a considerable problem for many uses and applications, including hydrological modelling, terrain indices, land surface characterisation, digital soil mapping and many other geomorphometric models, and thus these voids need to be filled to create a seamless DEM (MacMillan *et al.* 2000).

The "finished" version of the SRTM data (described more fully in below) provided by United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) still contains 3,399,913 voids accounting for 803,166 km^2 (an area comparable to Pakistan or somewhat larger than Texas), and in extreme cases, such as Nepal, they constitute 9.6% of the country area with some 32,688 voids totalling an area of 13,740 km^2.

Figure 1 shows the proportion of each 1 × 1 degree SRTM tile that is composed of void areas. Figure 2 shows two extreme examples of regions where there are many voids, Libya (upper) and Nepal (lower). Of the 210 countries covered by the SRTM data, two countries have void areas larger than 10% of their country size, nine countries more than 5% and 14 more than 2%. In total, 44 countries have 1% or more of their area covered by voids. The void size / frequency distribution of all voids in the SRTM dataset is shown in Figure 3.

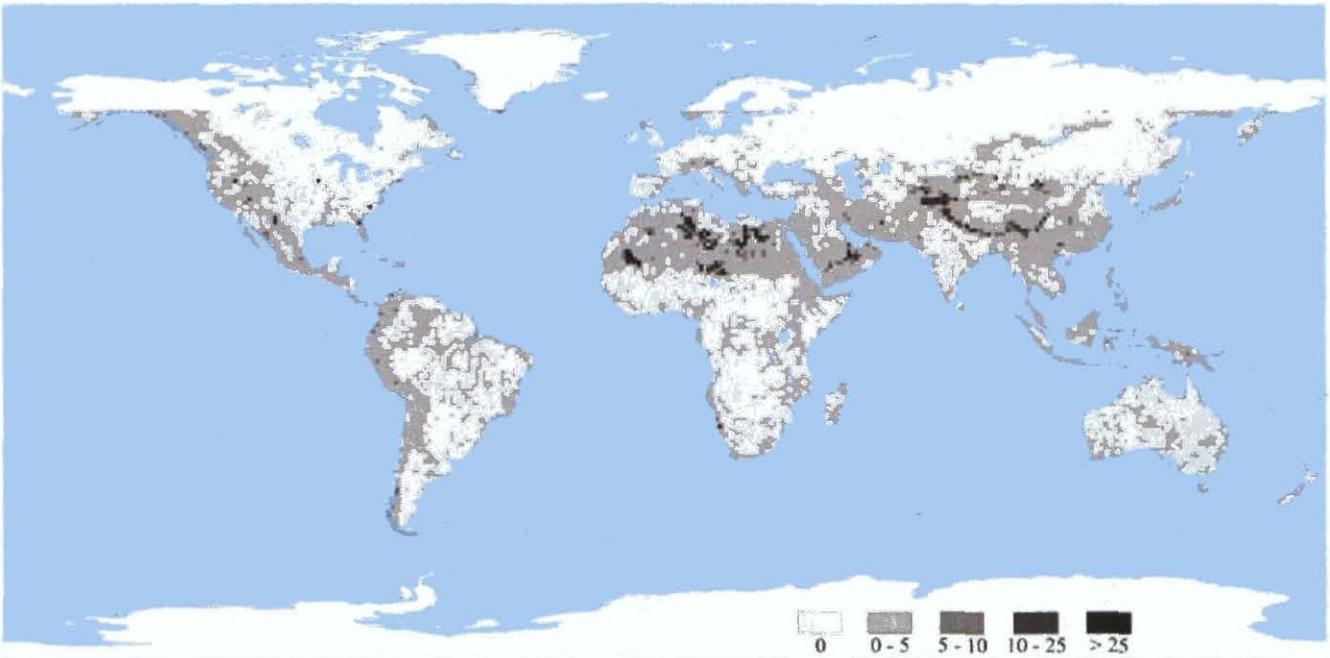

Figure 1. The global distribution of voids in the SRTM data, represented by the proportion of void area in each 1 × 1 degree SRTM tile. Note the clustering of voids over mountainous and desert areas and the northern extent of the SRTM data (60°N).

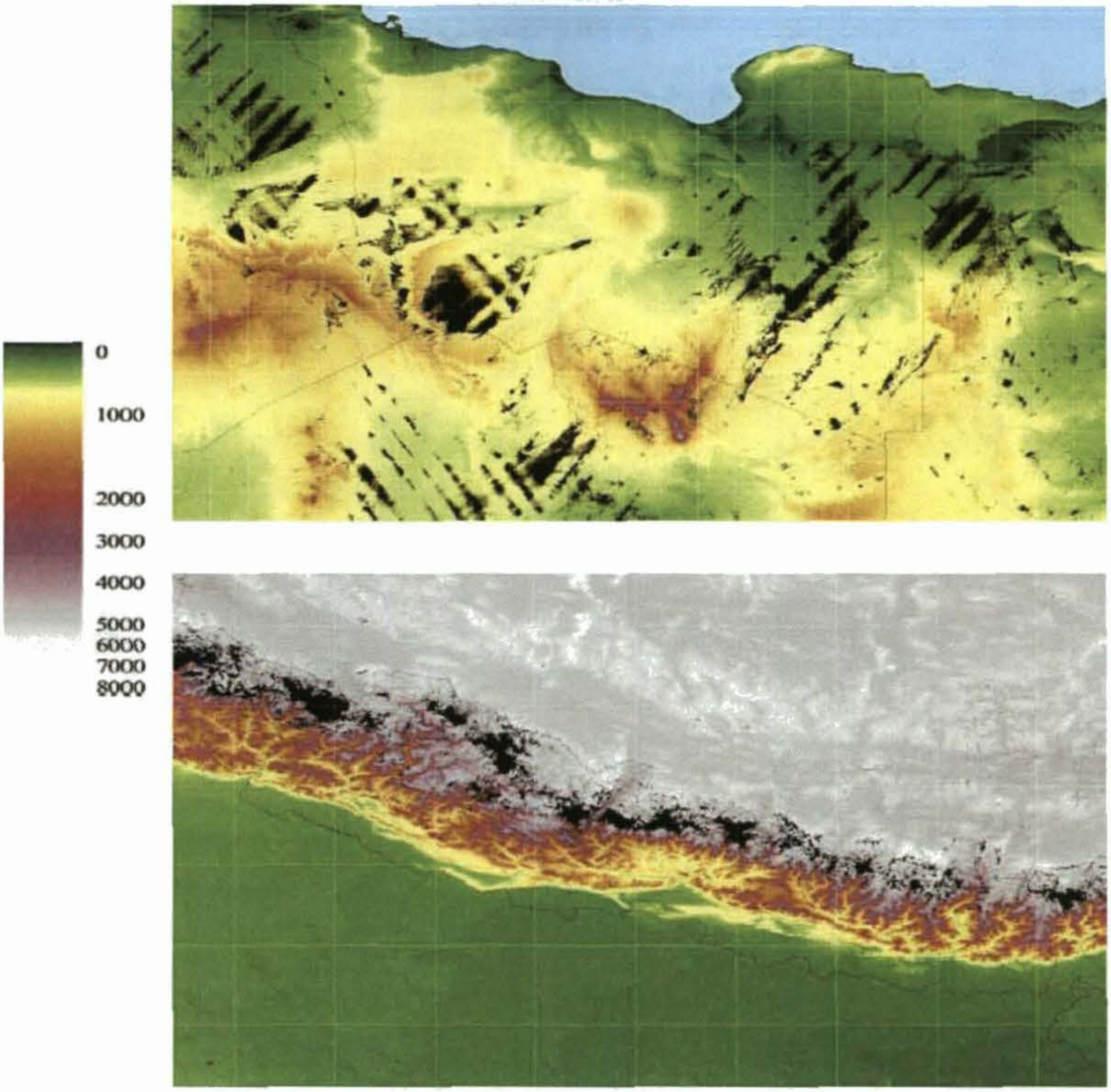

Figure 2. Voids (in black) overlaid on the SRTM30 elevation data for two extreme cases, Libya (upper) and Nepal (lower). The 1 × 1 degree SRTM tile boundaries have also been superimposed to express scale. The key shows elevation in meters above mean sea level.

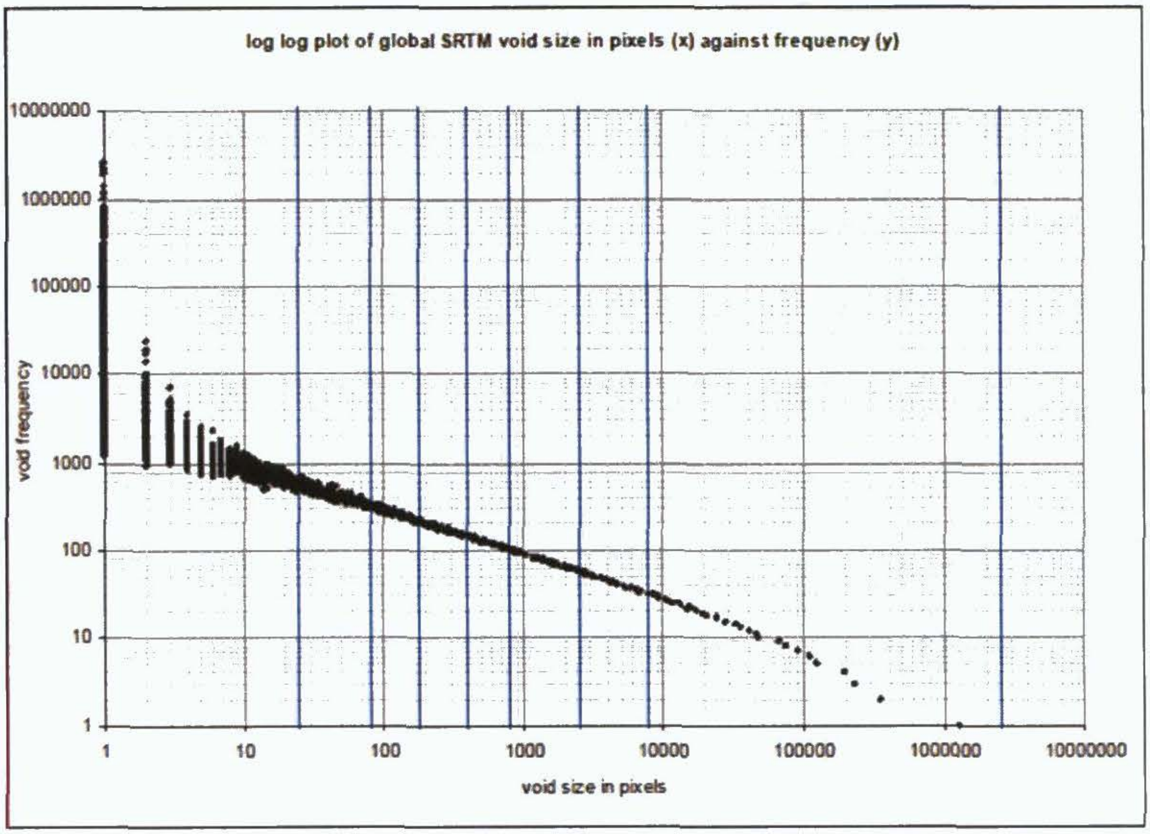

Figure 3. Log log plot of the void size against the frequency distribution for the global void dataset (n= 3,339,913).

Voids occur for different reasons in different terrain types. A void due to shadowing will more likely occur in mountainous areas, whereas a void due to complex dielectric constant is more likely to occur in desert areas like the Sahara. Void frequency with respect to elevation has been demonstrated to have a bimodal distribution with peaks of the distribution occurring in flat areas and in steeply sloping areas (Gamache 2004, Falorni *et al.* 2005). This distribution is clearly seen in Figure 1.

Since this study focuses on methods of void filling the SRTM elevation data, we will not discuss the accuracy or the errors in the SRTM data, though it is worth mentioning that the sensor error is stated to be +/-16m (USGS, 2006*b*). Further details on SRTM accuracy are available in the literature (Toutin 2002, Rabus *et al.* 2003, Gamache 2004, Falorni *et al.* 2005).

Fisher and Tate (2006) provide a thorough review of the causes and consequences of error in DEMs. They classify errors into three different groups: (i) gross errors (e.g. system malfunctions), (ii) systematic errors, which might be described by a functional relationship (Thapa and Bossler 1992, p836 in Fisher and Tate 2006), and (iii) random errors with or without spatial dependence that arise for different reasons. Voids are one type of systematic error, which can be overcome with specific algorithms.

Void filling methods

Interpolation methods are widely used in the generation of DEMs. However, void-filling (VF) methods contain a special subset of interpolation algorithms with certain restrictions, and also other methods such as the fill and feather approach (Dowding *et al.* 2004). All interpolation algorithms for VF DEMs use the elevation data surrounding the void in the interpolation process. If auxiliary sources of elevation (for example, ASTER DEMs, GTOPO30, digitised topographic maps and land survey measurements) are available, then some of these algorithms can incorporate this information to improve the accuracy of the interpolation. However, there are often severe differences between the DEM and the auxiliary data that need to be addressed before the VF algorithms can use auxiliary data. These differences can occur in: (i) the spatial resolution, (ii) the vertical datum, (iii) horizontal and vertical shifts, (iv) first or second order trends, (v) production errors, (vi) the type of surface model (SRTM is a surface model, whereas a DEM based on topographic data is a bare earth model) and, (vii) the spatial distribution of errors (see for example Hutchinson 1989, Kaab 2005, Fisher and Tate 2006).

VF algorithms can be categorised into surface (Katzil and Doytsher 2000), volumetric (Vedera *et al.* 2003) or example based methods (Sharf *et al.* 2004). Alternatively, Katzil and Doytsher (2000) divide the algorithms into polynomials (such as linear estimation, 1D and 2D polynomials of the third order, cubic splines, or iterative spline algorithms) and non-polynomial approaches (such as kriging, inverse distance weighting, fill and feather approaches or moving average).

Several authors have evaluated the quality of different algorithms to fill in voids for radar data as well as other DEM sources. Katzil and Doytsher (2000) tested linear estimation, kriging and cubic spline for elevation, but the evaluation was not performed on real voids. Instead a method called cross-validation was applied (removing one point and then comparing the elevation of the generated surface against the elevation of the point), which showed no significant differences between methods. Dowding *et al.* (2004) used a fill and feather (FF) approach (i.e. they used an auxiliary elevation dataset to patch the void area, and then smoothed the transition zone between both datasets) to incorporate auxiliary information into a VF algorithm. They selected seven voids with sizes ranging from 36 to 2,541 pixels and then compared the results both visually and against a reference DEM and ground control points. The results showed differences between 0 m and 22 m for the area of seven different voids against a reference DEM. Kuuskivi *et al.* (2005) used seven real world voids across different terrain types to evaluate the performance of a commercial fill and feather algorithm that used high quality auxiliary DEM data against three freeware programmes: 3DEM (Visualization Software LLC, 2004); VTBuilder (Virtual Terrain Project, 2004); and BLACKART (TerrainMap.com, 2004). The study clearly demonstrated the large differences in results that can occur when using different VF algorithms and the potential improvements that can be achieved with good quality auxiliary information. Grohman *et al.* (2006) presented a geostatistical algorithm (inverse distance weighting - IDW) together with a linear adjustment of the elevation height called Delta Surface Fill (DSF) and compared it against a FF approach using five artificially created voids in void-prone terrain types from the SRTM data. The authors concluded that the performance of the DSF algorithm produced better results based on visual interpretation and reduced the standard deviation of the error surface.

Several other studies have presented algorithms that are capable of filling void areas, but did not provide statistical results. For example Hofer *et al.* (2006) tested an advanced cubic spline method which keeps certain error bounds on nine voids and evaluated the VF results graphically. Almansa *et al.* (2006) evaluated four different artificial voids at different locations by comparing three different methods. Another example is Kääb (2005) whereby a simple replacement of SRTM by ASTER data was made without any further evaluation.

There are several observations that can be drawn from these studies. Firstly, each study typically compares three or four algorithms at most, whereas a GIS may contain many more suitable algorithms (e.g. IDW, Kriging, ANUDEM, Spline, and Trend Estimation). Secondly, some of the studies contain algorithms that are not easily reproducible within a GIS or image analysis system because their description is too vague or due to commercial interests. We argue that if an improved global DEM is to be produced from the SRTM data, then the VF algorithms should be accessible and repeatable. Thirdly, the studies presented results based on a handful of voids which may not be representative of the 3,339,913 voids in the SRTM data, and are not sufficient for robust statistical analysis. A much larger sample of real world voids is required before we can suggest one algorithm over another with any degree of confidence. Fourthly, occasionally these voids were artificial and hence may not be representative of real world voids. We realise that unless a high quality auxiliary DEM is available, then it is impossible to assess the veracity of the results from VF as there are no ground truth data. However, it is possible to create artificial voids that are representative of real voids in terms of size, shape and terrain location. Fifthly, terrain can have a large influence on VF results. Katzil and Doytsher (2000) acknowledged that terrain has an influence on the VF process; however, they could not suggest a recommended method across three terrain types (mountains, hilly and planar). Grohman *et al.* (2006) recognised the relief type for their five voids, which lead to decreasing average standard deviation from rugged to moderate to flat terrain. Again, the sample of voids should be sufficiently large across a range of terrain types in order to assess the influence of terrain ruggedness on algorithm choice and performance. Finally, void size is critical. It is much harder to fill a large void accurately than a small one. Grohman *et al.* (2006) recognised the importance of void size, but did not provide further insight. Again, the sample of voids should include sufficient numbers of voids of sizes that are representative of voids found in each terrain type.

In conclusion, there has been no thorough evaluation of the many (GIS ready) VF algorithms for DEM data using a sufficient number of voids of varying size across different terrain types in order to determine the most appropriate VF method(s).

Research objectives

The objectives of this study are to: (i) describe void characteristics in terms of size and terrain unit; (ii) determine which VF algorithm performs best without any auxiliary information on an exhaustive dataset, with respect to terrain unit and void size; (iii) determine if low-grade auxiliary information can improve the VF algorithm performance; (iv) determine which VF algorithm performs best with respect to terrain unit and void size using auxiliary information, and; (v) provide a global void dataset stating the best VF algorithm that should be used based on the results from (ii) and (iv).

Study area and data

As shown in Figure 1, data voids occur in all regions of the SRTM data, but after consideration of the spatial distribution of voids and terrain units and computational limitations, we limited our sample of voids to Africa, an area of approximately 29,800,000 km^2 and containing 1,168,136 voids. This provided a sufficient number of voids across a wide range of sizes and terrain units from which to perform the sampling.

SRTM data preparation

SRTM data are available in different formats from different distributors (a testament to its usefulness and popularity), and here we use the "finished" 3-arc second averaged SRTM data set that is available from the USGS EROS data server (USGS 2006*a*). The pre-processing and editing of this data is described by USGS (2006*b*), but the essential details are that spikes and pits in the data with surrounding elevation differences greater than 100 m were removed, voids smaller then 16 pixels were filled with a nearest neighbour interpolation while larger voids were left as were, and water bodies and coastlines were depicted as described by USGS (2006*c*). The data are available in one × one degree tiles in 16 bit integer BIL format. 3,250 tiles were downloaded from ftp://e0srp01u.ecs.nasa.gov/srtm/version2/SRTM3/Africa and were converted to ESRI™ grid format and mosaicked together in ArcGIS 9.1© to create a continental DEM for Africa with extents 39°N-35°S and 30°W-60°E. Since these data have been edited for small voids, coastlines and water bodies, we assume than any remaining land area that contains no elevation information is a void.

For each of the 1,168,136 voids we stratified the voids based on the natural logarithm of the number of void pixels and grouped them into eight size classes with the following number of pixels (numbers in parentheses are minimum, average and maximum) per class; [A] (1,10,25), [B] (26,50,80),

[C] (81,120,140), [D] (141,240,400) [E] (401,600,800) [F] (801,1100,2500), [G] (2501,4000,8000) and [H] (8001,10000,1267052).

Auxiliary DEM data

As stated in above, some VF methods incorporate auxiliary DEM information in order to improve the accuracy of the results. In this study we used the SRTM30 (Gamache 2004, USGS 2006*d*) and GTOPO30 DEMs (see the relevant sections on the SRTM and on the STRM data preparation above for more details on these two datasets), which were stored in ESRI™ grid format, as these are the only DEM datasets available for all of Africa.

Terrain typology

The terrain typology is based on the SRTM30 data. A half-degree resolution, 15-class terrain typology was derived from this DEM based on a combination of the average SRTM30 elevation within each half degree pixel and the relief roughness of the SRTM30 data within the pixel, defined as the range of SRTM30 elevation values in the pixel divided by half the pixel length connecting the centre of each grid pixel (Meybeck *et al.* 2001). For simplification, we aggregated these 15 classes into six major terrain units (TU), which have similar land surface characteristics. The relief classes (1) plains, (2) mid-altitude plains and (3) high-altitude plains were grouped into PLAINS; (4) lowlands, (6) platforms, (7) low plateaux, and (8) mid-altitude plateaux were grouped into PLATEAUX; (9) high plateaux and (10) very high plateaux were grouped into HIGH PLATEAUX; (5) rugged lowlands and (11) hills were grouped into HILLS, (12) low mountains, (13) mid-altitude mountains were grouped into MOUNTAINS, and; (14) high mountains, and (15) very high mountains were grouped into HIGH MOUNTAINS. Figure 4 shows the original 15 terrain classes for Africa and their grouping into six major terrain units.

The sizes of TU are quite different across Africa. Void size is also significantly different between TU. Therefore we used that as additional stratification factor, which allowed us to assess differences between TU (Figure 5). The highest percentage of void area per total TU area is reached in PLAINS, which can be attributed to the dunes in desert areas, followed by voids in HIGH MOUNTAINS. The PLAINS cover between 30- 50% of all large void areas (void-size groups G and H), with a percentage around 20 % for all other size classes. HIGH MOUNTAINS on the other hand covers shows an increase from 20% to 30% over all size classes (except theH size class). A decreasing percentage of voids can be observed for PLATEAUX, MOUNTAINS and HILLS with increasing void size, whereas the HIGH PLATEAUX show a strong increase in percentage of voids with increasing size class (Figure 5).

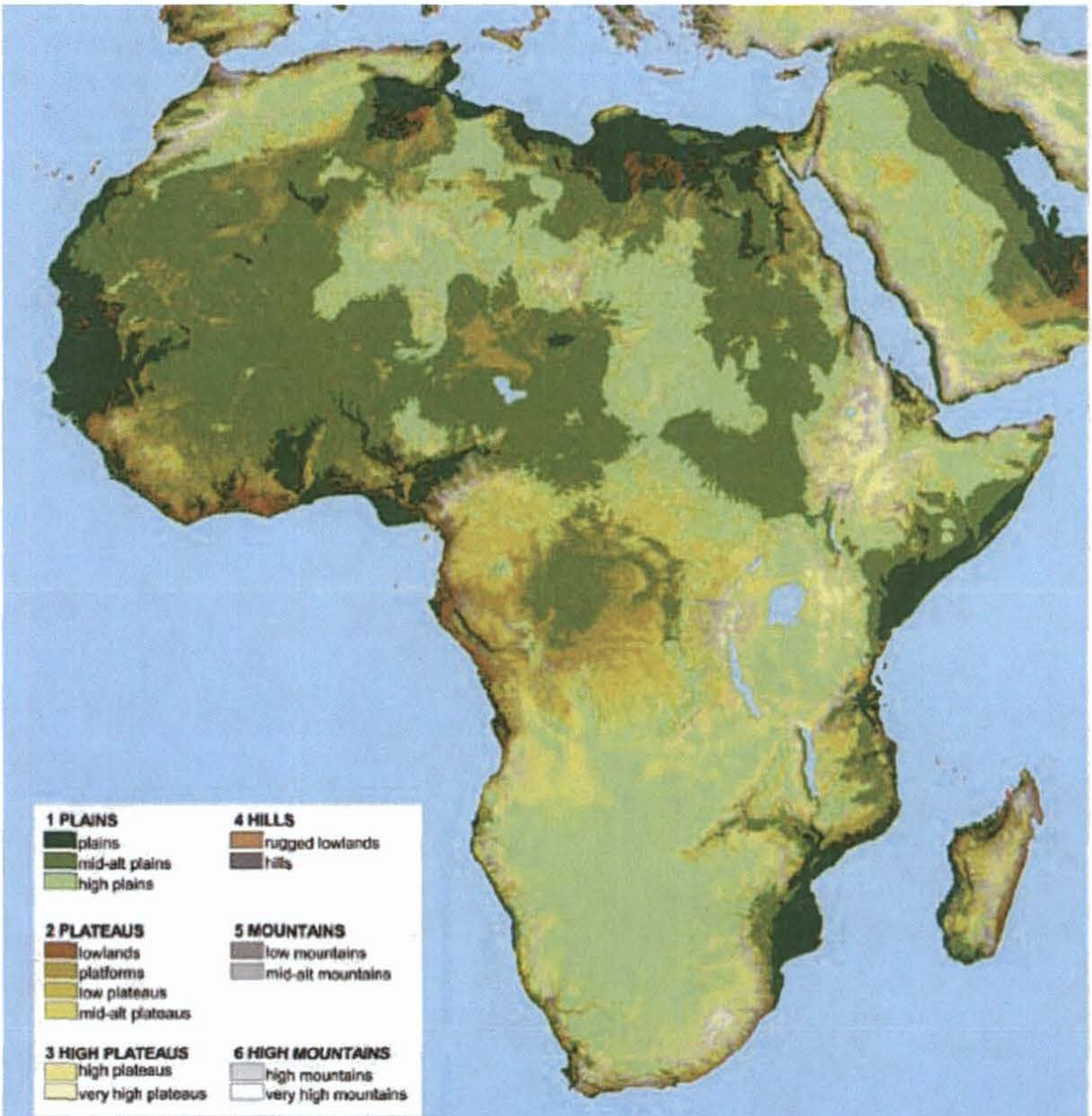

Figure 4. A 15 class terrain typology for Africa, based on the methodology proposed by Meybeck *et al.* (2000).

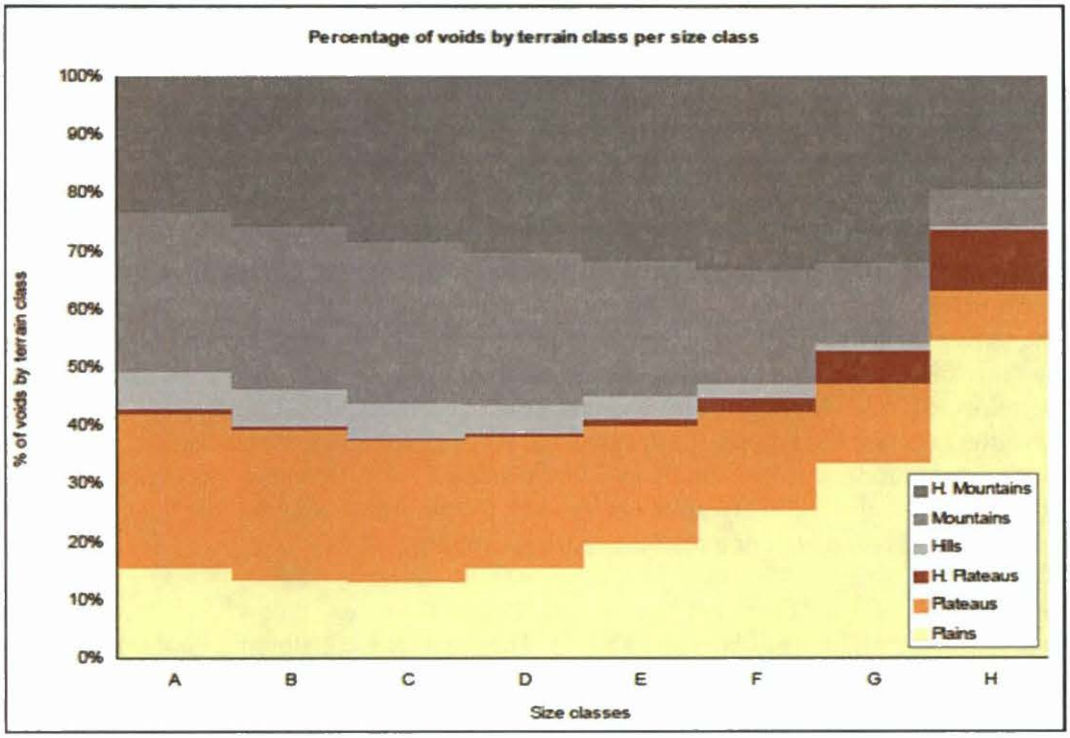

Figure 5. Percentage of voids per terrain unit and void size class for the global dataset.

Void selection

The voids were sampled using the following procedure. We first identified the terrain unit of each of the 1,168,136 voids. For the few occasions where a void lay in the boundary between two terrain units, it was assigned to the terrain unit in which the greater area of the void lay. No TU was assigned in the very few cases where a void was evenly distributed over two or more terrain units. In the cases where the half degree resolution TU map did not extend over coastal voids, the closest TU pixel (almost always PLAINS) was assigned to the void. Secondly, the previously discussed size class was assigned to each void. The distribution of all the voids by terrain unit and size class is shown in Table 1. The distribution by terrain units agrees with the findings of Falorni *et al.* (2005), but we have found no corresponding study for the distribution of void sizes and void size by TU.

Table 1. Number of global voids by terrain unit and void size (A-H).

	A	B	C	D	E	F	G	H	Sum
PLAINS	458,851	27,968	7,414	3,746	1,810	1,453	552	437	502,231
PLATEAUX	765,745	54,739	13,700	5,425	1,831	965	223	67	842,695
H. PLATEAUX	24,056	1,082	278	171	107	128	91	85	25,998
HILLS	195,055	13,097	3,286	1,157	339	157	21	5	213,117
MOUNTAINS	789,587	58,258	15,673	6,319	2,125	1,108	228	51	873,349
H. MOUNTAINS	680,952	53,497	15,825	7,235	2,869	1,888	523	154	762,943
Sum	2,914,246	208,641	56,176	24,053	9,081	5,699	1,638	799	3,220,333*

*The total number of voids in this table does not sum to 3,399,913 due to some voids not being assigned terrain units. The vast majority of these unassigned voids are in coastal areas and should be classed as PLAINS.

Within each terrain unit we randomly selected 15 voids based on their size distribution (i.e. we selected more small voids than large ones in a given terrain unit if small voids occurred more frequently). We then duplicated each of these voids a number of times, again in relation to their size distribution, and manually relocated them to neighbouring locations within the same terrain unit, ensuring that the void was relocated to a similar landscape and that it did not overlap with existing voids. For example, a small void (size class A) in TU PLAIN would be duplicated 15 times and moved to 15 neighbouring locations in TU PLAIN to create 15 voids for analysis. Duplication of real void areas ensures that the shape, size and orientation of the artificial voids are representative of real voids. However, it does risk the creation of artificial voids in areas of the terrain that are not representative of the terrain of the real void. To ensure that we relocated the voids to comparable terrain, we employed (i) visual inspection of the terrain and (ii) computed the mean and standard deviation of the elevation in a buffer zone surrounding the real void and compared it the mean and standard deviation of the elevation in buffer zones surrounding the relocated void. No significant changes could be observed in the standard deviation of the surrounding elevation between the groups of relocated and the real voids across the original 15 terrain types (based on a *t* test), except for rugged lowlands and low plateaux. No differences were observed when the results were aggregated into the six TU (results not shown). Therefore we assume that the visual relocation was an acceptable approach for generating realistic artificial voids.

In this way we created 1,304 artificial but realistic voids based on real void characteristics distributed across six terrain units and eight size classes (Table 2). These voids were stored as polygon coverages in ArcInfo.

Table 2. Number of artificial voids by terrain unit and void size (A-H).

	A	B	C	D	E	F	G	H	Sum
PLAINS	45	45	60	60	45	15	15	15	300
PLATEAUX	65	60	75	80	60	20	28	12	400
H. PLATEAUX	30	40	40	40	35	10	5	0	200
HILLS	15	20	25	20	20	0	0	0	100
MOUNTAINS	30	40	39	40	30	10	14	6	209
H. MOUNTAINS	15	15	20	30	5	5	5	0	95
Sum	200	220	259	270	195	60	67	33	1,304

Data pre-processing for the artificial voids

A working area for each single void was created by enlarging the maximum extent of the void by 100 pixels in all directions and extracting the underlying DEM data within this buffer zone. The number of pixels for this buffer was based on empirical testing of the algorithm under different TU (results not shown). We then 'punched out' the void from this buffered area and used the remaining 'ring' of DEM data to create (i) elevation spot heights or points, with one point for each DEM pixel, and, (ii) contours at 10 m intervals. There were occasions where it was not possible to extract contours from the buffered region, for example where the terrain was extremely flat. In these cases we employed an iterative process to decrease the contour interval until a contour layer could be created (the lower limit was 1 m). Where this process did not result in a contour layer, we extended the buffer up to a maximum threshold of 0.1 degrees. These contours were stored as line or point coverages in ArcInfo.

Auxiliary spot height elevation data was extracted from the SRTM30 and GTOPO30 at 30 arc second spacing unless either one of two restrictions were met. The first restriction is the size of the void (coarse auxiliary data will not help in the interpolation of small voids); and the second considered the shape of the void (e.g. a long, thin void is better filled with only the surrounding DEM data).

SRTM data have a high absolute accuracy in contrast to GTOPO30 and to account for such differences we adjusted the elevation values in the GTOPO30 DEM as follows. For each void, the auxiliary DEM was re-sampled to the resolution of the SRTM dataset and the void area was punched out from this re-sampled auxiliary dataset. The difference in elevation between both datasets was used to raise or lower the elevation values for the original resolution auxiliary dataset. We thereby accounted for some differences between datasets (i, ii, vii) as outlined in the section on the SRTM above. We did not make any adjustments for other errors (e.g. geometrical location or trends in the auxiliary data). The spot heights were stored as point coverages in ArcInfo.

The SRTM elevation from the void stamped area constitutes the 'truth' layer against which the results from the VF algorithms were compared. Essentially, this is equivalent to withholding pixels from the interpolation process and then comparing the results from the VF algorithms against them afterwards (see also Yang and Hodler 2000).

Thus, for each of the 1,304 voids we created a truth DEM, a set of contours and spot heights buffering an artificial void area, and where applicable, two auxiliary spot height datasets.

Void filling methods

The procedure for applying and evaluating the VF algorithms is outlined in Figure 6 and described in detail in the following sections. Unless otherwise stated, all processing was carried out in ArcInfo Workstation 9.1 using Arc macro language (AML) routines and standard ArcInfo interpolation functions from the Arc and Grid environments. The results of the VF methods were projected from geographic projection (latitude/longitude) into Mollweide Equal Area projection where the longitude of the projection centre was the longitude of the centroid of the void, and both vertical and horizontal units were in metres.

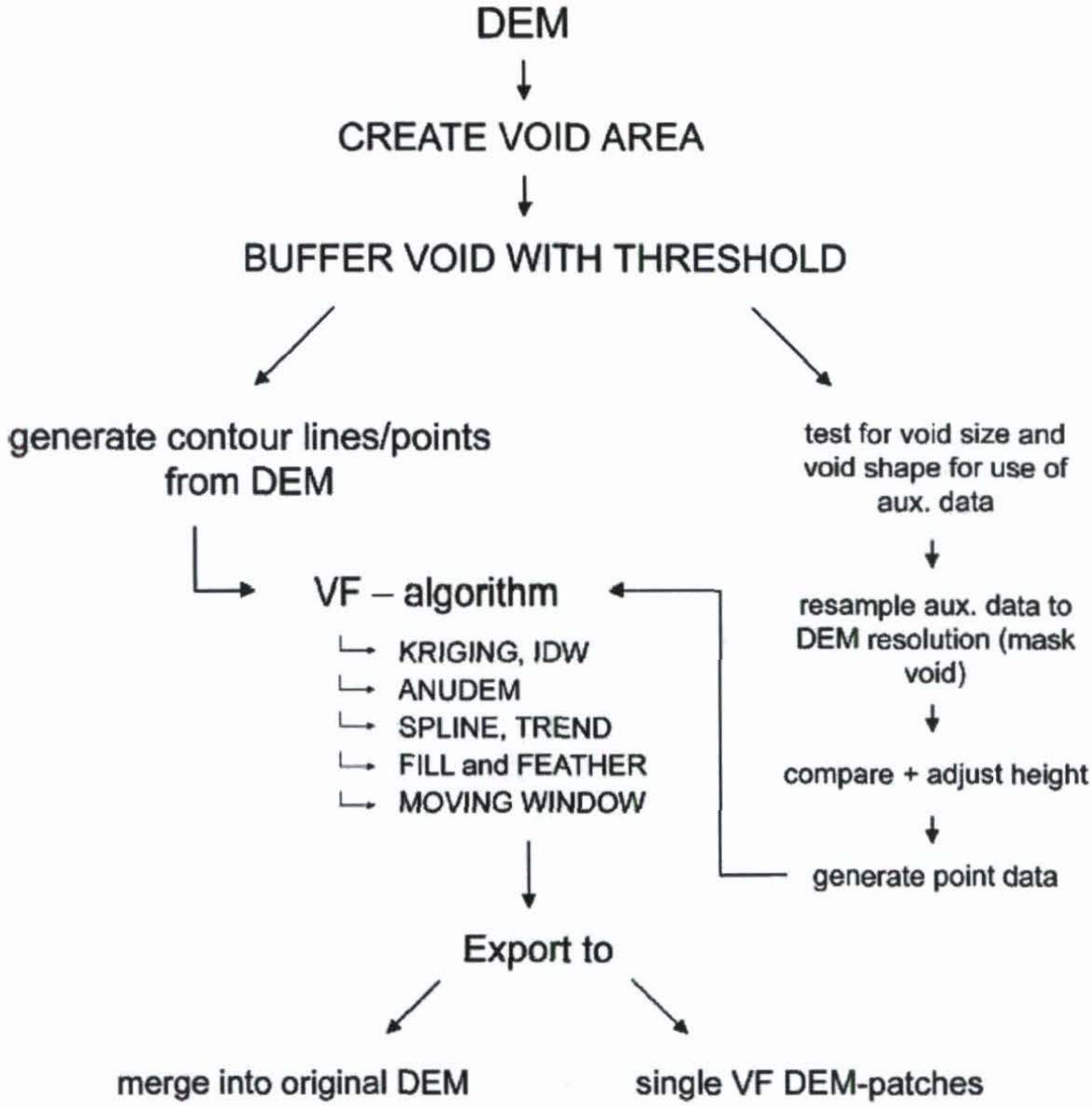

Figure 6. Flow diagram of the VF algorithm assessment methodology.

Void filling methods

The following eight VF algorithms were implemented:

i) Kriging (KR), ii) Spline (SP), iii) Trend (TR), iv) Inverse Distance Weighting (IDW), v) Moving Window Average (MW), vi) *Fill* and *Feather* (FF), *vii*) *Triangulated Irregular Network* (TIN) and viii) ANUDEM (ANU).

The geostatistical methods (KR, SP, TR and IDW) require several input parameters, but we used default values wherever possible, since it was too complex and too time consuming to adjust the parameters for each method and each void. One might criticise this approach since adjusting the parameters could improve the interpolations on a case by case basis. However since the VF algorithms are all well-known and long-standing implementations, we assume that the default values provide reasonable results under most conditions.

The implementation for KR is based on McBratney and Webster (1986), using a spherical semi-variogram model with an automatically fitted function. We used a tenth-order linear polynomial regression (based on manual testing, results not shown) for TR. The SP method follows Franke (1982) and Mitas and Mitasova (1988) and performs a two-dimensional minimum-curvature spline interpolation resulting in a smooth surface that passes exactly through the input points. In this case we used regularised splines, which yield a smooth surface. We did not test tension splines as in Mitasova and Hofierka (1993), even though it is available as an option in ArcInfo. IDW was implemented following Watson and Philip (1985) based on the 12-nearest neighbouring points.

MW interpolates the void area by computing elevation values in the void pixels next to the void boundary based on the local average of the neighbouring elevation pixels. This process continues inwards until all void pixels are filled. For FF, we re-sampled the auxiliary information to the resolution of the truth DEM, buffered it inwards, filled in the void using this re-sampled auxiliary DEM, and closed any remaining void pixels applying the MW method with a 3×3 pixel window. More advanced approaches are possible, which alter the surface of the original DEM (Dowding *et al.* 2004), however these were not implemented here. MW and FF are complementary in that MW is used where there is no auxiliary DEM, and FF is used where there is.

For TIN, which is by definition a triangular network of mass points with 3D-coordinates connected by edges to form a triangular tessellation, the weed tolerance (the minimal tolerance between two data points at a line) was set to 0.0001 of the maximum extent of the input data set, whereas the proximal tolerance (minimal distance between single data points) was set to the machine precision of the host computer.

The ANU approach (Hutchinson 1989, Hutchinson and Dowling 1991) is implemented in ArcInfo as TOPOGRID, and creates a hydrologically correct DEM using a multi-resolution iterative finite difference interpolation (extended spline) method, which ensures that ridges are maintained, streams are enforced and spurious sinks are removed. The ANU approach contains three parameters that are used for the smoothing of the input data and the removing of sinks (ESRI 2000). The TOL1 tolerance was initially set to 5 m (half the height difference between contours); however, if the maximum elevation difference observed in the data preparation dataset was below the contour interval, it was set to half that value. Values for the horizontal and vertical standard errors were set to one and zero respectively.

The authors limited the number of implementations to the above described algorithms, though even more advanced algorithms (Soile 1991, Hofer *et al.* 2006) look advantageous. If needed, more advanced algorithm e.g. conditioned simulations (Holmes *et al.* 2000) could be implemented in the processing chain.

Evaluation

For each void we applied the seven VF algorithms three times, once with no auxiliary data, and once each with the SRTM30 and GTOPO30 information, resulting in 21 DEMs, plus the reference DEM. A visual example of the results from each VF algorithm for a set of voids is shown in Figure 7. Figure 7a shows the void to be filled, whereas the other examples (b to i) present the different VF results. The effect of coarse resolution auxiliary data is clearly visible in Figure 7i with the Fill and Feather approach. In Figure 7h the extrapolation by moving window shows some limitation as extrapolation from the borders of the void occurs. The geostatistical algorithms in Figures 7d, e and f show only slightly different visual appearances, e.g. the representation of the peak on the left side of the large voids. Finally, the TIN and ANUDEM approaches show slightly different elevation surfaces, with TIN creating a ridge in the major void (Figure 7c), which is not visible in the hydrologically correct ANUDEM surface (Figure 7b).

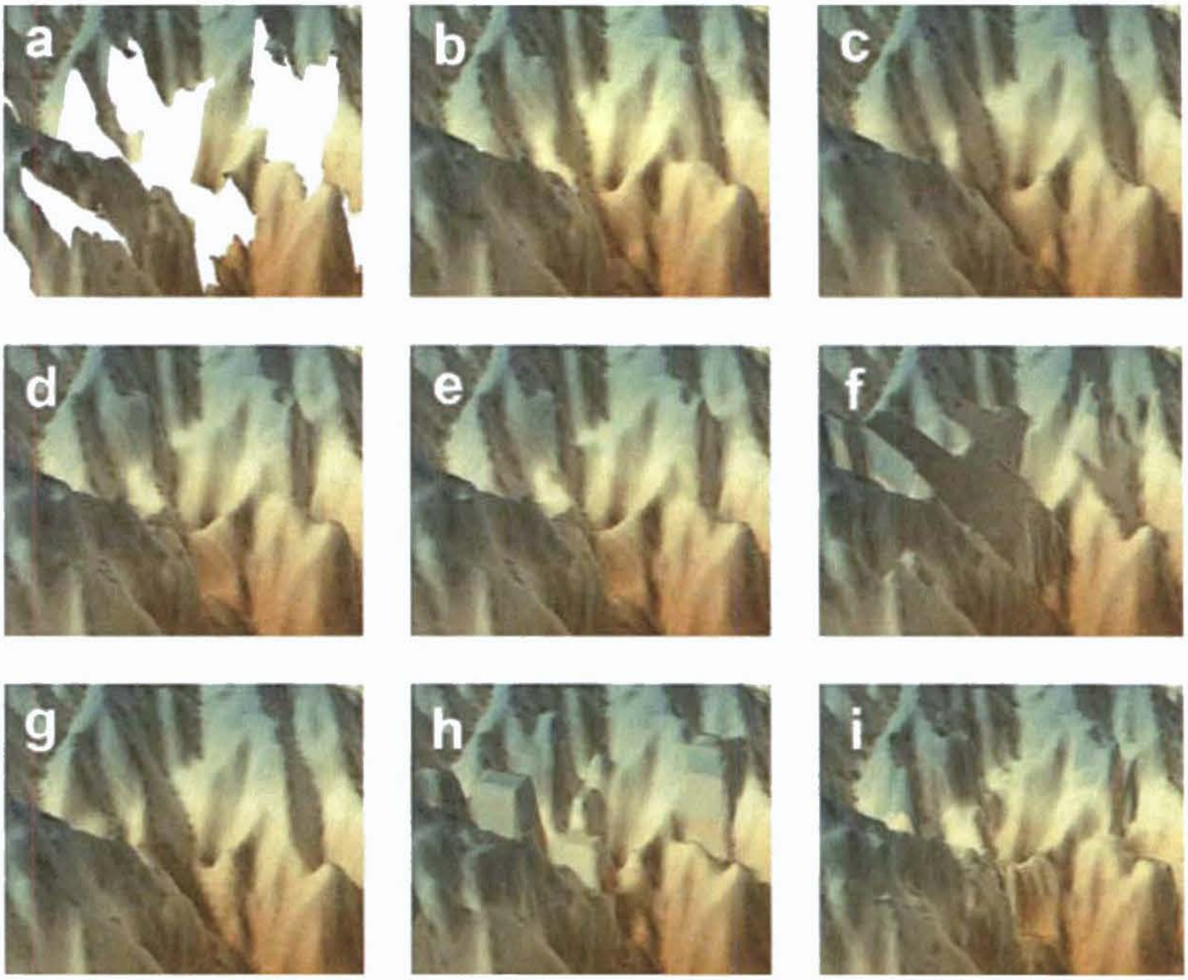

Figure 7. Examples of the VF algorithms applied to a test area (a) in the SRTM DEM. The methods are (b) TOPOGRID, (c) TIN, (d) IDW, (e) Spline, (f) Kriging, (g) Trend, (h) Moving Average, and (i) Fill and Feather.

We compared the elevation of the reference DEM (z_{Ref}) to the 21 DEM (z_{DEM}) by computing the root mean square error (RMSE), Pearson's correlation coefficient (ρ), the average difference (μ), the sum difference (γ) and the standard deviation of the difference between both surfaces (σ). Additionally, we computed the area for each void.

We chose an evaluation based on the total area of the void similar to Grohman *et al.* (2006) in contrast to a selected number of GCP (Dowding *et al.* 2004).

The RSME was computed between the reference elevation and the 21 elevation surfaces. Each void-filled DEM patch was ranked from 1 (lowest RMSE) to 7 - or 21 for a comparison across all variations - (highest RMSE). The distribution of the ranking relative to terrain and void size was assessed by summarising the ranking results by: (i) terrain unit, (ii) size class, (iii) terrain unit and size class and (iv) auxiliary datasets.

Fisher and Tate (2006) argue that the RMSE is not necessarily a good estimator of the error, recommending the mean error (ME) and the error standard deviation (S), where n is the number of pixels in the void:

$$ME = \frac{\gamma}{n}$$

$$S = \sqrt{\frac{\sum\left[(z_{Dem} - z_{\mathrm{Re}f}) - ME\right]^2}{n-1}}$$

We performed the comparative analysis based on RMSE, ME and S and observed consistent best VF results for different TU/void size classes for RSME and S. ME showed diverse rankings of different algorithms. For the remaining course of this paper we provide results for RSME only, and discuss the S and ME results where appropriate. We are aware that a global statistic was used to compare the filled voids against the truth surface, rather than evaluation methods that take the spatial pattern of errors into account or which identify the different factors which led to that error.

Results

Evaluation of the void filling algorithms with respect to terrain unit

Table 3 shows the statistical summary of the ranking results when the void is classified by its terrain unit, irrespective of the size of the void. The Table 3 shows the mean and standard deviation (in parentheses) of the ranking of each VF method for each terrain unit, with and without an auxiliary DEM. The geostatistical method KR and the mechanical method SP (e.g. no assessment of the uncertainty of the model is possible) are consistently the "best" methods, with KR performing better in flatter areas (PLAINS, PLATEAUX AND HIGH PLATEAUX) and SP performing better in mountainous terrains (HILLS, MOUNTAINS AND HIGH MOUNTAINS). Differences between VF methods in RMSE can triple (e.g. see first row differences between
KR (6.04 and SP 17.40), which agrees with the Fisher and Tate (2006) statement that no single interpolation method exists that is the most accurate for the interpolation of terrain data.

Still, the "best" method in Table 3 sometimes contains groups of two different VF methods, almost similar in RSME results. An example is the VF for PLAINS without any auxiliary DEM, where KR (6.04) and IDW (6.44) show similar results (similar results = ± 1 RMSE difference). On the contrary SP, MW and ANU are the most variable in terms of performance. On the other hand, for certain TU, e.g. in HIGH MOUNTAINS, the algorithm SP (4.06) shows the "best" performance, with results of all other algorithms being quite different.

Related to that last observation, the standard deviation, which is larger than for all other VF methods in that TU, suggests that there were several voids where SP performed poorly. Therefore the SD is a good indicator of the general applicability of the VF algorithm for a given TU. In this case, it would be advisable to check further to identify cases that are not well handled (e.g. it could be an effect of the void size) and to rerun the analysis.

Generally, the use of auxiliary information of the GTOPO30 dataset increased the RMSE for all VF methods except for small improvements in TR. This might be attributed to the different types of errors not accounted for in our methodology (see also the section on the SRTM above).

The use of SRTM30 as an auxiliary dataset decreased the RMSE/S for most case, and decreased the standard deviation indicating less variation in the level of improvement. This is not surprising since SRTM30 is an up-scaled and void-filled derivative of the SRTM data. One could argue that the use of SRTM30 should be preferred, however in practice this means that we are down-scaling data (SRTM30 to SRTM) from a previous up-scaling (SRTM to SRTM30)! This circularity may be acceptable in certain cases if we know how the SRTM30 data were generated in the area of the particular void we are filling. This problem is discussed further below.

Table 3. Mean and standard deviation (in brackets) of the RMSE ranking for each method by terrain unit. Best results are in bold.

	No auxiliary DEM						
	KR*	SP	TR	IDW	MW	TIN	ANU
PLAINS	**6.04 (3.82)**	17.40 (4.15)	9.79 (5.60)	6.44 (3.76)	10.6 (5.06)	8.52 (4.66)	10.00 (5.18)
PLATEAUX	**5.71 (4.12)**	9.79 (6.75)	16.40 (3.76)	10.50 (3.83)	10.70 (4.21)	6.74 (3.91)	7.02 (4.37)
H. PLATEAUX	**5.18 (3.56)**	6.23 (6.24)	17.50 (2.06)	11.50 (3.07)	11.10 (3.35)	6.88 (3.53)	7.01 (4.04)
HILLS	5.79 (4.39)	**5.36 (5.62)**	17.50 (2.18)	11.50 (3.35)	10.70 (3.95)	7.01 (3.41)	8.36 (4.17)
MOUNTAINS	5.95 (3.82)	**5.16 (5.77)**	17.10 (3.35)	12.20 (2.99)	11.30 (3.29)	7.14 (3.83)	7.78 (3.81)
H. MOUNTAINS	5.97 (3.50)	**4.06 (4.93)**	17.50 (2.28)	12.90 (2.46)	12.60 (2.79)	6.46 (3.31)	8.24 (3.95)
	GTOPO30						
	KR	SP	TR	IDW	FF	TIN	ANU
PLAINS	**7.25 (4.72)**	17.50 (4.02)	9.74 (5.51)	6.44 (3.76)	15.70 (6.48)	10.40 (5.30)	11.8 (5.39)
PLATEAUX	**6.00 (4.24)**	10.20 (6.98)	16.30 (3.69)	10.50 (3.82)	18.60 (4.37)	7.75 (4.54)	7.72 (4.74)
H. PLATEAUX	**5.83 (4.27)**	6.86 (6.83)	17.20 (2.23)	11.50 (3.06)	19.60 (2.46)	8.20 (4.21)	7.94 (4.46)
HILLS	5.83 (4.31)	**5.71 (5.90)**	17.40 (2.17)	11.50 (3.36)	19.30 (3.40)	7.25 (3.54)	8.44 (4.28)
MOUNTAINS	**6.39 (4.33)**	6.90 (7.26)	17.00 (3.15)	12.20 (2.98)	17.90 (4.79)	8.35 (4.59)	8.54 (4.03)
H. MOUNTAINS	6.14 (3.83)	**4.47 (5.77)**	17.40 (2.33)	12.90 (2.46)	18.60 (3.83)	6.91 (3.86)	8.53 (4.05)
	SRTM30						
	KR	SP	TR	IDW	FF	TIN	ANU
PLAINS	**5.67 (3.79)**	16.70 (4.30)	9.65 (5.49)	6.44 (3.76)	10.00 (6.38)	7.97 (4.98)	9.97 (5.31)
PLATEAUX	**5.28 (3.93)**	9.34 (6.39)	16.20 (3.72)	10.50 (3.82)	15.50 (5.58)	6.65 (3.99)	6.69 (4.49)
H. PLATEAUX	**5.22 (3.48)**	5.94 (6.03)	17.30 (2.20)	11.50 (3.06)	17.20 (3.78)	7.43 (3.81)	7.36 (4.18)
HILLS	5.68 (4.23)	**5.39 (5.51)**	17.40 (2.14)	11.50 (3.36)	16.30 (4.49)	6.88 (3.45)	8.30 (4.30)
MOUNTAINS	5.49 (3.86)	**5.02 (5.49)**	17.00 (3.22)	12.20 (2.98)	15.50 (4.74)	6.97 (4.05)	7.50 (4.03)
H. MOUNTAINS	5.63 (3.30)	**3.86 (4.49)**	17.50 (2.18)	12.90 (2.46)	16.70 (3.99)	6.38 (3.29)	8.00 (4.07)

Evaluation of void filling methods with respect to void size

Table 4 shows the statistical summary of the ranking results when the void is classified by size. Again, the table shows the mean and standard deviation (in parentheses) of the ranking of each VF method for each size class, with and without an auxiliary DEM. In this classification of voids, KR is consistently the best method for small and medium sized voids, regardless of the use of auxiliary data. If auxiliary data are used, KR performed best up to void-size class F compared with up to void-size class D without auxiliary information. The reason behind this is probably that the KR delivers an average elevation surface, which closer resembles the reference DEM, in contrast to the TIN dataset. In TIN the relationship between triangles and their adjacent neighbours are handled more stringently, more closely resembling the input dataset.

For large and very large voids, the inclusion of an auxiliary DEM has an obvious effect on the performance of the algorithms. TIN is better where there is no auxiliary information, IDW is better where GTOPO30 is used and TIN or ANU are best when SRTM30 is used. One might speculate on the differences between the auxiliary datasets. One possible explanation is that TIN/ANU requires 'good quality' auxiliary information, whereas IDW as a geostatistical algorithm that generates an "average surface" as mentioned earlier.

Evaluation of void filling methods with respect to terrain unit and void size

Table 5 shows the best method for the final classification based on both terrain unit and void size, resulting in 48 possible void typologies, although as can be seen from Table 5a, six of these typologies contain no voids (HIGH PLATEAUX in particular is a rare terrain unit) and the number of voids per typology varies from 80 to 3. Tables 5a to 5c show the best performing VF algorithm for each typology, again using no auxiliary DEM (Table 5a), GTOPO30 (Table 5b) and SRTM30 (Table 5c). The table cells are shaded to help interpretation.

Table 4. Mean and standard deviation (in brackets) of the RSME ranking for each method by void size class. Best results are in bold.

	No auxiliary DEM						
	KR*	SP	TR	IDW	MW	TIN	ANU
A	**6.20 (3.84)**	16.60 (4.74)	9.26 (5.97)	6.94 (3.89)	10.60 (5.45)	9.01 (4.89)	10.00 (5.45)
B	**5.56 (3.99)**	14.40 (6.74)	13.00 (5.23)	7.66 (4.52)	10.70 (4.71)	7.94 (4.40)	9.16 (4.82)
C	**5.74 (4.05)**	9.77 (6.74)	16.80 (3.30)	10.70 (3.53)	10.70 (3.89)	6.27 (3.48)	6.70 (4.18)
D	5.74 (4.28)	**4.49 (4.95)**	17.70 (1.35)	12.00 (2.99)	11.00 (3.70)	6.89 (3.26)	8.15 (4.10)
E	**5.52 (3.88)**	5.33 (5.73)	17.30 (2.77)	12.00 (3.16)	11.40 (3.39)	7.15 (3.81)	7.80 (4.05)
F	6.62 (3.50)	**5.86 (5.97)**	16.70 (4.29)	11.60 (2.95)	9.95 (2.84)	6.67 (3.80)	6.41 (3.23)
G	5.68 (3.36)	**4.22 (5.64)**	17.60 (1.72)	12.80 (2.48)	12.70 (2.98)	6.74 (3.40)	9.07 (3.85)
H	7.20 (3.64)	6.36 (6.53)	17.40 (3.24)	13.00 (2.37)	12.60 (2.32)	**6.00 (3.01)**	6.16 (3.14)
	GTOPO30						
	KR	SP	TR	IDW	FF	TIN	ANU
A	**6.53 (4.15)**	16.80 (4.69)	9.16 (5.93)	6.94 (3.89)	14.80 (7.07)	9.65 (5.35)	10.60 (5.56)
B	**6.89 (5.03)**	14.40 (6.66)	13.00 (5.11)	7.66 (4.51)	16.30 (5.94)	10.10 (5.12)	11.00 (5.43)
C	**6.14 (4.25)**	10.30 (7.05)	16.60 (3.22)	10.70 (3.53)	19.60 (2.78)	7.55 (4.44)	7.62 (4.68)
D	5.75 (4.20)	**4.81 (5.28)**	17.60 (1.37)	11.90 (2.99)	19.50 (2.54)	7.13 (3.40)	8.22 (4.21)
E	**5.83 (4.19)**	5.64 (6.08)	17.20 (2.82)	12.00 (3.16)	18.00 (4.85)	7.77 (4.14)	8.23 (4.19)
F	**8.31 (4.81)**	12.00 (8.39)	16.20 (3.62)	11.60 (2.92)	19.80 (1.63)	10.70 (5.32)	8.91 (4.31)
G	5.57 (3.26)	**4.11 (5.41)**	17.50 (1.79)	12.80 (2.48)	17.90 (4.26)	7.00 (3.65)	9.20 (3.87)
H	7.73 (4.44)	7.66 (8.02)	16.90 (3.30)	13.00 (2.37)	20.00 (1.66)	**7.43 (4.65)**	7.10 (3.99)
	SRTM30						
	KR	SP	TR	IDW	FF	TIN	ANU
A	**6.26 (3.84)**	16.5 (4.74)	9.21 (5.94)	6.94 (3.89)	10.50 (6.51)	8.85 (5.06)	10.10 (5.47)
B	**4.96 (3.81)**	13.40 (6.37)	12.80 (5.21)	7.66 (4.51)	11.20 (6.83)	7.35 (4.65)	8.90 (5.00)
C	**5.21 (3.84)**	9.20 (6.29)	16.60 (3.24)	10.70 (3.53)	16.00 (5.00)	6.15 (3.59)	6.32 (4.29)
D	5.64 (4.12)	**4.51 (4.82)**	17.70 (1.30)	11.90 (3.00)	16.80 (3.87)	6.79 (3.30)	8.09 (4.22)
E	5.53 (3.85)	**5.21 (5.63)**	17.20 (2.81)	12.00 (3.16)	16.60 (4.36)	7.43 (3.93)	7.96 (4.09)
F	**5.65 (3.80)**	6.65 (6.48)	16.30 (3.89)	11.60 (2.92)	14.70 (4.01)	6.46 (4.38)	5.95 (3.46)
G	5.17 (3.31)	**3.15 (3.50)**	17.50 (1.75)	12.80 (2.48)	16.20 (5.12)	6.38 (3.49)	8.64 (4.30)
H	6.10 (3.28)	**5.73 (5.66)**	17.20 (2.99)	13.00 (2.37)	16.00 (3.49)	5.76 (2.89)	5.40 (3.08)

*Methods are Kriging (KR), Spline (SP), Trend (TR), Inverse Distance Weighting (IDW), Moving Window Average (MW), Fill and Feather (FF), Triangulated Irregular Network (TIN), and ANUDEM (ANU).

The first observation is that KR outperforms any other VF algorithm for very small voids (Class A), except in High Mountains, where SP is better. Secondly, for very large voids in mountainous terrain (arguably the most difficult voids to interpolate), ANU and TIN are the best, with ANU being superior when SRTM30 is used. Other noticeable trends include IDW in planar areas for large voids with no DEM or GTOPO30, and SP for medium to large voids (Classes C to F) for all terrain units except Plains, and especially for Mountains and High Mountains.

A test of the SD of the RSME for the different methods showed a similar distribution across all VF methods, void sizes and terrain units, which allows us to be quite confident in the results presented here. One exception is however for the largest void class (H) in the terrain unit PLAINS and PLATEAUX for the VF method SP. The reason for that exception might be attributed to the relatively low number of investigated voids in that class.

Table 5. Best method results in terms of average rank by terrain unit and void size using (a) no auxiliary DEM, (b) GTOPO30 auxiliary data, (c) SRTM30 auxiliary data, and (d) across all data methods.

(a) No auxiliary	Void size							
Terrain unit	A	B	C	D	E	F	G	H
PLAINS	*KR 6.11	IDW 6.11	KR 5.70	KR 6.95	IDW 4.43	IDW 4.66	KR 4.80	TIN 5.00
PLATEAUX	KR 5.92	KR 4.98	KR 4.48	SP 5.34	ANU 4.31	ANU 5.30	ANU 5.60	TIN 6.75
H. PLATEAUX	KR 3.33	SP 3.65	SP 4.75		TIN 5.05			
HILLS	KR 4.83	KR 4.07	KR 4.05	ANU 4.40	SP 1.57	SP 4.80	MW 5.20	
MOUNTAINS	KR 5.30	KR 4.97	SP 3.84	SP 1.55	SP 4.86	TIN 6.00	TIN 4.88	ANU 8.33
H. MOUNTAINS	SP 2.40	KR 4.40	SP 2.35	SP 2.40	SP 2.40	ANU 2.20	TIN 7.20	

(b) GTOPO30	Void size							
Terrain unit	A	B	C	D	E	F	G	H
PLAINS	KR 6.11	IDW 6.11	KR 5.70	IDW 7.51	IDW 4.42	IDW 4.66	IDW 5.53	IDW 8.00
PLATEAUX	KR 5.82	KR 4.98	KR 4.48	SP 5.29	ANU 5.53	KR 6.80	IDW 8.18	KR 9.72
H. PLATEAUX	KR 3.36	SP 3.65	SP 4.75		IDW 8.95			
HILLS	KR 4.83	KR3.90	KR 4.05	ANU 4.40	SP 1.51	ANU 7.60	ANU 6.80	
MOUNTAINS	KR 5.30	KR 4.95	SP 3.84	SP 1.55	KR 7.06	KR 9.50	ANU 9.94	KR 7.00
H. MOUNTAINS	SP 2.40	KR 4.40	SP 2.35	SP 2.40	SP 2.40	IDW 10.60	ANU 4.60	

(c) SRTM30	Void size							
Terrain unit	A	B	C	D	E	F	G	H
PLAINS	KR 6.11	IDW 6.11	KR 5.70	KR 6.80	IDW 4.42	KR 4.00	KR 3.00	TIN 2.33
PLATEAUX	KR 5.77	KR 4.98	KR 4.48	SP 5.29	ANU 4.30	KR 4.95	ANU 3.53	ANU 1.83
H. PLATEAUX	KR 3.60	SP 3.65	SP 4.75		KR 5.90			
HILLS	KR 4.83	KR 4.02	KR 4.05	ANU 4.40	SP 1.57	KR 5.80	ANU 1.60	
MOUNTAINS	KR 5.30	KR 4.95	SP 3.84	SP 1.55	KR 4.86	KR 4.30	ANU 4.88	ANU 1.00
H. MOUNTAINS	SP 2.40	KR 4.40	SP 2.35	SP 2.40	SP 2.40	ANU 3.80	ANU 1.60	

(d) All cases**								
Terrain unit	A	B	C	D	E	F	G	H
PLAINS					IDW+no aux	KR+sr30	KR+sr30	TIN+sr30
PLATEAUX					ANU+sr30	KR+sr30	ANU+sr30	ANU+sr30
H. PLATEAUX					SP+gt30	SP+no aux	ANU+sr30	
HILLS					TIN+noaux			
MOUNTAINS					SP+noaux	TIN+sr30	ANU+sr30	ANU+sr30
H. MOUNTAINS					SP+gt30	ANU+noaux	ANU+sr30	

* Methods are Moving Window Average (MW), Kriging (KR), Spline (SP), Inverse Distance Weighting (IDW), Triangulated Irregular Network (TIN), and ANUDEM (ANU).

**No auxiliary DEM (no aux), SRTM30 (sr30) and GTOPO30 (gt30).

Looking across tables 5a to 5c, the use of coarse resolution auxiliary DEM data has little or no impact on the results for void size classes A through D, but the possible inclusion of such auxiliary information becomes important for the larger void classes (E through H). If a VF algorithm is to be recommended for these void sizes for global application, then we must differentiate between the three choices for auxiliary information.

Table 5d shows the best performing VF algorithm and the auxiliary information that was used for all terrain units for size classes E through H. Looking only at the auxiliary DEM results, we can see that SRTM30 is the preferred auxiliary DEM for very large voids (size classes G and H), whilst there is no one recommended auxiliary DEM for classes E and F. Looking at the VF method and auxiliary information together, KR always uses SRTM30, and ANU always uses SRTM30, except for the PLAINS, where a variety of methods is recommended based on the void size class. A mixture of VF algorithm is recommended for medium size voids (E-F) based on the TU (IDW for Plains, TIN for HILLS, and SP/ANU for the remaining TU).

It is interesting to see that certain algorithms deliver the best results without auxiliary information (e.g. recommending SP without any auxiliary information for size class F in high plateaux). Further investigation is required to determine why the errors without auxiliary information are less than with VF algorithms that use auxiliary information. One reason might be that we a have not sufficiently compensated for the errors in the dataset (cf. the section on the SRTM above) during the preparation of input data for the VF and this may bias the results. Another observation is that most of the recommended VF algorithms create a smooth surface which stays within the elevation range of the input data. This means that mountain ridges for example can not be represented properly, even if the RMSE/ME proves that the approximation is best for the VF patch, and that the local noise structure of the surrounding area is smoothed out. Finally, GTOPO30 is derived from a range of topographic sources, and the variation in quality of these sources across Africa is likely to have an impact on these results.

Evaluation of void filling methods with respect to auxiliary information

To determine if the inclusion of low quality auxiliary information has any improvement on the VF algorithms, for each void we computed the percentage difference between the RSME with no auxiliary information and (i) RMSE with SRTM30 and (ii) RMSE with GTOPO30. The results are summarised by void size class and terrain (Table 6) for all void sizes E through H.

Percentages lower than 100 indicate that the inclusion of auxiliary information resulted in an improvement and vice versa. A percentage equal to 100 means that the first restriction of the area threshold (cf. the section on data pre-processing for the artificial voids) has been met, however due to the second restriction (e.g. the shape of the void) the auxiliary data have not been used.

As expected, SRTM30 improves the VF results more overall than GTOP30, but surprisingly both auxiliary datasets also degrade the VF results in several cases (e.g. in mid-sized voids and in some TU - Table 6). This suggests that the area threshold should depend on the TU. For example, for VF algorithm KR in MOUNTAINS using GTOPO30, an increase in accuracy can only be observed if the void area is larger than void-size class F. Below that void-size class, GTOPO30 did not improve the VF results and even decreases accuracy. For GTOPO30, the area threshold should be only the largest class (H) for PLAINS, LOW PLATEAUX, HILLS and HIGH MOUNTAIN. For HIGH PLATEAUX no recommendation can be given (or even not to use coarse scale auxiliary information), and for MOUNTAINS the area threshold should be class G.

SRTM30 not surprisingly outperforms GTOPO30. Generally, the largest improvements for SRTM30 occur in large and very large void sizes (G and H). Similarly to GTOPO30, the area thresholds and when to use auxiliary information vary. For PLAIN, LOW PLATEAU and MOUNTAINS the void size class G is recommended; for HIGH PLATEAUX again no recommendation can be given and for HILLS and HIGH MOUNTAIN the area threshold should be set to H.

These results indicate that such coarse resolution auxiliary data is generally only applicable to extremely large voids, and highlights the need to use higher resolution auxiliary datasets in filling voids in the SRTM data, rather than the SRTM30 and GTOPO30 datasets used here.

Table 6. Average reduction in RMSE (in %) when auxiliary DEMs are used. Methods are Kriging (KR), Spline (SP), Triangulated Irregular Network (TIN), and ANUDEM (ANU).

Terrain Unit	VF Method	GTOPO30				SRTM30			
		E	F	G	H	E	F	G	H
PLAINS	KR	143	118	161	192	109	100	91	72
	SP	141	114	103	35	99	87	59	16
	TIN	171	144	218	279	107	100	99	89
	ANU	183	157	210	273	114	103	99	96
PLATEAUX	KR	105	103	119	107	99	94	95	87
	SP	110	134	157	84	99	105	96	58
	TIN	111	120	130	121	101	105	94	82
	ANU	107	115	126	120	100	100	94	81
HIGH PLATEAUX	KR	121				104			
	SP	138				100			
	TIN	144				120			
	ANU	128				112			
HILLS	KR	100	100	110	100	100	100	102	97
	SP	100	100	162	78	100	100	118	71
	TIN	100	100	112	106	100	100	101	94
	ANU	100	100	105	104	100	100	103	91
MOUNTAINS	KR	100	127	81		100	93	72	
	SP	100	161	137		100	101	84	
	TIN	100	155	94		100	114	77	
	ANU	100	149	85		100	120	71	
HIGH MOUNTAINS	KR	112	116	121	86	93	95	100	61
	SP	239	161	207	62	134	107	140	37
	TIN	122	137	235	91	95	100	180	64
	ANU	114	118	205	90	95	97	162	63

Application of the 'best' VF methods to the global SRTM data

One of the objectives of this paper has been to provide a worldwide database of voids, in which each void has an assigned "best" method based on terrain unit and void size. This has been performed based on the results in Table 5, and the database will be provided to the international user community at http://srtm.jrc.it/ and http://srtm.csi.cgiar.org/. The International Center for Tropical Agriculture (CIAT), through the Consortium for Spatial Information (CSI), has been providing ready-to-use seamless (i.e. void filled)

SRTM elevation data since 2003. These derived data have been gradually improved over three versions through the use of better interpolation algorithms (currently ANUDEM) and auxiliary DEMs.

The database of "best" VF methods could be used to create a fourth version of the seamless SRTM elevation data by identifying the voids where there is no high resolution auxiliary DEM information available (which is currently the vast majority of voids), and by then applying the recommended VF algorithm to the remaining voids. Where high resolution DEMs are available we recommend the ANUDEM procedure.

Conclusions

General conclusions

We assume that each void occurs due to a technical reason, which can be partly attributed to terrain, land use and other reasons. In the course of this analysis, void areas in the SRTM data set have been quantified in terms of their terrain and size, providing a statistically sound and extensive evaluation of different VF algorithms over a wide range of terrain units and void sizes (objective (i)).

Different VF algorithms have been implemented in a GIS, and used to analyse performance using RMSE/S on 1,304 relocated voids. Based on these results a decision table has been created, which provides an answer to an important question: which VF method can be recommended for a void of a given size in a given terrain unit? Contrary to some previous findings, the best methods can be generalised as: Kriging or Inverse Distance Weighting interpolation for small- and medium-size voids in relatively flat low-lying areas; Spline interpolation for small and medium sized voids in high altitude and dissected terrain; Triangular Irregular Network or Inverse Distance Weighting interpolation for large voids in very flat areas, and an advanced spline method (ANUDEM) for large voids in other terrains (objectives ii and iv).

We have shown that coarse resolution auxiliary information was only helpful if the void areas exceeded a certain size threshold (objective (iii)). Differences in decrease of RMSE could be observed between use of the SRTM30 and the GTOPO30 DEMs.

Finally, we have created a database that can be used to select a VF algorithm and auxiliary DEM to fill each of the 3,339,913 voids in the SRTM data (objective (v)).

Further work

Issues with the SRTM30 data. In this paper we tested only coarser scale resolution data as auxiliary information for the VF process. The VF using the SRTM30 obviously creates a better result than using GTOPO30 auxiliary information (Table 3). Still, SRTM30 is a seamless DEM based on the SRTM data product and is therefore also influenced by the voids. Most voids in the underlying SRTM data were interpolated in a 10 × 10 averaging process that re-sampled the data from 3 arc seconds to 30 arc seconds. Voids that were too large to be interpolated in this manner were filled using GTOPO30. Since the SRTM data do not have global coverage, GTOPO30 data from areas above 60°N and below 56°S were fused with the SRTM data to create the final SRTM30 data. No attempt was made to adjust the vertical datum of either dataset in this fusion. There are three observations to be made here. Firstly, the SRTM30 product will have variable quality in areas where there were reasonably large voids within the 10 × 10 re-sampling window. Secondly, there is no advantage in using SRTM30 instead of GTOPO30 as an auxiliary DEM for interpolating very large voids since the auxiliary information in these areas will be almost identical. Thirdly, if the recommended VF algorithms and all available auxiliary datasets are used to create a seamless 3 arc second SRTM dataset (as would be the case in a fourth version of the CSI SRTM data), this in turn can be used to create a higher quality SRTM30 dataset and other global coarse resolution derivatives.

Size thresholds for auxiliary data. A second question is the size of thresholds for higher resolution auxiliary datasets, which might an important influence on the results. A conservative threshold for using auxiliary elevation information (void-size class D) has been applied, which was obviously not large enough (Table 6) under certain conditions. Further research is required to provide better information on the required resolution and quality of auxiliary DEMs for filling voids of different sizes.

High-resolution auxiliary data. We assume that high-resolution DEM data (e.g. based on ASTER or SPOT satellite-derived data, or digitised from fine-scale topographic maps) should deliver superior results for void filling as the density and distribution of the auxiliary data are superior. The degree of improvement offered by these data has to be offset against the time and the cost of acquiring and processing such information. Higher resolution may not necessarily mean higher quality; relative ASTER DEM products show height differences of up to 600 meters between three different scenes for the same area and other ASTER DEM errors are specified in Lönnqvist and Törmä (2004). Inherent to the use of auxiliary information is the question of how different errors can automatically be compensated for, as outlined in the section on the SRTM above.

Better understanding of void-filling algorithms. This analysis has treated the VF algorithms as black boxes in that we have only looked at the results of the interpolation accuracy rather than attempted to investigate the reasons why one method performs better than another. Interrogation and analysis of the inner workings of these algorithms under different conditions would be a valuable aid to researchers who need to select an appropriate method for a given problem.

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Information management for product differentiation in supply chains: The case of speciality coffee

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Abstract

Prices of most of agricultural commodities show a long-term trend to decline. Increasingly markets are signaling demand for differentiated products and in order to increase their incomes farmers and traders are looking to higher value options, including differentiated products. Product differentiation occurs when a product offering is perceived by the consumer to differ from its competition on any physical or non-physical characteristic including price. The differentiation can be based both on perceptual differences and also on actual product differences based on measurable characteristics. The information requirements for supply chain management of differentiated high value products are much more stringent than for traditional commodities requiring a two way information flow running from the primary producer to the end customer. The conceptual base for information systems to support supply chain management of differentiated products is described. An internet-based coffee information system (CinfO), illustrates how these principles have been applied to the case of specialty coffees. CinfO provides farmers information on where and how to produce coffee with particular features, whilst at the same time providing traders with information on the availability of specialty coffees with particular traits. Furthermore, CinfO traces individual coffee batches indicating where and how the beans were produced, processed and distributed to the end consumer so as to facilitate identity preservation which is key to obtaining added value from differentiation.

Introduction

For many years the development workers talked of the subsistence farmer, staple foods and food security. We believe that at present there are very few truly subsistence farmers, that is those that consume all that they grow with no commercial contact whatever with others, and that this is not a new phenomenon. Most farmers, including the poorest, are in the business not only to feed and clothe themselves and their families, but also to make money or at least barter their goods. Markets, not production, increasingly drive agricultural development (World Bank 2006). However, the price of most commodities shows a long-term trend to decline (Figure 1[1]). A basket of various agricultural commodities that we have analyzed at different times show a general price decline of 1-3% per year. At the same time, largely because of major research efforts, yield potential of commodity crops is increasing at 0.2-2% per year (Evans and Fischer 1999) and actual increases in crop yields are of the same order (ASA 1999). Consequently, with rice as a partial exception, most of the major commodities are produced today on larger farms than previously, and these farms now employ less people per unit area. At the same time some farmers and communities, particularly those with limited access to land, have switched to higher value crops or activities so as to increase their income per unit land area.

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[1] Source: *Economist*. 10 February, 2005, http://www.economist.com/finance/displaystory.cfm?story_id=E1_PGVTRPG

Figure 1. Long-term commodity prices. Source: *Economist*. 10 February, 2005. URL: http://www.economist.com/finance/displaystory.cfm?story_id=E1_PGVTRPG

We define high value crops as crops that return higher gross margins per hectare and per unit labour input than traditional commodities. There appear to be two major types of high value crops. Firstly there are those which are, for some reason or other, difficult or expensive to produce. Examples include Brazil nuts and lulo, an Andean fruit, which are consistently high priced[2]. The product per se has a high value and the skilled producer who can overcome the difficulties of producing the crop can obtain large profits without having to differentiate his particular product in terms of specific quality. Secondly there are those crops where the high value is obtained by differentiating the quality of final product, as for example in organic specialty coffees. Their transactions involve usually smaller product volumes, higher costs and specific, difficult-to-meet quality standards, but with less flexibility to chain participants (Sonka 2003, Beurskens 2003). As this paper deals with coffee we shall only consider differentiating an already well-established product to obtain higher value.

So far we have argued that there is an increasing need to produce differentiated agricultural products, and that these offer the opportunity to increase incomes for producers and others involved in the supply chain. At the same time, lack of reliable information at all stages along the supply chain is a severe limitation on the development of differentiated products, in spite of the existence of modern information technology. The development of differentiated high-value crop products depends on:

- An overall organization framework;
- Excellent communication and information exchange within that organizational framework; and
- The ability to differentiate the product and to develop processes that ensure that the end customer obtains the desired product at an acceptable price in a timely manner.

[2] It is interesting to note that coca and cocaine are technically extremely easy to produce, but as it is an illegal crop it is difficult to produce and hence is a very high value crop. It is also risky!

Specifically, information is lacking on:

- How and where to produce and process products with specific characteristics;
- How to ensure that producers and processors are aware of consumer demands and preferences;
- How to raise the interest of processors if producers put forward a product with new characteristics; and
- Coordination of activities and logistic along the supply chain.

This paper first introduces briefly concepts related to product differentiation, then proposes a conceptual framework for information management systems in differentiated, high value crop supply chains. It then goes on to use a case study to illustrate how these concepts can be turned into reality using an internet-based information management system, CinfO, for speciality coffee.

Conceptual background

The provision of differentiated high value crop products is envisaged within the framework of supply chain management (SCM) and differentiation based on identity preservation.

Supply chain management

SCM is the integration of all key processes across the supply chain (Cooper *et al.* 1997) ranging from those involving end users to those that are original providers of products, services and information (Lambert *et al.* 1998). Supply chain management functions as a network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer (Christopher 1992). Much SCM work has concentrated on markets where products are valuable and differentiated, rather than in commodity markets due to the importance of business-to-business relationships in the supply of differentiated products (Woods 2004).

Furthermore, SCM emphasizes the overall and long-term benefit of cooperation and information sharing by all members of the supply chain replacing the adversary relationships common in traditional commodity markets with a spirit of collaboration so that all benefit. In the light of these advantages, SCM was chosen as an appropriate means to bring together the multiple actors in the supply chain to ensure that consumers obtain the differentiated products they desire, whilst at the same time using the network approach to make certain that primary producers and others along the supply chain reap just rewards for their efforts. Successful SCM manages the relationship between businesses, from farm level to consumers to ensure the efficient production and supply of products that meet consumer requirements in terms of quantity, timeliness, quality and price (Gunasekaran and Ngai 2004). Developing agricultural supply chains requires different types of knowledge of various aspects that include:

- Product design and packaging;
- Market requirements and customer preferences; and
- Production/distribution processes and their integration (Roekel *et al.* 2002).

Chain integration may improve the information flow concerning customer preferences and hence can help to market agricultural high value products (Trienekens *et al.* 2003).

In most supply chains there are points in the chain with different numbers of actors, for example there may be many primary producers but few processors and packers. Under these circumstances efficient SCM often requires formation of associations or close collaboration between the many small players at any one point in the chain (normally but not always at the primary producer level) so as to reduce the transaction costs involved in communicating individually with multiple actors. These associations or their equivalent may also reduce power imbalances that occur in interactions between a few large powerful players and many small individual growers.

SCM entails detailed descriptions, and mapping of flows of product, information and revenue throughout the chain. This information may be used to examine and appraise activities and services at each and every level. This provides all participants in the supply chain network with a broader understanding of the way in which customer value is created in the chain and may signal opportunities to create or develop value more effectively (Woods 2004). For effective SCM operations the activities of all partners in the supply chain need to be synchronized. This synchronization can only be through the implementation of a system that facilitates (a) information sharing on the various activities that add value along the supply chain and (b) the coordination between internal and external partners within the chain (Williamson *et al.* 2004; Gunasekaran and Ngai 2004).

Product differentiation and identity preservation

Markets are increasingly signalling demand for differentiated products. It is noteworthy that market segmentation, which implies heterogeneity in the demand function, can only be used as a strategy when accompanied by product differentiation (Dickson and Ginter 1987). If there is no product differentiation then demand functions will not differ and hence there is no heterogeneity of the demand function to be exploited by segmentation.

Product differentiation occurs when an offered product is perceived by the consumer to differ from its competition in any physical or non-physical product characteristic, including price. The differentiation can be based both on perceptual differences obtained from usage, word of mouth, promotion campaigns and also from actual product differences based on product characteristics[3] (Dickson and Ginter 1987, Clause 2003). "Credence attributes" or "process attributes" that relate to the process by which the products are produced (for example coffee produced in an ecologically sound and sustainable manner) are also value factors but can often only be measured through certified and auditable systems that accredit the process (Clause 2003). Sometimes these distinctions may become blurred, for example, although organically-produced products may be inherently similar to non-organic products, they may not only be perceived to be different but there may be a true physical difference in that the organic products have less toxic residues. Nevertheless, the broad classification of inherent physical characteristics and perceived attributes is useful for the purposes of managing the supply chain. In the case of the inherent physical characteristics it is important to know how products with these traits can be produced and delivered to the end consumer and which traits the consumer desires. In contrast, in the case of perceived attributes it is necessary to present the end consumer with convincing evidence that the product does indeed possess the attributes claimed.

The specific characteristics of coffee quality can be (i) product inherent, (ii) personal and (iii) symbolic (Daviron and Ponte 2005.). As is the case with wines, there are many traits that determine quality, but because of personal preferences there is no one particular coffee that has the best inherent quality. For example, one person may prefer a sightly bitter coffee with a chocolaty flavour whereas others may prefer a milder coffee with a touch of nutty almond flavour. It is precisely these different personal preferences that open up the possibilities for carving out niche markets for specialty differentiated products that cater to the personal preferences of individual consumers.

Symbolic quality characteristics are normally associated with a particular production area, production system or social context. The Jamaicans describe their Blue Mountain coffee thus "Toward the eastern end of the beautiful island of Jamaica runs the majestic range of hills known as the Blue Mountains ... the

[3] Some authors refer to product differentiation as only being for non physical characters, however, we follow the definitions of Dickson and Ginter (*op cit*) and include both physical and non physical attributes.

terrain, the rainfall pattern, the Blue Mountain mist, and the overall conditions are blessed by God to be perfectly suited for the cultivation of the world's most distinguished and delicious coffee." The perceived, or symbolic, differentiation of a product in a similar manner to that of the inherent characteristics will often depend on personal preferences, while the quality of the differentiated product depends on the personal individual preferences and desires of the end consumer. For example, a particular consumer may wish to establish a quasi-personal relationship with the producer. This idea is behind the highly successful marketing strategy of the Colombian Coffee Growers' Federation with the end customer empathizing with Juan Valdez (2006), "For years he has warmed our days and stirred our senses with the richest coffee in the world. ... Forever familiar and reliable. Like an old friend." Thus in broad terms products can be differentiated according to inherent physical characteristics or perceived attributes related to the process and circumstances by which they are produced, processed and marketed.

Differentiation can be achieved through three different pathways, segregation, traceability and identity preservation (Smyth and Phillips 2002) with traceability and segregation as means to preserve the identity of the product. However, it is identity preservation that aggregates value to the product in a sustainable manner (Smyth and Phillips 2002). Furthermore for identity preservation, the features that characterize that particular identity must be determined and described. The objective of identity preservation is to increase revenue by capturing the increased value associated with specific product traits. The consumer must be able to identify the value of the product, because if there is no way of identifying the particular product traits the consumer will not pay extra for them (Smyth and Phillips 2002, Goldsmith and Bender 2004).

An identity-preserved production and marketing (IPPM) system is a "closed loop" channel that facilitates the production and delivery of a certain assured quality through the characterization of the overall production, processing and marketing procedures and the product itself. This characterization covers all aspects of the process from the initial variety to the label on the product that the end consumers purchase. Because many of the product attributes in coffee are not visible or readily detectable in the product itself, systems are required to provide information to consumers about the provenance of a product.

The dynamics and complexity of the global food systems together with the use of new technologies and the opportunity to differentiate products at many stages along the supply chain means that information must be shared vertically in both directions along it. The question then becomes what information is required, how to obtain it and how to ensure that there is two-way information flow between all members of the supply chain including the all important end customer.

Several recent developments in low-cost radio frequency identification (RFID) technology systems make it possible to track and trace agricultural products (grain, fruit and meat) from farm to fork (Information Society and Media DG 2005, Society and Media DG 2004, The Board of Trustees of the University of Illinois 2004, IDTechEx 2005). GeoTraceAgri is a user-friendly system that allows interested people to track the origin of products on the Internet. GeoTraceAgri, tracks and traces European agricultural products at all stages of production processing, storage, and distribution. They use a variety of different platforms, languages, databases, mapping engines and spatial processing libraries. The data can be geo-localised and visualised on the Internet using geo-portals such as Google Earth (Information Society Technologies 2005). Until recently, small- and medium-sized companies and producers in rural areas have remained outside the advanced, integrated supply networks because the information technology solutions enabling this transparency in supply chains was expensive and unaffordable for them (Kärkkäinen and Ala-Risku 2005). With the Internet as a medium to deliver real-time information to consumers on the quality status of the products, the methodology now appears feasible for them and worthy of investigation.

Each field, each crop and its management are a unique experience, in that: no two crops are identical even if they are established at the same time, or at different times in the same field. In many cases of lowland agriculture, vast expanses of land are relatively homogeneous, and spatial and temporal variations in such factors as soil fertility and water availability can be minimized by irrigation, drainage and application of fertilizer. In these cases blanket recommendations can be used over wide areas to produce uniform products. On the other hand in the mountainous, coffee-growing areas no two fields and no two years are alike. The particular characteristics of the production environment and practices are reflected in the unique traits of the specialty coffee.This provides an opportunity to differentiate products, but also presents a problem in that there is little information on how the temporal and spatial variation affects product traits. Geographical information systems (GIS) provide the opportunity to make site-specific and time specific decisions. GIS can be used to reduce the chance of errors caused by generalization within areas or over different time periods.

Coffee growers already know that options for differentiating their commodity into specialty coffee are necessary; however, they know little about where and how they can satisfy particular niche markets such as the provision of lemony, acidic coffee. However, information about variation in coffee quality and the definition of the environment and the management practices that are associated with certain quality characteristics or coffee identities could provide a practical guide for producers to decide what options are feasible under their specific local conditions. This information is not at present readily available and systems to capture and analyse this information are needed. Moreover, to obtain the added value of their differentiated product its identity must be preserved. This is achieved through segregation and traceability.

Segregation: Lin (2002) defines segregation as keeping crops separately to avoid any commingling at all stages from planting to the end customer. Segregation systems have a formal structure and can act as regulatory standards. Segregation can be used both to ensure food safety and forestall liability claims and also to guarantee a pure product that is not contaminated by lower quality dross or blended with different qualities. The segregation system can ensure that all participants at all stages of the supply chain maintain standards of quality and food safety. As food safety and quality are of interest to both producers and consumers, segregation systems must have two-way information flow. Segregation systems are common for niche markets and are typified by small production areas and low volumes (Smyth and Phillips 2002).

Traceability: The International Organization for Standardization (ISO) defines traceability as the ability to trace the history, application or location of an entity by means of recorded identifications. The economics literature on supply-chain management sees traceability as an information system that provides the history of a product or a process from its site of origin to the point of final sale. Traceability in agricultural products initiates in the primary production phase and continues through the processing and marketing stages along the supply chain. Traceability is crucial for differentiating new categories of products and preserving their identity. Information is provided to end consumers, processors and to supply chain regulators. Products have to be labelled to ensure that they possess the characteristics and meet the standards associated with a particular identity. In addition labels provide the consumer with information to identify special product features (Smyth and Phillips 2002).

The complexity of transport and handling patterns of the food industry imply intense effort to ensure traceability. Typically the raw material is produced and harvested in one place and is then pre-processed, transported, refined, processed, and repacked along a long chain of members of the agribusiness supply chain (Wagner and Glassheim 2003, Opara 2003). Agricultural traceability implies the collection, documentation, maintenance, and application of information related to all processes in the supply chain in a manner that guarantees the origin, location, life history and quality of a product. to the consumer and other stakeholders. It represents the ability to identify the farm where the primary product was grown, the source of input materials, the social and environmental conditions all along the supply chain as well as the ability to conduct full backward and forward tracking to pinpoint problems that occur along the chain.

Supply chain traceability facilitates data and information exchange by providing a mechanism for recording, storing, analyzing and transmitting relevant data on products and process activities to designated stakeholders (Ketkar *et al.* 2003). Traceability may initially add value to products but once most producers adopt the system it does not on itself add value to the product. Nevertheless, the ability to differentiate a product that results from traceability may well add value compared with similar products that do not provide traceability.

Conceptual outline of information systems to innovate[4]

To support supply chain management and product differentiation we envisage a modern information system that compiles valuable information and knowledge from multiple sources. The system must have the power to interpret that information in a relevant manner and thereby provide rural producers and their supply chain partners with answers pertinent to their questions on how to increase their incomes.

Value of information: The value of better information and an improved information system for SCM is that it provides a solid base for decision-making, and thereby enables the discovery of income-generating opportunities or avoids costly errors. In statistical analysis type I and type II errors are well known. A type I error occurs when an alternative hypothesis is accepted due to a chance observation, whilst a type II error is when an alternative hypothesis is rejected even though it is the true state of nature. We have adapted these type I and II errors to make them relevant to the choices faced by producers (Table 1).

Table 1. Type I and II errors as applied to a choice of action confronted by a producer.

	Benefit occurs	No benefit occurs
Act	Correct action.	Type II error, loss caused by the cost of acting.
Do not act	Type I error, lost opportunity to benefit.	Correct not to act.

A type I error occurs when a producer fails to act in a way that is of potential benefit, for example, by failing to change when (s)he should have done so. Poor farmers are commonly thought to make type I errors due to risk aversion (Antle 1987, Kingwell 1994). While it is logical to assume that farmers with virtually no financial assets have to be extremely careful to avoid 'taking the wrong step' there is increasing evidence to question this generalization of risk aversion even in the poorest segments of the rural population (Henrich and McElreath 2002). If this is the case, then it seems that most type I errors are due to ignorance of better options, suggesting that improved access to pertinent information could reduce type I errors. A type II error occurs when a farmer does something that is harmful, or at least non-beneficial.

An example of a Type I error could be that a coffee farmer sees that a neighbour, who failed to use integrated control of coffee berry borer, nevertheless had an excellent crop. Unknown to him, his neighbour's experience was just a chance occurrence, but he decided not to control coffee berry borer on his farm. His crop then suffered a heavy infestation with disastrous results. A type II error may occur when a farmer perceives that the new rust resistant varieties are not suitable for his conditions and continues to plant susceptible varieties that then succumb to heavy infestation with deleterious effects on production and quality. Many examples exist of the type II error in agricultural development, due to insufficient information about the likely effects of a particular decision (see, for example Dent and Young 1981).

[4] Much of this section is based on the CIAT *Strategic Background Paper: Learning to Innovate: Knowledge to Raise Incomes and Increase the Assets of the Rural Poor* by James Cock with the assistance of Boru Douthwaite, Mark Lundy, Nathan Russell, Thomas Oberthür and others who formed part of an *ad hoc* working group at the Centro Internacional de Agricultura Tropical (CIAT) during the period 2003-2004

All farmers wish to avoid these errors, yet we suggest the errors persist because farmers are unaware or are uncertain of the most probable outcomes resulting from their decisions.

Relevance of information: It is evident that effective development in rural communities is closely related to active participation of the members of the community and their ability to make informed decisions (For example, see World Bank 2006). The growers and producers and their supply chain partners are essentially interested in what will function well under their particular conditions, that is they are not interested in prescriptive, generalized information that may or may not be pertinent for their particular circumstances. Modern information management systems, particularly GIS, provide the opportunity to target site-specific results from one specific site to other similar sites that may be geographically distant from the original area of development. Furthermore, feedback from farmers can be linked into GIS systems, so that the immense local knowledge on what works and, equally important, what fails under particular conditions can be used as a guide to rural communities for technology specific to their individual conditions. The use of this knowledge of what works and does not work on well-characterized sites with knowledge of the particular management practices is conceptually a mainstay of the development of information systems for differentiated agricultural products. However, information about variation in the production system in order to identify and target what works well is only relevant for producers if it is new and describes variation that is important and manageable.

Provision of information: There are several reasons why specific interventions are needed to provide rural communities with improved and more effective knowledge systems. First, there is a plethora of available knowledge, but much of it is not relevant to the particular circumstances of the poor. Second, relevant knowledge may not be available to the poor, that is they may simply not have access to the knowledge, the knowledge may not have entered into easily reached information systems or the way it is presented and shared may make it unintelligible or and not credible and therefore suspect. Third, asymmetry in access to knowledge may disempower the growers and producers. Fourth, the social, economic and environmental conditions of rural communities are very diverse and hence the specific knowledge relevant to each community is distinct. Thus general ized prescriptive knowledge systems are not effective. Fifth, effective systems must allow people to query the knowledge systems and at the same time people must know how to formulate questions and seek answers and become confident in doing this. Finally, much potentially useful information is in the minds of an enormous number of people ranging, *inter alia*, from *campesinos* (rural smallholders) to local and international experts, technologists, social scientists and researchers. Each segment of the information on its own is often of limited value, however when the many sources of information can be accessed and the resulting data analysed very powerful knowledge can be obtained. A major challenge is to harness advances in information management to combine information from multiple sources so as to benefit from the immense stores of local knowledge and other information. Technically there is little doubt concerning the capacity to handle vast amounts of information and put it into a useful context if the resources are dedicated to this task, however, major efforts are required to capture that information.

The case of the Coffee Information System (CinfO)

CinfO was established to provide

a) Information flow along the supply chain to facilitate supply chain management;
b) Information that supports product differentiation through identity preservation; and
c) Guidelines on how and where distinct differentiated products with known traits can be produced.

Technical specifications. CinfO is a prototype internet-based information management system for high value agricultural products. It consists of a central database and an internet interface that provide general data management functions, user tailored information presentation, data input and export functions and simple analysis tools. It is based on a security framework, which ensures data privacy through a multi-level security system. CinfO offers a highly flexible structure for managing the dynamic and sensitive content tailored to the users' demands. Users are only provided access is to uspecific information that (s)he is allowed to see (Niederhauser, 2004).

Content and functionality. The CinfO platform provides general information related to the coffee tracking project and specific information about coffee production in pilot regions. A series of set queries have been established, which enable simple statistical analyses, and an information presentation interface has been set up and adapted to specific user-groups. The specific information section provides each user-group with detailed information on management practices, coffee production and quality (including flavour) for specific farms. In addition, historic data on the quality of coffee from specific farms are available. Farm and production data are stored in a relational data model (Figure 2), allowing consistent and storage and dynamic linkage of data. CinfO manages basic farm data including the description of the post harvest process, management units (e.g. GPS coordinates), field data (e.g. varieties and shade system), harvest (coffee) lots (harvest date, lot quantity, certification), cupping quality data and physical quality data.

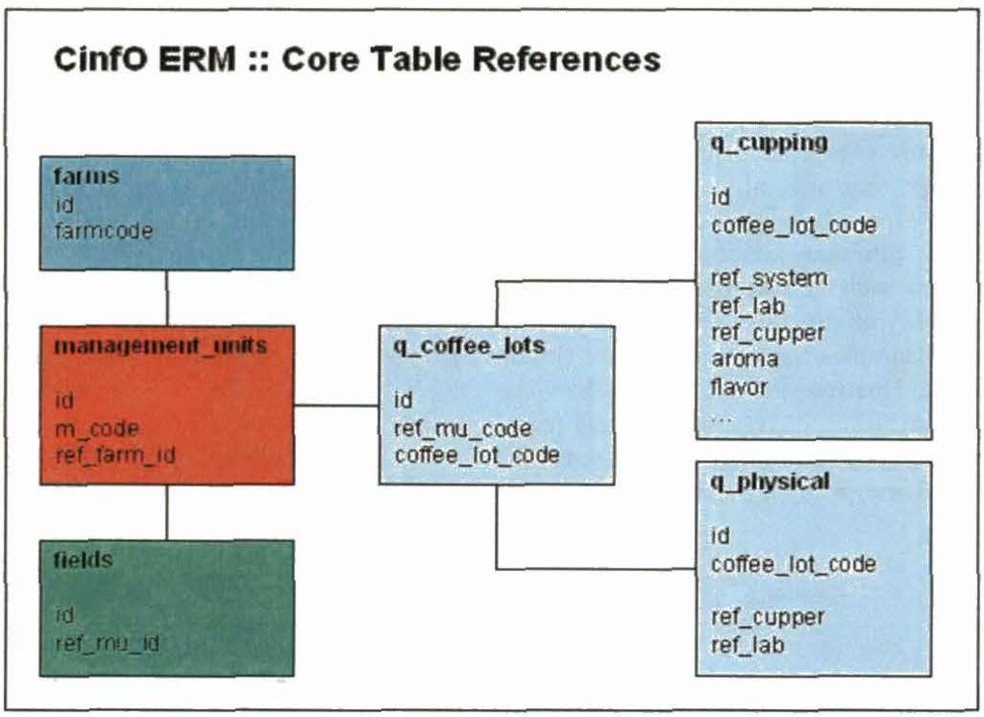

Figure 2. CinfO's core table structure.

Different information management modules enable and support product differentiation. The modules are grouped under three domains, inherent, symbolic and personal product information, with each module closely interlinked with the others. Inherent product quality data such as sensorial attributes (cupping data) and physical coffee quality (grain size) are captured for each lot of coffee produced on each participating farm. Separately-managed fields or production units are processed separately. The cupping data allow different quality characteristics of lots to be identified and targeted to specific markets segments. Production practices and harvest date are tracked separately for each coffee-lot, as well as symbolic product attributes for preserving product identity through product certification and labeling (organic, fair trade etc.).

Photographic images of the farm and the production area and environment as well as farm maps are available and can be linked to each particular batch of coffee so as to add personal symbolic value to the product. The coffee buyers (customers, roasters) can search the database, online, for their specific taste and flavour preferences, preferred growing region, environmental conditions and symbolic traits. The potential buyers also may review farm history data that include quality characteristics and production volumes over time. The product quality and production data are also available to enable qualified feedback to producers so that they can adapt the production practices to meet market needs in terms of both quality and quantity. Thus CinfO facilitates a two-way information flow and network communication, and provides the actors in the supply chain with the means to obtain their specific preferred product whilst at the same time providing the farmers with information that allows them to develop products that are demanded by specific high-value segments of the market. The following sections illustrate in more detail some of the specific functions of CinfO.

Coffee quality module. The coffee quality module manages sensorial cupping data (e.g. flavor, acidity, sweetness, body) supporting several data input and storage formats (SCAA, CoE, and several CinfO proprietary formats) for these data. Key attributes of coffee appraised by all the common cupping schemes can be compared thus allowing simple searches and statistical analysis to be carried out. In addition physical quality data for each harvest lot (e.g. humidity, physical defects and screen size) are maintained in the data base. The quality module also displays key quality attributes like aroma, flavour, balance, defects, etc. of one or multiple samples for a selected farm (Figure 3). The graphic display facilitates rapid quality profile appraisal and evaluation of homogeneity between samples. A similar function presents important physical coffee data for coffee buyers and roasters (e.g. humidity and "factor de rendimiento" as well as physical coffee bean defects). Each physical and sensorial cupping dataset is linked to farm and production data, including certification, with GPS coordinates for spatial analysis and map presentation.

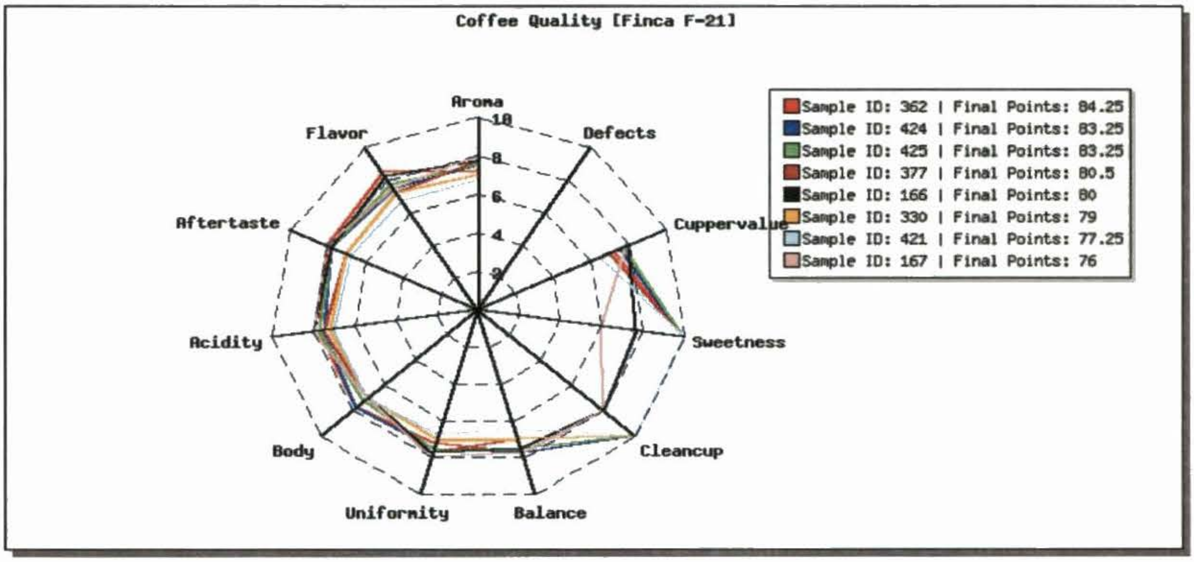

Figure 3. Coffee quality of several samples from Finca Santa Luisa.

Image and farm map modules. The image module manages images of farmer, farm facilities, coffee fields, landscape, etc. The farm map module stores maps, images of aerial view, farm sketches, etc. to show how the farm is distributed and organized in terms of production units. The images enable the coffee consumer to become familiar with the environment where the preferred coffee is produced. These modules are accessed through specific central and separate interfaces. The farm map interface (Figure 4) enables the authorized CinfO user to search for farm subsets, that meet certain product quality characteristics or geographical attributes. The resulting set (one or more farms) is displayed on an interactive map with several functions including zooming, panning or loading different spatial information layers such as altitude models, county and cities borders and rivers. By clicking on a certain farm, basic farm information (farm name, municipality, GIS data), farm images, farm maps, cupping quality data, appear.

Quality control mechanisms for tracking and segregating. CINFO enables product identity preservation through a variety of technologies including an integrated product-tracking system and product-segregation functions. The coffee tracking system collects and compiles product data along the product supply chain from production units until the end-point product with unique tracking tags. Product data can be tracked over space and time. The coffee-lot module accepts the input of several coffee-lots per farm, thus a single farm can produce several batches with different production units, treatments and harvest methods. All data are linked to GIS data (geo-reference coordinates) that enable presentation of the data on digital (web) maps.

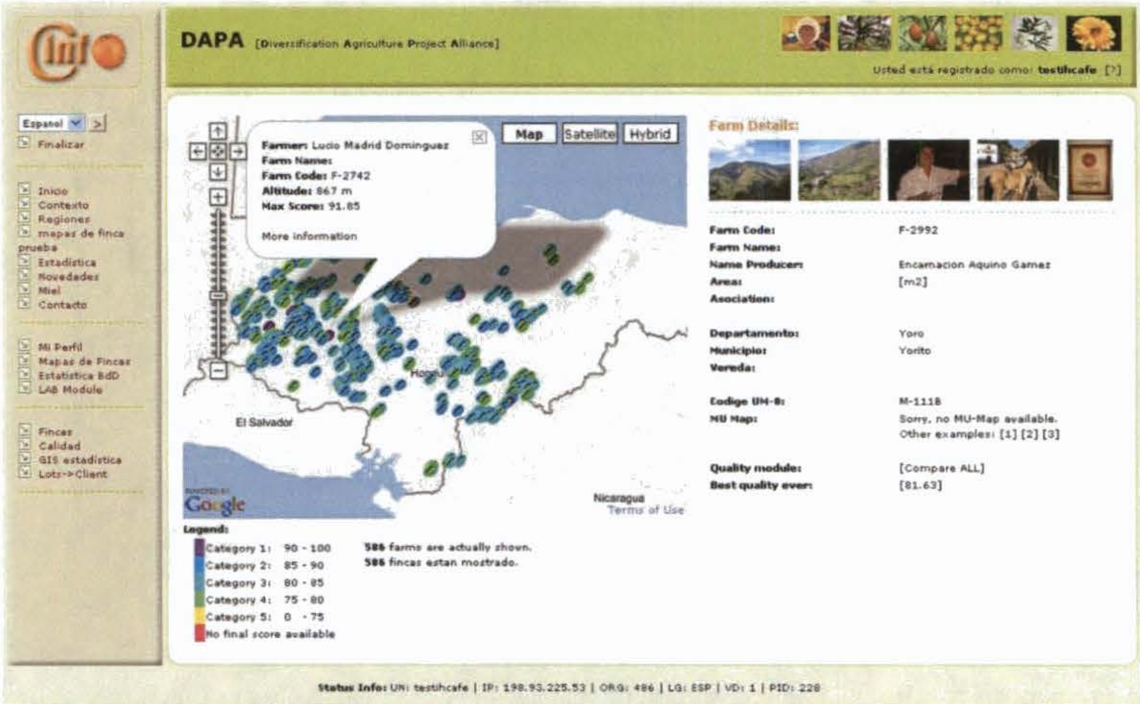

Figure 4. CinfO online farm map interface.

The coffee product track runs from the field where coffee is grown to consumers all over the world while the physical state of coffee changes from the green, fruit pulp-covered coffee bean to a wide variety of roasted, blended, ground and packed coffee of different flavours for different uses. The main product tracking nodes through which coffee runs are production in the field, (on-farm) post-harvest processing (fruit pulp peeling, fermentation, and washing, drying), further processing in coffee cooperatives (sorting, quality determination, peeling and others), change of ownership and transportation through exporters to importers to roasters (roasting, blending, grinding), and finally the marketing process with the end-point sale to a customer (general public or food industry).

To link the final product to geographical origin and processing information a set of product tracking codes are applied. These codes are directly attached to the product and participants can obtain information about the product from the central data storage and monitoring system (CinfO database).

CinfO distinguishes three different code systems (Figure 5), the management unit code, the coffee-lot code (also named cupping code) and the product code. The management unit code is used for linking all production and processing data as well as geographic information about the production zones to a specific environment or site in time, defined as the management unit. The coffee-lot code links the management unit code with the harvest date and lot quantity enabling the tracking of quality data and other harvest-dependent parameters. The product code is mainly for roaster and end customer use to identify the origin of the packed and ready-to-sell product. Due to the fact that many coffee roasters use a mixture of coffee from different regions and producers, this code is needed to link several coffee-lots with the help of a new code that appears on the coffee pack.

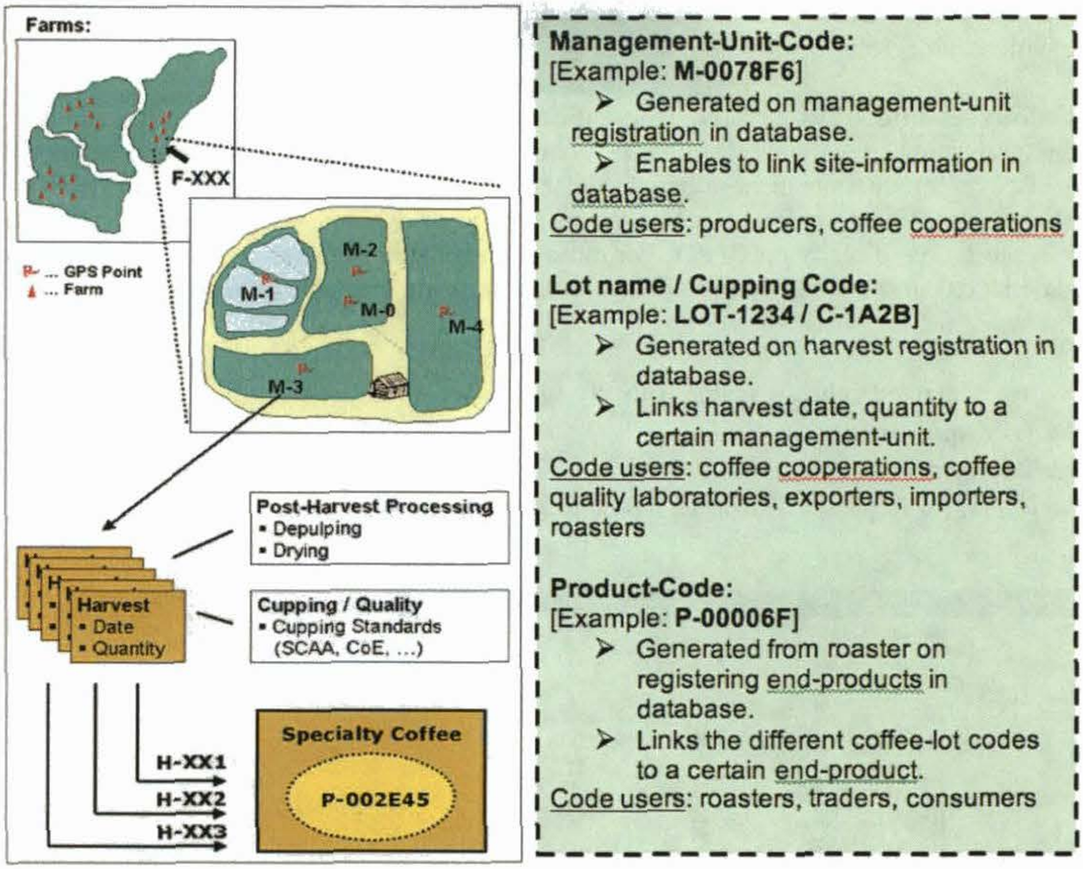

Figure 5. Basic code system enabling product tracking along the coffee supply chain.

The management unit code has to be a simple code, easy to read and process. Furthermore the code is unique system-wide and comes with a simple error detection mechanism. The checksum method was selected to provide an easy to implement the error detection mechanism (for details see Tanenbaum and Goodman 1999). On registering a new field in the CinfO system, a new system-wide unique number is generated. Afterwards a checksum bit is added to this number and the whole expression is converted to a hexadecimal number. The hexadecimal format is shorter than purely numeric formats and the alphanumeric presentation is easier to read.

The coffee-lot code (cupping code) follows a different scheme. It is designed to facilitate objective coffee quality determination through "blind cupping" and determination of physical characteristics. It consists of one number (between 1-9) followed by a character (A-Z). This number-character-combination is repeated depending on CinfO's demand for codes. The prefix "C-" is used to identify this code as coffee-lot code.

There are two possible ways of creating the product code. The roaster can either select the corresponding coffee-lot codes for all coffees used for some blend and receives a product code from the CinfO system, or the roaster chooses a bar or other code unique for that particular batch and links it with the coffee-lot codes from the CinfO database (Niederhauser, 2004). Wagner and Glassheimer (2003) explain a similar but more generic approach for a food tracking system.

The code is presented in hexadecimal numbers. Electronic scan devices and RFID technology are not currently available for the CinfO pilot project phase, however current hexadecimal codes are compatible with these technologies and have the advantage of incorporating an error detection system, which is essential for use with scan devices.

Geographical analyses and data export. If specific product characteristics (e.g. coffee quality) are linked in real time to existing spatial models (altitude model, climate, political division) the combined data can be used to discover production niches for particular types of coffee. Since computing power and software technology for real time applications like the generation of dynamic web content is still limited, only basic models can be run directly on CinfO. For more sophisticated analyses or data interchange with other systems, data stored in the central CinfO database can be made available as a downloadable file in different formats:

- CSV-file (comma separated value, readable with any spreadsheet program);
- Shape-file for GIS software (Fig 6);
- Google-Earth® format (Fig. 7); and
- A special file format for Expector – a software program for statistical analyses.

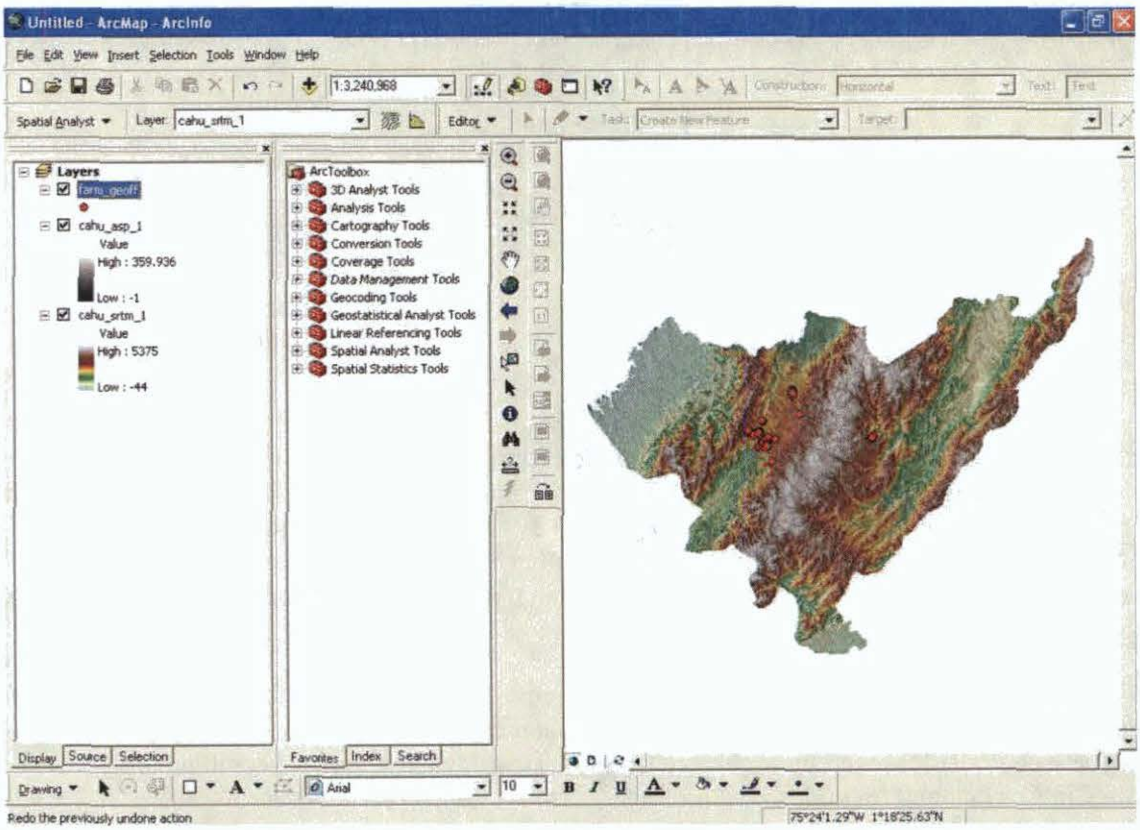

Figure 6. GIS analyses on CINFO data.

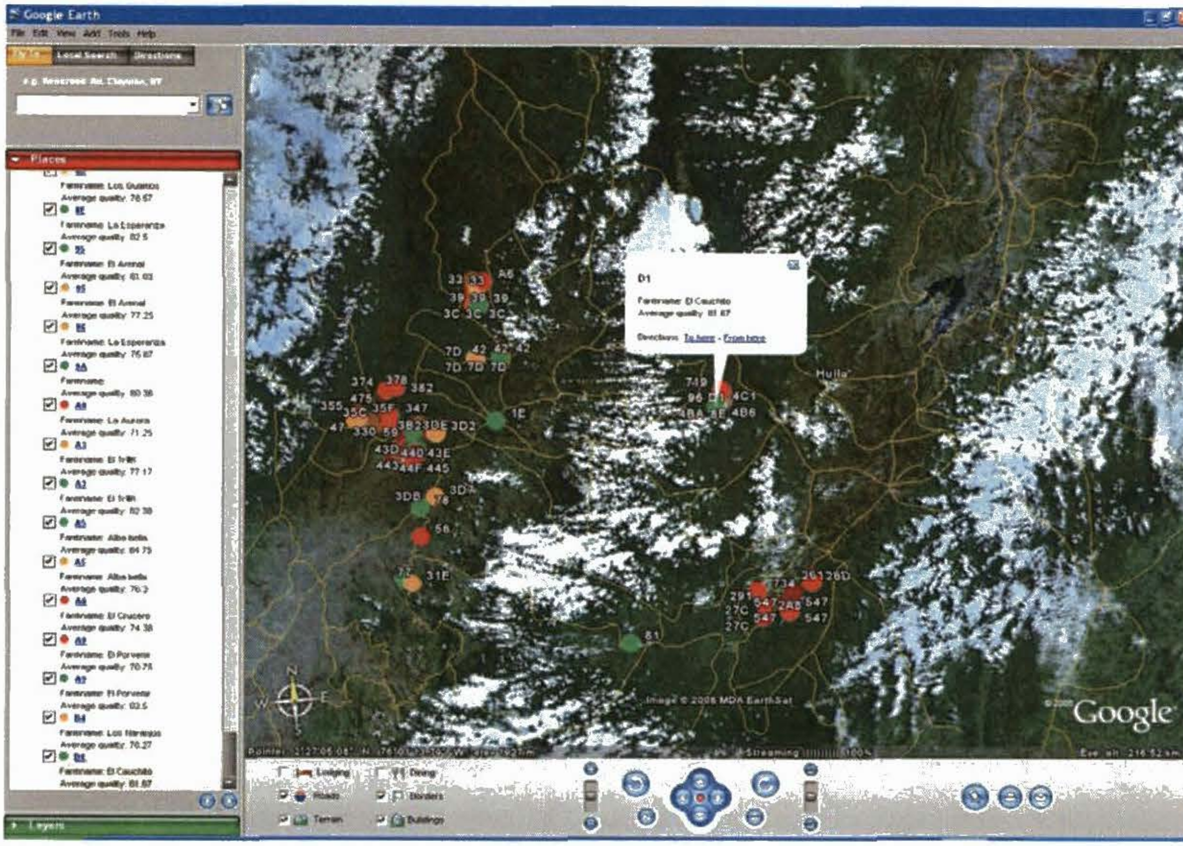

Figure 7. CinfO data on Google-Earth®

For example, an intelligent feedback (two-way dialogue) system provides the farmer with a quick overview of his productivity status in terms of yield and quality compared with others with similar conditions, thus increasing his knowledge about his potential opportunities for profitable differentiation. Complex automated data-analysis processes produce easily understandable and powerful reports in different presentation. An example is demonstrated in figure 8, a farm map that indicates the productivity and quality status of different management units.

Discussion

System uptake

The development of the system and its presentation to specialty-coffee supply-chain actors has spurred considerable interest in the adaptation of the whole system or of specific modules. Producers' associations use the system to monitor and document their production better in order to address variation in product quality systematically. Large associations representing producers at a national scale are currently considering the option to research with the project team the feasibility of implementing denomination of origin concepts based on improved information management. Specialty coffee exporters are using components of the system to (a) control product quality upstream and (b) provide their downstream buyers traceability of the product to the field. Large specialty coffee roasters are considering using principles developed under CinfO to design sourcing strategies.

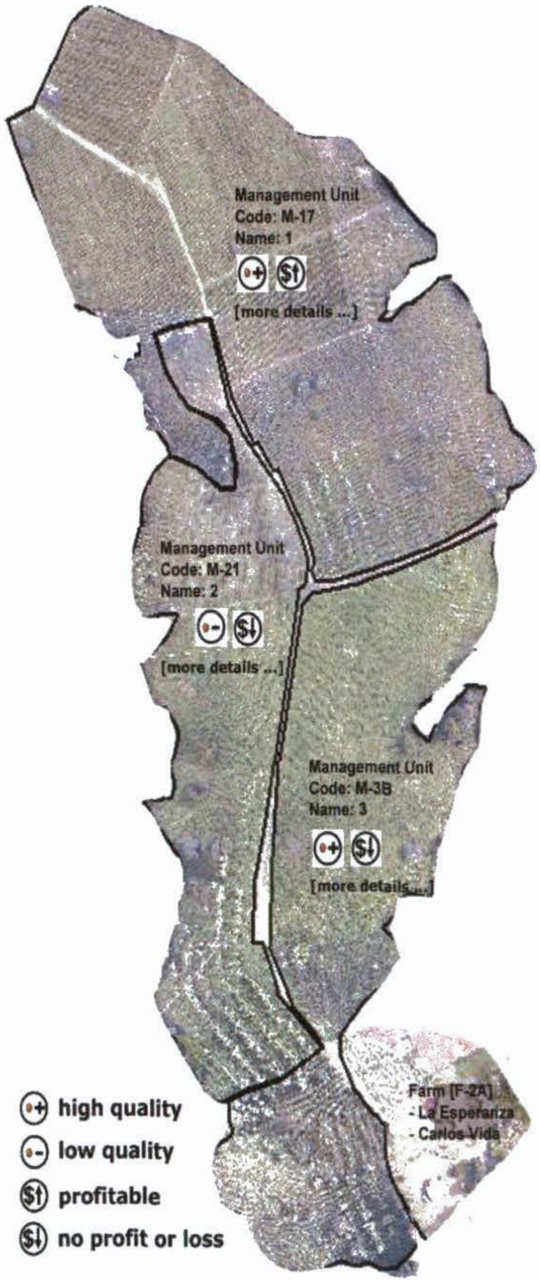

Figure 8. Aerial view image of farm management units and their rating in production and quality.

Information asymmetry

The CinfO system is set up and functional. Both producers and users have found it a useful tool for managing their businesses with special emphasis on improved management of the supply chain for differentiated coffee products. Nevertheless, it is still in the early stages of development and several areas could be improved and various deficiencies need to be addressed: One of the principal aims of CinfO is to facilitate harmonious dialogue along the whole extent of the supply chain including the end user.

Up to now the roasters and buyers provide the information related to end users' opinions, preferences and whims. This is not ideal as the filtered information can cause asymmetries and a lack of transparency in the information flow along the supply chain. For example, it may not be in a roaster's best interest to pass on the information that a particular coffee from a few special farms was extremely highly rated by a particular group of end customers as this would possibly raise the farm-gate price of the coffee and reduce his margins. Or on the other hand if the roaster does not obtain information directly from the end customer the whole supply chain may never know that they have a particular niche product for that group of consumers and everyone loses out. In the future, in the same manner as cupping schemes were set up in this project to determine the quality of the coffee from individual farms, it may be necessary to establish coffee-cupping sessions for end customers.

Harmonizing communication

The experience gained in this pilot phase indicates that there are differing views about what constitutes coffee quality at the different nodes along the supply chain. To give an example, some farmers say coffee is of good quality when it does not smell like chemicals whilst others associate good quality with sophisticated management. On the consumer side, coffee quality is often associated with a distinct cupping quality profile coupled with excellent product presentation. To make the information flow along the supply chain it is crucial to know what information is needed at a certain node, and how to present or deliver this information in respect to the knowledge and needs of the supply-chain member at this node. Sophisticated information engineering is needed to model and transform information to suit the varied needs of supply chain members without distorting that information and losing its intrinsic value.

Information generation

Up to now, members of the pilot scheme team have supervised much of the data collection at the farm level. Furthermore, much of the data have been tabulated by hand for later digitalization. If the pilot scheme is to become a standard for the whole sector, then this close supervision will be impossible, and data collection will surely have to be in the hands of the chain actors themselves, who will have to use digital data-capture systems. It is only when the producers themselves, the roasters and taster and all the others along the supply chain perceive the benefits of collecting and supplying data to CinfO that they will enthusiastically and consistently feed the system with reliable information.

The initial results already indicate tangible benefits for all members of the supply chain and hence the future potential of CinfO. Experience with more enterprising producer groups suggests that this is possible. Groups we have visited have established their own cupping and physical quality-testing laboratories and in preliminary trials with portable computing devices such as PDAs were promising. Specialized software for these systems will need to be developed to facilitate data capture, but it does seem highly probable that producer organizations will accept and adopt these technologies. Already groups such as the San Roque group in Oparapa, Huila have seen the advantages of carefully evaluating and grading their coffee so as to sell into specialized markets at higher prices. Furthermore, they have been able to associate certain growing conditions and management practices with particular qualities that are sought after and have been able to focus production goals on these particular niche markets.

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Satellite imagery and information networks for monitoring climate and vegetation in Colombia

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Key words: MODIS, Colombia, climate, vegetation, NDVI, remote sensing.

Abstract

This paper describes a proposal for establishing a network of researchers and analysts for monitoring weather and vegetation for Colombian agriculture. Opportunities for using satellite images and other data products are evaluated. The paper suggests how such a network could be put together. Some preliminary pilot studies have been conducted to assess the feasibility of the proposed project.

Introduction

Weather and vegetation monitoring for agriculture and food security

Agricultural and environmental scientists, market analysts, farmers and others monitor weather and vegetation change throughout the growing season. The information can be used by the Ministry of Agriculture to plan extension activities. Market analysts use the data to estimate shortfalls in production or likely effects on prices of the coming harvest. Researchers use weather and vegetation information to understand better how climate affects crop growth and yield, and other factors related to agroecosystem health.

Scientists and professionals in developed countries have made great progress in developing weather and vegetation monitoring systems for agriculture. Some of the demand for these systems has come from market analysts who want to know how reduced or increased harvest might affect farm and food prices in different parts of a country or the world. One example of such a system is the United States Department of Agriculture's Crop Explorer, which provides data for users throughout the world (Foreign Agricultural Service, 2006). Other uses of weather and vegetation data are food security professionals. The Famine Early Warning System developed for Africa and Central America provides information from satellites for countries to plan their food aid programs in the context of expected harvests due to weather conditions (FEWSNET, 2006).

Weather and vegetation monitoring for Colombia

As with many countries, networks of weather stations cannot cover the full range of agricultural environments throughout the country. A satellite-based weather and vegetation monitoring system that could provide data for places without ground stations would be of great benefit to agricultural areas that lack monitoring infrastructure.

Food security monitoring systems like FEWSNET are not yet available for Colombia. Although it is possible that Colombia could become a partner in FEWSNET in the future, it is unlikely to happen soon. Colombia is of lower priority for food security monitoring since the country has relatively less drought than other countries. Some information from Crop Explorer is available for Colombia, but often researchers need access to the raw data. Another problem for Colombia is the lack of use of satellite imagery by the research and development community. Sometimes raw data is inaccessible to people outside of the country in which it was produced. Shipping data by Internet or mail courier may present additional problems to acquiring satellite data. Language barriers, lack of training and other factors may also contribute to less use of satellite imagery.

How might some of these limitations be overcome? How could we facilitate increased use of remote sensing data for monitoring climate and vegetation in Colombia?

Proposal

A proposal for a climate and vegetation monitoring network for Colombia

We propose to develop a network that would improve decision-making for Colombian farmers by providing researchers and analysts with useful near-real time satellite data on weather and vegetation. The project would support the larger goal of providing information that supports increased productivity and food security in Colombian agriculture.

Data for monitoring vegetation and weather

Governments and data providers are increasing the number of satellites and imagery products that are available to users of these data throughout the world. Countries with a long history of satellite imagery programs, like the United States, Russia and France, are making more of their products available to users. More recently countries such as China, Brazil and India have made new imagery products available. The availability of these data is creating new opportunities for monitoring weather and vegetation.

Two data products for monitoring weather and vegetation would be appropriate for Colombia. MODIS imagery and the Tropical Rainfall Measuring Mission (TRMM) data sets provide data on vegetation vigor and rainfall respectively. Vegetation indices can be developed from the MODIS imagery to estimate the vigor or water status of plants. The MODIS images are available at 250, 500 and 1000 meter spatial resolutions. Other variables available from MODIS include reflectance, temperature, aerosols and others. Imagery for a given MODIS satellite image product is taken every 16 days. The TRMM data is available every three hours from the NASA web site (NASA, 2006). Rainfall is reported in millimeters for 3-hour or greater time periods for the entire globe. One advantage of this data set is for areas where no ground rain gages are available. TRMM is therefore a viable alternative for countries that have poor coverage of weather stations or have otherwise been unable to maintain stations.

The MODIS and TRMM data have been processed for Colombia as a pilot study at the International Center for Tropical Agriculture (CIAT). With the assistance of the United States Geological Survey (USGS), we were able to process fully vegetation indices from MODIS images. Processing requires selecting high quality imagery, stitching together image tiles, re-projecting the data to a standard Colombian coordinate system and converting the images to formats appropriate for digital image processing and geographic information systems software. Many of the processing algorithms are provided by the USGS. Figures 1a and 1b shows January 2004 images of the enhanced vegetation index (EVI) and the normalized difference vegetation index (NDVI) for Colombia.

Without the assistance of USGS scientists it would have been very difficult for us to put together these images. But with better-documented programs, the processing algorithms could be applied by a wide range of potential users. One difficulty in developing these images is in acquiring the raw data itself. We acquired these data by special arrangement with EDC. Standard download times are too slow to acquire the images over the Internet. They were therefore sent to Colombia by international mail courier on DVDs. We discuss potential solutions to acquiring the data more efficiently later in this document.

We have also acquired TRMM data for Colombia and the surrounding regions (Figure 2). These data sets were developed by colleagues at the USGS. Each digital map shows the 10-day rainfall accumulation in millimeters. Pixels are 15 arcminutes, about 27 km a side near the equator. The rainfall maps have adequate temporal and spatial resolution for vegetation and climate monitoring.

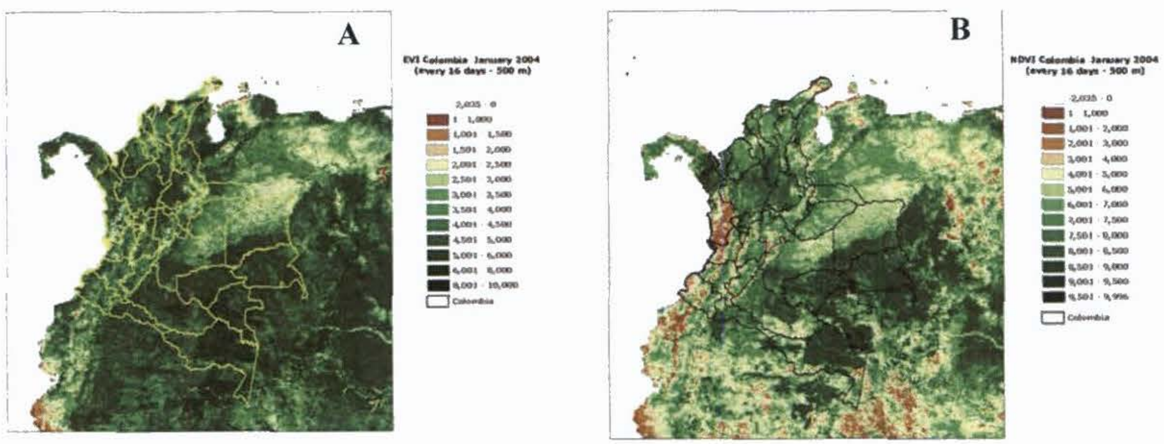

Figure 1. Vegetation indices of Colombia for January 2004. (A) shows the enhanced vegetation index (EVI), (B) shows the normalized difference vegetation index (NDVI).

Necessary elements of any satellite monitoring program are ground data to calibrate and validate information from imagery. Some measures could be direct comparisons. TRMM data can be compared against any weather station that maintains suitable records. Vegetation indices can be compared with different measures collected in the field, such as soil water and field spectrometer data. An inventory of available ground data would need to be developed. Most of these data would likely come from government agencies such as the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) or the Ministry of Agriculture. Some of the information could come from farmer organizations and their research institutes, such as the Coffee Federation and the association of sugar cane growers. An important source of ground data will be universities and advanced research institutes. The next sections discuss how satellite-derived data products, ground station data and the people that work with this information can be integrated into a functioning network.

High speed Internet networks for data exchange

Colombian users of remote sensing data have traditionally found difficulties in acquiring satellite imagery for environmental analysis. In the past the cost of the data product itself has been prohibitive. But that is changing with new policies from countries providing data. The cost of sending the data from the producer to the end user is also a substantial obstacle. Some data providers may not send data overseas. In a project on vegetation change for South America, CIAT requested MODIS imagery for all of South America. Due to policies of the USGS and lack of other options, the imagery was copied onto 500 DVD's. The costs included the price of the DVD's, the time for technicians to upload the data to the DVD's and download it once it arrived at its destination, as well as the shipping fees. Downloading images over the Internet at standard speeds could work in cases where the images are small. But current bandwidth limitations prevent using this option in most cases.

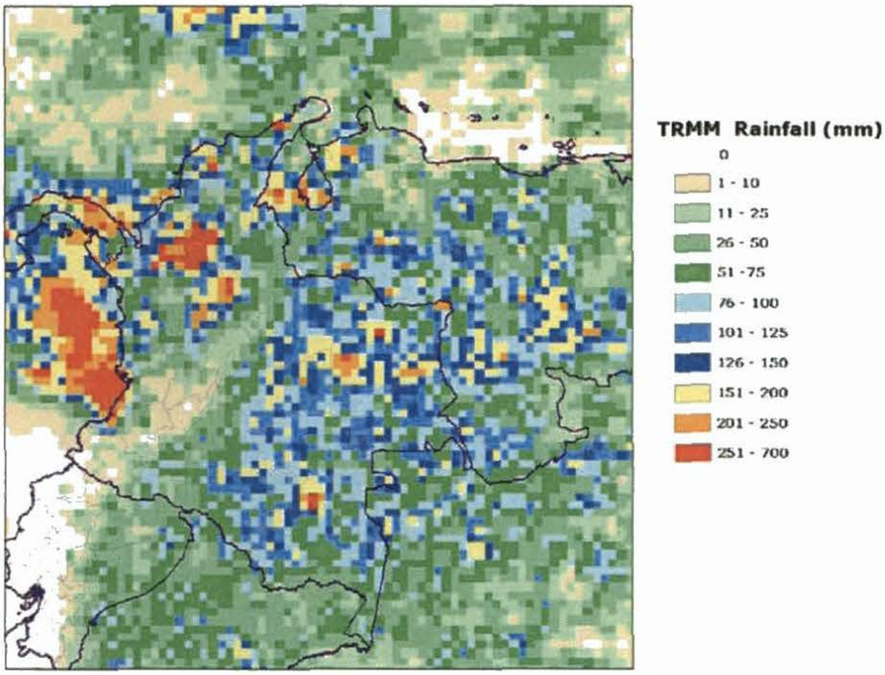

Figure 2. Accumulated rainfall between June 10th and 20th of 2005 from the TRMM satellite. Data set courtesy of Diego Pedreros, USGS.

We are proposing to utilize high speed Internet connections for downloading imagery. Colombia recently joined international efforts to develop high speed Internet. The system is called Internet II in the United States. Colombia's network is called the National Academic Network of Advanced Technology or RENATA for its Spanish acronym (RENATA, 2006). The network connects 25 universities and advanced research institutes by high-bandwidth communication lines. The network has nodes in six regions centered on the cities of Bogota, Barranquila, Bucamaranga, Cali, Medellin and Popayan. Other regions are expected to join the network in later phases. Table 1 shows how the characteristics of high speed Internet fit well with a research and development project that uses enormous and difficult to manage remote sensing data sets for monitoring vegetation and climate.

Table 1. Characteristics of normal Internet and high speed Internet

	Internet	High speed Internet
Use	general	academic, research
Technologies	proven, common	proven, common, advanced
Quality of service	variable	advanced
Connection type	personal, ISP	1 connection per country (RENATA)
Connection speed	normal	very fast
Content	any	non-commercial, academic, research, educational

Since the EDC is an Internet II node, the Colombian network can be connected to the main data provider of MODIS imagery. EDC provides other potentially useful image products from United States satellite programs. Although we have been able to establish the connection between EDC and Colombia, we have yet to test the speed of the connection.. The next step is to benchmark download times and further evaluate the possibility that Colombia and the United States could set up a project to provide MODIS and other imagery for vegetation and weather monitoring. A Colombian high speed Internet network for remote sensing specialists could open up new opportunities in addition to those described above. Distributed data storage and maintenance, dynamic mapping and grid computing are three applications that seem to be well suited to our proposed network.

Groupware for information exchange

A climate and vegetation monitoring network for Colombia will need a mechanism to share information among researchers and analysts throughout the country. We propose the development of software for image storage and inventory, sharing technical information, participation in ground verification and validation activities and other forms of collaboration among the remote sensing community of Colombia. Figure 3 shows a prototype Web site that could serve as the communication mechanism for the project (http://198.93.225.109/valle/tiki-index.php). This prototype was developed using open source Tiki Wiki software.

The site includes capacities for file transfer, image viewing and collaboration in groups. Partners can download images using the file transfer protocol (FTP). An interactive map interface permits users to view "quick look" images in order to assess cloud cover or other image characteristics before downloading. Vector GIS files of roads, towns and other reference layers can be overlaid on these "quick look" images. The site includes file galleries where partners in the network can share technical information, data and any other digital files related to vegetation and weather monitoring in Colombia. The site includes other groupware tools such as forums, surveys, calendars and many others. The groupware tools would be used to integrate data, methods, hardware, software and people into a functioning network for monitoring vegetation and climate in Colombia.

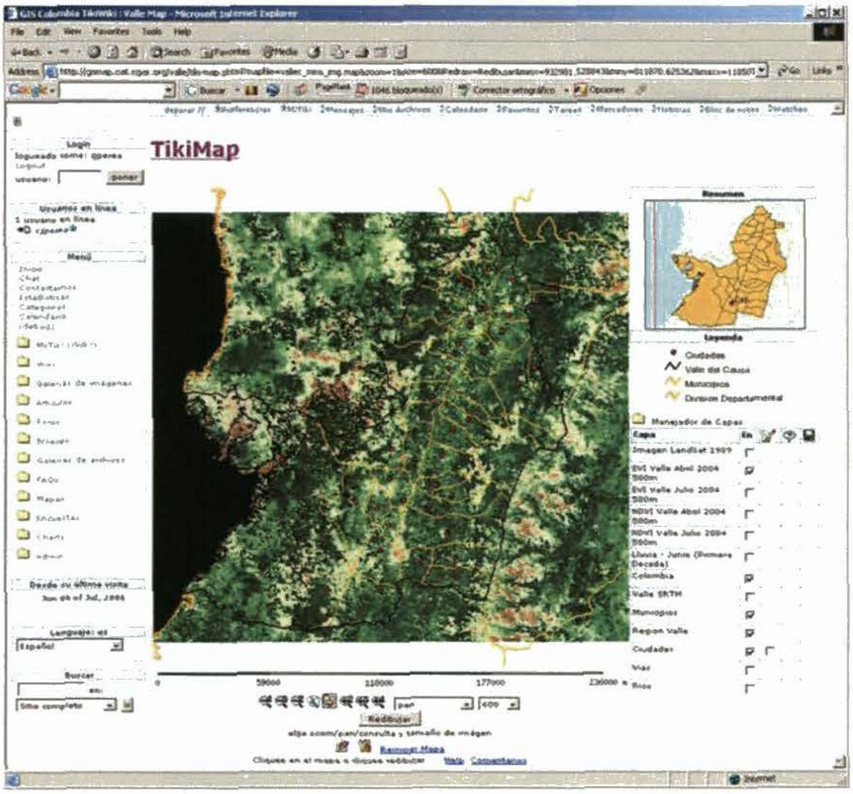

Figure 3. Prototype Web site for weather and vegetation monitoring.

Conclusions

This paper described a proposal for setting up a Colombian network to monitor vegetation and weather during the growing season from satellite and ground data. The network would provide MODIS, TRMM and other satellite image products to Colombian researchers and analysts. Ground data would be shared for calibrating and validating the images. The network would take advantage of Colombia's high speed Internet for exchanging image files. The community of researchers and analysts will use groupware for exchanging information, data, imagery and results from the project.

The concept and methods of the proposed project could be replicated in other developing countries. Almost all the mainland Latin American countries are developing high speed Internet networks. Recent trends in information and communication technologies suggest that this type of network would receive broad support from governments, universities and advanced research institutes. The next step is to gauge the interest of potential partners and seek funding for future development.

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Assessment of high speed internet for remote sensing data acquisition and exchange in Colombia and Latin America

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Keywords: Benchmark, MODIS, Colombia, bandwidth, remote sensing.

Abstract

This paper assesses the potential of high-speed Internet as a medium for transferring large satellite imagery data sets between the United States and Colombia, between Colombia and other Latin American countries and within Colombia. Our analysis suggests that Colombia and Latin America's recent development of high speed Internet for universities and advanced research institutes has great potential for improving the efficiency of use of remotely sensed imagery.

Introduction

Capacities to carry out remote sensing science and technology have increased substantially over the last decade due to the combined influence of many factors. The availability of data has perhaps been the most important reason for this improved capacity (Chen 2005). New data programs from non-traditional providers like China and Brazil are adding to globally-available content. Data sets at finer resolutions have also helped to increase capacities to conduct analyses. Improvements in computing, such as improved software, faster processors, larger storage mechanisms, more efficient networks, have also helped to increase the capacity to use remote sensing for science and technology applications.

Despite these improvements, substantial gaps remain in access to remote sensing technology and data, especially in developing countries. While satellite programs in Brazil, China and India have improved capacities in those countries, a great many nations do not have their own satellites. One difficulty is that often property rights or commercial interests prove to be an obstacle to disseminating data (USDA 2003). However, much of the problem for developing countries is simply the logistics of the international transfer of remote sensing imagery. Poor public postal systems in many countries hamper dissemination of tapes, CDs and DVDs. Commercial courier services are often expensive. Because of these problems. the Internet will likely be the solution to data transfer problems. But current data transfer speeds on the Internet are insufficient for transferring the large files that are typical of remote sensing imagery.

Our proposal is to increase capacity in remote sensing science and technology by taking advantage of high speed internet for non-commercial use by universities and research institutes in Colombia and throughout Latin America. The initiative would build on recent efforts to build high speed Internet connections among the academic and research communities of the region. Government data providers could participate when their data dissemination policies and goals are in line with supporting public research in the region.

This paper addresses the question of how this Internet bottleneck could be resolved. It reports some initial connectivity tests that were made between research institutes and data providers in Colombia, Peru, Mexico, Guatemala and the United States.

Data Access Problems

Several difficulties create obstacles to accessing remote sensing data. Acquiring data through government postal service is not an attractive option in most cases. In many countries the postal service is unreliable.

Courier service is an option, but can be expensive. The logistics of making payments for shipping tapes, CDs and DVDs can be difficult to arrange for the data user due to different financial transfer processes between the country of the data provider and that of the user.

The Internet would seem to be the ideal solution. But data transfer velocities for the Internet are often too slow. Acquiring more than a few image scenes could potentially take from a half day to several days to weeks to download. In many parts of the world, Internet connections fail. With long download times, this is even more likely. Moreover, downloads may be interrupted if the Internet connections are unstable, as they often are in the tropics where electrical storms cause problems.

Our experience with a vegetation analysis of Latin America illustrates the difficulties of acquiring satellite imagery. CIAT and its partners are conducting a continental analysis of vegetation change using the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. The research requires 250 m resolution image products captured every 16 days for the entire mainland of the continent. The products include vegetation indices in four spectral bands (EVI and NDVI), quality data and metadata, all provided by the United States Geological Survey's (USGS) Eros Data Center (EDC) in Sioux Falls, South Dakota, USA. The combined imagery corresponds to more than 2 terabytes of data. Obviously we could not download such a huge volume of data. EDC rejected our offer to send a hard drive to Sioux Falls for copying the data, a solution that conflicts with their data processing policies. The solution was for EDC to burn 500 DVDs, shipping them by commercial courier to CIAT headquarters in Cali, Colombia. It should be noted that this solution was worked out in the context of a visiting scientist program between CIAT and EDC. Acquiring these images would have been difficult without the close collaboration that the two institutions have built up over the years.

This pragmatic solution had several drawbacks. One problem is the time that it takes EDC to burn the images to DVDs. Then, when the data arrived at CIAT, a technician was employed to upload the DVDs to our servers. Since the project will continue into the future, new images will be needed every 16 days. The costs of technical labour, DVD disks and mail shipments as well as the time to carry out the exercise would be prohibitive.

New opportunities to access data

Recent developments in networking infrastructure could solve many problems in accessing remote sensing data for Latin America. At the regional level, universities and advanced research institutes have developed the project "Cooperation in Advanced Networks in Latin America" (CLARA, 2006: Figure 1). The project is equivalent to Internet 2 in the United States.

Figure 1. CLARA Network

Eighteen Latin American countries in the region participate. The Latin American group has also forged high-speed Internet links with Europe and the United States. Colombia's high speed Internet network is "Red Nacional Académica de Tecnología Avanzada (RENATA) and comprises six subnational networks (Figure 2). These sub-networks are cantered around the cities of Barranquilla, Bucaramanga, Bogota, Medellin, Cali and Popayan. The network consists of 47 nodes, mostly universities, but also including some advanced research institutes.

Figure 2. RENATA Network (Colombia's high-speed network)

The Latin American and Colombian high-speed Internet networks are still in the initial stages of development. In Colombia, connectivity problems are being addressed to make the system run more smoothly. Developers of the system are working on applications in grid computing, videoconferencing, interactive distance learning, virtual laboratories and other applications. The system is made efficient by excluding spam, commercial Web sites, peer to peer programs and all other non-scientific content. The initiative seems to be well suited to applications in geographic information systems (GIS) and remote sensing, fields that deal with very large files. Since much of this technology is for non-commercial use, researchers in universities and advanced research institutes could take advantage of high-speed Internet to build capacities.

How such a system might work

To be feasible, data providers must also participate in any effort to launch high-speed networks for remote-sensing research in Latin America. Most satellite imagery providers have some kind of mandate to support partner countries in the use of remote-sensing technology. For example, the United States' remote-sensing policy acknowledges the need to share data as part of overall diplomatic efforts (USDA 2003). Other countries like Brazil, China and India also make special arrangements to provide data for non-commercial use.

The developers of high speed Internet must also be willing to provide the infrastructure support for using the network to support remote sensing science and technology. In principle, this kind of support is a key objective of groups like CLARA, RENATA and Internet2. For example, CLARA and Internet2 signed a memorandum of understanding with the objective of supporting non-commercial research and development between Latin America and the United States (CLARA 2003).

CIAT and partners recently tested high speed Internet connections to assess the viability of transferring satellite imagery (Table 1). Tests were made between CIAT headquarters and our partners in Peru, Mexico, Guatemala and the United States. The connection with the USGS-EDC is particularly important since they are one of the world's leading satellite image data providers. At present, making these connections is not simple or straightforward. A considerable amount of electronic mail correspondence was necessary to set up all the connections that were involved.

Table 1. Institutions participating in the connectivity tests.

Name of Institution	Acronym	Purpose	Location
International Center for Tropical Agriculture	CIAT	Agricultural research and development for the tropics	Cali, Colombia
Eros Data Center	USGS-EDC	Study landscape, natural resources and natural hazards	Sioux Falls, South Dakota
International Potato Center	CIP	Root crops research for small farmers.	Lima, Peru
Universidad Mariano Galvez	UMG	University	Guatemala
International Wheat and Maize Improvement Center	CIMMYT	Research in Wheat and Maize improvement	Texcoco, Mexico
Institucion Universitario Politécnico GranColombiano	POLIGRAN	University	Bogotá, Colombia

Our tests of standard and high speed Internet connections were carried out under current conditions of the network in CIAT, which uses fibre optic cable and a FastEthernet interface to the Internet on a 100 Mbps channel. These conditions are similar to what we would expect in Colombian universities. However, they could be improved greatly using existing technology. The tests should therefore be considered in the context of relative improvement in download velocity.

Our tests included satellite image files of 150 Mbytes from the MODIS platform. Data transfer speeds from our tests showed improvements two to four faster than convention Internet (Figure 3). Data transfers from Cali, Colombia to Mexico and Peru were twice as fast. Connections between the United States and Bogota were four-fold faster.

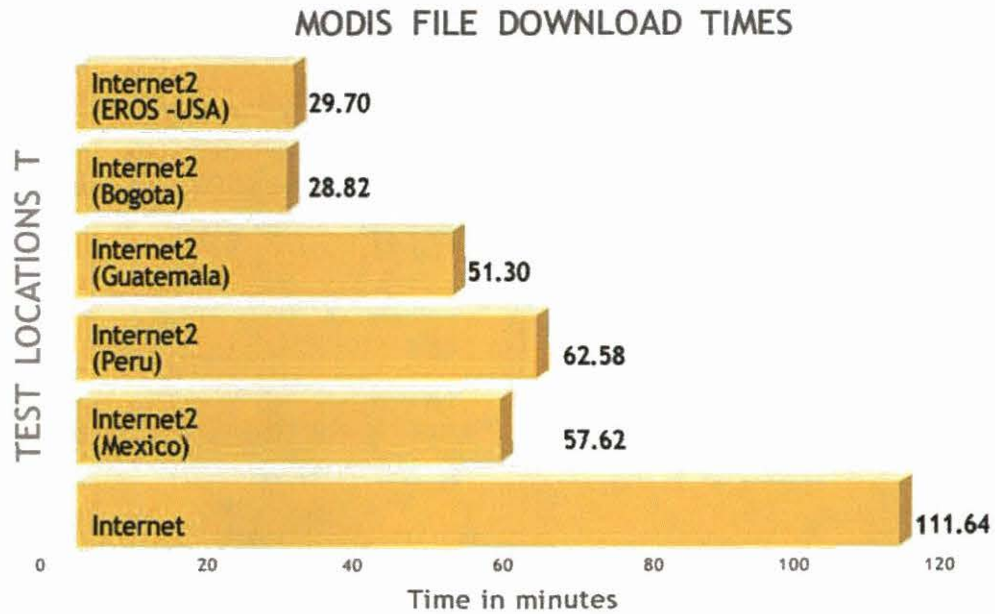

Figure 3. Times to download MODIS files of 150Mbytes on Internet 2 to institution in various countries compared with normal Internet.

Download times could be further improved to give a ten-fold or greater increase over conventional Internet when the Colombian and Latin American networks are fully implemented. The contrasting download times for the different sites shown in Figure 3 are partly due to the different bandwidths used for the initial stages of development. Current bandwidth is 10 Mbytes/sec shared amongst all the universities in Colombia. Future increases in bandwidth will depend on the quantity and type of applications that will use the network. Increasing the bandwidth is not a technical limitation. Currently, it is possible to increase the link up to 155Mbytes/sec, but this depends on user requirements and funding resources.

Remote sensing applications in Colombia and Latin America

While high-speed Internet could solve imagery access issues, there are many other applications for remote sensing and geographic information science and technology. For example, the system could decentralize data, models and processing throughout the region. Decentralization would be in line with broader trends in computing and networking. Another application is grid computing. Computing-intensive digital image processing could take advantage of a grid computing network over high speed Internet connections. Processes that take days or weeks to run could be conducted in a few hours or less. High-speed Internet also opens up possibilities to collaborate with colleagues in different institutions. Groupware and collaborative tools are becoming increasingly popular, and would run particularly well on high-speed networks. For example, interactive maps are notoriously difficult to use over conventional Internet connections. Drawing graphics and accessing data needs high velocity computing that RENATA, CLARA and Internet2 are providing.

Acknowledgements

Mark Beverage and Larry Tieszen at the USGS-EDC arranged for testing connections between Sioux Falls, South Dakota and Cali, Colombia. The entities that participated in these tests as well are: the International Potato Center (CIP)-Rolando Navarro, the International Maize and Wheat Improvement Center (CIMMYT)-Fermin Segura, Institución Universitaria Politecnico GranColombiano (POLIGRAN)-Alvaro Francisco Quiroga, Universidad Mariano Gomez (UMG)-Ivan Morales, CLARA technicians-Eriko Porto, Eduardo Villegas, Hans Reyes and Colombia Telecomunicaciones- Luisa Fernanda Lozano and Jose Francisco Guevara.

High-speed Internet access at CIAT (International Center for Tropical Agriculture, the International Potato Center (CIP) and the International Maize and Wheat Improvement Center (CIMMYT) were developed under the Consultative Group on International Agricultural Research (CGIAR) program on Information and Communication Technology and Knowledge Management (ICT-KM).

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Method of processing MODIS images for Colombia

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Abstract

MODIS images play an important role in land systems analysis, deforestation monitoring, global change prediction and for scientific information for environmental policy-making.

Vegetation indices are designed to provide a consistent comparison of temporal and spatial changes in vegetation as a response to the quantity of photosynthetically active radiation in a given pixel, the chlorophyll content, leaf area and structural characteristics of plants. The MODIS system has two types of vegetation indices: normalized difference vegetation index (NDVI), sensitive to chlorophyll and the enhanced vegetation index (EVI), focused on plant structural variation such as physiognomy and leaf type and area.

How can these images be processed for different institutions and users in Colombia? In a partnership between USGS-EROS Data Center and CIAT, methods were applied to the processing of MODIS images for all of Colombia in the *Marco Geocéntrico Nacional de Referencias – Sistema de Referencia Geocéntrico para América del Sur* (MAGNA-SIRGAS) projection. The method allowed us to acquire imagery for 23 periods of 16 days each in 2004. The images were developed in the GeoTiff format, compatible with most GIS software. The image products generated include NDVI, EVI, MIR reflectance band #7, EVI Quality, NDVI Quality MODIS mixed cloud, NDVI Quality MODIS Aerosol, MIR reflectance band #7, NIR reflectance band #2, Blue reflectance band #1, NDVI Quality QA and EVI Quality QA, which can used to extract information on clouds, aerosol quality and vegetation indices.

An important step is to re-project the images to standard coordinate system for Colombia that is compatible with image processing and GIS software. Colombia recently replaced the Bogotá Datum adopted in 1941 with a modern system compatible with international standards and current technologies. Known as MAGNA-SIRGAS, this system supports the exchange of georeferenced information between users in Colombia.

In the case of MODIS images for Colombia, the conversion to a standard national projection system and the creation of a mosaic of seven tiles that cover the entire national territory are key pre-processing steps. We demonstrate methods that can be replicated for different years. The data could be made available for the remote sensing community in Colombia.

The EVI improves vegetation monitoring by separating spectral signals of soils and atmosphere from that of vegetation. The combined use of EVI with other indices can be used for modeling crops and climate variability and its effect on harvests. All this information is useful for different communities of experts working in Colombia.

Introduction

The purpose of this work is to obtain products for Colombia, that will be used in crop modeling and in turn to estimate the effects of climate variability on yield. The images will be made available on a website using open source tools and groupware. This will permit sharing with the expert community in Colombia and with partners who work in projects monitoring vegetation and climate.

Materials and methods

The study area was focused mainly on the Cauca valley (*Valle de Cauca*) but it also covers of all Colombia and in the future will cover all of South America.

Moderate resolution imaging spectroradiometer (MODIS) includes data from two satellites (MODIS Terra and MODIS Aqua) that take images of the whole surface of the globe every one or two days. These images contain information of high sensitivity radiometry in 36 spectral bands and at three different resolutions, 250 m, 500 m, and 1000 m. The coverage is 10 arc-degrees tiles of the whole globe. For Colombia we selected images with a resolution of 500 m each 16 days according to the Julian calendar for 2004 giving a total of 23 periods. MODIS contains various products that are currently available. This article is mainly focused on the vegetation products at 16 day intervals derived from the normalized difference vegetation index (NDVI), sensitive to chlorophyll and the enhanced vegetation index (EVI).

For preprocessing the images in a format compatible with GIS software it was necessary to obtain software code from the US Geological Survey (USGS) (http://LDPAAC.usgs.gov), which are available for different users' operating systems. In the case of Colombia we used Linux as the operating system because of its capacity to handle large files and because it uses command line instructions, which facilitates batch processing through scripts.

The software programs were:

a) MODIS Reprojection Tool (MRT)
b) MODIS Land Data Operation Product Evaluation (LDOPE)
c) MODIS Swath Reprojection Tool (MRT Swath)
d) MODIS Data Pool Extraction Tool (MODextract)

These tools can be installed on the Windows 2000, Windows XP, Linux, SGI IRIX 6.5 and Solarios 2.7 operating systems.

The methodology used is based mainly on written code of command line instructions, which allows the execution of each of the programs above. The outputs are images in formats compatible with GIS software and with a coordinate system designed for the whole country. Before initiating the program in Colombia it was necessary to take into account the following requirements:

- Vegetation indices EVI and NDVI
- Temporal resolution sufficient to understand the progress of the growing season at a spatial resolution of 500 m
- The year 2004
- Coverage for Colombia and the Valle del Cauca re-projected to the MAGNA-SIRGAS coordinate system (Table 1);
- Output format: GeoTiff

Table 1. Parameters for re-projection on to the MAGNA-SIRGAS projection.

	Colombia	Valle del Cauca
Projection:	Transversal Mercator	
	Parameters:	
False_Easting	1000000.000000	1000000.000000
False_Northing:	1000000.000000	1000000.000000
Central_Meridian	-74.077508	-77.077508
Scale_Factor:	0.999600	0.999600
Latitude_of_Origin:	4.596200	4.596200

Once the requirements were defined and the programs installed on the Linux platform, the MODIS images can be downloaded. The MODIS website provides a search engine that permits the user to search the MODIS product for particular areas of interest and to select the resolution of the data and specific dates. Note that products earlier than the current year are available from the USGS at the website http://lpdaac.usgs.gov/main.asp. The download options for data stored in the "Data Pool" can be accessed through an FTP server of the USGS. To give an example, the selected product of interest for Colombia was: "*Vegetation Indices* 500m" MOD13A, for the whole of the year 2004 and the specific tiles we needed were h09v09, h10v07, h10v08, h10v09, h11v07, h11v08 y h11v09. Figure one shows how these tiles are distributed within a Cartesian coordinates starting in the position (0,0) in the upper left-hand corner and continuing to (35,17) in the bottom right-hand corner. Each "tile" covers 10 arc degrees with rows denoted by the letter "h" and columns by the letter "v" to select the tiles detailed above.

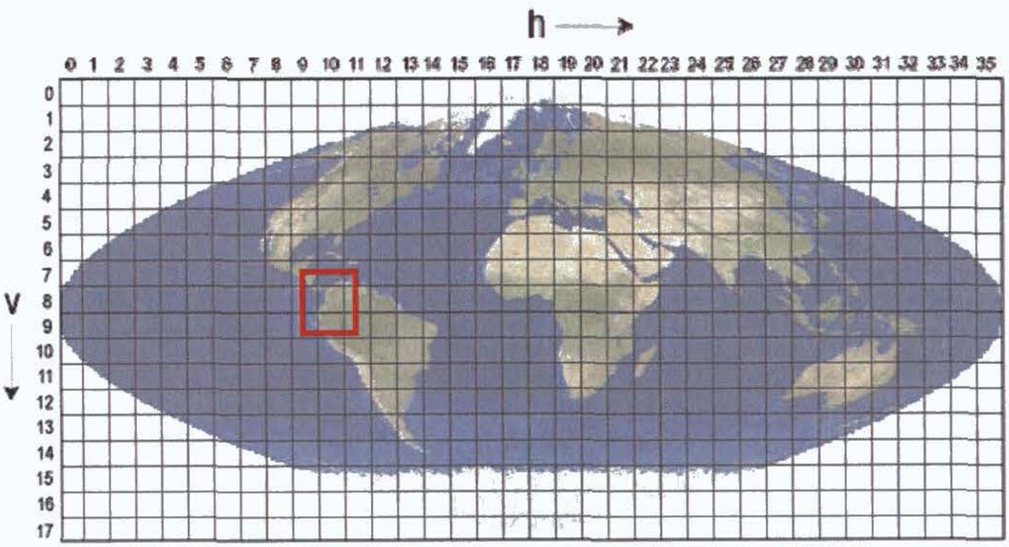

Figure 1. Cartesian system for selecting tiles in the MODIS product. The area marked in red corresponds to the tiles for Colombia.

The downloaded MODIS data are stored in a compressed format with the extension HDF. The next step is to define the information stored within each file that is needed for the study in question. In the case of Colombia we extracted the following data:

- 500m 16 days **NDVI**
- 500m 16 days **EVI**
- 500m 16 days **NDVI Quality**
- 500m 16 days **EVI Quality**
- 500m 16 days **red reflectance MODIS Band #1, 620-670 nm**
- 500m 16 days **NIR reflectance MODIS Band #2, 841-876 nm**
- 500m 16 days **blue reflectance MODIS Band #3, 459-479 nm**
- 500m 16 days **MIR reflectance MODIS Band #7, 2105-2155 nm**

The programs used to process the data for the required images are controlled by scripts to extract information, generate mosaics and re-project the data. The output data files are in GeoTiff format, so that they can be used for spatial analysis in the different GIS software packages.

Figure 2 shows an example of one of the scripts used with the tool MODIS Data Pool Extraction Tool (MODextract), which generates an archive log of the HDF formats that might be used to generate the mosaic for Colombia.

The MODIS Swath Reprojection Tool (MRT Swath) generates a mosaic of tiles specified in the archive log created by the script shown in Figure 1. The archive log that contains the tiles corresponding to the study area is used with the instruction *mrtmosaic* on the command line, for example:

/> mrtmosaic –i MODextract.log –o TmpMosaic.hdf –s '1 1 0 0 1 1 1 1 0 0 0'

This instruction creates a mosaic from the data NDVI, EVI, red reflectance, NIR reflectance, blue reflectance and MIR reflectance. The values 1 in the instruction parameters indicate the data selected for extraction, while zeros indicate the data that will be skipped in the process. The output data are stored in a new HDF file, not by individual tiles, but as a mosaic for the entire area under consideration.

```
MOD13Q1.004        #input dataset and version –avg size 125 MB

2004.01.01         #start date
2004.12.25         #end data

09,09              #horizontal, vertical grids (09,09)
10, 07 08 09       #horizontal, vertical grids (10,07) (10,08) (10,09)
11, 07 08 09       #horizontal, vertical grids (11,07) (11,08) (11,09)
```

Figure 2. Code used to generate the log file for the HDF format.

The MODIS Reprojection Tool (MRT) is used to re-project the data SIN (Sinusoidal) to one of the more common projections, in the case of Colombia to UTM MAGNA-SIRGAS. It is necessary to use a new script to generate each one of the GeoTiff files with the selected parameters.

The command line scripts generate GeoTiff files corresponding to EVI, NDVI, NDVI Quality, EVI Quality, red reflectance MODIS Band #1, NIR reflectance MODIS Band #2, blue reflectance MODIS Band # 3, and MIR reflectance MODIS Band #7.

Note that the MODIS EVI and NDVI data have additional qualitative information that can also be extracted from the images such as:

0-1	VI Quality (MODLAND Mandatory QA Bits)
2-5	VI Usefulness Index (Indice de utilidad)
6-7	Aerosol Quality
8	Atmosphere (Adjacency Correction)
9	Atmosphere (BRDF Correction)
10	Mixed Clouds
11-12	Land/Water Mask
13	Snow/ice
14	Shadow
15	Compositing Method

These qualitative data may be extracted using the MODIS Land Data Operational Product Evaluation (LDOPE) tools, using SDS commands with 35 parameters for the command line instruction.

The processes, especially the MRT Tool, can cause problems by exceeding the size limit on files. To avoid this, one must consider the study areas to be processed by reducing the number of tiles and the extraction parameters. This is especially important for spatial information with resolutions less than 500m.

Results

Each HDF-EOS file was re-projected using scripts as described above to generate output files in GeoTiff format with the same names as the input files (but different extensions). The output files correspond to each sixteen day period between 1 January and 31 December 2004. The SDS commands in the LDOPE tool generated masks of cloud and the amount of aerosol, which can be combined with maps of EVI and NDVI. These combined processes were carried out in the ESRI tool of ArcGIS (Figure 3).

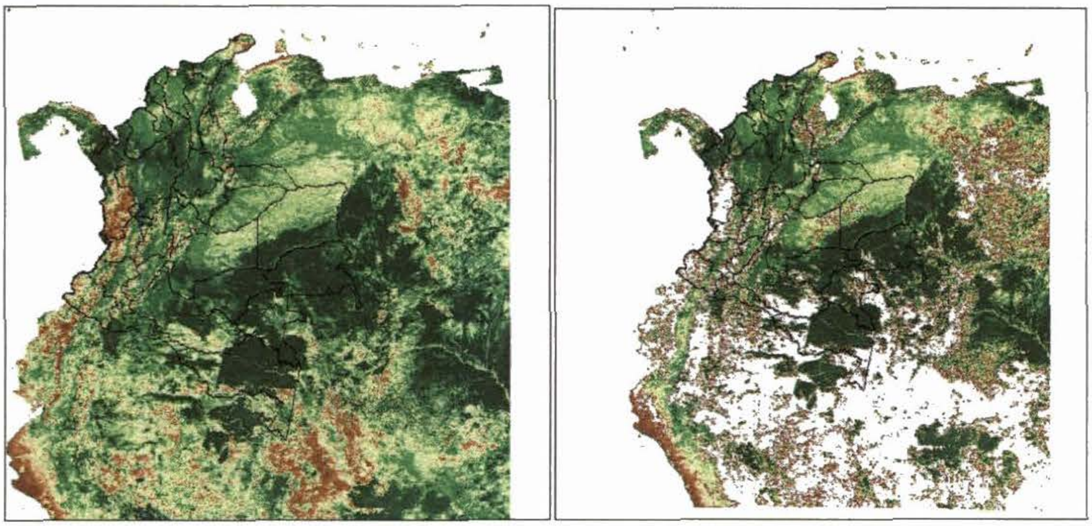

Figure 3. Example of an EVI map of Colombia and the same image overlain with a mask of cloudiness corresponding to the first 16 days of January, 2004.

One of the objectives of this work is to distribute the images through a website where users are not only able to access data but as well visualize them in a web mapping tool like MapServer. For this application, the problem of large size of the image files must be eliminated, since this prevents them from being displayed in the common web navigators. The solution was to convert GeoTiff data to JPEG2000 using the GDAL library of MapServer (an OpenSource tool) with kakadu software, which creates images with better resolution and smaller size.

All the data were integrated within a collaborative tool and made available to different users through the website http://gismap.ciat.cgiar.org/valle. While this work is in its preliminary stages, it is possible to access some images for the Cauca valley. The images available are for the first sixteen days of each month and are available to whoever wishes to access them.

Conclusions

Having a methodology to process MODIS images has added greatly to the value of the different research projects in CIAT's Land-use project as well as being able to make the data available to whoever needs them.

Without the help of the USGS it would have been difficult to generate the maps and mosaics and to extract information on vegetation indices.

Our use of the USGS programs often required modifications, depending on the resolution of the data, the size of the data files to be processed and the inherent limitations of the platform used. It was not possible to give more detail in this paper of the scripts we used. Future use of these scripts would benefit from additional documentation on the types of problems that can be encountered.

We found that the method has the advantage that it can be replicated easily and at present we are generating data for all of South America. Moreover, thanks to the experience gained in this exercise, CIAT was able to obtain in native format data for the whole of South America for the years 2000 to 2005 (500 DVDs in HDF-EOS format) and for the whole Africa for the years 2000 to 2006 (more than two terabytes of image data).

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Identifying Critical Issues to Promote Technical Change and Enhance the Efficiency and Competitiveness of the Beef Sector in Costa Rica

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This inter-institutional study ILRI-CIAT-CORFOGA was concluded in 2006. During this year, surveys were executed in cattle auctions, slaughterhouses, butcheries, and supermarkets. Based on the information collected, a value-chain analysis was performed in order to determine costs, risks, and profits along the different segments of the beef value chain of Costa Rica. The study is now being edited for publication.

Highlights

- Costa Rica's livestock and beef industry performs very unsatisfactorily.
- At the farm level, beef production systems generate an annual gross income of \$37/ha in the dual-purpose system to \$125/ha in the fattening system. Such gross incomes are extremely low if we take into account that the commercial value of beef farmland ranges between \$1,000/ha and \$2,000/ha. As a result, the gross income cannot recover the opportunity cost of the capital invested in the land, making this beef activity uncompetitive.

Objectives

This study aims to:

a) Describe the economic agents of the meat chain in Costa Rica as well as its commercial and legal relationships;
b) Identify the inter-relationships between links, technological levels, efficiency indicators, installed capacity (scale), and level of occupation;
c) Characterize and estimate cost and price structures and the generation of value along the different links of the chain;
d) Identify critical costs that can be modified through technological interventions, policies, or other actions; and
e) Determine biological and economic risk factors throughout the chain.

A methodology that identifies and determines the costs and benefits in each segment was developed to estimate the generation of value in monetary terms throughout the meat chain.

Results

Costa Rica's meat sector has clearly suffered a downward trend since the mid-80s, with an annual decrease in production of 0.1% over the past 20 years despite the reduction of the herd inventory, which decreased from 2.3 million head in 1985 to only 1.1 million in 2004. Government investment in the sector fell from

5% of the national budget in the early 1990s to only 1.5% at the beginning of the present decade. Total farm credit of both public and private sectors has suffered a marked decline. In 1990 it represented 15% of total loans (4% in livestock production) and in 2002 these had fallen to only 5% (1.7% corresponding to livestock credit).

Productivity indicators reflect the poor dynamics of Costa Rica's livestock sector. The annual gross earning per unit area was estimated at US$44/hectare for cattle ranches, at $126/hectare for dual-purpose farms (including income from sale of milk), and at $135/hectare for farms where development and cattle fattening activities were carried out. Gross income at these levels is extremely low considering the commercial value of land on beef farms, which ranges between US$1,000 and $2,000/hectare. The biological inefficiencies of low calving percentages and poor liveweight gains, combined with the high cost of land, hinder the recovery of the opportunity cost for capital invested in the land, making meat-related activities relatively uncompetitive. Because of its low productivity, and based on the assumption that the only cost in cash is for labor, the cattle-raising system pays family labor wages only 60% the legal minimum. Therefore it is imperative that the public and private sectors join efforts throughout the supply chain to increase the productivity and efficiency of this primary sector by facilitating the adoption of improved technologies.

Auctions yield a relatively good profit; however, when analyzed on a calendar-day basis, they are not so attractive because of the low use of installed capacity (Table 1). A strategy that could prove useful to improve the efficiency of Costa Rica's auction system would be to integrate the different events in order to share fixed operational costs. Administrative and operational staff could rotate among existing auctions since their dates are different. This scheme would help reduce fixed costs and the commission charged, without affecting profits but improving efficiency in this link of the chain.

Table 1. Operational characteristics of auctions: type of animals bought or sold, operating costs, and income.

Indicator	Auction					Average
	1	2	3	4	5	
Year of establishment	1997	1993	1984	2001	1993	1994
Commission collected (%)	4	3.5	3.8	3.5	4.0	3.8
Installed capacity (# animals/day)	900	500	600	500	800	660
Average no. transactions per event (# heads)	500	390	300	290	750	446
Capacity used (%)	55	78	50	58	94	68
Weekly operation (# of days)	1	2	1	1	2	1.4
Real capacity used (%)	9.2	26	8.3	9.7	31.3	15.8
Categories of animals bought or sold at the auction (%)						
* Culled cows	10	60	35	6	30	28
* Weaned calves	25	15	15	20	15	18
* Weaned female calves	20	5	5	9	10	10
* Young bulls for finishing	30	5	10	25	20	18
* Heifers for slaughter	10	10	30	33	20	21
* Finished males	5	5	5	7	5	5
Most frequent distance from the auction to the farm (km)	25	40	30	60	50	41
Labor at the auction (# people)						
* Auction day	32	25	29	16	34	27
* Day without auction	9	9	6	4	12	8
Monthly operational costs[1] ($)						
* Labor	7,440	6,200	5,790	3,500	11,363	6,859
* Services	250	220	240	200	290	240
Gross monthly income[2] ($)	22,733	36,151	14,679	12,076	76,048	32,337
Net income per event ($)	3,474	3,433	1,997	1,934	7,437	3,655
Net income per animal bought or sold per event ($)	6.94	8.80	6.66	6.67	9.92	7.80
Net income per animal bought or sold per calendar day ($)	0.99	2.51	0.95	0.95	2.83	1.65

[1] Estimate based on an average cost of US$550/permanent worker, *including social benefit* costs for days without auction and US$25/day for transitory workers on auction days.

[2] Estimate based on the proportion of animals, according to category, that arrive at the auction, number of animals bought or sold per event, 2005 sale price, and commission collected by each auction.

The industrial sector (municipal and industrial slaughterhouses) shows a low occupation of installed capacity, which results in high operational costs and very low labor efficiency. Estimates of total operational costs of slaughter range between US$32 and $66 per animal (Table 2). If the estimated unit costs are compared with the rates collected for slaughtered beef (US$15-$23), municipal slaughterhouses would appear to operate at a loss although industrial slaughterhouses do make a very low margin of profit thanks to sale of the by-products (*hides and viscera*).

Table 2. Operational characteristics of several municipal and industrial slaughterhouses of Costa Rica.

Variable	Municipal slaughterhouses			Industrial slaughterhouse
	1	2	3	
Volume slaughtered (head/month)	45	150	650	7,635
Days of operation per month (#)	17	13	26	26
Capacity of daily slaughter (head)	7	50	85	500
Capacity currently used (heads	38	23	29	59
Initiation of operations (year)	1985	2002	1974	1964
Annual proportion of post-slaughter rejections (%animals)	<0.1	<0.1	<0.1	<0.1
Origin of cattle slaughtered (%)				
Small producer			4	NA
Medium producer		50	12	NA
Large producer			54	NA
Butcher's shops	100	50	30	NA
Supermarkets				NA
Others				NA
Agent of the chain that assumes the post-slaughter risks of confiscation	Cattle owner	Cattle owner	Cattle owner	Cattle owner
Availability of insurance policy (Yes, No)	Yes	Yes	Yes	Yes
Permanent employees (#)[1]	3	16	33	757
Productivity of labor (# of animals slaughtered per worker)	15	9.4	19.7	76.3
Operational costs ($/month)				
Labor	1,650	8,800	18,150	416,350
Electricity	140	1,070	2,525	64,080
Cost of slaughter ($/head))	39.80	65.8	31.8	62.9
Cost of maquila ($/head)	20	23	20	15

[1] Of the total number of employees, about 100 work in slaughter-related activities.

The retail sector (butchers and supermarkets) present the best performance in terms of efficiency and profitability. The gross profit margin, expressed as the fraction of the final price paid by the consumer that remains in hands of the butcher as retribution for his/her work, varies widely from 3% to 40%, with an average of 32% (Table 3). If these rates of profit are compared with those of other alternative retail businesses (approximately 8%), then this type of activity generates excellent margins of profit at very low risk.

Table 3. Monthly operational costs, break-even point, and profits of urban and rural butcher's shops in Costa Rica (US$).

Variable	Butcher's Shop							
	Urban neighborhood	Urban neighborrhood	Urban neighborhood	Urban market place	Urban market place	Rural market place	Rural market place	Average
Workers	22	13	3	24	5	2	4	10.4
Labor cost[1]	7150	12100	1650	13200	2750	1100	2200	5735
Energy cost	787	886	886	591	303	290	394	591
Lease of locale	3937	4000	3937	350	295	300	280	1871
Cost of insurance policy	157	158	160	158	157	150	140	154
Operational cost	12031	17144	6633	14299	3505	1840	3014	8351
Beef sales (kg/month)	6495	25980	3464	30310	8660	4243	3810	11852
Total sales of (kg/month[a]	12990	43300	4619	43300	12371	7072	6350	18635
Breakeven[2] (kg	4500	4500	800	5000	1400	1200	1200	2800
Operational cost kg meat sold g)[3]	0.93	0.40	1.44	0.33	0.28	0.26	0.47	0.45
Average cost of dressed carcass viscera[4]	3.06	3.05	3.06	3.06	3.06	3.06	3.06	3.06
Average sale price kg meat for point[5]	3.99	3.45	4.50	3.39	3.34	3.32	3.53	3.51
Average sale price[6] consumer of dressed carcass plus	4.63	4.63	4.63	4.63	4.63	4.63	4.63	4.63
Net earnings per meat sold	0.64	1.18	0.13	1.24	1.29	1.31	1.10	1.12
Net earnings per meat sold	16.0	34.2	2.9	36.6	38.6	39.5	31.2	31.9

a. Includes all species.

[1] Assuming an average cost per month of US$550 per worker, including social benefit costs.

[2] No. kg beef that should be sold monthly to cover operational costs of butcher's shop.

[3] Calculated by dividing total operational cost of butcher's shop by kg meat of all species sold monthly.

[4] Calculated on the basis of the sale price of one 276-kg carcass at $611 by the slaughterhouse to the butcher's shop plus 16 kg viscera at $35 for a total of $646 divided by 211 kg salable meat (267 kg carcass multiplied by 78% salable meat minus 6% fluid loss). The survey did not ask for this value, but it was estimated on the basis of carcass sales of slaughterhouses.

[5] Calculated on the basis of the sum of operational cost per kg beef sold plus average cost of purchasing kg meat from the slaughterhouse.

[6] Estimate based on Table 4 for a young bull and does not reflect the differences of prices that exist between butcher's shops; as a result, this is an approximate indicative.

The value generated throughout the chain. The percentage of the final retail price of young bulls is distributed as follows (Figure 1): rancher (19%), auctioneer (1%), fattener (34%), transporters (6%), slaughterhouse (7%), and retailers (33%). The distribution of the value generated along the meat chain is completely inequitable and is not consistent with the risk faced by the different actors forming the chain. The inequity observed in the distribution of the added value reflects a clearly dominant position in the market of several actors of the chain, which allows them to capture a very high fraction of the benefits. The generation of value along the chain ranges from US$0.28/animal per day for the rancher to US$46/animal per day for the butcher. The highest proportion of added value is concentrated at the final end of the chain. The butcher or supermarket obtains 164 times greater value from the same animal in the same time unit than the rancher but faces a lower risk because his/her raw materials, equipment, and infrastructure are usually covered by insurance policies.

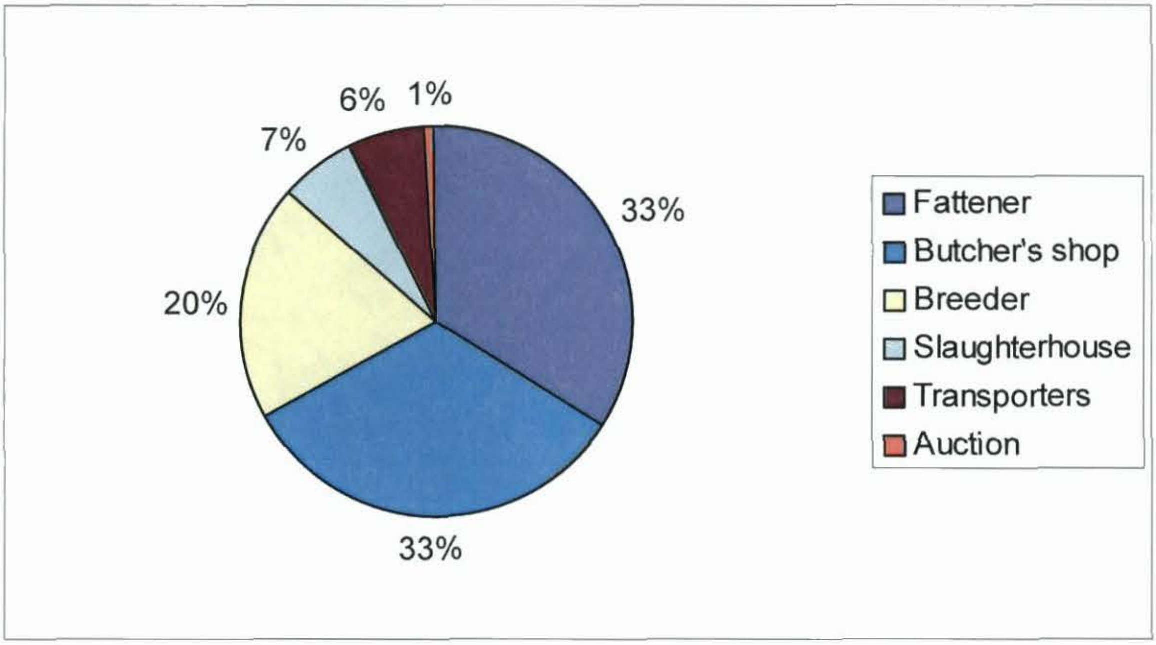

Figure 1. Value generated throughout the chain as percentage of the final value of a fat young bull at retailer price.

The competitiveness of this meat chain is the sum of the efficiency and productivity of all the links that form it. A weak and rather poor demand for beef at the final link of the chain hinders the adoption of technology in the primary link of the chain, so it becomes a vicious cycle that generates low productivity and competitiveness.

The low demand for beef implies reduced levels of slaughtering, which impedes the full use of the installed capacity of slaughterhouses and processing plants. This, in turn, hinders the generation of economies of scale and causes high unit costs that reduce the competitiveness of meat products in both domestic and foreign markets.

To promote technical change and enhance the efficiency and competitiveness of the value chain of Costa Rica's beef sector, we recommend the following:

(a) Learn from other chains, for example the poultry chain, by identifying actions that could improve the meat chain;

(b) Milk breeding cows when a milk market exists as a mechanism to increase family income because wages are currently below the legal minimum;

(c) Promote the creation of livestock funds as a mechanism to create social capital, reduce transaction costs, and improve chain productivity and profitability;

(d) Promote massive adoption of forage species with an emphasis on summer feeding to reduce weight losses of the national herd, improve farm profits, and promote modernization through the adoption of improved technologies; and

(e) Establish a standard systems for beef cuts based on quality and price, allowing the differentiation of offers for different consumer groups, among others.

New systems of agricultural production and environmental services: an economic evaluation in the Altillanura[1] of Colombia

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Abstract

In the general context, the Ministry of Agriculture and Rural Development (MADR) of Colombia proposes a mega project *The Rebirth of the Altillanura of the Orinoco* with the main objective to generate environmental services associated with the fixation or sequestration of carbon to mitigate the effects of progressive global warming. In this mega project, large-scale sowing of plant species that fix carbon in the aerial parts (foliage) and in the roots is proposed as a commercial product in international markets. The proposal calls for establishment of trees on 6.3 million hectares over a period of 20 years. It is expected at the end of this process 5 million people will be settled in the region and 1.5 million jobs created. The total cost of the agricultural component of the project is estimated as US$15 billion dollars, aside from the investment required for physical and social infrastructure and public services. This initiative provides the setting for the national policy for productive forestry development, which counts Forestry Incentive Certificates (CIF) among the main instruments to stimulate the sector. This policy intends to stimulate employment and the national offer of forestry products at the same time as generating environmental benefits associated with the control of erosion, conservation of water resources, carbon fixation, reduction of tree felling and pressure on natural wood lands. Within the global framework, this study evaluates new farming system models with an economic, social and environmental focus. The new models include diverse components of grazing, agriculture and forestry for the production of food and primary products and, in addition, environmental products such as the sequestration of carbon.

Introduction

An analysis of new systems of agricultural production in the Altillanura of Colombia, which included various technological components developed by CIAT and its collaborating institutions, started in 2005 was finished in 2006. Given the imminent signing and entry into force of the free-trade agreement (FTA) with the United States and the possible effects of this agreement on prices and national agricultural production, various alternative scenarios where added to the study. These included the effects of falling agricultural prices and increases in productivity on net incomes, production and land use in different farm models in the Altillanura.

Outstanding aspects

- The incorporation of new technological elements into the traditional ranching systems of the eastern plains is a powerful tool to encourage regional agriculture and at the same time to conserve and improve the productive capacity of the soils.
- Crop–pasture rotations within a strategy to create arable layers[2] significantly improve the performance of current production systems in terms of productivity, profitability, cash flow and generation of employment.

[1] There are basically two broad ecosystems on the eastern plains of Colombia, the poorly-drained and the well-drained savannas. The Meta River, a tributary of the Orinoco, runs east from the Andes and divides the poorly-drained savannas to the north from the well-drained savannas to the south. The term *Altillanura* refers to the southern, well-drained savannas. To avoid a contrived translation, we continue to call them the Altillanura.

- An outstanding aspect of the intensification of productive systems of the region is the increase in their capacity to generate employment and contribute to social objectives such as improved equity and poverty reduction contrasted with traditional systems, which have low capacity to offer employment.
- The objective of this *ex ante* evaluation is to generate relevant information to support investment decisions in the public and private sector. This will permit implementation of sustainable and competitive development of the region with high economic, social and environmental impact. Techniques based on linear programming were used to address the basic economic problem of efficient allocation of scarce resources between multiple alternative uses.
- The inadequate regional road system impedes the transport of machinery, agricultural inputs and products and makes transport more expensive. The scarcity of agricultural machinery and the difficult to rent it during seeding and harvest present a serious bottleneck, especially for less well-off producers.

Methods

The theoretical model has the following form:

Maximize $Z = CX$, subject to: $AX \leq b$; $X_1, X_2 ...... X_n \geq 0$; where Z is the objective function, which in the present case is defined as the net total benefit resulting from the implementation of diverse production options at the farm scale. Vector C contains the coefficients of net return for each of the generated products in vector X.

The modified model used in the study increases the evaluation period to nineteen years and limits the analysis to the alternatives of cattle ranching, agriculture, forestry and carbon sequestration by different vegetative covers. The following variables are included:

1. Decision alternatives, also known as activities, which are under the direct control of the producer and comprise the production plan of a particular farm amongst which are crop-pasture rotations, purchase of inputs and sale of products, obtaining credit and the use of cash flow over time; and
2. Internal (endogenous) variables and restrictions, which include all those variables resulting from the internal functioning of the model and the economic, technical and environmental restrictions.

Among productive activities that are reasonable to develop in the Orinoco region of Colombia are the following:

1. Distinct alternative uses of land resources and how their efficient use can generate social economic and environmental benefits;
2. Potential uses of land in ranching, crops and reforestation or natural woodland;
3. The alternatives that generate commercial products such as meat, milk, timber and environmental services such as the sequestration of carbon by pasture and woodland; and
4. Benefits derived from economic social and environmental land-use at the level of farm, region and country.

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[2] The arable layer strategy aims to use management techniques such as stubble mulching and minimum till to create and maintain a layer at the soil surface that is physically and chemically apt for cropping. URL: www.ciat.cgiar.org/riceweb/memorias/d_molina.pdf.

For the evaluation of ranching we consider two cattle systems:

1. Dual-purpose, which includes the production of meat and milk, emphasizing milk production by improving the productive capacity of cows through the incorporation of genes from milk breeds and feeding the herd a high quality diet.
2. Breeding beef cattle, which is the first phase in cattle production directed towards the production of store-condition cattle for farms that specialize in cattle fattening.

Forage on offer for the cattle can come from the following alternatives:

1. Pastures alone either native savanna pasture, improved *Brachiaria* and the association *B. decumbens*-legume; and
2. Pastures in rotations with crops within which we consider several rotations. Rotation 1 starts with a period of seven years of native savanna followed by a cycle four years of biennial crops rice-soybean and maize-soybean in rotation, finishing with a pasture association *B. decumbens-D. ovalifolium* that remains productive for eight years. Rotations 2 and 3 are similar, both starting and finishing with a cropping cycle of six years each and including an intermediate phase of improved pasture which for rotation 2 is improved *Brachiaria* and for rotation 3 a pasture association of *B. decumbens-D. ovalifolium*. The pastures alone are evaluated for a period of nineteen years with renovation in the eighth and fifteenth years. The forestry component consists of a plantation of Caribbean pine, which produces timber and environmental services in the form of carbon sequestration. To improve the soil physically and chemically, an improved grass pasture is sown initially, which remains in production for four years before establishing the pine plantation.

For the analysis, progressive incorporation of new technological components in the current grazing systems is simulated by constructing diverse sequential scenarios. It starts with the grazing model, which can be either breeding or dual-purpose, based on extensive use of pastures alone. In the subsequent phase the model adds a component of rotations between pastures and crops in a process oriented towards progressive soil improvement through the creation of arable layers. The incorporation of trees and sale of environmental services in the form of carbon sequestration is represented in the following stage of the transformation pathway towards productive systems. Finally, to evaluate the impact of economic policy on production systems and on land-use, we constructed scenarios in which the production systems, besides including new technological components, are assisted by promotional policies such as Forestry Incentive Certificates or through schemes of advance payment for environmental services. The model considers a farm of five hundred hectares operating with average regional costs and with operating capital that can vary in the range US$5000 to US$300,000.

Results

The results show, amongst other possibilities for the region, that:

1. Incorporation of new technological components into traditional ranching systems of the upland eastern plains gives a significant increase in farm net return, in employment, production and productivity. In the traditional ranches, as might be expected, the use of improved pastures is controlled by the availability of financial capital. The incorporation of crop-pasture rotations excludes native savannas from the optimum solution and, on improving cash flow, facilitates the expansion of improved pastures in farms with fewer economic resources.

2. Breeding, compared with dual-purpose systems, represents an inferior level of technological development, and for this reason the introduction of improved technologies has a relatively greater economic effect.
3. Establishment of forestry plantations for sale of timber and the capture of carbon is more likely to be adopted on farms currently devoted to breeding. The simulation exercise showed that trees could enter these systems at all levels of available capital, and as such is a promising alternative to breeding, which is generally relegated to areas that are isolated and far from markets. The latter emphasizes the need for state investment in roads and transport infrastructure with parallel development of complementary services, especially those for processing, managing and commercializing forest products.
4. Technical progress significantly improves net farm income, the objective function of the model, but especially in those with less available capital. For example, the implementation of crop–pasture rotations in breeding systems increased by 1.8 times the net income on farms with high available capital but by six-fold in those with greater financial limitations.
5. The intensification of productive systems increases the capacity to generate employment, which constitutes a relevant impact in achieving the social aims of equity and poverty reduction.
6. The CIF forestry promotion policy has a greater impact in production units with better endowment of operating capital in that it permits them to increase their land under forest. When operating capital falls below US$20,000, the impact is nil.
7. The price of carbon in the international market at present is low and according to some experts will remain stagnant until 2012.

On-farm research and *ex ante* economic studies have demonstrated the feasibility of new technological options. Nevertheless, the process of adoption of new technologies in the region still does not have the necessary dynamism that permits an observable impact in production, productivity, employment and prices.

Agriculture in the Altillanura is risky since it confronts numerous technical, economic, physical infrastructure and social restrictions such as documented in the rapid appraisals carried out by CIAT in 2004 and 2005. Many of the producers interviewed see the entry into force of the FTA as a menace that would increase risks to regional agricultural production. Nevertheless, this bilateral agreement also offers great possibilities for the production of meat, milk and its products, fruit and forestry, activities that are well-suited to the resource endowment of the Altillanura. In a scenario in which grain prices fall more than t10%, the contribution to net income by crops in the rotation would become negative. In spite of this, rotation 1 (native savanna–crops–improved pasture) would continue to be profitable owing to its strong beef cattle component.

Research to improve the yield of current crops and the search for new options of highly-productive, adapted crops to establish rotations with pastures, are alternatives to confront the economic risks of prices and the objectives of the FTA. It is expected that a period of growth supported by policies of investment in physical and social infrastructure, state programs of credit and compensation to those sectors affected negatively by the bilateral treaty, grain production will continue to be economically viable in the uplands. For the advantages of participation in a broad and high-value market and to take maximum advantage of the natural resource endowment of the Altillanura, it is necessary that the nation underwrite integral programs of development that, besides promoting new alternative technologies at the farm scale, applies appropriate policies to overcome the restrictions that limit technical advance.

Reference

Rivas, L., Holmann, F. and García, J. (2006). *Nuevos Sistemas de Producción Agropecuaria y Servicios Ambientales: Una Evaluación Económica en la Altillanura Colombiana.* Centro Internacional de Agricultura Tropical (CIAT) and International Livestock Research Institute. (ILRI), Cali, Colombia. Working Document No. 204. 60pp.

Communities and Watershed project

During the wind-down phase of the Communities and Watershed project, focus has been on the impacts of climate and land-use change on watersheds. The goal of the team during this time will be to contribute to the understanding of how agro-ecosystems are responding to climate change and land-use impacts with a focus on water resources.

The strategy for research on water resources and adaptation to climate and land-use change is to compare responses of agro-ecosystems components such as soils, water and vegetation under different climatological and land management practices, using the watershed as the unit of analysis. This will be accomplished through a combination of CIAT-based research activities and the participation of local, regional and national partners to make research results relevant, applied and used for decision making.

Strategic partners in this process include national organizations such as IDEAM, Ministry of Education; regional environmental agencies such as CVC and CRQ; local partners such as municipalities, water districts and farmer communities; universities such as Universidad del Valle – CINARA, University of British Columbia and NGOs such as CARE, ECOPAR and Agua Bolivia.

Our current special projects and those under development in research and education are complementary in this context. They contribute to the scientific knowledge base on impact and implication of climate and land-use change, and the uptake of this information by users. We see the educational and institutional components as critical to information management and to the assimilation of research results for development and decision-making.

Continued research is on water availability and hydrologic response as well as the options available for water-efficient technologies relevant to local conditions. In addition to the monitoring of established networks, we undertake, baseline surveys on the use of water, land, and resources and analysis in pilot watershed. Through these activities we make available to water-user associations data on water quality). The pilot watershed in which we work in Colombia are Garrapatas and El Dovio in the Valle del Cauca, Barbas watershed the Central Cordillera. We also work in Tiquipaya watershed in Bolivia

Protocol for the characterization of carbon and water in high mountain ecosystems

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Partners: *CIAT, IDEAM, UBC, World Bank and GEF*

A protocol for the monitoring of carbon and water cycles was developed to acquire a scientific information base about the processes that affect the cycles, their interactions, dynamics, variability, the practices that optimize storage, the effects of land use, vulnerability to perturbations and potential impacts.

The conceptual model focused on the pools and flow paths and the potential impacts of climate and land use change on the compartments of the cycles in high elevation ecosystems (Figure 1).

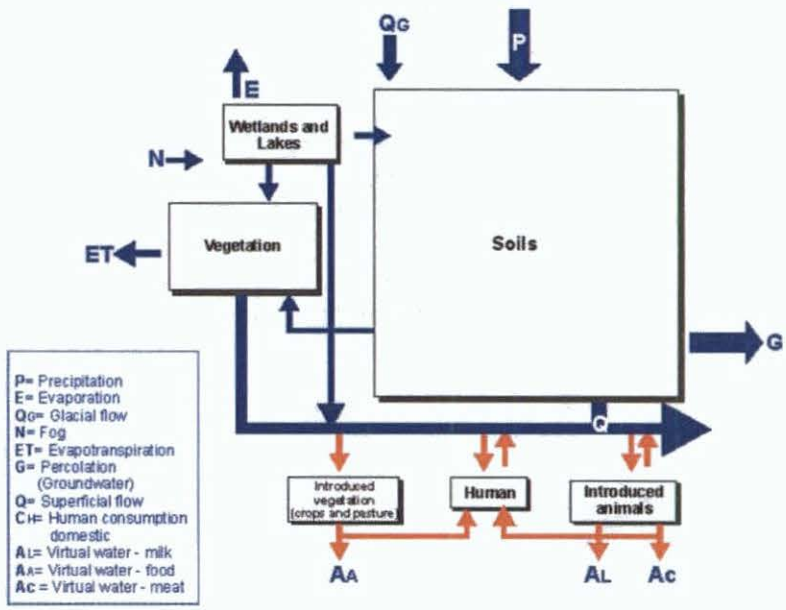

Figure 1. Pools and flows of water in páramo with human intervention.

Anthropogenic activities such as ploughing, burning, forest harvesting and grazing have impacts on the water and carbon pools and modify the natural cycles through changed vegetative land cover, introduced animals, and human consumption of water and biomass.

An algorithm was developed incorporating the selection of sub-watersheds and ecosystems to monitor and research relevant questions, the collection of secondary data, design of the monitoring network, installation of the monitoring program, data collection, systematization and analysis of information (Figure 2). Each block in the chart represents a flow of activities, analysis and decisions taken. Norms and criteria, procedures, formats for data capture and instructions for the measurement of variables are associated with the blocks.

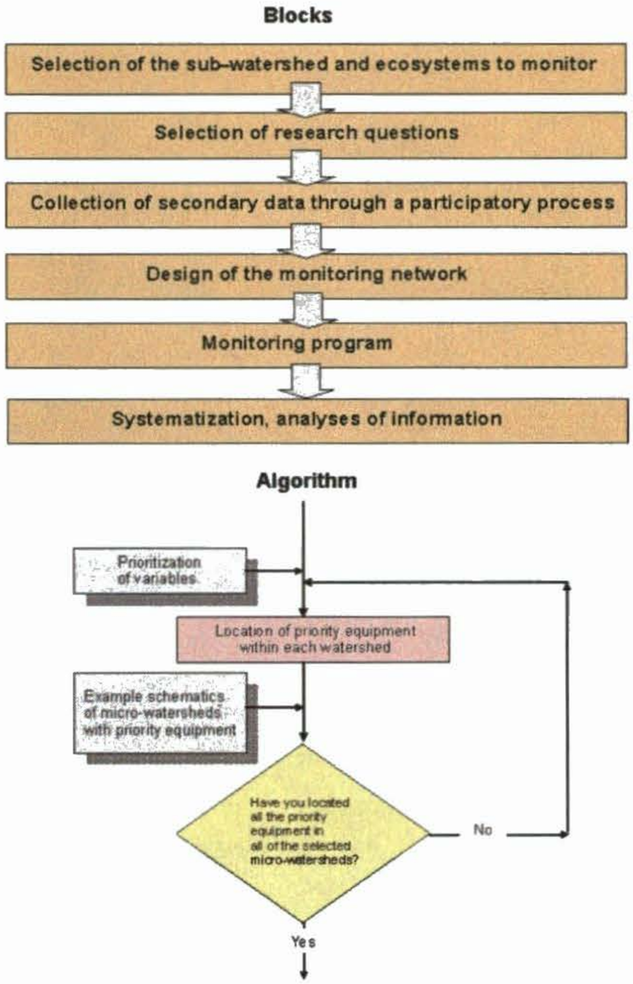

Figure 2. Algorithm of the protocol.

The selection of the sub-watershed and ecosystems to monitor aims to account for the relative importance of the high elevation ecosystems and their variability, and logistics for implementing monitoring. The research questions are defined based on the characteristics of the selected micro-watersheds for monitoring and for comparison between ecosystems. The collection of secondary data is done in a participatory process, which includes:

- Identification and involvement of interest groups;
- Creation of a learning alliance;
- Validation of indicators at the local level;
- Assignment of responsibility for data compilation; and
- Creation of metadata and quality control.

For each selected sub-watershed and the relevant research questions, the monitoring network is designed in accordance with prioritization of variables (Figure 3). Variables are prioritized based on a weighted index that includes: contribution to a flow or compartment within the cycles and scientific understanding of these processes, complexity of measurement, and equipment cost(s). Data collection includes information on biophysical, socio-economic and geographic variables.

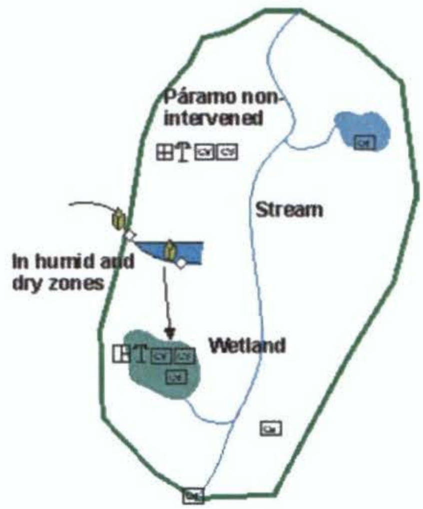

Figure 3. Schematic monitoring design for non-intervened páramo

The monitoring program provides the detail for the installation of equipment and procedures for the collection of data corresponding to each selected variable.

The systematization of data refers to the collection and transfer of information to a central database, and the analysis and synthesis of monitored variables to consolidate information at the project scale, for the carbon and water cycles.

Youth Bolivia: alliance for water-science and the future CGIAR - CIDA Canada Linkage Fund

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Partners: *Communities and Watersheds, CIAT Colombia; Institute for Resources andEnvironment, UBC Canada and CGIAB, Agua Bolivia*

Achievements y activities 2006-07

Leadership

The second leadership workshop consisted of two parallel programs: one for facilitators and one for young people. The objective of the facilitators' workshop was to build capacity among teachers, Asiritic (the irrigation users' association) members and adult facilitators, to understand and encourage the development of leadership abilities in youth, to facilitate leadership action, exchange experiences, and generate new ideas. Teachers working in the high altitude sections of the Andes in general had little experience in oral expression, and members of Asiritic tended to lead youth involvement rather than facilitate processes. The workshop focused on methodological tools for young people to work through the steps of a research project including: problem trees, flow charts, stair diagrams, chronograms, activity lists, questionnaires, strength and weakness analysis, and participatory appraisal.

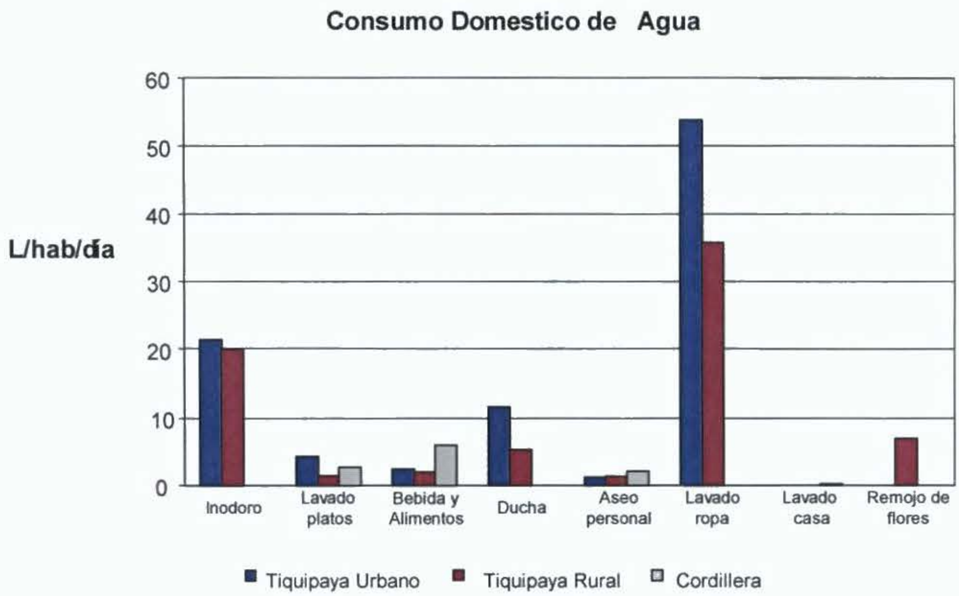
The youth workshop focused on creation of self awareness, affiliation within the group, self-confidence, goal setting and teamwork (Figure 4). The exercises reinforced public speaking skills, leadership roles and responsibilities, group participation, team work, and the process of designing and conducting a research project. The workshop aided in the development of individual skills, the generation and expression of new ideas, integrating youth from the cordillera and valley, and further involving female youth within the group.

Water rights, customs and use

The irrigation systems of Machu Mit'a, Lagun Mayu and Chankas and their use were mapped and analyzed to understand further the history of the traditional irrigation systems, water allocation within individual communities, and water use and customs with respect to irrigation. Youth "regained" knowledge of the irrigation systems, their use and potential limitations within their own communities (Figure 5). This sub-project permitted the youth to reflect on the socio-economic and environmental challenges associated with the timely distribution of water of good quality.

Water consumption

Water consumption in the cordillera (>4,000 m) is very low due to socioeconomic conditions, climate and cultural practices. Despite all families having access to water either from the piped network or private springs, they do not have flush toilets or showers and clothes are always washed in small streams. The animals drink water from natural sources: streams, khochas or bofedales. By contrast in the valley (urban and rural Tiquipaya), water consumption is significantly higher (Figure 6).



Food security

The production of vegetables in protected environments was undertaken as an alternative for food security in the Cordillera (4100-4200 m). A tunnel type greenhouse (7.5 x 4 m) appropriate for regions with strong winds was constructed communally at the school in Titiri (Figure 7). Organic seed beds (2 m x 4 m) with agro-film cover were also constructed with the local youth in Titiri and Totora. The first seeding included lettuce, onion, cabbage, carrots, beets, achojcha, locoto, tomato, and aromatic herbs.

The greenhouses provide the possibility for the youth to generate small amounts of income and expand lettuce production targeted for market, taking advantage of the good water quality in the Cordillera (poor water quality used in the valley to irrigate lettuce has been associated with human health risks).

Social forum

The "Social Summit for the Integration of Communities" was held December 6 to 9, 2006. Exhibitions included water resources, gender, sovereignty and integration with the participation of indigenous, women, youth and small producer groups. As part of the exposition, the youth project along with *Agua Sostenible* (Sustainable Water) presented their activities related water use and water customs.

Soils and water holding capacity

The water-holding capacity of soils in high elevation ecosystems is being investigated in relation to downstream availability of water. Steps in the process include: delineating watersheds, inventory of khochas, characterization of khochas, wetland coring, wetland age determination, and determining soil organic matter and downstream flow. The watershed delineation and inventory exercises use detailed (0.7 m resolution) imagery. Youths, a GIS student and indigenous farmers from La Cumbre worked together to delineate natural boundaries and canal systems (Figure 8). Khochas are being inventoried and characterized using the imagery together with field verification. Relic wetlands were cored and samples taken for ^{14}C dating and organic matter composition (Figure 9). Downstream water flow in the canal system was analyzed using salt tracer/conductivity measurements and flow rates were determined from the time required for small reservoirs to fill.

Role of Andean wetlands in water availability for downstream users, Barbas watershed Colombia

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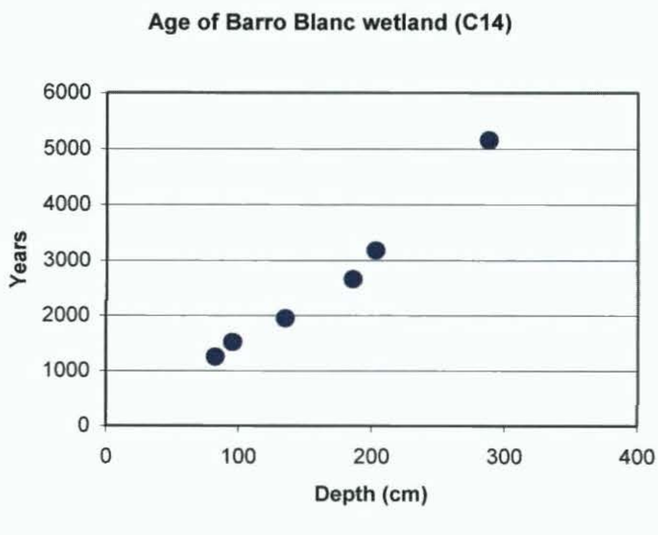
Partners / Donors: *Municipio de Filandia, Quindio, CRQ, UBC, IDRC, USAID, IFC*

Small, high-elevation headwater catchments are the preferred source of water for a large portion of the Andean population, due to less impact of human activities on the water quality and the advantage of elevation for water distribution. However, the lack of process-based water balances has implications for water allocation and the protection of ecosystems that play an important role in water flow regulation. Decisions about water allocation for human use impact ecosystems and decisions about upland ecosystem management impact the availability (quantity and quality) of water for human use and for the maintenance of downstream ecosystems. In view of the increasing water demand, there is an urgent need to use a more scientific approach to provide evaluations of water supply and demand.

Water demand for irrigation in the productive Cauca valley is large and increasing, as well as increased demand due to urban growth. In many headwater areas, forests are being converted to grazing land, small wetlands are being drained. However, the effects of these land-use changes on hydrology are not well documented.

The headwater catchments of the Barbas River in Quindio department were selected as a case study because wetlands have been relatively preserved from drainage or have been restored. Moreover, there is interest by the regional environmental agency, *Corporación Autónoma Regional del Quindío* (CRQ), to understand the contribution of these wetlands to the annual water balance. CRQ also wishes to acquire management tools that can be incorporated into the watershed management plan particularly for the conservation of key water source areas. The catchment of the Barbas River has a strategic importance for the provision of water to rural and urban communities both up and downstream (Figure 10). Its headwaters are located in an area classified as very humid in terms of annual precipitation (2,800 mm). Considering that the highest altitude of the catchment is only about 2,300 meters, the amount of rain in the headwaters is higher than reportes at other climate stations at similar altitudes in the Central Cordillera.



The terrain is undulating and can be described as hummocky. There are many small flat and concave areas between steeper hills, which with the high precipitation have turned into wetlands. Individual wetlands in the upper Barbas average less than one hectare with a total area of 57 hectares (CRQ, 2001). A detailed land-use map was made using a Quickbird satellite image with resolution of 0.6 meters. Subsequent field survey showed that the wetland area in the headwaters of Rio Barbas covers 7.2 hectares (Figure 10). The water storage capacity of wetlands in each catchment was estimated using the land use map. The Quickbird images of three selected catchments was printed at 1:1,000 scale for use in the field to mark polygons of land use, which were later digitized in ArcGIS. For each of the selected wetlands we described the area, water source, water outflow, relative location in the catchment, type of protection, dominant vegetation, duration of saturation and surrounding land use. Assuming that each monitored wetland was representative for their catchment, we calculated the spatial distribution for all the wetlands for each. We then calculated for each hydroperiod (wet season and dry season) the dynamics of water storage in wetlands throughout the year. In collaboration with the University of Geneva, Switzerland, we assessed the age of the wetlands using carbon 14 dating. The data show that the organic matter accumulation over the impermeable clay layer has occurred over the last 5,000 years with a rate of accumulation of 0.6 mm of organic matter per year. This suggests that these ecosystems are highly vulnerable to changes in precipitation patterns or to temperature.

Analysis of the water balance was undertaken at the wetland scale to understand the response of water storage to precipitation, surface runoff, sub-surface runoff and evapotranspiration. We used water level recorders both inside and in the surface outflow of the three representative wetlands. Together with the wetland profiles and the porosity of the wetland soils we made an analysis of the wetland water storage and its fluctuations throughout the year. The following field measurements are on-going:

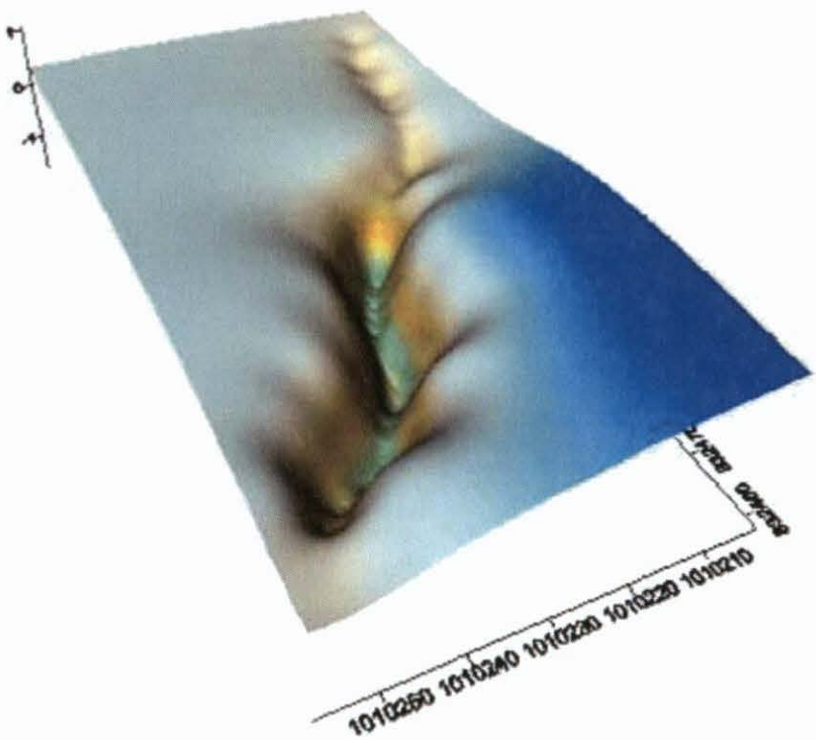
Water level in the wetland: An Odyssey© capacitance water level recorder was installed in each of the three monitored wetlands to record continuously changes in water level (Figure 13). These automated measurements are complemented with manual measurements. Six pipes were installed in each wetland to measure water level changes spatially and temporally. These measurements are taken every 2 weeks starting from 30 September, 2004 using a wooden ruler that is inserted into the bottom of each pipe. The water level is recorded from the mark that water leaves on the ruler.

Wetland volume: Each wetland has a particular topography, which determines the water storage capacity. For each wetland, a 3-dimensional model was generated using Surfer© and depth measurements taken with an extended Russian peat corer. These measurements were taken across transects at fixed distances. The depths of the organic matter layer of the wetland soil were entered into the program together with their relative location.

Water storage capacity: Water content of each wetland soil was measured using a number of soil samples that were analyzed for water content and soil porosity. These data were then extrapolated to the wetland volume calculated with Surfer.

Using the 3D model, the equivalent water content of the calculated wetland volume, and the measurements of water depth and wetland area taken every 2 weeks, and the wetland water storage calculated. This information shows the response of the wetland to seasonal variations in precipitation, or hydroperiod (Figure 14).

Once the wetland water balances are completed, the water balance will be done at the catchment scale and particular attention will be paid to dry seasons when water scarcity is experienced downstream by the municipality of Filandia, both in rural and urban areas. The comparison of the wetland outflow to the catchment hydrograph will show the influence of wetlands on base flow.



Reference

Corporación Regional del Quindío – CRQ, 2001. Estudio hidrológico de los humedales cuenca superior Río Barbas, Municipio de Filandia, CRQ, Armenia, Quindío.

Youth, leadership and research: Improving education for development[1]

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Partners / Donnors: *INTEP, CERES El Dovio and CERES Barragan, municipalidades Genova, Versalles and El Dovio, Kellogg*

General objective

Improve tertiary education in rural areas by helping in the processes of natural resources research that contributse to sustainable management and improvement in the population's quality of life.

Specific objectives

- Create a systematic methodology for research in natural resources management in the Regional Centers of Higher Education (*Centros Regionales de Educación Superior* CERES) in El Dovio and Barragán.
- Guide research in natural resources management and water resources in the chosen watersheds.
- What kind trustworthy data of this research over 1-1/2 years.

Project advances

The project is working in three sites, where they have incidents in the rural youth population of the Colombian Andes: Versalles and El Dovio, Valle del Cauca (CERES El Dovio) and Genova, Quindio (CERES Barragán).

Selection of watersheds to monitor and the research themes

Watersheds of interest for research have been defined through workshops where criteria for the selection of these watersheds has been evaluated and they have defined the research themes of interest focused on water resources and climate change. These workshops were conducted with the participation of the CERES students, the municipality and other local organizations (Table 1).

Figura 1. Taller de inducción para el manejo de programas de los diferentes equipos

[1] This article is not BP2 research but is a contribution from the now-defunct project PE3.

Table 1. Micro watershed selection criteria

Criteria	Micro watersheds				Classification		
	Weight	San Juan	Gris	Rojo	San Juan	Gris	Rojo
Strategic importance (benefits to user populations, water volume, dependent economic activities)	7	2	3	2	14	21	14
Existence and % of strategic ecosystem	6	2	3	2	12	18	12
Productive activities/impacts/land use	5	3	2	2	15	10	10
Viability of comparative study	4	3	3	3	12	12	12
Community and institutional participation	3	3	2	2	9	6	6
CERES-Sena students	2	3	1	1	6	2	2
Available information	1	2	3	2	2	3	2
Total					70	72	58

Points:

High	3
Medium	2
Low	1

Table one shows the priority selected in Genova for the watershed should in the area.

The research themes chosen for the work in micro watersheds of the three municipalities are related to the following themes:

Water resource and demand

What variations in the water resource can be identified in the micro watersheds and how do they affect beneficiaries?

What is the difference between the wooded micro watersheds and high moor with and without intervention with respect to regulation of the water resource?
What is the micro watershed water resource during the year in the higher parts?
What is the water consumption in the high, medium and low parts?

Characterization of the vegetation of representative ecosystems (wetlands and cloud forests).

Geo-referencing the location of water sources land-use homesteads in micro watersheds and sub watersheds

Water quality

What is the difference between the wooded micro watersheds and high moor with and without intervention with respect to water quality?

Human interventions

How to make people aware of and conscientious about and the high and the low parts for protection of water?

Starting with the results of water consumption, what are the practices in water use in the different zones (high medium and low) and according to the productive activities and in what form is it possible to make the population conscientious about it?

Environmental standards

What other current regulations regarding the supply of water and protection of its sources?

Does the population know the legislation that concerns it? Utilization? Benefits?

Is it profitable for a countryman to protect a water source of a minimum of 1 ha by applying an incentive of a reduction in land tax?

Sustainability of CERES

Is CERES sustainable with its current resources? What measures need to be taken in case it is not sustainable?

Choice of micro watersheds

Once the watersheds to monitor and the research questions were determined, field visits will made for the selection of micro watersheds that would be unable to answer the questions.

Definition of the methodology for use by the CERES students

The economic, training and supervisory help that CIAT will provide the CERES students who participate in the project was defined, as well as the help (advice, follow-up and academic validation) they will receive from the teachers and the university. Equally the research methodology that must be followed, including the presentation of reports, was defined.

Youth involvement in each research theme

Twenty four young people were selected from the CERES (9 from CERES Barragán in Genova and 4 from CERES in El Dovio and Versalles) to start the research process taking questions that can be resolved initially. These young people make presentations on the specific theme of a preliminary project demonstrating the objectives in the methodology to be used for the research. Training workshops were carried out however the themes involved in the research.

Purchase and installation of the monitoring equipment

Monitoring equipment was installed in each of the micro watersheds (Table 2 and Figures 2 and 3).

Table 2. Equipment installed in the project. (MWS = micro watersheds).

Equipment	Versalles MWS Patuma	El Dovio MWS La Esperanza	Rio Gris				Rio San Juan		Total
			Below Genova intake	El Retiro wetland	El Tapón woodland	El Espejo high *moor*	Below Genova	MWS Juntas	
Level meter 1.5m	2	1	-	3	1	2	-	3	12
Ruler level meter 1.0m	2	1	-	1	1	1	-	2	8
Level meter 2.0m	-	-	1	-	-	-	1	-	2
Ruler level meter 1.0m	-	-	1	-	-	-	1	-	2
Pluviometer	1	1	-	1	1	1	-	1	6
Climate station									
Pluviometer						1			1
Temperature						1			1
Relative humidity						1			1
Solar radiation						1			1
Pan evaporation						1			1
Max/min temp						1			1
Anemometer						1			1
Manual rainguage						1			1

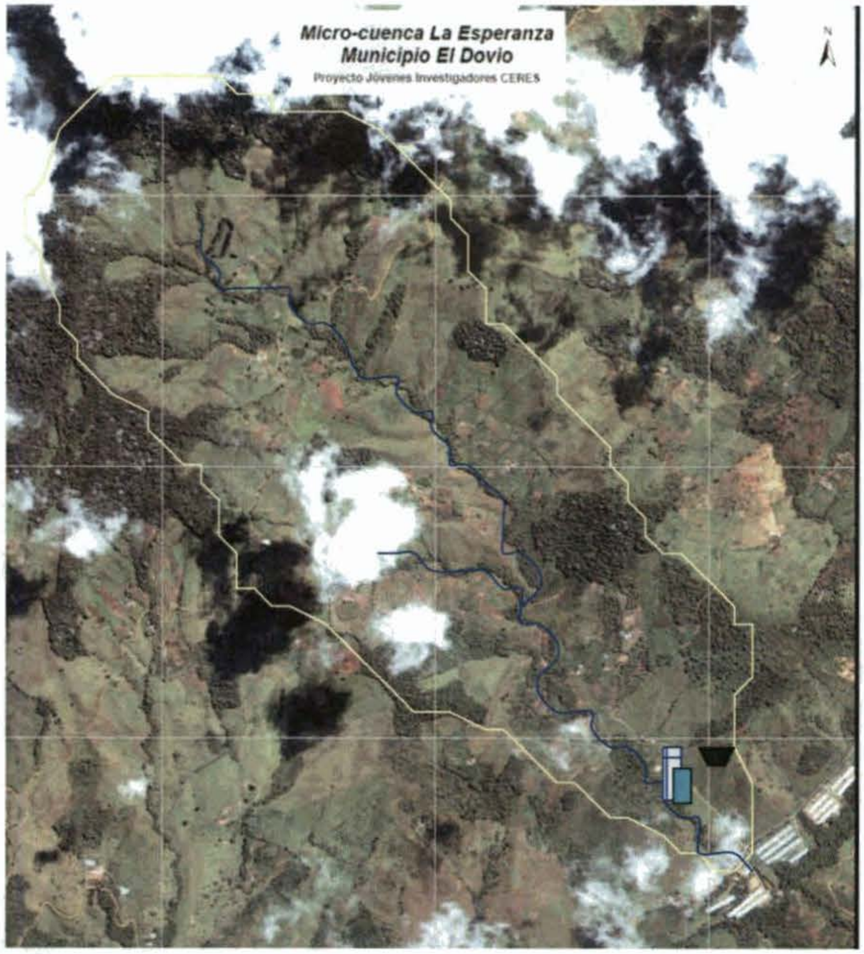

Figure 2. Location of the measuring equipment installed in the micro watershed Patuma at Versalles

Rainguage Odyssey Ruler

Figure 3. Monitoring in the micro watershed El Retiro, in the Río Gris watershed.

Achievements of the project

- The CERES students presented corrected written proposals for the development of the research questions set out above.
- Fieldwork related to each of the proposals was initiated and continues.
- Data re being collected from each of the monitoring units installed in the micro watersheds.