CHAPTER

2

Eco-Efficient Agriculture and Climate Change: Conceptual Foundations and Frameworks

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Contents

Abstract

The concept of eco-efficiency is explored, in terms of its history of use, its bio-physical meaning, and its utility as a concept in the pursuit of enhanced productivity, profitability, and sustainability of agricultural practice. Eco-efficiency is a multi-dimensional concept relating the efficiency with which a bundle of desired outputs is produced from a bundle of inputs, with minimal generation of undesired outputs. An analysis framework based on efficiency frontiers relating outputs to inputs (or where relevant, outputs to risk) is presented and this framework is used to identify six pathways for system improvement—all addressing some dimension of eco-efficiency. The paper concludes with an analysis of how climate change impacts and adaptation can be factored into this eco-efficiency framework.

Introduction

The notion of "efficiency" has always been a force shaping the world's food and fiber systems. Hunter-gatherer societies sought efficiencies in labor by changing their location, diet, and hunting and gathering practices to match seasonal and spatial patterns in food supply. Early cultivation practices evolved in ways that made the most efficient use of labor, enabling human society to

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direct time and energy into creative and practical activities beyond securing a sufficient food supply. As settled agriculture evolved, seeds were selected, land was cultivated, and crops were managed to further enhance the efficiency with which limiting resources were deployed. Human labor has been a dominant limiting resource for much of agriculture's history. Animal traction and, more recently, mechanization off the back of fossil fuels relieved the human labor constraint and the efficiency focus has shifted to the efficiency by which a complex set of land, labor, capital, energy, nutrients, and water resources are combined to produce economic products in a sustainable way.

This paper proposes a conceptual and analytical framework to support the desired goals of enhanced eco-efficiency in agricultural systems and of economic and ecological drivers considered at a range of decision scales. While the challenges and opportunities to improve eco-efficiencies under the threat of climate change are considered, particularly for smallholder production systems, the paper focuses on the bio-physical dimensions of eco-efficiency. Social and political drivers strongly influence agricultural decision-making and so will influence the eco-efficiencies that can be attained in each agricultural system.

The Eco-Efficiency Concept

Eco-efficiency in the context of agriculture grows out of the deep historical pursuit of efficiency in the world's food and fiber systems, but places particular focus on economic (productivity and profitability) and ecological (environmental sustainability) drivers of efficiency.

The World Business Council for Sustainable Development claim first use of the term "eco-efficiency" in the lead-up to the 1992 Rio Earth Summit (WBCSD, 2000). In that setting, the intent was to develop synergies between the private sector or business world's focus on efficiency with wider concepts of sustainable development and ecological integrity. In simple terms the focus was on "creating more goods and services with ever less use of resources, waste, and pollution" (WBCSD, 2000). The World Business Council saw eco-efficiency as a management philosophy that encouraged business to search for environmental improvements that yielded parallel economic benefits. They acknowledged that the term and concept did not capture all the issues relevant to sustainable development.

An early application of eco-efficiency in an agricultural research context comes from CIAT in setting their research and development goals in terms of eco-efficient agriculture for the rural poor. CIAT's Medium-Term Plan (CIAT, 2009) states:

> "Eco-efficient agriculture increases productivity while reducing negative environmental impacts. Eco-efficient agriculture meets economic, social, and environmental needs of the rural poor by being profitable, competitive, sustainable, and resilient. It harmonizes the economic, environmental, and social elements of development, and strives toward solutions that are competitive and profitable, sustainable, and resilient, and generate benefits for the poor. Eco-efficient agriculture cannot effectively address the needs of the poor without taking into account the particular needs of women."

Keating et al. (2010) noted that eco-efficiency was not a tightly defined concept—instead it was highly multidimensional. As such, there is unlikely to be a single measure that characterizes the eco-efficiency performance of an agricultural system. Instead, a set of measures are likely to be relevant in particular circumstances and these are likely to change in relation to differences in the most limiting set of biophysical, economic, or human resources (Park et al., 2010).

Eco-Efficiency Metrics

Any measure of eco-efficiency involves some measure of outputs (desired or undesired) related to some measure of inputs or alternative independent variables against which outputs are assessed. Figure 1 presents a set of output–input relationships, nominally representing crop and environmental responses to increasing nitrogen supply. The shape of these response functions, their intercept, and scale, will depend on the measures being used and the responses observed under the spatial and temporal drivers of variability (e.g., climate).

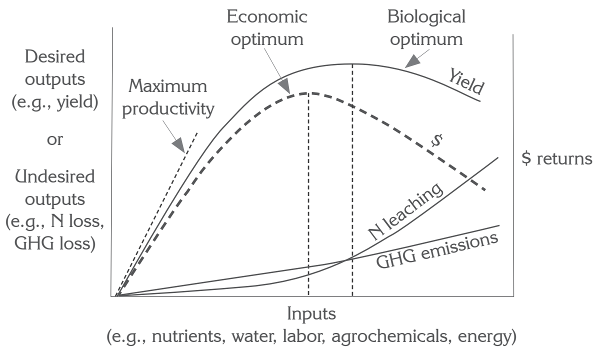

Figure 1. Output–input relationships relating desired and undesired agricultural outputs to the level of resource supply of soil nitrogen (N).

Desired output measures might typically include some measure of harvested product, some measure of profit or return on investment, or some measure of the security of a food system. Measures could extend beyond food quantity and include measures of quality in meeting nutritional needs. A broader suite of "ecosystem services" can also be considered as desired outputs, such as services around biodiversity conservation, carbon sequestration, freshwater flows, pest management, or pollination services (Costanza et al., 1997). Markets are emerging for some such ecosystem services whereby they would represent direct opportunities for economic return (Herzog, 2005). This is most developed in the carbon-sequestration domain (Hamilton et al., 2007). Other services are encouraged through non-market policies such as agri-environmental stewardship payments (Hajkowicz, 2009), while yet other services remain outside an institutional mechanism.

Input measures typically involve a unit of land but equally importantly could be expressed in terms of nutrients, water, energy, labor, or capital investments (Figure 1). Production functions relate agricultural outputs to the level of resource and other inputs (Dillon, 1977) and, at one level, are a measure of eco-efficiency. In analyzing production response curves to multiple inputs, de Wit (1992) argued that the resources are utilized most efficiently when their supplies are all close to yield-optimizing levels.

Importantly, while eco-efficiency carries the notion of "more with less" (Keating et al., 2010), there is the risk of this being misinterpreted to mean only higher outputs with lower inputs. This is too narrow an interpretation, as at least four different scenarios can be envisaged for raising eco-efficiency (Table 1).

Table 1. Eco-efficiency scenarios expressed in input/output terms.

Input/output descriptor	Explanation and example(s)
More desired outputs and/or less undesired outputs with less inputs	Reducing over-fertilization, such as N-fertilizer use on cereals in China (Ju et al., 2009), or over-irrigation such as with irrigation volumes on sugarcane in north-west Australia (Smith, 2008)
A lot more with a little more	Raising production levels through careful targeting of production inputs such as "micro-dosing" maize or sorghum with N fertilizer in southern Africa (Twomlow et al., 2008)
More with the smarter use of the same	Raising the effectiveness of current agricultural inputs through better targeting these inputs in space, such as via precision agriculture (Bramley, 2009), or time, for example with a seasonal climate forecast (Ash et al., 2007)
Less with much less	Lowering production in those regions or systems where inputs are not efficiently used (e.g., for climatic or soil reasons) and redirecting resources to areas of greater eco-efficiency (Oliver et al., 2010)

Agriculture produces a range of products (food, fiber, bioenergy, medicines, etc.) but not without broad and, at times, unsought consequences for land and society. Thus, alongside the desired outputs from agriculture are possible undesired outputs such as biodiversity loss, greenhouse gas (GHG) emissions, nutrient or soil loss, and other forms of land degradation. These undesired outputs often are also a function of relevant input levels (Figure 1).

The range of outputs from agriculture, both desired and undesired, can be assessed in trade-off relationships (Groot et al., 2007), often where production outputs are counterbalanced against the state of a system in environmental or social terms (Kelly et al., 1996). When represented graphically (Figure 2), an outer efficiency frontier can be drawn to represent the outermost desirable system outputs for the range of known (undesired) system states. Any point under the efficiency frontier represents room to move, with resultant wins and/or losses for both production and environmental outputs (Figure 2).

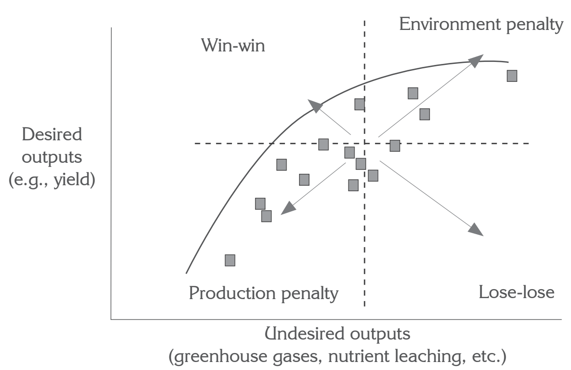

Figure 2. Example of a trade-off relationship between a desired output and an undesired output (points) resulting in an efficiency frontier of outermost points (line).

An Eco-Efficiency Framework

Keating et al. (2010) introduced an eco-efficiency diagnosis framework drawing on the types of relationships represented by production functions and trade-off relationships. A return–risk space formed the supporting analytical structure to assess system performance—mean economic returns are plotted against their associated variance, used as a measure of riskiness. An efficiency frontier of outermost points was envisaged where mean returns are maximized for any given level of variance in returns. This eco-efficiency diagnosis framework is represented in Figure 3. Keating et al. (2010) and Carberry et al. (2010) used the stylized return–risk framework to propose four pathways to improve system performance; two more are added here in Figure 3.

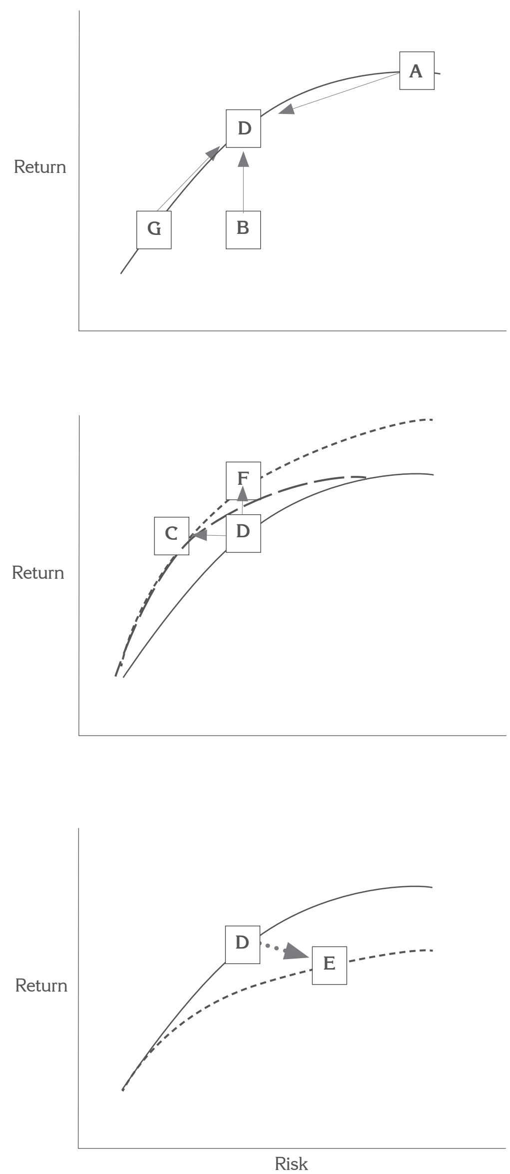

Figure 3. A stylized return–risk framework demonstrating six pathways to improve system performance relative to a measure of risk.

SOURCE: After Keating et al. (2010).

At the field and farm scale, the position of individual farmers relative to the efficiency frontier is largely determined by their attitude to risk and operational performance. To achieve the environmental potential or maximum possible output from a farm (Point A, Figure 3) necessitates acceptance of maximum risk, and thus a preference for risk-taking, as well as exemplary management. More likely, a region's best farmers choose acceptable-risk investments that return less than the potential (Point D). If farmers are operating close to the efficiency frontier, at their chosen level of production risk, they are achieving the expected level of return for the technologies deployed and the environmental conditions experienced. However, many farmers in a region would operate at positions below the efficiency frontier (Point B). These farmers invest as much in their production systems as the better farmers but achieve poorer returns by falling short in their agronomy and operational management.

A first and most important pathway to improve system performance is to increase the number of farmers performing close to attainable best practices (Pathway 1: B→D). Their transition to performing on a par with the better farmers will likely require both evidence of such inefficiencies and access to better agronomic advice. A second pathway is to encourage farmers to move along the current efficiency frontier to higher returns while acknowledging and addressing the added risks (Pathway 2: G→D). This pathway largely consists of good farmers adopting the practices of those farmers operating further up the efficiency curve. Such farmers need to be convinced that the increased investment needed to achieve the returns of the best farmers justifies their higher risk exposure. In a case study of Australian wheat crops, Hochman et al. (2011) reported that 36% of crops failed to achieve close to their attainable yield at the rate of nitrogen fertilizer applied and a further 21% of crops were under-fertilized—opportunities for efficiency improvements along pathways 1 and 2, respectively.

Under existing production systems and relevant efficiency frontiers, the third pathway for improved system efficiencies is to encourage farmers to reduce their investment in inputs where they are overinvesting (Pathway 3: beyond A→D). Although uncommon, excess use of fertilizers is evident in some agricultural systems, as in nitrogen fertilizer use in China (Ju et al., 2009).

Increasingly, more efficient resource use has been a mainstay of agriculture's response to the cost–price squeeze. For a region's better farmers, who currently operate on existing production frontiers, a real and ongoing requirement is to create new efficiency frontiers that generate similar returns for less investment and risk (Pathway 4: D→C). Such technologies generally enable cost savings and have no impact on production potential. On this pathway, technologies are sought to increase productivity from the existing resource base by reducing biotic constraints or to improve efficiencies in nutrient, water, or labor use. Such technologies can be developed through both agronomic (Bramley, 2009) and breeding approaches (Fageria et al., 2008).

A key role for agricultural research is to help discover the practices that will result in the next step-change in productivity and profitability. Thus, the fifth pathway is to create new efficiency frontiers by increasing the production potential and by helping farmers take this productivity step (Pathway 5: D→F). Most see this pathway as the hope for genetically modified crops (Phillips, 2010). In reality, furthering the frontiers of productivity will likely evolve from the synergies between novel plant genetics and innovative management technologies. Moving farmers to new efficiency frontiers will require research into and delivery of new technologies that increase production for much the same level of investment.

Maintaining current levels of productivity for a desired level of investment requires ongoing effort to prevent situations that could substantially limit productivity. The sixth and last pathway for investment in research, development, and extension is to protect against any loss of current production systems (Pathway 6: D $\neq$ E). Indeed, significant current effort is targeted either at preventing any breakdown in existing disease, weed, or pest management strategies, or at maintaining facilities to rapidly respond to future outbreaks of exotic diseases, weeds, or pests. Either threat could dramatically dampen the efficiency-frontier prospects of farmers. Likewise, practices that threaten the natural resource base for agriculture will result in an unavoidable loss of productivity. Issues such as soil salinity, acidification, and nutrient rundown require research investment to ensure productivity levels are maintained.

Eco-Efficiency and Climate Change

Keating and Carberry (2010) projected food demand out to 2050 and estimated likely increases in the order of 64–81%, with the variation dependent on assumptions of population growth, consumption increases, food wastage along the value chain, and food diversion to biofuels. The Food and Agriculture Organization of the United Nations (FAO) estimated that food demand will increase by 70% between 2000 and 2050 (FAO, 2009). These increases will need to be achieved in the face of increasingly constrained and contested land, water, nutrient, and energy resources. The threat of dangerous climate change also means the food-security challenge has to be met while reducing the GHG load on the atmosphere and in the face of uncertainties generated by the climate change that is already happening. These intertwined challenges necessitate an eco-efficiency imperative for global agriculture, where more food and fiber are produced with more efficient use of natural resources and less impact on the environment.

The climate-change challenge facing agricultural land use encompasses both adaptation to current and predicted new climates and the mitigation of GHG through both reductions in direct emissions and biosequestration of carbon. Globally, agriculture, including fertilizer production, directly contributes 10–12% of GHG emissions; and this figure rises to 30% or more when land conversion and emissions beyond the farm gate are added (Smith et al., 2007). The consensus on the climate science is that global GHG emissions would need to peak before 2015 and be reduced by something in the order of 50–85% (on 2000 levels) by 2050 if dangerous climate change (i.e., temperature rise > 2.4 °C) is to be avoided (IPCC, 2007). The relationship given as an example in Figure 2 depicts a trade-off between agricultural production and GHG emissions. A win–win outcome for agriculture and its emissions will require eco-efficient solutions that create new efficiency frontiers of reduced GHG intensities of food production. These new efficiency frontiers are required to generate similar outputs for less emissions risk (Pathway 4, Figure 3) or to increase production potential without emissions growth (Pathway 5).

Agricultural production may have to intensify efficiently on a smaller land area in order to free up land, water, and other resources for carbon biosequestration and environmental services (Pretty et al., 2011). Nevertheless, there are indeed win–win outcomes through the synergies between agricultural productivity and GHG mitigation by increasing soil carbon (Lal, 2004), reducing livestock methane (Beauchemin et al., 2008), or better managing livestock and manure (Monteny et al., 2006). That said, Campbell (2009) points out that win–win outcomes will not be feasible in all cases and so winners and losers are likely in programs such as the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+).

The challenge of adaptation to climate change has largely focused on ameliorating the negative impacts of climate that is likely to be drier and hotter, although the benefits of CO_2 fertilization and improved agroclimatic environments will be evident in some locations (Howden et al., 2007). Simple (negative) impacts of climate change are depicted in the production response functions shown in Figure 4 together with an indication of the likely effect of adaptation options identified by Howden et al. (2007) and others. Such adaptation actions aim to maintain current production outputs through management changes that better respond to the new environments (Pathway 6, Figure 3). However, in reality, all six pathways identified for efficiently increasing agricultural returns will contribute to the adaptation options for climate change—i.e., the long-held imperatives for increasing agricultural productivity through both incremental and transformational research and uptake will likely lead to appropriate responses to a future probable change in the climate risk. Thus, the imperative for research to help farmers to better deal with current seasonal climate variability will likely enable them to adapt to future climate change (Howden et al., 2007).

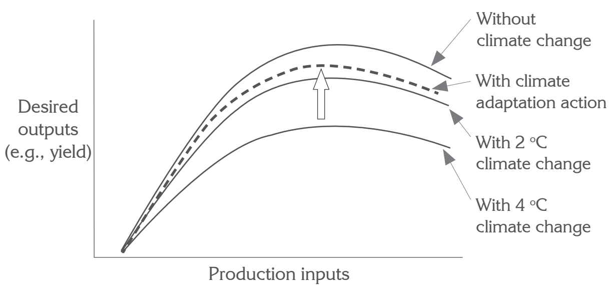

Figure 4. Production functions under two climate change scenarios and an adaptation response.

The need for targeting transformational research specifically to adaptation to future climate change must pass the test of additionality; the notion that such added investment should be additional to what is already being done. Changes in frequency and magnitude of climate extremes, and thus agricultural systems crossing thresholds (Tubiello et al., 2007), may be the driver for such additional and specific response.

Explicit treatment of uncertainties in a decision-making context is needed to ensure that adaptation action now does not get ahead of our confidence in locally-specific expectations for the future. In smallholder tropical environments with large numbers of biophysical and institutional factors constraining development, it would be unwise to focus on adaptation to an uncertain future climate if it meant that certain current constraints to agricultural development were ignored. Building a longer-term climate-change perspective into current efforts to raise agricultural productivity, sustain the natural resource base, and overcome rural poverty is, however, a wise counter to the risk of development proceeding down maladaptive pathways (Stafford Smith et al., 2011).

Eco-Efficiency and Smallholder Farmers in the Tropics

In the generally low-input, low-output situations of smallholder farmers in the tropics, natural resources are co-opted to meet food production needs. Thus, while nutrient inputs may be used most efficiently for the first unit of addition in these systems (Twomlow et al., 2008), the coincident inputs of land, water, and labor are used inefficiently in many smallholder systems. Eco-efficiency needs to be an integrating concept, extending beyond single-factor production functions to a measure of the efficiency with which food production needs are met with the least environmental impacts.

The six pathways for enhanced eco-efficiency (Figure 3) are relevant to smallholder farmers in the tropics. The large yield gaps identified in tropical systems (Neumann et al., 2010) testify to the prospects for moving overall farmer performance closer to the attainable efficiency frontiers (Pathway 1). However, given that smallholder systems are often low input, especially in sub-Saharan Africa, there is likely as much to gain from encouraging farmers to move along currently attainable efficiency frontiers in order to increase returns to individual farmers and aggregate production from smallholder farming systems (Pathway 2) (Keating et al., 1991; Tittonell et al., 2008). Addressing farmer perception and management of the added risks from such practices is a critical endeavor for success in this pathway. Similarly, encouraging farmers to reduce their investment in unnecessary inputs (Pathway 3), as in nitrogen fertilizer use in China (Ju et al., 2009), will require comparable persuasive communication of the benefits of a significant change to established practices.

Creating new efficiency frontiers that improve returns, lower risks, or both (Pathways 4 and 5) can benefit smallholder farmers by enhancing the incentives for adoption—the Green Revolution is the exemplar case of the impacts of these pathways for improved productivity (Evenson and Gollin, 2003). Certainly the needs of Green Revolution smallholder farmers in tropical Asia and Latin America now mirror the demands for productivity innovations from large-scale commercial farmers in developed countries. Agricultural productivity in the past can be pinned to the development and adoption of specific technologies and practices and it is critical today that new technologies continue to be identified, developed, and adopted over the coming years (Carberry et al., 2010).

In contrast to Asia and Latin America, sub-Saharan Africa has not gained the same benefits from the Green Revolution. Despite the arguments for significant returns from Green-Revolution-type investments to improve smallholder productivity and infrastructure in Africa (Diao et al., 2008), it is difficult to see traction for such pathways (4 and 5) without prior priority given to improving basic agronomic performance and to changing perceptions of investment risk (Pathways 1 and 2). Here, the increasing role of the private sector and input/output markets in Africa may hold hope for progress (Gabre-Madhin and Haggblade, 2004).

Finally, the mitigation and adaptation challenges of climate change and their relation to the food security imperatives in tropical landscapes are a mix of synergies and trade-offs (DeFries and Rosenzweig, 2010). As argued previously, an eco-efficiency imperative utilizing all available pathways will need to be brought to bear.

Conclusions

We have focused on biophysical issues around the efficiency with which natural and human inputs are transformed into desired food and fiber outputs and environmental services, with a minimum of undesired outputs such as natural-resource degradation or GHG loads on the atmosphere. In the context of global or regional food security in the face of climate-change mitigation and adaptation challenges, this serves as a useful framing for a key global challenge. However, social and economic circumstances are going to shape decision-making in a particular farming situation and efficiency optima are often going to be different for production, productivity, profitability, or risk tolerance criteria.

In a broader view of eco-efficiency, spatial and temporal scale becomes important. In terms of spatial scale, what might be an eco-efficient solution at a local level may be ecologically inefficient at national or global scale if the production activity is more productive and less environmentally demanding at other locations. In terms of temporal scale, short-term efficiency in resource use that leads to longer-term natural-resource degradation will end as up ecologically inefficient due to the longer-term negative feedbacks to productive capacity.

The proposed eco-efficiency diagnosis framework (Figure 3) allows these different perspectives to be contemplated in terms of pathways for change. The challenge for smallholder farmers in the tropics (and for this CIAT publication) is to turn these concepts into practice.

References

Ash A; McIntosh P; Cullen B; Carberry P; Stafford Smith M. 2007. Constraints and opportunities in applying seasonal climate forecasts in rural industries. Australian Journal of Agricultural Research 58:952–965.

Beauchemin KA; Kreuzer M; O'Mara F; McAllister TA. 2008. Nutritional management for enteric methane abatement: a review. Australian Journal of Experimental Agriculture 48:21–27.

Bramley R. 2009. Lessons from nearly 20 years of precision agriculture research. Crop and Pasture Science 60:197–217.

Campbell BM. 2009. Beyond Copenhagen: REDD+, agriculture, adaptation strategies and poverty. Global Environmental Change 19:397–399.

Carberry PS; Bruce SE; Walcott JJ; Keating BA. 2010. Innovation and productivity in dryland agriculture: a return–risk analysis for Australia. Journal of Agricultural Science 149:77–89.

CIAT (Centro Internacional de Agricultura Tropical). 2009. CIAT's medium-term plan 2010–2012. Cali, Colombia. (Available at www.ciat.cgiar.org/AboutUs/Documents/mtp_2010_2012_jun09_full_version.pdf; accessed 16 January 2012.)

Costanza R; d'Arge R; de Groot RS; Farber S; Grasso M; Hannon B; Limburg K; Naeem S; O'Neill RV; Paruelo J; Raskin RG; Sutton P; van den Belt M. 1997. The value of the world's ecosystem services and natural capital. Nature 387(6630):253–260.

de Wit CT. 1992. Resource use efficiency in agriculture. Agricultural Systems 40:125–151.

DeFries R; Rosenzweig C. 2010. Toward a whole-landscape approach for sustainable land use in the tropics. PNAS 107:19627–19632.

Diao Xinshen; Headey D; Johnson M. 2008. Toward a green revolution in Africa: what would it achieve, and what would it require? Agricultural Economics 39:539–550.

Dillon JL. 1977. An analysis of response in crop and livestock production. 2nd edn. Pergamon, Oxford, UK.

Evenson RE; Gollin D. 2003. Assessing the impact of the Green Revolution, 1960 to 2000. Science 300:758–762.

Fageria NK; Baligar VC; Li YC. 2008. The role of nutrient efficient plants in improving crop yields in the twenty first century. Journal of Plant Nutrition 31:1121–1157.

FAO (Food and Agriculture Organization of the United Nations). 2009. World Summit on Food Security. www.fao.org/wsfs/world-summit/en/

Gabre-Madhin EZ; Haggblade S. 2004. Successes in African agriculture: results of an expert survey. World Development 32:745–766.

Groot JCJ; Rossing WAH; Jellema A; Stobbelaar DJ; Renting H; van Ittersum MK. 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—A methodology to support discussions on land-use perspectives. Agriculture, Ecosystems & Environment 120:58–69.

Hajkowicz S. 2009. The evolution of Australia's natural resource management programs: towards improved targeting and evaluation of investments. Land Use Policy 26:471–478.

Hamilton K; Bayon R; Turner G; Higgins D. 2007. State of the voluntary carbon markets 2007: picking up steam. New Carbon Finance, London; The Ecosystem Marketplace, Washington, DC.

Herzog F. 2005. Agri-environment schemes as landscape experiments. Agriculture, Ecosystems & Environment 108:175–177.

Hochman Z; Carberry PS; Robertson MJ; Gaydon DW; Bell LW. 2011. Prospects for ecological intensification of Australian agriculture. European Journal of Agronomy (in press) (available online 6 December 2011: http://dx.doi.org/10.1016/j.eja.2011.11.003).

Howden SM; Soussana J-F; Tubiello FN; Chhetri N; Dunlop M; Meinke H. 2007. Adapting agriculture to climate change. PNAS 104:19691–19696.

IPCC (Intergovernmental Panel on Climate Change). 2007. Mitigation of Climate Change. Summary for Policy Makers. Working Group 3 – 4th Assessment Report. Geneva, Switzerland. 36 p.

Ju XT; Xing GX; Chen XP; Zhang SL; Zhang LJ; Liu XJ; Cui ZL; Yin B; Christie P; Zhu ZL; Zhang FS. 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. PNAS 106:3041–3046.

Keating BA; Carberry PS. 2010. Sustainable production, food security and supply chain implications. Aspects of Applied Biology 102:7–19.

Keating BA; Godwin DC; Watiki JM. 1991. Optimizing nitrogen inputs in response to climatic risk. In: Muchow RC; Bellamy JA, eds. Climatic risk in crop production: models and management in the semi-arid tropics and subtropics. CAB International, Wallingford, UK. p 329–358.

Keating BA; Carberry PS; Bindraban PS; Asseng S; Meinke H; Dixon J. 2010. Eco-efficient agriculture: concepts, challenges and opportunities. Crop Science 50 (Supplement 1):S-109–S-119.

Kelly TC; Lu Y-C; Teasdale J. 1996. Economic–environmental tradeoffs among alternative crop rotations. Agriculture, Ecosystems & Environment 60:17–28.

Lal R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

Monteny G-J; Bannink A; Chadwick D. 2006. Greenhouse gas abatement strategies for animal husbandry. Agriculture, Ecosystems & Environment 112:163–170.

Neumann K; Verburg PH; Stehfest E; Müller C. 2010. The yield gap of global grain production: a spatial analysis. Agricultural Systems 103:316–326.

Oliver YM; Robertson MJ; Wong MTF. 2010. Integrating farmer knowledge, precision agriculture tools, and crop simulation modelling to evaluate management options for poor-performing patches in cropping fields. European Journal of Agronomy 32:40–50.

Park SE; Howden SM; Crimp SJ; Gaydon DS; Attwood SJ; Kokic PN. 2010. More than eco-efficiency is required to improve food security. Crop Science 50 (Supplement 1):S-132–S-141.

Phillips RL. 2010 Mobilizing science to break yield barriers. Crop Science 50 (Supplement 1): S-99–S-108.

Pretty J; Toulmin C; Williams S. 2011. Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability 9(1):5–24.

Smith AJ. 2008. Rainfall and irrigation controls on groundwater rise and salinity risk in the Old River irrigation area, Northern Australia. Hydrogeology Journal 16:1159–1175.

Smith P; Martino D; Cai Z; Gwary D; Janzen H; Kumar P; McCarl B; Ogle S; O'Mara F; Rice C; Scholes B; Sirotenko O. 2007. Agriculture climate change mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Stafford Smith M; Horrocks L; Harvey A; Hamilton C. 2011. Rethinking adaptation for a 4°C world. Philosophical Transactions of the Royal Society A 369(1934):196–216.

Tittonell P; Vanlauwe B; Corbeels M; Giller K. 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant and Soil 313:19–37.

Tubiello FN; Soussana JF; Howden SM. 2007. Crop and pasture response to climate change. PNAS 104:19686–19690.

Twomlow S; Rohrbach D; Dimes J; Rusike J; Mupangwa W; Ncube B; Hove L; Moyo M; Mashingaidze N; Mahposa P. 2008. Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. Nutrient Cycling in Agroecosystems 88:3–15.

WBCSD (World Business Council for Sustainable Development). 2000. Eco-efficiency: creating more value with less impact. Geneva, Switzerland. (Also available at www.wbcsd.org/web/publications/eco_efficiency_creating_more_value.pdf; accessed 16 January 2012.)