Title:

A Way Forward on Adaptation to Climate Change in Colombian Agriculture: Perspectives Towards 2050

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Abstract

Policy measures regarding adaptation to climate change include efforts to adjust socio-economic and ecologic systems. Colombia has undertaken various measures in terms of climate change mitigation and adaptation since becoming a party of the Kyoto protocol in 2001 and a party of the United Nations Framework Convention on Climate Change (UNFCCC) in 1995. The first national communication to the UNFCCC stated how Colombian agriculture will be severely impacted under different emission scenarios and time frames. The analyses in this document further support that climate change will severely threaten the socioeconomics of Colombian agriculture.

We first query national data sources to characterize the agricultural sector. We then use 17 Global Circulation Model (GCM) outputs to quantify how Colombian agricultural production may be affected by climate change, and show the expected changes to years 2040-2069 ("2050") under the A2 scenario of the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES-A2) and the overall trends in both precipitation and temperature to 2100. We then evaluate expected changes within different regions and measure the proportion of area affected within each crop's distributional range. By 2050, climatic change in Colombia will likely impact 3.5 million people, 14% of national GDP corresponding to agriculture, employment of 21% of the population, agro-industries, supply chains, and food and nutritional security. If no adaptation measures are taken, 80% of crops would be impacted in more than 60% of their current areas of cultivation, with particularly severe impacts in high value perennial and exportable crops.

Impacts also include soil degradation and organic matter losses in the Andes hillsides; likely flooding in the Caribbean and Pacific coasts; niche losses for coffee, fruit, cocoa, and bananas; changes in prevalence of pests and diseases; and increases in the vulnerabilities of non-technically developed smallholders. There is, however, still time to change the current levels of vulnerability if a multidisciplinary focus (i.e., agronomic, economic, and social) in vulnerable sectors is undertaken. Each sub-sector and the Government need to invest in: (1) data collection, (2) detailed, regionally-based impact assessments, (3) research and development, and (4) extension and technology transfer. Support to vulnerable smallholders should be given by the state in the form of agricultural insurance systems contextualized under the phenomenon of climate change. A national coordination scheme led by (but not restricted to) the Ministry of Agriculture and Rural Development (MADR) with the contributions of national and international institutions is needed to address agricultural adaptation.

Keywords: Colombia, UNFCCC, Kyoto protocol, climate change, adaptation, impacts, vulnerability

Introduction

The latter part of the 20th Century saw international debates and new policy frameworks in response to how global climate change might affect human activities[1]. In 1998, the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established the Intergovernmental Panel on Climate Change (IPCC) to asses scientific, technical and socio-economic information relevant to risks associated with human-induced climate change. Climate change policies have since focused on two basic responses: mitigation and adaptation strategies (IPCC 2007).

On the mitigation side, policies agree that Greenhouse Gases (GHGs) emissions should be globally limited and/or reduced. Responses include measures such as Clean Development Mechanisms (CDMs), reduction in deforestation, land use changes and crop management (UN, 1992). Recently, the world nations reached an agreement to "cut emissions and deliver funds for adaptation in developing countries" during COP-16 (Cancún, Mexico), further ratified in Durban (COP-17). Additional agreements as per dates, emission peaks, and available budgets are still to be defined.

Human activities are now threatened by irreversible climate change. Temperatures are predicted to increase between 0.5 and 1ºC in the best case scenario, and between 3 and 6ºC in the worst case scenario (IPCC, 2000, 2001, 2007). According to the IPCC (2007), in Latin American countries these changes could lead to loss of plant genetic resources (high confidence), desertification and salinization of agricultural lands (high confidence), reductions in rice yields by the 2020s (medium confidence), loss of coffee growing environments (e.g., Mexico, Nicaragua, Peru, Colombia, and Brazil) (IPCC, 2007; Laderach et al., 2011; Schepp and Laderach, 2008; Schroth et al., 2009), increases in incidence of coffee berry borer (*Hypothenemus hampei*) (Jaramillo et al., 2009), and increase in the risk of *Fusarium* head blight in wheat in Brazil and Uruguay (IPCC, 2007).

The first communication to the UNFCCC (IDEAM, 2001) revealed that for Colombia there will be flooding and salinization risks in the Pacific and Caribbean coasts; changes in the variability and thus availability of water resources; changes in glacial, forest and mountain ecosystems; and reduction in fertility of agricultural lands. The new National Development Plan (2010-2014) now includes a whole framework under which a National Adaptation Plan should be developed. In addition, the agricultural sector now includes various projects to (1) evaluate the impacts of climate change and (2) define and evaluate specific adaptation strategies. However, the delay in proposing and developing these projects (which are not at final stages) has left the country behind others in Latin America and the world. Detailed information on impacts and adaptation is needed as the agricultural sector has been selected by Colombia as the key sector for the UNFCCC.

[1] World Climate Conference (WCC) and United Nations Framework Convention on Climate Change (UNFCCC). International agenda in 1979 issued declaration of how climate change might be adverse to the well-being of humanity.

Colombia's temporal and spatial climatic variability makes it difficult to assess national adaptation pathways (Motha, 2007; Pabon, 2003; Poveda et al., 2010); hence, an entry point could be characterization by natural and/or agro-climatic region that considers the uncertainty of climate predictions. Climate model skill assessment is also needed. Despite the perceived importance of adaptation of agriculture globally and the rates at which the sector may become affected by climate change (Gerald, 2009; IPCC, 2007; Sivakumar et al., 2005), very little research has focused on climate change impacts on Colombian agriculture. Only a few references have somehow addressed this issue (Eslava and Pabon, 2001; Pabon, 2003, 2005; Pabón et al., 2001; Ruiz, 2007).

Needed is a comprehensive evaluation of the impacts of climate change on the most vulnerable sectors of Colombian agriculture, and of the most appropriate adaptation measures. In this document, we analyze the impacts of climate change on Colombian agriculture using a set of 17 global circulation models (GCMs) for the SRES-A2 emission scenario ("business as usual") and the 2050s time frame. Reasons for these decisions are given in supporting material (Sect. 1). We propose a set of adaptation measures that include the definition of key financial flows and stakeholders.

A vulnerability assessment for Colombian agriculture in the face of climate change

As in other developing countries, agriculture has traditionally been a significant component of the Colombian economy, contributing with about 10 to 14% (not specified if includes agroindustry or not) of the National Gross Domestic Product (GDP) and the jobs and livelihoods of at least 3.7 million people (DANE, 2011). Agriculture is a mainstay for food and nutritional security and is a part of the national industrial sector. Much of agricultural GDP comes from trade, comprising 40% of total Colombian exports (DANE, 2011).

Colombian agriculture features inequality, and diversity of farming systems, vulnerabilities, rates of occupation, deforestation rates and trends, crop management, and organizational levels. Predicted climate change will threaten the entire Colombian socio-economic system, with particularly severe impacts on agriculture (IPCC, 2007). The impacts could be diverse and widespread across the country.

In spite of the very little published research on Colombian agriculture, current vulnerability (here defined as the susceptibility of the agriculture sector to the biophysical and hence economic impacts of climate-related issues) is known to be high. Extreme weather events are stated to be a constraint for Colombian agricultural systems, particularly for those in Valleys and in areas very close to rivers (Hoyos-Rincon and Baquero-Bernal, 2011; Hoyos and Baquero-Bernal, 2010; IPCC, 2007). Pests and diseases, another important issue in the context of climate change (Garrett et al., 2009; Gregory et al., 2009), constitute a major portion of the production costs for some crops (e.g. maize, *Musa*, potatoes, among others). Smallholders with low technology level are commonly the most affected by these issues due to their low response capacity. Further, climate change is expected to cause shifts in the geographic distribution and incidence of pests and diseases (Gregory et al., 2009; Hijmans et al., 2000; Ramirez-Villegas et al., 2011b) and extreme weather events (IPCC, 2007; Timmermann et al., 1999), which in turn are determinants of crop yields (Baigorria et al., 2007; Herrera Campo et al., 2011; Moriondo et al., 2011). This all, requires substantial and continued governmental support aimed at reducing short-term vulnerability and maintaining and enhancing food-security.

To assess the potential impact of climate changes on agriculture, we first carry out a literature and statistical data review, and describe the sector and its importance. Secondly, we use the first communication to the UNFCCC (IDEAM, 2001) as a baseline to then add detail to descriptions of likely impacts. We then perform an analysis of climate model data to draw conclusions on climate model skill in Colombia. We then consider Colombian perennial and annual crops (see Table S1) and analyze climatic changes and their distribution within these cropped surfaces as derived from the latest census of the National Administrative Department of Statistics (DANE, 2007). We conclude by analyzing the impacts and proposing major adaptation strategies for the sector, whilst at the same time assessing the possible political constraints that the sector could face when seeking adaptation to climate change.

Analysis of climatic changes in Colombian croplands

The GCM data (see Supporting material, Table S2 and Sect. 2) were downscaled to a 10 arc-minute (~20 km) resolution using the method of Ramirez-Villegas and Jarvis (2010). The downscaling method relies upon the assumptions that (1) patterns of change do not have large spatial variations and (2) relationships between variables hold in time. According to other studies, quality of results is not expected to be affected (Mulligan et al., 2011; Ramirez-Villegas et al., 2011a). These data were then used to determine temperature, precipitation, and seasonality changes on cropped lands by region and altitude zone for years 2040-2069 ("the 2050s") under the SRES-A2 emissions scenario according to methods outlined in the Supporting Material (Sect. 4). Multiple GCMs were preferred instead of the one (or few) Regional Climate Model for the reasons stated in Sect. 3 of Supporting Material.

Findings and main results

National and regional level agricultural production

Given the lack of detail in the available data and the complexity of the Colombian agricultural system, here we analyzed the agricultural system in two different dimensions: (1) departments (and natural regions) where crops are grown, and (2) groups of agricultural goods. Agricultural goods, although diverse, can be divided into five fundamental groups (Table S1): (1) cereals (annuals), (2) oilseed and legumes (annuals), (3) high value export perennials, (4) non-export perennials, and (5) livestock production. From the total value of the agricultural production (in US dollars of 1994), 55% corresponds to crop production and the remaining 45% is livestock. In 2007, 54% of national cropped lands (3.8 million ha) was occupied by perennial crops (export and non-export) and 47% by annual crops (cereals, oilseeds and legumes) (Table S1). Livestock production occupied 91% of total agricultural lands in 2007 (DANE, 2007), of which 82% was reported under improved pastures, and 18% is under fallow (DANE, 2007). The livestock production area is thus 10 times greater than that of croplands.

Cacao, sugarcane, coconut, banana, plantain, rice, cotton, tobacco, cassava, and most of the nation's meat cattle are produced in the warmer regions located from sea level to 1,000 meters elevation. The temperate regions (i.e., between 1,000 and 2,000 meters) are better suited for coffee, flowers, maize, fruit, and some vegetables. The cooler elevations (between 2,000 and 3,000 meters) produce potatoes, wheat (although very little), barley, cold-climate vegetables, flowers, dairy cattle, and poultry.

In 2007, 17% of the total value of crop production corresponded to coffee production (1,451 million USD of 1994), making coffee the highest value crop nationally. Most of this production features use of "the best technologies" in order to meet export demand. Fruit production is second in terms of economic importance (13% of the total value). Fruit production is dispersed throughout the country, is highly diversified, and occupies only 5% of national cropped area. Cattle slaughter in 2007 (DANE, 2007) was 2.4 million head (representing an increase of 8% since 2005). Milk production ranges were 20 to 23 million liters, with an average production rate of 4.5 liters/animal/day (MADR and IICA, 2005). Additional facts about Colombian agricultural production are described in Supporting Material (Sect. 1.1)

Why is agriculture a key sector for Colombia?

Colombian agriculture features considerable inequality in terms of farm size, income, yields, and rates of growth of those yields (Berry, 1995; Deininger and Lavadenz, 2004). Crops such as African oil palm are grown on large farms (average 525 ha), while crops such as cacao, coffee, and rice are produced on smallholdings of 3 to 11 ha (MADR and IICA, 2005). The great majority of producers are smallholders with farm sizes less than 10 ha. For export crops (generating 41% of agricultural GDP), only sugarcane is grown largely on large farms (MADR and IICA, 2005). Additional information can be found in Supporting Material (Sect. 1.2).

Sustainability in Colombian agriculture must be seen from two different standpoints: (1) commercial agriculture, using large quantities of chemical and weed control products and fertilizers, conventional tillage, and also surface residue burning at the expense of environmental and soil (physical, chemical and biological) degradation; and (2) low-input smallholdings agriculture in which limited inputs together with traditional crop landraces are used at the expense of agricultural yields and (probably) response capacity (Berry, 1995; Gregory et al., 2005). Hence, analyzing vulnerabilities and achieving (at least at partially) sustainability in Colombian agriculture (particularly in the context of climate change) and synergy between commercial and low-input production, requires the adequate targeting of management practices, the usage of improved germplasm to close the yield gap yet stimulating the usage of traditional landraces among communities to maintain genetic diversity, whilst at the same time establishing clear policies that limit the input usage and burning of crop residues and stimulating and financing and the establishment of site-specific agriculture programs that allow the input optimization (Camacho-Tamayo et al., 2008; Erickson, 2006).

Agriculture is important in providing employment (21% of the total national) (DANE, 2011), from which 92% is generated by crop and livestock systems; and 8% comes from agroindustries. Meat and coffee accounted for 50% of total agriculture-related jobs in 2004; while 32% was generated by panela, vegetables, plantains, cereals, and cotton (MADR and IICA, 2005).

Small-scale producers of maize, upland rice, beans, cassava, potatoes, and non-export plantains (all using “traditional” technologies) also play an important role in national food and nutritional security. Such production is less technologically developed, less capable of responding to climate variability and progressive climate change without proper governmental support, and hence (under current socio-economic conditions) more sensitive to climate change overall. For these sectors, governmental support (i.e., agricultural insurance, adaptation loans, and subsidies) will be a key issue as well as tax protection (i.e. increases of import taxes for a better local marketing of certain products) if necessary.

Projected future climate conditions, climatic variability and future key issues in the Colombian agricultural sector

The average estimated increase in annual mean temperature to the 2050s is 2.5ºC, with a maximum of 2.7ºC in the Arauca department and a minimum of 2ºC in Chocó and Nariño (Table 1, figure 2a and 2b). Precipitation is projected to increase 2.5% by the 2050s, with a minimum change of -1.4% in Cesar and a maximum of 5.6% in Huila. Driest periods throughout the year will be likely less dry, while the wettest periods are projected to become wetter.

[TABLE 1 AND FIGURE 2 HERE]

The regions with the largest increases in annual precipitation are projected to be Orinoquia (Llanos Orientales), Amazonia, and the Andean region. The southwest and the Pacific coast will likely have the least increases in annual mean temperatures. In all cases, increases in annual maximum temperatures will be more severe than increases in annual minimum temperatures (Table 1, Figure 3), indicating that warm periods (i.e., heat stress periods) will likely become warmer, especially in the Andes, Amazonia, and the Llanos Orientales. More severe increases in temperatures are expected below 1,000 m.a.s.l, and between 2,700 and 4,500 m.a.s.l; while precipitation changes are expected to be stronger between 2,200 and 4,000 m.a.s.l. (Figure 3).

[FIGURE 3 HERE]

The Caribbean region will likely be the only area with decreases in precipitation. All other departments will likely face increases in annual precipitation (except Norte de Santander with a very small decrease). Wet periods in the Caribbean region could drastically decrease their current amount of rainfall, while dry periods will likely face increases in precipitation (except in Cordoba and the San Andres Islands, with very limited decreases). For temperature, GCM time series indicated that the largest change rates occurred in 1990s and the 2010s (Jarvis et al., 2011b). Annual precipitation variability will continue to be relevant for the whole country.

Impacts of climate change on Colombian agriculture and regional adaptation measures

Expected impacts

Table 2 presents a classification of changes in both precipitation and temperature for Colombian agriculture (see methods in supporting material, Sect. 5). For example, for rice, 65% of the current production areas will have likely increases in temperatures between 2 and 2.5ºC, and some 61% of the areas that could feature 3% greater precipitation.

[TABLE 2 HERE]

In addition to the current vulnerability of the Colombian agricultural sector, especially in regards to smallholders, climate change will impact agricultural production at different levels. Twenty-two (79%) out of the 28 crops listed in Table 2 are mostly (more than 60%) located in areas in which likely temperature changes up to the 2050s are predicted to be between 2 and 2.5ºC, indicating that only a few crops and a few departments would be severely impacted. Increases between 2 and 2.5ºC, however, would significantly affect some crops. Precipitation is expected to be a fundamental factor driving impacts and adaptation mainly in three respects: (1) change in precipitation will affect plant growth biomass production and exerting stresses during key physiological periods, (2) change in precipitation will change soil water availability, likely enhancing drought in some regions (e.g., the Caribbean region) and flooding risks in others (e.g., the Pacific region); and (3) change in precipitation will affect biotic factors (e.g., pests, diseases, weeds) in the different production systems (accounting for 20-40% of production costs).

Although we did not consider changes in inter-annual variability, these are of very high relevance for Colombia, as flooding and slide risks are high in hill areas of the Andes and in poor drained soils in the Valleys. Uncertainty in the context of extreme events and inter-annual variability is high, mainly because models lack skill in representing these factors (Boo et al., 2011; Reifen and Toumi, 2009). It is acknowledged that more intense and frequent extreme events are likely to be observed, although the extent at which this could occur is highly uncertain (IPCC, 2007).

We have identified seven major impacts on the Colombian agricultural sector (Table 3). Amongst the most clear expected impacts are the changes in phenology. Whilst in some regions (highlands) changes in phenology due to higher temperatures could shorten the growing season even to the extent that farmers could plant an additional short-cycle crop, hence enhancing the agricultural systems (Ibáñez et al., 2010), in other areas (lowlands) with higher temperatures, increases in temperature could increase the duration of the growing season, thus making the crop more vulnerable to short periods of drought or heat during susceptible development stages.

[TABLE 3 HERE]

In addition, pests and diseases are also expected to change towards the future. Crops likely facing substantial increased pest and disease prevalence are *Musa* (black Sigatoka, *Mycosphaerella fijiensis* M.) in areas above 500 m.a.s.l (Ramirez-Villegas et al., 2011b); coffee (berry borer, *Hypothenemus hampei* F. and coffee leaf rust *Hemileia vastatrix*) in areas above 1500 m.a.s.l. (Jaramillo et al., 2009); potato (*Phytophtora infestans,* potato late blight) in areas below 2500 m.a.s.l (Antioquia, Boyacá, Cauca, Nariño, Santander, Cundinamarca, Tolima) (Hijmans et al., 2000); cacao (*Moniliophtora perniciosa)*; maize (spikelet carbon); cassava (whitefly in the Atlantic coast and green mite in the Andean region) (Herrera Campo et al., 2011); and citrus (*Phytophtora* spp.*)*. Yield reductions and increases in production costs are expected due to increased disease prevalence and loss of crop climatic niches, especially for very niche-specific crops such as coffee. Data to perform quantitative assessments of these problems are needed. Sugarcane, an important cash crop for the Cauca river valley will likely be affected by changes in climates. Yield loss is predicted in the Cauca river basin (Cock J., 2009, personal communication) if temperatures rise above +1°C. Flooding in coastal areas, increased climate variability-related vulnerability in small producers, and progressive losses of crop and pasture suitability are amongst the most important expected impacts (Table 3).

In spite of the expected negative impacts, there could be some yield-reduction mitigation due to the increases in atmospheric CO_2 concentrations. Photosynthesis is a process that depends on light, water and CO_2 to produce biomass. At adequate water and light availability, the increases in CO_2 stimulate the production of more biomass in the plant (Challinor and Wheeler, 2008; Jarvis et al., 2010). With climate change, higher CO_2 concentrations could increase yields, although the actual yield increases and the trade-off between temperature stress and CO_2 fertilization effects is still not clear and sometimes overly-stated (Prasad et al., 2002).

Regional adaptation measures

Advancing in the understanding of impacts is critical so that the sector can adapt to changed climates. Varietal changes have proven to be a successful adaptation strategy (Bedõ et al., 2005; Challinor et al., 2007; Krishnan et al., 2007), as have proven changes in planting dates (Byjesh et al., 2010; Srivastava et al., 2010) in various regions of the globe. Hence these are adaptation options that need to be tested in the Colombian context and that could work for crops such as beans, potatoes, *Musa* and citric fruits (Table 3).

Changes in planting dates and irrigation systems to manage specific stresses during the growing season would reduce the impacts of phonological alterations, whereas the establishment of adaptation subsidies to help smallholders in managing climate variability needs to be a transversal strategy covering all sectors and crops (this would ensure sustainability and vulnerability reduction).

Recent work of CIAT has showed that for rice adaptation strategies such as building irrigation systems and establishing a rice genetic improvement and research center are completely off-set by the increases in agricultural yields and income by 2030s (Tapasco J., personal communication, 2011). Similar results have been reported by EMBRAPA for various crops (maize, soybean, common beans, cassava, and sugarcane) (Assad E., personal communication, 2011).

Coffee will require special attention given its national economic importance. Adaptation strategies in coffee are varied. In recent decades, given the specificity of the coffee climatic niche, altitudinal migration of coffee lands in some regions of Colombia (i.e. Cauca) has been observed (Palmer N., personal communication, 2010); under a future with +2-3°C, coffee may also require altitudinal migration. Shading could be a key strategy in areas in which production is mostly by smallholders. Temperature increases will require buffering, especially during summer periods and between 500 and 1,500 m.a.s.l. Migration of cropped lands towards cooler (i.e. higher) areas in the Andes, if considered as a viable strategy, will need to be environmentally and socially sustainable.

For sugarcane, the most technologically viable option would be the development of new varieties with resistance to lodging and with higher yields at high temperatures. The Sugarcane Research Center (Cenicaña) will need to perform a progenitor selection process, and crosses and varietal evaluation in "homologue" zones to future conditions of the Valle del Cauca to obtain varieties with adequate agronomic performance under climatically modified conditions. The costs of this approach have been estimated to completely offset the costs of not adapting (Assad E., EMBRAPA, personal communication, 2011) or mal-adapting (Jarvis et al., 2011a).

Addressing national political issues in the face of adaptation

Two levels of adaptation are needed at the national level given the diverse impacts of climate change: (1) specific adaptation measures (described above), and (2) transversal measures. The latter need to be applied by all sectors and by the government to facilitate adaptation of small and vulnerable producers. Sector-based adaptation needs to address the economically and socially important sectors that may become vulnerable up to the 2050s. As transversal measures, the Colombian government, particularly the Ministry of Agriculture and Rural Development (MADR), should promote:

- Investment in a comprehensive climate change impact assessment, including biophysical, social and economic impacts, and in the development and evaluation of relevant technologies. International and national institutions need a plan of action to develop, test, and transfer technologies.

- Funding strategies to favor adaptation of smallholders through the MADR, along with the Colombian Institute for Rural Development (INCODER). The MADR, through INCODER has subsidized the rural poor to acquire land (1,417 families and 13,991 ha, with a total funding if 20 million US dollars. Ideally, recipients will be able to actively participate in the formulation of projects to perform necessary adaptations in their production systems.

- National extension mechanisms to achieve an adequate level of technology transfer to producers (especially small producers). Universities and their respective extension offices (e.g., *Universidad Nacional de Colombia*, *Universidad del Cauca*, *Universidad del Valle*), and other governmental extension offices are key actors in terms of technology transfer and will act as bridges among big producers, small producers, and research centers.

- Establishment of agricultural insurance systems for smallholders, with special emphasis on coffee, *Musa*, traditional maize, and upland rice.

Constraints and suggested future focus

Information-related constraints

In order to assess adaptation priorities within the national context, input information and data are required at three different levels: (1) socioeconomic, (2) production, (3) agronomic, (4) and climatic. Lack of information should not preclude from impact assessments being carried out. Available socioeconomic and production level data are adequate to produce a national adaptation pathway. The DANE and the MADR have provided not only needed national population surveys, but also national agricultural surveys that allow disaggregation and identification of populations (e.g., Afro-Colombian and indigenous), poverty prevalence, and sub-national distribution of agricultural and agroindustrial activities. Such data provide the current status of the national agricultural economy. Large scale agricultural sectors also contribute detailed and useful census data to the DANE. However, data access can be a problem: we suggest the establishment of a unique portal with free access to all socioeconomic national and sector-specific data. The *Instituto Geográfico Agustín Codazzi* (IGAC) and the establishment of SIGOT (Geographic Information System for Territorial Ordering and Planning) exemplify what is needed. We suggest strengthening this system, as well as the SINA (National Environmental Information System), as key sources of primary data.

In relation to climate data, a clear improvement is needed in two different respects: (1) improvement of the data itself (i.e. quality control, collection of new data, and expansion of the IDEAM's agrometeorology network), and (2) a much better inter-institutional networking between IDEAM and national (i.e. Universities, Cenicafé, Cenicaña, Cenibanano, amongst others) and international (i.e. IICA, CIAT) research centers that allows the flow of data in two directions. A clear re-structuring of the IDEAM scientific aims needs to be done and accompanied by more investment in the institution: more processing and storage capacity, more research staff, and better internal policies regarding the usage and sharing of data. A first step towards this was done in the National Development Plan (2010-2014), but clearly, more control and coordination between the MAVDT and MADR is required to ensure IDEAM targets correctly the needs of the country.

Suggested future focus for the sector

The focus of the Colombian government with respect to agriculture (Arguello and Lozano, 2007; Norton and Balcázar, 2003) and climate change should be on the formulation of a National Adaptation Plan (NAP) in which details on investment needs and financial flows are fully addressed. This plan should include:

1. A climate change adaptation and assessment network that involves national institutions (IGAC, IDEAM, Corpoica), private institutions (Cenibanano, Cenicafé, Cenicaña, Cenipalma), international institutions with headquarters in the country (World Wildlife Fund, CIAT), and other international institutions (Global Environmental Facility, The World Bank). Clear objectives, and definition and division of tasks and obligations will be needed. Corpoica and other institutions within the sector, and researchers at the National University, the Cauca University, Nariño University, IDEAM, and CIAT created an Inter-institutional Network of Climate Change to support the MADR (RICCLISA). Workshops involving different institutions and stakeholders per production system and with coordination by the MADR are needed and should emphasize knowledge sharing, national data inventories, and analyses of climate change impacts at the sub-national level for all crops.

2. A clearer role of the Agriculture Secretaries and Municipal agencies in climate change adaptation. To date, there is very little or no support from regional or local agencies in terms of support agriculture (i.e. subsidies and technical support) in most departments. A better control from the government on the allocated funds to the abovementioned offices would ensure this issue is steadily addressed, hence facilitating future adaptation to climate change.

3. Specific assessment and adaptation strategies for each sector and adequate technology transfer options.

4. Evaluation of adoption levels and performance of developed technologies with selected stakeholders.

5. Workshops with the selected stakeholders to elicit feedback regarding strategies and conclusions.

6. Validation within other environmental zones, and technology transfer to other producers within each sector.

7. Feedback on the overall process, and general conclusions regarding adaptation.

The Ministry of Agriculture is the national authority in charge of most of the investment flows: supported by other national and international institutions, and federations and producers organizations, the MADR should act as the coordinator of a framework (so that a level of centralization is achieved), but should allow participating institutions (local, national and international research and extension centers, and agriculture secretaries and municipal agencies) to take part and responsibility in climate change adaptation. This framework should exert control on the participating institutions, yet allowing them to act freely and enticing the institutional networking (i.e. data sharing, scientific collaboration). Such framework should define the capacities for stakeholders (i.e. farmers) to adapt to climate change and should prioritize efforts in research and development, and technology transfer. Efforts should be strongly focused on small producers with limited access to new technologies supporting national food security. National and international institutions should formulate projects and obtain funds for research, development, validation, and transfer of technologies. Available national financial sources to address adaptation are:

- Colciencias funds for assessments of the impacts of climate change on a sector basis;
- Governmental funds from the MADR to develop adaptation technologies. The MADR has co-funded 14 research projects on climate change and agriculture with more than 2.5 million US dollars;
- MAVDT funds that have already been allocated to the IDEAM (~1.5 million USD);
- Private intra-sector funds to finance both research (*ex-ante* impact assessment) and adaptation (deployment and implementation of technologies);
- International funds for small producers and for research. Interactions among organizations such as CIAT, Corpoica, IDEAM, the new CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) (Jarvis et al., 2011a), and governmental organizations such as the National Planning Directorate (DNP) are fundamental in order to access these funds.

Comprehensive and holistic (including economic, biophysical and social) sector-based assessments and regional assessments need to be developed to determine both negative impacts and future possible opportunities. Prioritization of geographic areas and crops is needed in order to obtain the required national and international funds (under discussion internationally) to fully address adaptation-related issues.

Conclusions

Comprehensive, sector-based and regional assessments of the impacts of climate change are needed. Although such analyses have been done for a limited number of crops and regions (e.g. coffee, sugarcane), availability of information remains problematic. There are ongoing initiatives (which results are not formally published yet) that will certainly contribute to enhance the knowledge base on impacts and adaptation in Colombia. Here we have done a numerical (although limited) analysis and a qualitative assessment of impacts and adaptation options. Our findings indicate that changes in crop phenology in lowlands, changes and shifts in distribution of pests and diseases, changes in the climatic niche of coffee, and possible (although not severe) decreases in sugarcane yields are expected. Governmental support to research and creation of an agricultural insurance scheme is critical for adaptation to happen in the sector.

Figures on impacts and adaptation costs are rather scarce in Colombia, mainly because data and modeling approaches are not tuned for such assessments. Multidisciplinary approaches are needed: a diverse range of impacts are expected for the agricultural sector—reflecting different regions and production systems. All impacts need to be addressed; and specific financial flows need to be determined and, more importantly, they need to be put together. Coupling of adaptation strategies with mitigation options will be required to produce efficient and sustainable production systems.

Data availability is critical to adaptation plans on a sector basis. Detailed field data on the response of crops to high temperature stress, drought and the effects of CO_2 fertilization are needed to model the likely impacts of climate change on agricultural production at the regional level, and these data need to be coupled with socio-economic and crop distribution data, and with future climate downscaled projections. This could be expensive, but the cost of not doing it could be greater given the risk of mal-adapting. Currently, data is not publicly available (this poses a constraint for University research groups working on the topic). Regional climate modeling, field evaluations, technology deployment and transfer, and uncertainty assessment are also relevant issues to be taken into account in the face of climate change.

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Table 1 Projected climate changes by administrative departments and ecogeographic regions in Colombia by 2050 (2040-2069)

Department (region*)	AMT[1] change (ºC)	MxAT[2] change (ºC)	MnAT[3] change (ºC)	ATR[4] change (%)	MxAR[5] change (%)	MnAR[6] change (%)	PS[7] change (%)	CV[8] (%)
Amazonas (A)	2.6	3.9	2.3	0.8	1.6	1.8	2.9	25.7
Guainía (A)	2.6	3.3	2.0	2.7	-0.3	22.8	-9.6	28.8
Guaviare (A)	2.6	3.0	2.3	3.2	1.0	75.4	-11.9	**32.6**
Putumayo (A)	2.4	3.1	2.1	1.9	5.5	4.9	1.2	26.6
Amazonas region	2.6	3.3	2.2	2.2	2.0	26.2	-4.4	28.4
Antioquia (An)	2.3	3.1	1.9	1.4	0.7	5.2	-4.8	27.7
Boyacá (An)	2.6	3.4	2.3	4.1	3.6	13.4	-4.5	**30.8**
Cundinamarca (An)	2.5	3.3	2.2	4.7	3.0	14.1	-5.3	28.2
Huila (An)	2.3	3.0	2.0	5.6	6.1	5.0	-1.2	26.4
Norte de Santander (An)	2.6	3.4	2.3	-0.4	2.2	-8.5	2.2	**30.7**
Santander (An)	2.6	3.5	2.1	1.6	1.0	8.3	-1.6	28.0
Tolima (An)	2.3	3.2	1.9	5.1	1.4	9.1	-6.9	26.9
Andean region	2.5	3.3	2.1	3.2	2.6	6.7	-3.2	28.4
Atlántico (Cb)	2.1	2.5	1.8	-1.2	-1.5	133.7	-6.8	**36.7**
Bolívar (Cb)	2.4	3.0	2.0	-0.2	-0.3	11.5	-4.7	**30.7**
Cesar (Cb)	2.5	3.1	2.1	-1.4	-1.4	0.1	-2.5	**33.3**
Córdoba (Cb)	2.2	2.8	1.9	1.2	-0.1	-1.8	-7.5	**31.8**
La Guajira (Cb)	2.0	2.4	1.8	-2.6	-3.1	9.3	-2.5	**32.0**
Magdalena (Cb)	2.3	2.8	1.9	-1.0	-0.9	17.2	-5.3	**33.7**
San Andrés Islands (Cb)	2.5	3.1	2.1	-1.3	1.0	-1.1	-5.5	27.6
Sucre (Cb)	2.3	2.7	2.0	0.7	-0.2	9.2	-7.4	**35.1**
Caribbean region	2.3	2.8	2.0	-0.7	-0.8	22.3	-5.3	32.6
Caldas (CoB)	2.3	3.3	1.8	3.6	0.9	5.6	-6.3	26.2
Quindío (CoB)	2.2	3.2	1.8	5.2	1.7	9.0	-6.5	27.1
Risaralda (CoB)	2.2	3.2	1.7	3.8	1.7	2.7	-6.5	25.7
Coffee belt region	2.2	3.2	1.8	4.2	1.4	5.8	-6.4	26.3
Arauca (O)	2.7	3.4	2.3	4.7	3.7	49.6	-7.1	**34.4**
Caquetá (O)	2.5	3.2	2.2	2.1	2.1	23.3	-6.1	28.8
Casanare (O)	2.6	3.3	2.1	5.3	3.8	84.0	-9.6	**36.8**
Meta (O)	2.5	3.0	2.2	4.0	1.3	62.5	-10.9	**31.7**
Vaupés (O)	2.6	3.5	2.2	1.4	0.8	11.7	-6.1	27.2
Vichada (O)	2.6	3.1	2.1	4.5	1.4	61.4	-10.1	**33.8**
Orinoquia region	2.6	3.3	2.2	3.7	2.2	48.8	-8.3	32.1
Chocó (P)	2.0	2.6	1.7	1.7	2.4	2.8	-2.5	24.2
Cauca (Sw)	2.1	2.6	1.9	3.1	2.2	5.1	-3.2	24.0
Nariño (Sw)	2.0	2.5	1.8	2.9	3.0	2.5	-0.6	23.7
Valle del Cauca (Sw)	2.1	2.8	1.8	4.2	1.6	6.8	-7.5	24.7
South-west region	2.1	2.6	1.8	3.4	2.3	4.8	-3.8	24.1

National average	2.5	3.2	2.1	2.5	1.5	13.7	-6.3	26.4

*A: Amazon, An: Andean, Cb: Caribbean, CoB: Coffee belt, O: Orinoquia, P: Pacific, Sw: Southwest. [1]AMT: Annual mean temperature, [2]MxAT: Maximum annual temperature, [3]MnAT: Minimum annual temperature, [4]ATR: Annual total rainfall, [5]MxAR: Maximum annual rainfall, [6]MnAR: Minimum annual rainfall, [7]PS: Precipitation seasonality, [8]CV: Coefficient of variation (numbers in bold indicate high uncertainty).

Table 2 Proportion of croplands under different changes in temperatures and rainfall by 2050s under the SRES-A2 emission scenario

Crop	Current			Temperature (%)		Precipitation (%)		
	No. Depts.	Surface (ha)	Production (Ton)	2-2.5ºC	2.5-3ºC	-3-0%	0-3%	3-5%
Perennial (exports)								
Coffee	17	613,373	708,214	84.7	15.3	8.2	28.8	63.1
Sugarcane	6	235,118	3,259,779	99.6	0.4	1.1	0	98.9
African oil palm	14	154,787	598,078	54.8	45.2	54.2	36.3	9.5
Cocoa	27	113,921	60,218	40.2	59.8	17.3	53.2	29.5
Bananas	2	44,245	1,567,443	100	0	26.9	73.1	0
Plantains	1	19,187	209,647	100	0	0	100	0
Flowers	2	8,700	218,122	100	0	0	16.1	83.9
Dark tobacco	5	5,376	9,648	33.6	66.4	17.9	75.2	6.9
Perennial (others)								
Sugarcane (panela)	24	219,441	1,189,335	77.8	22.2	6.1	33.8	60.2
Fruits	18	148,574	1,417,919	72.5	27.5	7.7	22.5	69.8
Plantains	31	375,232	3,080,718	79.8	20.2	7.2	36.1	56.6
Yam	9	25,105	261,188	100	0	46.7	53.3	0
Fique	8	19,651	21,687	78.1	21.9	0.3	55.1	44.6
Coconut	10	16,482	127,554	100	0	10.7	69.3	19.9
Annual (cereals)								
Maize	31	626,616	1,370,456	80.5	19.5	27.7	37.1	35.2
Rice	26	460,767	2,496,118	64.6	35.4	15.7	23.6	60.7
Sorghum	14	44,528	137,362	97	3	33.8	3.8	62.4
Wheat	6	18,539	44,374	69	31	0.2	68.4	31.5
Barley	4	2,305	3,939	47.2	52.8	0	28.5	71.5
Annual (oilseeds)								
Common beans	25	124,189	146,344	84.6	15.4	10.7	40.4	48.9
Cotton	15	55,914	126,555	98	2	14.6	55.7	29.7
Soybeans	6	23,608	42,937	0.3	99.7	0	0	100
Sesame	6	3,216	2,771	100	0	69	28.5	2.5

Table 3 Expected impacts and adaptation measures for Colombian agriculture in 2050s.

Expected Impacts	Crops likely to be impacted	Adaptation measures
Changes in crop phenology and subsequent impact on product flows to markets and supply chains	Coffee, *Musa* crops, upland rice, maize, soybeans, common beans, fruit trees	Changes in harvest and sowing dates. Infrastructural changes for perennial crops (irrigation, drainage).
Flooding of agricultural lands due to increases in sea level and salinization of underground water	African oil palm (Pacific coast), *Musa* crops (Urabá)	Re-location of activities according to new territorial ordering plans. Walls and barriers construction to prevent salinization and protect coastal ecosystems.
Changes in pests and diseases: increases and displacement to new regions	Coffee (above 1,500 m.a.s.l.), *Musa* crops (above 500 m.a.s.l.), potatoes above 2,500 m.a.s.l., cassava, fruit trees	Find out pest and disease resistant and/or tolerant materials. Implementation of monitoring and early-warning systems in order to implement sustainable management.
Intensification of land degradation processes and desertification	Potatoes and cassava in Andean mountain hillsides	Increase soil resilience by improved and sustainable agronomic management (i.e. optimized used of inputs and barriers to avoid soil erosion).
Increased vulnerability of small producers to climate variability and climate change	All crops (sectors with significant dispersion within the country should be addressed in the first place)	Creation of adaptation subsidies and an agricultural insurance system for mountain hillside producers and for very dry areas. Big producers and the government should invest on research, extension and technology transfer to support smallholders.
Risk of loss (extinction) of not currently *ex-situ* conserved or underrepresented plant genetic resources	Prioritization of activities that require genetic improvement: fruit trees, avocado, *Musa* crops, coffee, potatoes	The government should stimulate the better conservation of plant genetic resources and should provide funding for such purpose. National and international institutions within the country should perform analyses on high risk areas, incomplete collections and organize collecting missions.
Gradual loss in crop and pasture suitability and productivity, including possible abandonment of current crop lands.	Sugarcane, coffee (above 1,500 m.a.s.l.), potatoes (below 2,500 m.a.s.l.), *Musa* crops (below 500 m.a.s.l.), citric fruit trees (highlands), livestock	Locate heat resistant varieties in relevant genebanks. Currently conserved plant genetic resources should be queried in order to determine the likely gene sources and to further establish genetic improvement strategies.

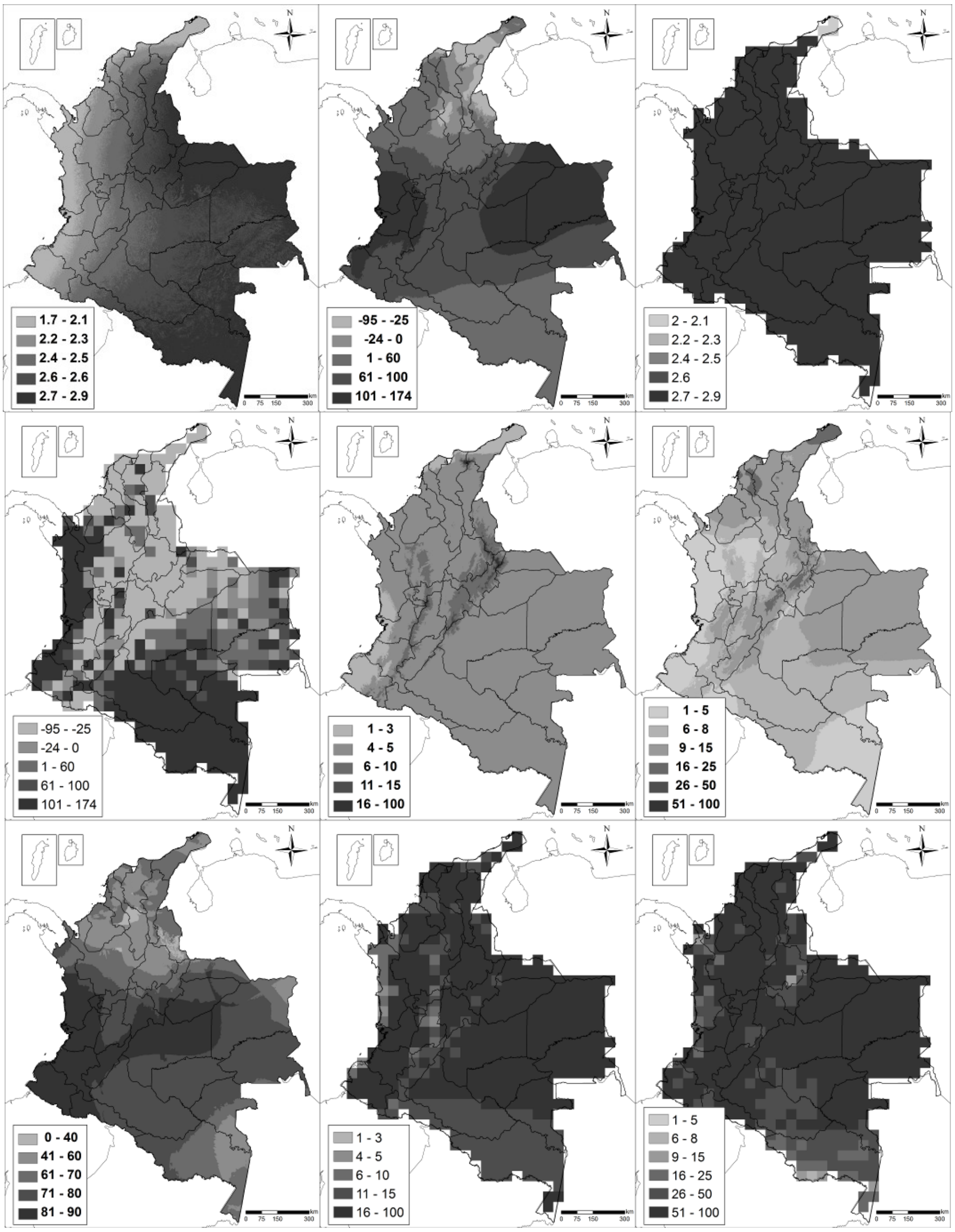

Figure 1 Predicted changes in climates and associated uncertainties. (A) change in annual mean temperature as average of 17 GCMs; (B) change in annual total rainfall as average of 17 GCMs; (C) change in annual mean temperature as average of 4 PRECIS runs; (D) change in annual rainfall as average of 4 PRECIS runs (see sect. 2 supporting material); (E) coefficient of variation (%) of GCM temperature predictions of (A); (F) coefficient of variation (%) of GCM rainfall predictions of (B); (G) Percent models agreeing in direction of rainfall changes; (H) same as (E) but for PRECIS runs; (I) same as (F) but for PRECIS runs. For details on the reasons we used GCM and PRECIS, the reader is referred to Sect. 4 of supporting material.

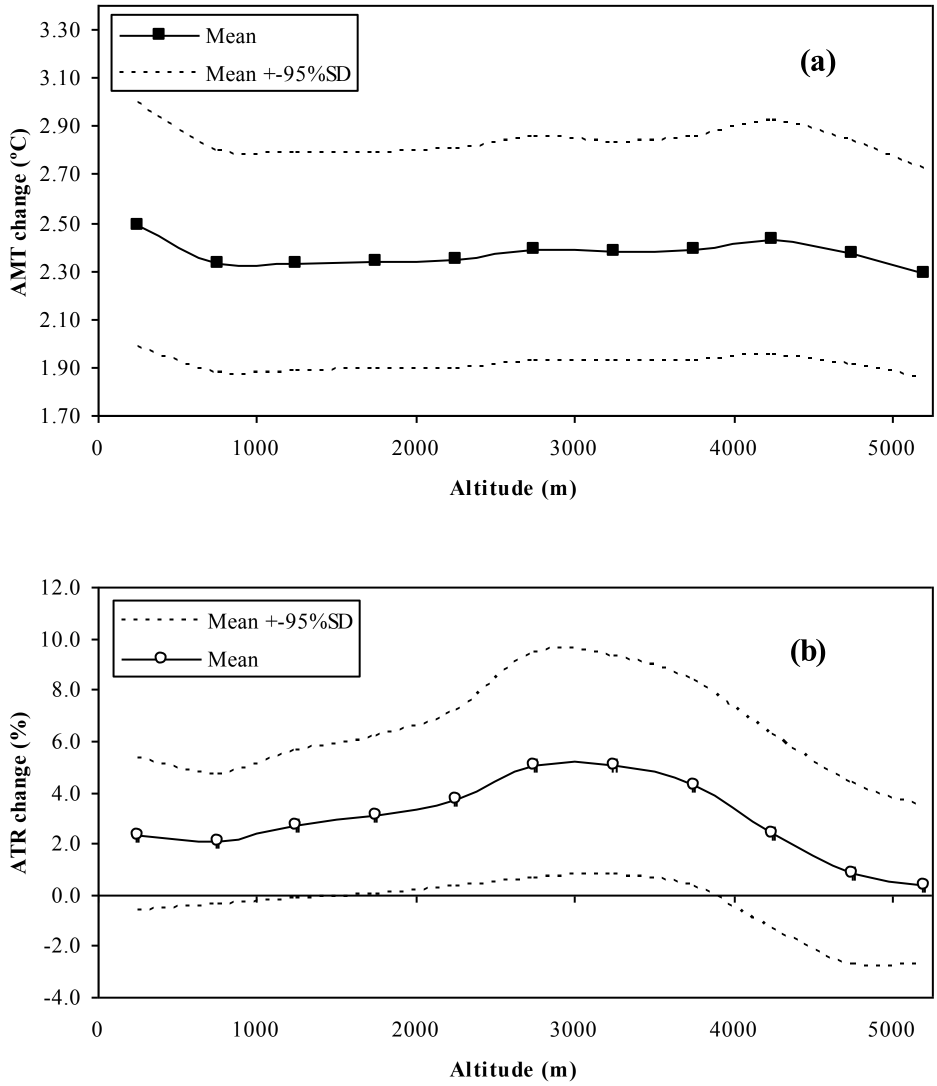

Figure 2 Projected changes in (a) annual mean temperatures and (b) annual total rainfall by 2050s across different altitudes under the SRES-A2 emission scenario. Average of 17 GCMs (continuous line), 95% confidence interval around the mean (dotted line)