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Impacts of Climate Change on Brazilian Agriculture – Refocusing Impact Assessments to 2050

Inception Report

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Executive Summary

Agriculture is a major sector of the Brazilian economy accounting for about 5.5% of GDP (25% when agribusiness is included) and 36% of Brazilian exports. As per the 2006 agricultural census, Brazil has 5 million farms of which 85% are small holders and 16% are large commercial farms occupying 75% of the land under cultivation. In 2009, Brazil enjoyed a positive agricultural trade balance of $55 billion. In the second quarter of 2010, Brazil's economy recorded 8.8 percent growth with agriculture making a major contribution (11.4 percent) relative to the industrial (13.8 percent) and services (5.6 percent) sectors.

Because agriculture is vital for national food security and is a strong contributor to Brazil's GDP growth, there is growing concern that Brazilian agriculture is increasingly vulnerable to climate variability and change. For example, under a 'plausible but pessimistic' climate change scenario, the "Economics of Climate Change in Brazil" 2010 study revealed that climate change is very likely to reduce area of cropland with low production risks that are currently used to produce 85% of Brazil's major food and export crops. In addition, the productivity of subsistence crops in northeastern Brazil will also decline. The projected impacts will be felt as early as 2020 and certainly by 2050. The best agricultural option identified in the study was to breed better adapted crop and pasture varieties that are both heat and drought tolerant. Producing and releasing an adapted variety requires around ten years and investments need to begin now!

To meet national development, food security, climate adaptation and mitigation, and trade goals over the next several decades, Brazil will need to significantly increase per area productivity of food and pasture systems while simultaneously reducing deforestation, rehabilitating millions of hectares of degraded land, and adapting to climate change. Because of the projected magnitude of the agricultural impacts and investments required, and the decadal response time of best adaptation options available, this report evaluates the requirements for a state of the art, assessment of climate change impacts on agriculture to guide policy makers on investment priorities and phasing. The current projections of climate change impacts for Brazil are based on climate models that were available prior to 2008. Since then, not only has the science and quality of global, regional, and local modeling advanced significantly, but also improved land quality and climate data are now available. Two significant limitations in the previous climate change modeling and a major innovation opportunity to overcome the limitations are identified. **Key limitations** include:

a. **The high level of complexity in modeling climate change in the face of uncertain future greenhouse gas emissions has resulted in a lack of consistency in projected changes and likely impacts especially when projected beyond 2050.** While global models perform adequately at continental scales, their coarse resolution (100-300 km) makes it difficult to capture regional and local climate forcing drivers, processes and impacts. The use of Regional Climate Models (with a resolution of 50 km or less) in combination with GCMs (nested RCMs) is an improvement over GCMs alone but because RCMs are downscaled from or 'constrained' by GCM projections, there is still a problem with biases and errors that need to be validated and corrected. The currently available assessments of climate change impacts on agriculture were based on projections of one GCM and one RCM (the best that was available pre 2008).
b. **A significant "climate data deficiency" nationally and regionally** continues to compound the effects of inherent uncertainty in complex models designed with global and regional scale processes and data inputs. Even though Brazil is generally well endowed with meteorological data recording stations and long term data sets(some areas like the Amazon and the Cerrado have sparse data coverage), most neighboring countries have serious climate data gaps (data limited to few locations and/or data records that are not long term i.e. less than 20 years), which make it very difficult to validate and properly calibrate the current regional model projections.

The challenges posed by the modeling limitations identified above, suggest **a methodological opportunity and innovation for the Agricultural sector to couple the on-going 'top down' climate modeling involving Global Climate Models (GCMs) and Regional Climate Models (RCMs) with a 'bottom up' Brazilian approach** involving:

(i) ***robust 30 year local data*** sets on rainfall and temperature, high resolution soil data for agriculturally important States, and robust estimates of eligible crop areas that exclude legally protected riparian zones, forest reserves, and indigenous lands. EMBRAPA is currently assembling such datasets.

(ii) ***long term crop modeling recently improved to integrate temperature at flowering stages (critical to yield), field measurement, and field observations to derive Agro Zoning based on crop suitability and production risk*** by national and state agencies involved in agriculture,

(iii) ***a state of the art Brazilian Regional Atmospheric Modeling System (BRAMS) that has a validated and robust capacity to incorporate the biogenic, biomass burning and anthropogenic emissions (trace gases and aerosols) and improve climate projections at locally relevant scales.*** Because existing GCMs and RCMs projections are still inconsistent for the climate change impacts on rainfall, and as locally generated aerosols (from vegetation burning) are known to significantly impact clouds and rainfall, the coupling of BRAMs with the best available GCMs and RCMs shows promise for ameliorating the uncertainties and inconsistencies for both rainfall and temperature changes over key agricultural regions of Brazil.

Brazil is currently implementing programs to (a) comprehensively monitor its forests, (b) halt deforestation, and (c) provide public and private investments for rehabilitation of degraded lands and for strategic reforestation of deforested areas. **An integrated approach to upstream climate change modeling coupled with land use and land cover change and the interactions with climate change drivers, provides an operational framework for a broad focus on landscape level and agroecosystem resilience** to reduce the potential impacts of climate variability and change on society.

Four key **integrated and linked** interventions are needed in the short term to significantly improve the assessment of climate change impact on agriculture in Brazil to 2050. These include:

1. **Refine the climate model projections via the coupling of global, regional, and local scale modeling and validated field data**. Two components are necessary:
   a. Harness the emerging Global and Regional climate modeling platforms being developed and tested by the Brazilian National Institute for Space Research (INPE) in Brazil and the CREAS program for South America.

b. Integrate the INPE and CREAS suite of tested global and regional models with the state of the art Brazilian developments in Regional Atmospheric Model (BRAMS) that incorporates aerosol and land cover/land use feedbacks for much improved local weather and climate (especially rainfall) projections.

2. **Make the EMBRAPA/UNICAMP Agro Zoning Model <u>Climate Smart</u> by integrating the** high resolution climate projection outputs from the suite of global climate and tested regional climate models and include:
   a. the recently available disaggregated land (soil) quality data at State and municipal levels, and
   b. the meteorological data from all calibrated and validated ground stations of the Brazilian Water Agency (ANA) and the National Institute of Meteorology (INMET).
3. **Make the existing Brazilian Land Use Model (BLUM) <u>Climate Sensitive</u> by coupling it with state of the art outputs from 1 and 2 (above)** to assess:
   a. Climate change induced changes in supply and demand of agricultural products at a national level
   b. Changes on the distribution of land use and production within Brazilian territory for given supply and demand scenarios.
   c. Economic effects on agricultural production and profitability
4. **Improve the collection, verification, and the assembly of critical climate (rainfall, temperature, solar radiation, wind speeds), land cover and land use dynamics, and land quality and land area data and information.** Based on the review and synthesis of the most recent peer reviewed publications on climate change for Latin America and Brazil, this report highlights the important fact that the lack of good quality and long term climate data in Latin America is hampering regional and local climate modeling efforts as well as the calibration and validation of current projections that are being used to inform policy and investment decisions to 2050 and beyond. Because the climate forcing factors operate both within and external to national frontiers, there is an urgent need for coordinated and **targeted climate change investments over the next 1-5 years for instrumentation, data assembly, data sharing and data access systems. National, bilateral, and multilateral investments agencies need to coordinate their investment strategies to support this specific and urgent need**.

This report presents a synthesis of the current state of knowledge, the recent and emerging scientific advances, and the opportunities for better understanding and quantifying the magnitude, spatial distribution, and time horizons of predicted climate change stresses and impacts for agriculture.

The need for improved and integrated climate change impact assessments is especially urgent for the agricultural sector. A recent survey carried out by the Brazilian Enterprise for Agriculture and Animal Research (EMBRAPA), revealed that even with advanced breeding techniques, it takes approximately 10 years of R&D and costs at least US$6 million to develop, test, and release a new crop cultivar or variety that is heat and/or drought tolerant. The review synthesis from this report suggests that within the next decade, Brazilian agriculture will already be dealing with a significant level of climate induced crop and livestock productivity stresses. Much of the crop improvement work to date has focused on drought tolerance and a great deal still remains to be done for heat tolerance.

1. Introduction

Agriculture is a major sector of the Brazilian economy accounting for about 5.5% of GDP (25% when including agribusiness) and 36% of Brazilian exports. Brazil is the world's largest producer of sugarcane, coffee, tropical fruits, frozen concentrated orange juice, and has the world's largest commercial cattle herd at 170 million head. Brazil is also an important producer of soybeans, corn, cotton, cocoa, tobacco, and forest products. Between 1996 and 2006 the total value of the country's crops rose 365 percent from 23 billion reais to 108 billion reais (US$ 64 billion). Brazil accounts for about a third of world soybean exports and supplies a quarter of the world's soybean trade from 6% of the country's arable land. The remainder of agricultural output is in the livestock sector, mainly the production of beef and poultry, pork, milk, and seafood. Brazil is currently the world's largest exporter of beef, poultry, sugar cane and ethanol.

In 2009, Brazil enjoyed a positive agricultural trade balance of US$55 billion. In the second quarter of 2010, Brazil's economy recorded 8.8 percent growth with agriculture making a major contribution (11.4 percent) relative to the industrial (13.8 percent) and services (5.6 percent) sectors. **There is growing concern, however, that increasing short term climate variability and medium to long term climate change will have significant negative impacts on the Brazilian landscape and on Brazilian agriculture, national economic growth, and associated livelihoods (Assad and Pinto, 2008; Margulis and Dubeux, 2010).**

The increase in Brazil's agricultural productivity since 1996 is due to:

1. An increase in the amount of land under cultivation by a third, mostly in the *cerrado*.
2. A tenfold increase in production via the systematic and rapid development and deployment of cutting edge agricultural technologies (land and water management, lime and fertilizer use, new varieties and animal breeds).

Agriculture and livestock raising, however, are two important sources of 75 percent of Brazilian greenhouse gas (GHG) emissions because of the associated land use changes that result in the direct loss of plant biomass and soil biomass carbon, and other greenhouse gases such as nitrous oxide and methane from ruminant digestive processes and nitrogenous fertilizer use.

Given the link between GHG emissions, global warming, and projected negative impacts of climate change on Brazilian agriculture and associated livelihoods, the Brazilian government is taking action to stop further deforestation and expansion of agricultural land. In 2009, under its climate change policy, Brazil committed to reducing deforestation by 70 percent by 2020 with the explicit goal to reduce GHG emissions by 36 to 39 percent.

The reduced emissions goal implicitly targets any new clearing of cerrado and rainforest for agriculture and is backed by fiscal instruments and safeguards being implemented by both government and private banks. For example, in 2009, Brazil's national development bank (BNDES), mandated a zero-deforestation policy for cattle production that obligates meat producers to have a traceability system to ensure cattle production does not result in new deforestation. In 2009, *Banco do Brasil* announced that farmers applying for credit are required to certify the origin of their produce so that negative impacts on ecologically sensitive areas can be prevented. Private Banks are also imposing more stringent environmental criteria when lending to farmers.

Avoiding deforestation is by far the best option to reduce GHG emissions in Brazil (de Gouvello, 2010). According to the detailed "Low-Carbon" study's sector estimates, a new land use dynamic in Brazil would reduce deforestation by up to 68% by 2030, compared to the reference scenario estimated for that same year. Public policies and planning are essential, especially with regards to managing land competition and forest protection. On-going research suggests that Brazil will need to nearly double productivity on cattle pastures between 2010 and 2030 to accommodate future demand without clearing further forest. Squeezing the current cattle population onto half as much pasture — which is possible from a technical stand point — could free up enough land to more than double grain production, without further deforestation. Understanding how climate change might impact such a strategy, however, is vital to location, scale, and phasing of future investments.

Against the backdrop of the need to increase agricultural productivity to meet growing national, regional, and global food demands while at the same time not increasing the agricultural area via deforestation, the Brazilian Government is pursuing the following agricultural development pathways:

1. significantly increase per area productivity of existing agricultural lands,
2. rehabilitate the productivity of deforested and degraded lands, and
3. use the rehabilitated lands for productive agriculture, forestry, and agroforestry, while simultaneously reducing the vulnerability of ecologically sensitive areas in the Amazon, the Cerrado, the Atlantic Forest, the Pantanal, and the Pampas.

Although Brazil is currently using a fraction of its potential arable land and renewable water resources, a significant proportion of these resources are separated by vast distances and cannot be readily harnessed without significant additional investments in technology and infrastructure. Less than 4% of Brazil's agricultural area is irrigated, underscoring both the difficulties and the investment opportunities for possible intensification and adaptation. The 2006 agricultural census revealed that Brazil has 5 million farms of which 85% are small holders and 16% are large commercial farms occupying 75% of the land under cultivation.

At a continental scale, the International Panel on Climate Change (IPCC) Assessment Report 4 (2007) and other researchers (Jarvis et al., 2010) note that climate change in Latin America will affect a number of ecosystems and sectors over the coming decades, with specific impacts on agriculture resulting in:

- Reduction in the quantity and quality of water flows and thus irrigation potential;
- Increasing aridity, land degradation, and desertification;
- Increasing incidence and impacts of crop pests and diseases.
- Decreasing plant and animal species diversity and changes in biome boundaries, agroecozone area and boundary shifts, and perturbations to ecosystem services (e.g. carbon sequestration, functional biodiversity, environmental flows) needed to sustain the productivity of current agricultural areas.

A key challenge and opportunity for Brazil is the need to better understand, quantify, and map the locations of projected impacts on currently productive agriculture and to better quantify the magnitude and uncertainty associated with current projections of both positive and negative impacts. Two recently published studies (Assad and Pinto, 2008; Margulis et al., 2010) concluded that eight of the nine major Brazilian food and export crops will suffer negative effects, resulting in significant production declines in their preferred agroecological zones between 2020 and 2050. Important to note, however, that both studies used the same single GCM and single RCM climate models for projecting climate changes – these were the best available models pre 2008. Current knowledge and efforts are focused on enhancing robustness of projections via the use of at least three RCMs.

As discussed previously, Brazil is currently implementing programs to (a) comprehensively monitor its forests, (b) halt deforestation, and (c) provide public and private investments for rehabilitation of degraded lands and strategic reforestation. Such an integrated and proactive approach to managing land use and land cover change coupled with robust climate change modeling and impact assessments provides an operational framework for enhanced landscape level productivity and agroecosystem resilience to reduce the potential impacts of climate variability and change on society (Pielke, 2009).

2. Scope of Report

This report provides a review of the literature on climate change modeling approaches, climate impact assessments, and projections for Brazilian agriculture and presents a synthesis of challenges and methodological opportunities. The review:

a. Highlights the methodological limitations and resulting difficulties to provide consistent climate change impact assessments at regional to national scales,
b. Identifies the knowledge gaps and limitations in the most recent estimates of climate change impacts on Brazilian agriculture, and the on-going efforts to improve the climate models for use in Brazil, and
c. Identifies the opportunities for a state of the art, high resolution evaluation of agricultural impacts and possible consequences for:

i. induced changes in supply and demand of agricultural products at a national level
ii. economic effects on agricultural production and profitability, and
iii. Changes in the distribution of land use and production within Brazil for given supply and demand scenarios

3. The Evolution of the Farming Sector in Brazil and Implications to 2050

In recent decades, this growth in the Brazilian agricultural sector has increasingly been driven by productivity gains in cereals, coarse grains, sugarcane, oilseeds and milk sectors. Brazilian production has grown more than 1.5 times the rate of world production (figure 1 and 2). In meat sectors, the average growth has been 1.8 times faster than the world production.

Total output has grown 2.5 times (figure 3) since the 70s while the use of labor is decreased and the use of capital and land has slightly increased. More importantly, the productivity of all production factors has strongly increased for the same period (Figure 4) (Source of data: FAO/FAOSTAT accessed December 2010)

Figure 1. World and Brazil Agricultural Production: Expansion from 1990 to 2009 (1990=100)

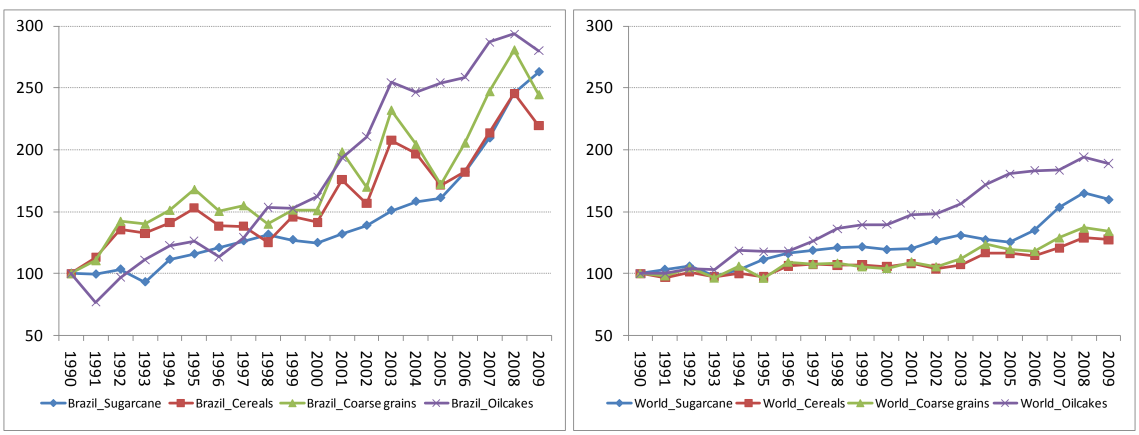


Figure 2. Brazil's and World Meat and Milk Production: Expansion from 1990 to 2009 (1990=100)

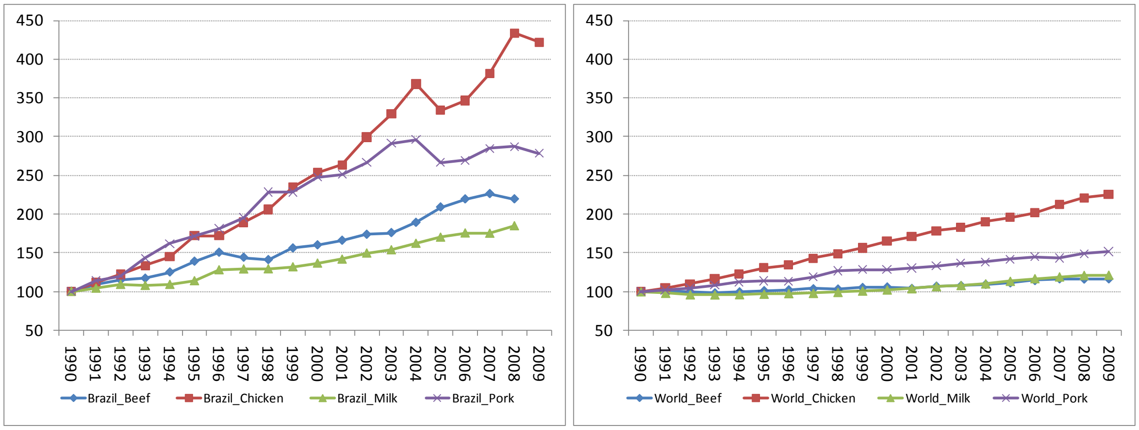
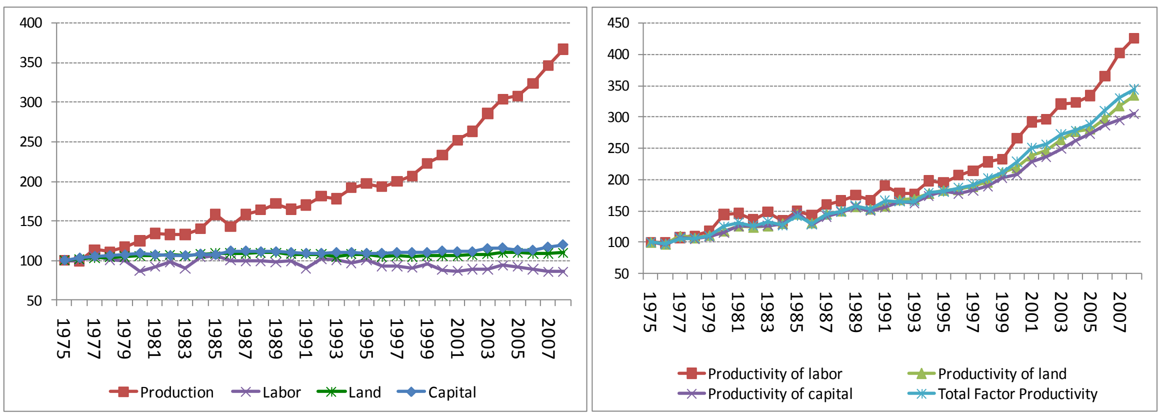


Figure 3. Brazilian Agricultural Sector: Total Production and Use of Labor, Land, and Capital and Total Factor Productivity (1975=100) Source: Gasques et al. (2009)



The 2006 Agricultural Census indicated that the number of rural households is increasing again despite the reduction observed from the 80s to 90s. With respect to the distribution of households according to farm size, the agricultural sector is clearly becoming less concentrated. For example, between 1995 and 2006, the number of smaller households (less than 100 hectares) has increased. In terms of land occupied, both the smallest and the largest size classes have decreased from 1995 to 2006, while the middle classes (10 to 1,000 ha) have increased.

Table. 1. Evolution of the Structure of the Brazilian Agricultural Sector

	Number of Rural Households (units)						Land Occupied (ha)	
	1970	1975	1980	1985	1995	2006	1995	2006
Total	4,924,019	4,993,252	5,159,851	5,801,809	4,859,865	5,175,489	353,611,246	329,941,393
Less than 10 ha	2,519,630	2,601,860	2,598,019	3,064,822	2,402,374	2,477,071	7,882,194	7,798,607
10 to 100 ha	1,934,392	1,898,949	2,016,774	2,160,340	1,916,487	1,971,577	62,693,586	62,893,091
100 to 1000 ha	414,746	446,170	488,521	517,431	469,964	424,906	123,541,517	112,696,478
More than 1000 ha	36,874	41,468	47,841	50,411	49,358	46,911	159,493,949	146,553,218

Source: IBGE Agricultural Census 2006

Will the Brazilian agricultural landscape in 2050 and beyond resemble current agricultural landscapes in Australia, Canada, and the USA that are dominated by few large, technologically advanced farms with national value added derived from land, capital, and skilled labor? The data presented in Figures 1-3 suggest that productivity gains and production growth is taking place in the agricultural sector as a whole. Interestingly, the rural sector in Brazil is becoming more capital and labor intensive across all the scales of farms small and large (see Figure 3 above). It is difficult to envisage the structure of Brazilian farms in 2050 but the above trends suggest that simulations on the long term future of the Brazilian agricultural sector need to focus on the sustainable intensification of the production rather than the likely changes in the structure of the households and the size of farms.

Small holder farmers are generally more vulnerable to economic and environmental shocks and have access to fewer resources to adapt to climate variability and change when compared to large scale farmers. However, relative to large scale producers that rely on one or two crops planted over thousands of hectares, small holder farmers can play a vital role in providing landscape scale resilience through a diversity of production approaches that harness a wider spectrum of agrobiodiversity while also preserving and harnessing ecosystem services and the emerging markets for these services (carbon and biodiversity offsets, hydrological flows for reduced floods and/or improved water quality). In addition to emerging markets for ecosystem services, the emergence of a global demand for "functional foods" (foods that have direct health benefits like reducing cholesterol, improving liver function, reducing hypertension) could result in major economic windfall for smallholder farmers. Many of the functional foods are "low volume, high value" products that are well suited to smallholder cropping systems.

Another issue that is often overlooked in the discussions on future scenarios for Brazilian agriculture is the prevailing legal and land administration framework in Brazil (Sparovek et al., 2010). The legal framework dictates what can and cannot be done in the rural and agricultural landscape (e.g. maintaining riparian zones, legal (forest) reserves, securing indigenous lands etc.) and the Brazilian Government is aggressively enforcing the legal aspects via a range of monitoring actions, policies, and fiscal instruments. The two main legal frameworks are (a) the Forest Law and (b) Preservation Areas such as state and national parks, and indigenous reserves.

The Forest Law, which covers all natural vegetation (the Amazon, the Atlantic Forest, the Cerrado (savanna), the Caatinga (the scrub woodland in northeastern Brazil), the Pantanal, and the Pampas (grassland of southern Brazil), delineates rural private land into land for production and land that must be preserved. The land that must be preserved with natural vegetation on all private farmland is further subdivided into (a) conservation areas (Legal Reserves) and (b) Areas for Permanent Preservation (APP) that include (i) riparian zones defined as vegetation strips along rivers and other water bodies with varying width depending on type and size of the water body, (ii) any land with slopes >45°, (iii) hill tops, and (iv) any land above 1800m above sea level.

The goal for the APP is to protect parts of the landscape with strategic value for freshwater recharge and thus the APP cannot be used for any type of production activities and must be maintained with the original native vegetation. Legal Reserves are established to promote biodiversity conservation. Although the primary goal is to maintain the native vegetation, **Legal Reserves can be used for some low-impact production systems, such as managed low-impact forest extraction, selected agroforestry systems, and apiculture. These are suitable for smallholder family agriculture and possibly alternative production schemes aiming at niche markets.** Conventional mechanized agriculture employing intensive inputs or forestry operations employing complete forest removal are not allowed.

It is possible to envisage a ‘paradigm shift’ for a productive, resilient, culturally appropriate and inclusive Brazilian rural and farming landscape that has **both large farmers ensuring efficient high volume growth and smallholders ensuring resilience to climate change shocks via a range of cropping systems that are productive and profitable on the basis of payments for ecosystem services (e.g. Reduced Emissions from Deforestation and Degradation – REDD plus) and the emerging markets to meet the growing global demand for functional foods!** Understanding the evolving intensification, vulnerability, resilience, and investment issues and better mapping projected climate change impacts across relevant spatial and time scales, will be critical to enhancing and sustaining Brazil’s agriculture and rural sectors and their competitive regional and global advantage. This short section is included to highlight the importance of the legal aspects on future expansion and diversification of Brazilian agriculture. The Forest Law (Legal Reserves and APP) is currently under debate in the Brazilian parliament with the objective of revising the law. A full discussion of the evolving legal framework and its potential influence on the future structure of Brazilian agriculture is beyond the scope of this report (see Sparovek et al., (2010) for a detailed review and discussion).

This report highlights the work required to provide more robust and quantitative information on how and where the drivers of agricultural production growth are more likely to be impacted by changing climate. The goal is to better inform policy makers and thereby facilitate action to ensure that the farming sector has access to the knowledge and resources to undertake the adaptation that will be necessary across both large-scale and smallholder farms to cope with unavoidable climate changes while simultaneously contributing to economic and ecological sustainability.

4. Literature Review of Climate Change Impacts on Agriculture – Brazil Focus

The general literature on assessing the impacts of climate change on agriculture focuses on two major approaches:

1. The "Agronomic Model or Production Function (Decker et al., 1986), and
2. The Hedonic Model (Mendelsonh et al.,1994)

In the agronomic (Production Function) model approach, environmental factors/inputs are varied to examine the impacts on production functions resulting in estimates of weather on specific crop yields. The advantage of this approach is that bias is avoided if agricultural outputs are driven by factors beyond the farmers' control. However, since farmers´ adaptations are completely constrained in the production function approach (i.e. the estimates do not account for management changes likely to be made by farmers in response to climate change), it is likely to produce estimates of climate change that are biased downward.

The hedonic (Ricardian) model, on the other hand, examines how climate in different places affects the value of farmland. The clear advantage of the hedonic approach is that if land markets are operating properly, prices will reflect the present discounted value of land rents into the infinite future thereby accounting both for the direct impacts of climate on yields of different crops as well as the indirect substitution of different activities. Because unmeasured characteristics are important determinants of agricultural output and rural land values, however, the hedonic approach may confound climate with other factors, and the sign and magnitude of the resulting omitted variable bias is unknown (Deschênes and Greenstone, 2007).

There are relatively few published studies on the impact of climate change on agriculture in the Latin America and Caribbean region. For example, de la Torre et al., 2009 quantified the expected losses in the sector, exclusive of losses due to natural disasters or losses to noneconomic sectors, and inclusive of private adaptive responses by farmers and estimated that the projected total losses in the LCR are in the order of $111 billion (or 1% of GDP) by 2050 if warming reaches 1.79 degrees above 1900 levels.

1997-2007 studies and projected impacts of climate change on Brazilian Agriculture

Two studies over a decade ago:

- Sanghi et al. (1997) estimated the effects of climate on Brazilian agricultural profitability using the hedonic method. They estimate the impacts of a 2.5ºC temperature increase and a 7% increase in precipitation, and reported that the net impact of climate change on land value is negative, between -2.16% and -7.40% of mean land values.
- Evenson and Alves (1998) extended the Sanghi et al. (1997) exercise to include the effects of climate change on land use, and the mitigating effects of technology on the relationship between climate change and agricultural productivity. They modeled land value as well as the profit-maximizing share of farmland in different land uses (perennials, annuals, natural pasture, planted pasture, natural forest, and planted forest) as a function of climate, technology, and control variables. They jointly estimated the six land use functions and the land value function and showed that a combined increase of 1°C and 3% rainfall will lead to a 1.84% reduction in natural forest and an increase of 2.76% in natural pasture. Their analysis suggested that increased investments in research and development would partially mitigate the loss of natural forest due to climate change. This relatively mild climate change is predicted to reduce land values by 1.23% in Brazil as a whole. As in Sanghi et al. (1997), the North and Northeast and part of the Central and Western Brazil face the most severe negative impacts.

- Feres, Reis and Speranza (2008) tested the fixed-effects model proposed by Deschênes and Greenstone (2007) and the hedonic model proposed by Mendelsohn et al. (1994) for a panel of municipalities covering the period 1970-1995. The estimated coefficients were then used to simulate the effects on agricultural profitability and land value of projected changes in precipitation and temperature from simulations of spatially differentiated climate scenarios (A2 and B2 emission scenarios defined in the IPCC Third Assessment Report) and four General Circulation Models (GCMs). The simulation results indicated that:
    - the consequences of climate change will vary across Brazilian regions. The North and the Center West regions may be significantly harmed by climate change. This is somewhat expected, since in both regions production is undertaken under high-temperature conditions. On the other hand, the Southeast and South regions may benefit mildly from climate change.
    - the overall impact of climate change for the projected climate for the period 2040-2069 will result in agricultural profit losses of between 0.8% and 3.7%. The impacts are considerably more severe, however, for the projected climate in 2070-2099, when estimated agricultural profit could be reduced by 26%.
- The analysis suggested that there would be significant climate change impacts on land values although the estimated values varied greatly depending on the sample. Such lack of robustness provides some evidence on the existence of an omitted bias variable in the hedonic model specification, as pointed out by Dêschenes and Greeenstone (2007).
- Generally speaking, the empirical evidence from the above studies indicates that the net impact of climate change on Brazilian agriculture is negative, although there are varying regional consequences. However, these studies present the following important limitations. In the studies by Sanghi et al., and Evensen and Alves:
    - the simulations regarding climate change are based on scenarios of uniform increase in temperature and precipitation and did not use geographically differentiated climate projections.
    - the studies used climate data that is significantly less precise than what is currently available.

  - The studies were based exclusively on Global Climate Models (GCMs) for projections of future climate change impacts.
- Although simulations with GCMs are appropriate tools to address global to sub-continental scale climate change and impacts (Giorgi et al. 2001), the results of long-term multimodel GCM simulations must still be treated with caution as they do not capture the detail required for regional impact assessments, due in part to the coarse resolution (~300 km x 300 km) in the majority of the models used. The concern about the low spatial resolution of GCMs is especially relevant for heterogeneous regions, such as South America, where the distributions of surface variables such as temperature and rainfall are often influenced by local effects of topography, and thermal contrasts, which have a significant effect on the climate (Alves and Marengo, 2009).
- To address country, sub-country and local scale climate change consequences or impacts, higher resolution (e.g. 50 km x 50 km) regional climate models (RCMs) have been employed. It is important to note, however, that although the results for Brazil demonstrate that RCMs show good skill in the simulation of the present-day climate, they still require adjustments and calibration (based on local data and field observations) to the settings used by the model in order to correct for the systematic errors inherited from the GCM form which they were derived and ultimately to produce useful estimates of regional, seasonal to inter-annual climate projections (Marengo et al., 2009b).

2008-2010 Estimates of Climate Change Impacts on Brazilian Agriculture and Land Cover in the Amazon

Several flagship studies were published in the period 2008 to 2010 that potentially improved the biophysical and economic impact estimates highlighted in the work of the previous decade. These studies used combinations of GCMs, RCMs, coupled climate-vegetation models, and ultra high resolution (60 km x 60 km) ensembles of 20 or more GCMs.

The EMBRAPA-UNICAMP study published in 2008

One of the more recent published studies for Brazil (Assad and Pinto, 2008) used an agronomic model approach that evaluated how the current climatic risks, based on projected temperature increases in IPCC's scenarios, may be altered in the coming years due to global warming. The key elements of the study were as follows:

- The climate projections were derived via a Regional Circulation Model (RCM), the HadRM3P regional model developed at the UK's Hadley Centre and part of the regional climate modeling system PRECIS (Providing Regional Climate for Impacts Studies). The model has 19 vertical (atmospheric) levels and a horizontal resolution of 50 km (relevant to most municipality sizes). The RCM was nested in the Hadley Center HadAM3P GCM. The use of coupled GCM and RCM approaches helps to reduce some of the low resolution issues associated with using GCMs alone for regional to sub-national impact assessments.
- 35 crops were assessed in terms of climate risks but nine major crops (cotton, rice, coffee, sugarcane, beans, sunflower, cassava, maize and soybean, as well as pastures and beef cattle) representing 86% of the planted area in Brazil, received special focus.
- Based on a 2007 baseline, climate risk zone mapping in 5,000 municipalities for these crops, the agricultural scenarios in Brazil were simulated for the years 2010 (closest representation to the current conditions), 2020, 2050 and 2070 and two IPCC Third Assessment Report scenarios: A2 the most pessimistic, and B2, slightly more optimistic. In scenario A2, the estimated temperature rise variation is between 2°C and 5.4°C; and in B2, between 1.4ºC and 3.8ºC.

The results showed that:

i. Projected climate change impacts on all currently produced food grains will amount to US$ 4 billion by 2050 with the soybean sector alone accounting for almost 50% of the losses;

ii. Under a pessimistic Climate Change scenario (A2), the best current coffee production ("low risk") areas are expected to shrink by at least 30%, which could result in losses of close to US$ 1 billion by 2050. Interestingly, even under a pessimistic A2 scenario, the area suitable for sugarcane could double by 2020.

The Economic Cost of Adaptation Study published in 2010

The study (Margulis and Dubeux, 2010) used the EMBRAPA 2008 study methods based on a single GCM-RCM combination and the A2 and B2 IPCC Third Assessment Report scenarios. The climate modeling outputs were used to drive a computable general equilibrium (CGE) model to better assess the likely economic impacts due to projected climate change to 2020, 2050, and 2070. The simulations showed that Brazil's GDP in 2050 will approximate US$9.4 trillion and that in the worst case (IPCC Scenario A2) the country could lose about 2.5% every year due to temperature increase impacts. At a discount rate of 1 percent per year, this is equivalent to the loss of one whole year's GDP over the next 40 years. The study's findings also projected a significant reduction in the best crop areas currently characterized by low production risk, for 8 of the 9 major food and export crops (Table 1).

Table 1. Impact of climate change on current "low risk" areas suitable for cultivation (Margulis et al., 2010)

Crops	Variation relative to current productive area (%)					
	SRES B2 (+1.4ºC to +3.8ºC)			SRES A2 (+2°C to +5.4°C)		
	2020	2050	2070	2020	2050	2070
Cotton	-11	-14	-16	-11	-14	-16
Rice	-9	-13	-14	-10	-12	-14
Coffee	-7	-18	-28	-10	-17	-33
Sugar cane	171	147	143	160	139	118
Beans	-4	-10	-13	-4	-10	-13
Sunflower	-14	-17	-18	-14	-16	-18
Cassava	-3	-7	-17	-3	-13	-21
Maize	-12	-15	-17	-12	-15	-17
Soybean	-22	-30	-35	-24	-34	-41

The projected reductions in cultivation area of low risk and associated economic losses to 2050 as summarized by Margulis et al., 2010 are sobering (Table 2 below).

Table 2. Reductions in area of low cropping risk and associated economic losses to 2050 (Margulis et al., 2010) (1 US $ = Br$ 1.8)

Crop	Reduction in "low risk" cultivation area (%)	Scenario A2 Annual Economic loss (Millions Reais)*
Rice	-12	530
Cotton	-14	408
Coffee	-17.5	1,597
Beans	-10	363
Soybean	-32	6,308
Maize	-15	1,511
Sugar cane	145	0

The Margulis and Dubeux (2010) study was a pioneering contribution to the Brazilian knowledgebase on climate change impacts on a range of sectors (agriculture, biodiversity, energy, and hydrological resources) and the macroeconomic growth implications at a national scale. The authors nevertheless identified the following opportunities for improving future climate change economic impact assessments:

1. The use of a suite of GCMs and RCMs for improving the robustness of climate change projections rather than the single GCM and RCM used for the study.
2. The improvement in projected rainfall impacts as there was no consensus in the magnitude and direction of the projected rainfall impacts – a problem that continues to plague most other studies.
3. An explicit treatment of uncertainty and the magnitude and frequency of extreme events
4. Improvement in the data density (crop area, land quality, rainfall, temperature, runoff, infiltration, biodiversity, land cover dynamics) and data accessibility for model parameterization, calibration, and validations.

The "Assessment of the Amazon Dieback" study published in 2010

The "Assessment of the Amazon Dieback" (Vergara et al., 2010) focused on the Amazon forest region and although not directly related to agricultural impacts of climate change, the study provides important insights into the effects of Amazonian climate change-driven forest dynamics and the potential future climate impacts of Amazonian forest dynamics on rainfall (and consequently on agriculture) elsewhere in Brazil. In addition, the study used ultra high resolution climate modeling techniques and the lessons learned can serve as useful reference baselines for other studies wresting with the complexity of modeling climate change and land use dynamics.

Specifically, the study employed a high resolution general circulation model developed by the Meteorological Research Institute of the Japanese Meteorological Agency (MRI/JMA) with a horizontal grid size of about 20 km (Mizuta et al. 2006), offering an unequaled high-resolution capability to project climate in the Amazon basin to mid-century (2035–2049) and to the end of the 21st century (2075–2099). The model projections and analyses were done primarily to assess rainfall, runoff, and extreme events, and to estimate the anticipated impact on stream flows induced by climate change. To further reduce uncertainties in simulated rainfall, 24 GCMs currently in use by the International Panel on Climate Change- IPCC (and included in the Coupled Model Intercomparison Project 3 - CMIP3 archive) were used to develop **Probability Density Functions** (PDFs) for future Amazonian rainfall.

The outputs of the study showed that for Amazonia as a whole, the remaining tropical forest area relative to its original extent is progressively reduced as climate change impacts, deforestation, and fire effects are combined. **Substantial impacts are projected to occur by 2020 and the situation worsens by 2050. The effect of climate change alone would contribute to reduce the extent of the rainforest biome by one third by the end of the century**. In the absence of CO_2 fertilization, a reduction in vegetation carbon is anticipated in most of the geographical domains. It is expected that the Amazon region will experience an intensification of the water cycle with increased occurrence of heavy rainfall and consequent flooding and a lengthening of drought periods. **The projected outcome is a substantial probability of Amazon dieback (conversion of forest to savanna type vegetation).**

Despite the use of very high resolution GCM and a 24 GCM ensemble for rainfall probability density functions, the authors reported **"considerable uncertainty over future rainfall projections. Most of the climate models used, projected substantial changes in rainfall patterns, but these do not coincide: some models project increases, others project decreases, and the spatial pattern of these changes also varies between the models."**

Two important inferences can be drawn from the outputs of the Amazon Dieback study:

(1) The multitude and complexity of interactions among the various drivers of climate change (e.g. increasing CO2 levels, land cover and land use changes, smoke and dust aerosols) are not easily and reliably simulated even with very high resolution and simultaneous comparisons (ensembles) of GCMs. **Recent Brazilian experiences suggest that coupling GCMs and nested RCMs with local scale weather and climate forecast models and verifying projections against local data and observations could help to offset some of the uncertainty and improve reliability of projections.**

(2) Although not a focus of the dieback study, the projected forest to savanna conversion could significantly reduce the amount of water vapor pumped into the atmosphere by the forest (evapotranspiration) and this in turn could impact rainfall patterns and rainfall amounts both within and outside the Amazon basin (Werth and Avisar, 2002). In addition, early results from on-going Brazilian studies to quantify the transport of water vapor ("Flying Rivers") from evapotranspiration in the Amazon to other parts of Brazil suggest that a significant amount of the water in rainfall over central and southern Brazil originates in the Amazon. For example, Van der Ent et al., (2010) estimate that the Río de la Plata basin depends on Amazonian evapotranspiration for 70% of its water resources. If a significant portion of the Amazon converts to a savanna, the amount of evapotranspiration currently contributing to rainfall over central and southern Brazil could show a significant decline and thereby impact rainfall patterns and thus have significant effects on agriculture and hydropower sectors among others.

The potential impacts of climate change on the Amazon forest and the reverse impacts of forest dieback and/or deforestation on climate and especially rainfall highlighted above need to be integrated in on-going and future studies in Brazil and the region as a whole. **The use of regional to local scale models that incorporate climate-vegetation dynamics-aerosol interactions and feedbacks will be important for generating robust simulations and scenario outcomes.**

5. Limitations of the existing climate change impact projections for Brazilian Agriculture

The recent advances in climate change modeling for Brazil have improved the knowledge base (e.g. data assembly and accessibility, coupled and better calibrated GCM and RCM models) on likely climate change impacts across Brazil. Despite these advances, however, there are several methodological constraints that have been identified in the climate change and crop impact estimates used for the most recent published studies. For example:

Skill of the current suite of GCMs for simulating future climate at regional and local scales

A key constraint to the use of GCMs to provide regional climate change scenarios is that of coarse horizontal resolution. Despite the increased availability of supercomputers, Atmosphere–Ocean General Circulation Models (AOGCMs) or GCMs (commonly used abbreviation) are still run at horizontal grid intervals of 100–300 km. While this resolution is sufficient to capture processes and climate statistics down to the sub-continental scale (approximately a few thousand kilometers), it is inadequate for regional, sub-national and local scales, where there is an urgent need for targeted climate change projections to guide adaptation and mitigation investments. Climatically important phenomena occur on much smaller scales. Examples include 'rain' clouds, which are far smaller than a GCM typical grid cell; and the substantial thermal differences between cities and the surrounding countryside. Because all physical properties are averaged over a single grid cell, it is impossible to represent these "sub-grid scale" phenomena explicitly within a model.

To simulate future climate, GCMs require information about future atmospheric composition, which is dependent on a scenario of future emissions of GHGs into the atmosphere. Since future emissions are dependent on future population and economic growth, energy use, technological development and land use change, the <u>uncertainty associated with estimates of future emissions increases over time</u>.

There are numerous future emissions scenarios which are plausible and could be used as the basis for GCM climate change experiments. However, the sheer cost and data storage requirements for running GCMs precludes their use for simulating climate for many emissions scenarios: instead, a small number of plausible emissions futures have been selected by the Intergovernmental Panel on Climate Change (IPCC) and have been used by the international global climate modeling community. In addition, a common approach among several national and international efforts e.g. the European Projects PRUDENCE (Christensen et al. 2007b), STARDEX (Haylock et al. 2006), and the UK Climate Impacts Programme (Hulme et al. 2002) have used one or two GCMs to drive various regional models for dynamically downscaled regional climate projections. Typically, a present day (e.g. 1961–1990) and a future climate (2071–2100) time slices are simulated to project changes in temperature and rainfall.

Interpolation techniques (e.g. Morales et al. 2007) are then used to derive information for shorter time frames e.g. 2020-2050 and to provide future **impacts–vulnerability–adaptation (IVA)** information for policy makers and investment decisions. Hence the focus on 2050 in this report as climate impact projections to 2100 are not only subject to significantly greater uncertainty, but decision and policy makers think and act in sub-decadal time scales and many adaptation investments being made today will have 10-40 year lifespans.

Improving the robustness of projections from available Regional Climate Models (RCMs) for Brazil

There is a consensus that for assessing regional and national scale impacts, the use of RCMs is the most appropriate option. The hypothesis behind the use of high-resolution RCMs is that they can provide meaningful small-scale features over a limited region at affordable computational cost compared to high resolution GCM simulations. The value-added information from RCMs is generally due to both enhanced spatial resolution and better time-based variability. This variability aspect is often a weakness in GCMs.

It is important to note, however, that relying on just one RCM can be problematic because RCMs are also subject to systematic errors. For example, although the RCM that was used for the most recent simulations of climate impact on agriculture (Assad and Pinto, 2008; Margulis and Dubeux, 2010) is consistent with the GCM for projections of the spatial and temporal patterns of the precipitation and temperature and the main features of large-scale circulation, the regional model nevertheless fails to reproduce the observed rainfall amounts and rainfall variability over Central Brazil and underestimates rainfall over the Amazon.

Lack of integration and feedback effects of land cover and land use dynamics, and aerosols when simulating future climate

Aerosols (e.g., smoke from biomass burning, dust from land use/land cover management and change, black carbon from inefficient combustion, and ocean spray) are important drivers of global climate (Rosenfeld et al., 2008, Pielke, 2009). Traveling on wind currents, aerosols move from their source and into the atmosphere, where they become individually encased by water and turn into the droplets that combine to create clouds. Cloud microphysics makes clear that the larger the number of aerosol particles suspended in air the less water in the atmosphere is available for condensation on each individual particle. Under these conditions, a cloud will have a much larger number of small droplets. The smaller the droplets, the longer it will take for a cloud to rain. Aerosol-rich clouds like this spread out by winds, produce less rainfall, and last longer, creating more cloud cover.

However, aerosols also influence clouds through their ability to absorb heat from the sun. The trapped heat causes the atmospheric layer to warm up, and changes the environment in which the cloud develops. The overall result is to make the environment less hospitable for cloud growth. Even the smallest resulting changes in cloud cover can significantly warm or cool the atmosphere and change when and where fresh water will be available in the region.

As a consequence of the complexity and highly dynamic impacts of aerosols on cloud behavior, the climate change impact studies reviewed in this report have largely ignored regional aerosol impacts. The inclusion of a mesoscale meteorological model that has the ability to integrate aerosol effects as a function of land cover and land use changes may enhance the robustness of projections especially for rainfall.

Lack of reliable and sufficiently numerous data points for models.

Alves and Marengo (2009) have cautioned that the scarcity of ground station climate data is a significant constraint when evaluating the performance of climate models. Large areas of tropical South America are "data limited" with respect to the data needs for high quality climate modeling. Currently, **only some** of the meteorological services in South America are performing the major task of locating, quality checking, and digitizing climate data series that are currently in analog form (paper reports and magnetic tapes). In addition, there is a major need for good data on crops, soils, meteorology, land quality and land cover dynamics to validate and better calibrate regional to global scale climate model impacts (Marengo et al., 2008). Any modeling outcomes are only as reliable as their underlying data. Currently the following databases need to be urgently improved:

- Biophysical data—current climate and future scenarios, land use, soil characteristics, ecosystem services
- Socioeconomic data—demand and supply parameters; links to and from agriculture to other sectors; macroeconomic trends

New initiatives are underway for a consolidated hydrometeorological data bank in Amazon countries, organized by the Amazon Cooperation Treaty, and in Southern South America as part of the *Europe-South America Network for Climate Change Assessment and Impact Studies* (CLARIS EU) project. The goal is to provide high quality data for South America for trend analyses that would be useful for the computation of extreme weather events and for the crucial regional inputs to IPCC's Fifth Assessment Report due in 2013. **It is vital that the sub-national to regional data sharing efforts are adequately resourced and supported**.

6. Opportunities to Improve Climate Change and Agricultural Impact Projections in Brazil to 2050

Based on the literature review findings highlighted in the preceding sections, and the emerging outputs of on-going work in Brazil, there are significant opportunities to improve both the quality and the robustness of the currently available projections for climate change impacts on Brazilian agriculture over the next three to four decades. The key areas of opportunity include:

Refining climate change impact projections via global, regional and local scale modeling.

As discussed in section 5.1, the relatively coarse resolutions of GCMs pose limitations to the explicit simulation of mesoscale climate processes and to the representation of topography, land cover, land use, and land–sea distribution.

One option has been to develop regional climate models (RCMs) nested within a GCM to facilitate more robust projections at national to sub-national scales (Christensen et al. 2007). Various national and international programs have used RCMs to help quantify better regional climate change and provide regional climate scenarios for assessing climate change impacts and vulnerability. These have all followed a standard experimental design of using one or two GCMs to drive various regional models from meteorological services and research institutions in the regions to provide dynamically downscaled regional climate projections over Central and South America (Marengo et al., 2009; Soares and Marengo, 2009; Urrutia and Vuille, 2009).

The Regional Climate Change Scenarios for South America – CREAS.

Regional climate change projections for the last half of the twenty-first century have been produced for South America, as part of the CREAS (*Cenarios Regionalizados de Clima Futuro da America do Sul*) regional project. In this on-going work, three RCMs: (1) **Eta for Climate Change Simulations—Eta CCS**—(Pisnichenko and Tarasova 2009, (2) **RegCM3** (Seth and Rojas 2003, Pal et al., 2007) and (3) the public version 3 of the UK Met Office Hadley Centre **HadRM3P** (Jones et al. 2004; Alves and Marengo 2009) were nested within the public version of the atmospheric global model of the UK Met Office Hadley Centre HadAM3P (Marengo and Ambrizzi 2006; Marengo 2009). Figure 1 below presents a conceptual framework for the CREAS approach to generating high resolution RCMs for regional and sectoral impact assessments.

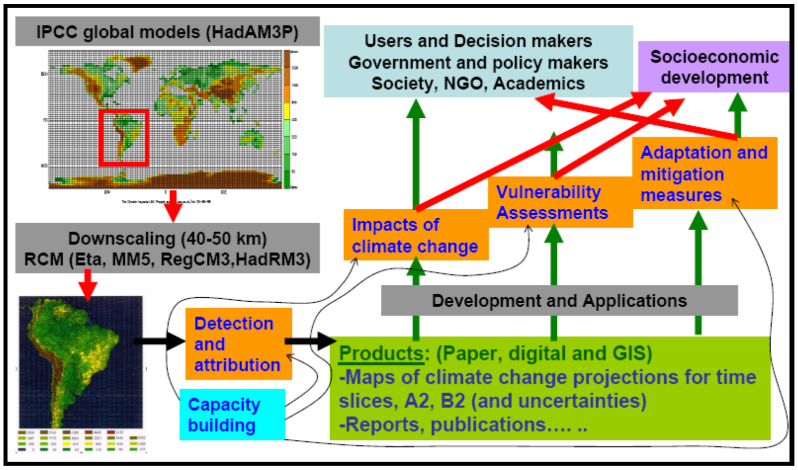
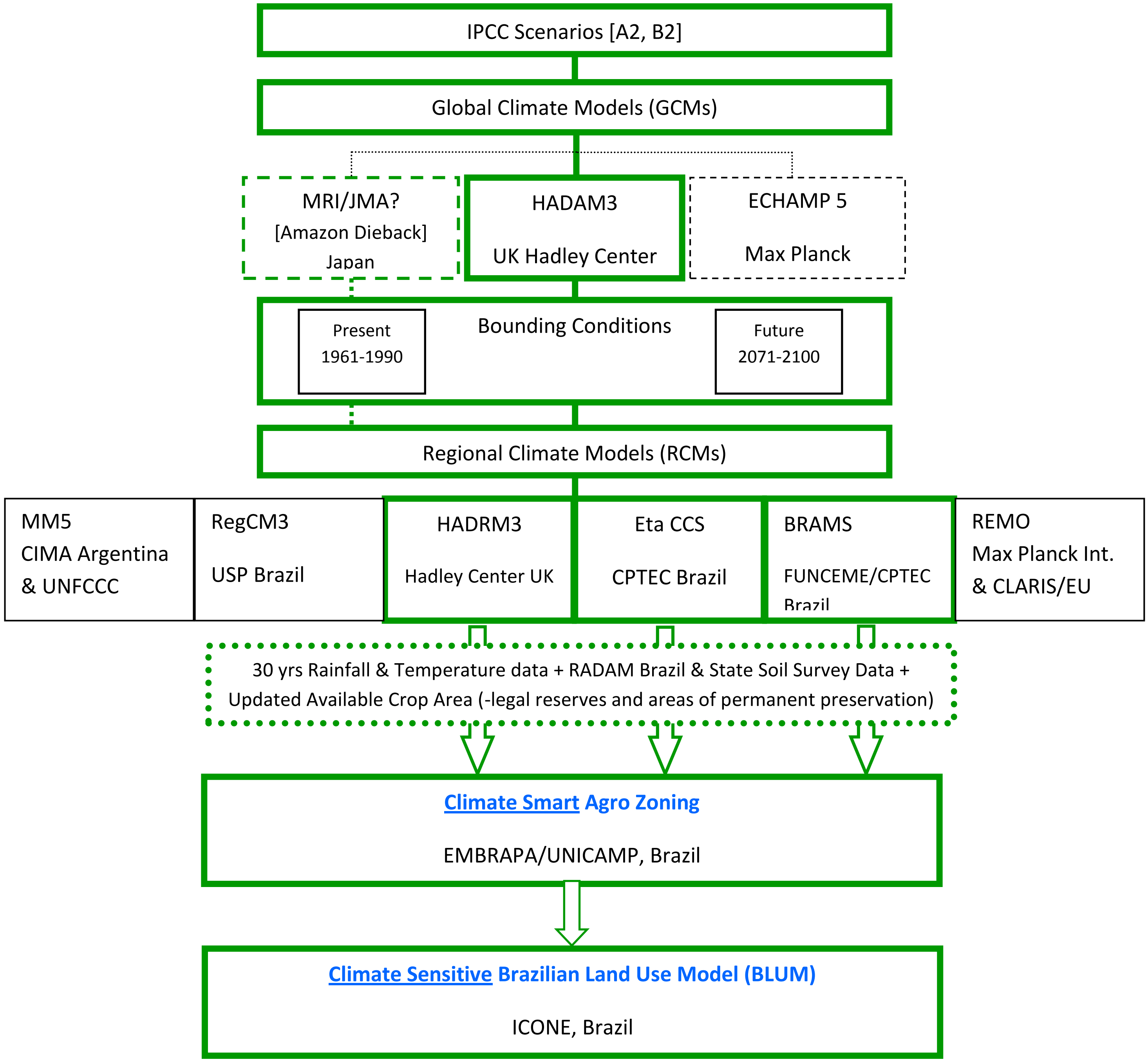


Figure 1. Conceptual Framework of the CREAS project for the regionalization of future climate change scenarios in South America and impact assessment applications (Marengo 2004).

The CREAS effort aims to provide high resolution climate change scenarios in South America for raising awareness among government and policy makers in assessing climate change impact, vulnerability and in designing adaptation measures. The rationale for the choice of global model HadAM3P is because (a) the model adequately reproduces the seasonal distribution and variability of rainfall over large areas of South America, even though some systematic errors persist, (b) the model has been investigated quite thoroughly in various regions in previous downscaling experiences.

The **Coupled Model Intercomparison Project** Phase 5 (CMIP5) is also assisting groups in South America to facilitate the evaluation of existing models and to develop new models with higher resolution and with representation of the carbon cycle to provide near-term (decades) and long-term projections (century or longer.) These on-going regional efforts notwithstanding, Brazil is pioneering the adaptation of a mesoscale (less than 50 km gridscale) regional atmospheric meterological model to provide more robust and reliable inputs to the GCM and RCM modeling efforts (Freitas et al., 2009; Longo et al., 2010). The on-going CREAS program provides an excellent opportunity for Brazil to harness and supplement the outputs of the CREAS work for South America and to develop a **new generation assessment of climate change impacts** on Brazilian agriculture to 2050. Figure 2 below highlights a conceptual framework for nesting the agricultural impacts assessments within the on-going CREAS program for a "bottom up" approach to calibrate and validate the RCM projections while also providing robust projections for agricultural adaptation priorities and investments.

Figure 2. Conceptual Framework for a State of the Art Assessment of Climate Change Impacts on Brazilian Agriculture (**outlined in green**) in the context of the regional program (CREAS)



The Brazilian developments on Regional Atmospheric Modeling System (BRAMS) and the Coupled Aerosol-Tracer Transport model (CATT-BRAMS)

Because of the aerosol impacts on clouds and precipitation, Brazil is refining the BRAMS mesoscale meteorological model used in weather and climatology forecasting that is currently **in use by several universities and research centers in Brazil**. BRAMS is based on the Regional Atmospheric Modeling System (RAMS), (Walko et al., 2000) and integrates several new functions dedicated to tropical and sub-tropical regions. The BRAMS system is able to incorporate aerosol effects on radiation balance and the hydrological cycle thereby helping to overcome a significant source of inconsistencies in the rainfall projections. The model is equipped with a multiple grid nesting scheme which allows the model equations to be solved simultaneously on any number of interacting computational meshes of differing spatial resolution. It has a complex set of packages to simulate processes such as radiative transfer, surface-air water, heat and momentum exchanges, turbulent planetary boundary layer transport, and cloud microphysics.

BRAMS has also high resolution and updated topography, land use, soil type and normalized difference vegetative index (NDVI) data sets. The biophysical parameters maximum stomatal conductivity, leaf area index, albedo, roughness, biomass and soil heat capacity, soil porosity, hydraulic conductivity and moisture potential at saturation and root distribution associated with the vegetation and soil parameterizations of RAMS were adapted for tropical and sub-tropical biomes and soils, using observations or estimations obtained in recent field campaigns, mostly associated with the LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia – www.lba.cptec.inpe.br) program.

Coupled to BRAMS is the Coupled Aerosol-Tracer Transport model (CATT, Freitas et al., 2009, Longo et al., 2010). CATT is a numerical system designed to simulate and study the transport and processes associated with biogenic, biomass burning and anthropogenic emissions (trace gases and aerosols). These features make BRAMS system able to incorporate the aerosol effects on radiation balance and regional hydrological cycles. This modeling system is operational at CPTEC/INPE to provide weather and air quality forecast on a daily basis (meioambiente.cptec.inpe.br). The CATT-BRAMS modeling system was used in the Brazil Low-Carbon study (de Gouvello, 2010) to provide the impact of the land-use/land-cover changes and the smoke aerosols from deforestation on fires on the thermodynamic properties of atmosphere and hydrological cycles over Brazil and neighboring areas (see BRAMs sub regional map below).

The Brazilian National Water Agency (ANA) and the National Institute of Meteorology (INMET) meteorological database.

The Brazilian National Water Agency (ANA) and the National Institute of Meteorology (INMET) have daily rainfall and temperature data spanning around 30 years (see Figure 4 below for distribution of the met stations). Few developing countries have the quality (in terms of reliability and distribution of data points) as well long term continuous data sets on rainfall and temperature. These data sets are critical for both calibrating and validating the climate models.

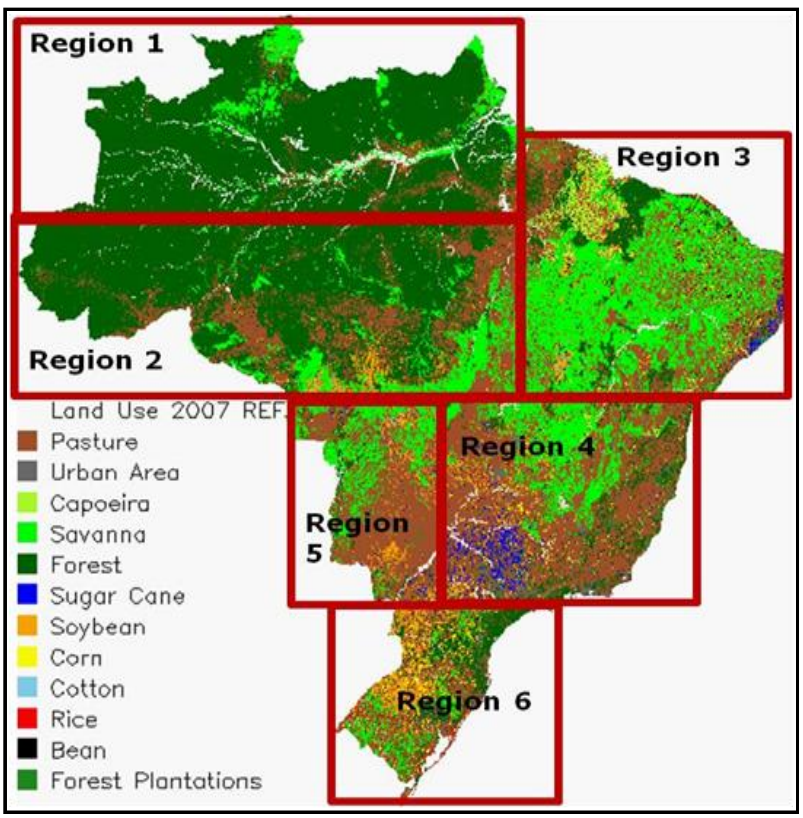


Figure 3. The BRAMS land-use map for the analysis of model simulation results. (Freitas et al., 2009)

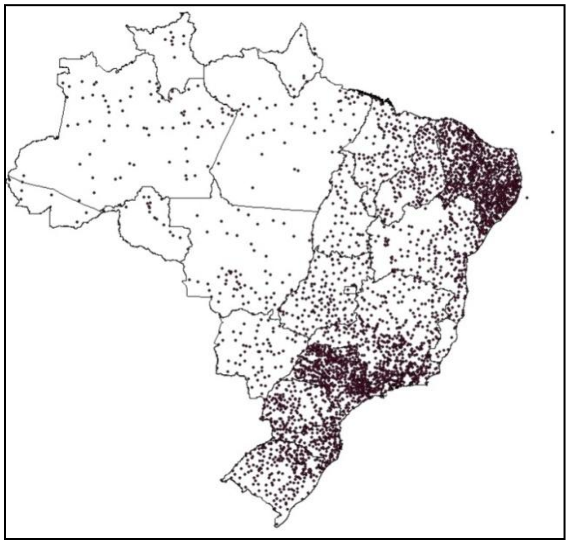


Figure 4. Distribution of the ANA meteorological stations

Comparison of BRAMS model simulation with ANA Observations

Overall, the BRAMS model is able to replicate the seasonal cycle of precipitation over Brazil with good skill across most of regions. Figure 5 below, depicts monthly mean precipitation simulated by BRAMS and compared against the ANA dataset for the 6 regions delimited on the map (Figure 3). For regions 1 and 2 the projection skill is very good, while for regions 3, 4 and 5 it is satisfactory. Region 6 is where the model underestimates rainfall. In Figure 5 below, the red and blue are model results using low and reference carbon scenarios, respectively. The green color is the data from the ANA meteorological stations network.

The "Assessment of the Amazon Dieback" study projects with a high likelihood that a sizeable amount of the current Amazonian rainforest will be converted to a savanna by 2050. Current research suggests that such a reduction in forest area and the evapotranspiration function of the Amazon could significantly alter rainfall over central and southern parts of Brazil, Uruguay and northern Argentina. In addition, if as predicted, the Amazon basin gets drier, the incidence of fires is likely to increase and aerosols generated via the burning of the vegetation could also impact rainfall both close to and at some distance away from the fires. These major but uncertain impacts highlight the importance of including aerosols and land cover changes when modeling climate change impacts. **Adding an improved rainfall simulation capability via CATT-BRAMS for Brazil's sub-regions 1-5 (see Figure 3) to the GCM and RCM projections could result in <u>a significant improvement over existing RCM</u>** approaches that have demonstrated low skill in regions 4 and 5 in Figure 3 above.

In addition, the rainfall probability density functions (PDFs) generated via ultra high resolution GCM used in the Amazon Dieback study, could be used to further compare the outputs from the suite of RCMs proposed above. The comparison will need a careful evaluation of the assumptions and boundary conditions of the ultra high resolution GCM.

Figure 5: BRAMS precipitation simulation for the 6 regions and comparison with the Brazilian National Water Agency (ANA) data. The unit is millimeter (mm) of liquid

water. This figure shows monthly mean and the standard deviation (vertical bars) over the 6 regions delimited on the BRAMS map (Figure 3). The red and blue columns are model results using low and reference carbon scenarios, respectively. The green column is the data from the observational network.

Agro Zoning Model (EMBRAPA/UNICAMP)

The Agro Climatic Risk and Vulnerability Zoning Model (Assad and Pinto, 2008) developed by EMBRAPA and UNICAMP currently underpins all financial lending to the agricultural sector in Brazil. The Central Bank of Brazil requires mandatory agricultural zoning throughout the country for access to rural credit and the EMBRAPA/UNICAMP model indicates "what, where and when" to plant a crop variety according to a zoning system. Three types of zoning are defined:

a. **Agro-ecological** - uses the data base of soil, topography, climate, environmental law.

b. **Agroclimatic** – based simply on climate information without evaluating the potential crop risk.

c. **Climatic** - uses climate, soil, and crop culture by assessing the risk analysis taking into account mainly the information about rainfall, temperature and water balance of derivatives that indicate the deficiencies and surpluses of water for agricultural crops.

Agro Climatic Zoning integrates crop growth models with refined climate simulations described above and uses a crop risk matrix based on a *state of the art* soil and land quality typology, weather station data, crop water needs, and crop phenology.

The Water Needs Index (ISNA) of the Agro Climatic Zoning Approach

The basis for the zoning is a crop water supply (Vulnerability) index based on the ratio of actual to maximum evapotranspiration per crop is used to derive a crop risk and suitability zoning. The risk zones set for each municipality in the country indicate which of the 9 major food and export crops that are at least 80 percent likely to provide an economically acceptable harvest. Each crop or variety has a pre-defined set of climate conditions based on long term research and field observations. The complete length of a crop cycle is divided into four phenological (growth) phases (Initial Development, Vegetative Growth, Reproduction and Maturity) where the third phase is normally considered as critical mainly due to the high sensitivity of flowering to dry spells and/or high temperatures. The length of each phenological phase is defined by degree-days or heat units. The incidence of extreme temperatures can cause the loss of production due to flower abortion in the case of high temperatures or frost by low temperatures. In addition, each municipality has a basic soil classification and map system.

Soil Classification and Map of the Agro Zoning Approach.

The soils are classified into three types - sandy, medium and clayey – or with low, medium or high capacity for water retention capacity respectively. The crop coefficient (Kc) is defined according to the typical soil and is a measure of water consumption for each phase of the crop development. The ISNA values are based on the rainfall stations and estimated by a specific sowing period produced by the water balance for a fixed combination of soil type and phenological cycle.

Identifying cropping areas that are less vulnerable to climate change impacts

Based on temperature effects to 2020, 2030 and 2050 are identified and the area quantified. The principles for determining climate risk are as follows:

a. Areas with the least risk are those that do not have a soil water deficiency that results in good germination as well as flowering and grain filling. This risk should not exceed 20%. To characterize the risk, agro meteorological indices are developed by calculating evapotranspiration of the crops.
b. Using the above criteria, it is possible to assess the risk of planting any crop within Brazil. In addition to soil moisture, the projected temperatures for 2020, 2030, and 2050 are also used to refine risk assessments.
c. The major advance of the above approach relative to the existing methods is that each low risk agroecological zones are also being screened for soil types, steep slopes, legal reserve, riparian zones (APPs), indigenous areas, and

protected areas thereby greatly increasing the precision of the estimates of crop productivity and climate impacts at national, state, and municipal levels.

d. For current modeling efforts, the baseline for the crops planted, area planted, and value of production is the 2008 IBGE survey.

The Brazilian Land Use Model (BLUM) – Agricultural Productivity, Land Use Change and Projected Climate Change to 2050.

The Brazilian Land Use Model (BLUM) is a partial equilibrium econometric model developed by the Institute for International Trade Negotiations (ICONE) and used in the Brazil Low-Carbon Study (de Gouvello, 2010) to measure the impacts of climate change on the performance of the agricultural sector (**see Appendix 1, for full description**). The outputs from the **Climate-Smart Agro Zoning modeling platform** described in the previous sections can be harnessed to yield a climate-sensitive BLUM for the following analytical outputs (Figure 6):

a. Climate change induced changes in supply and demand of agricultural products at a national level.
b. Changes in the distribution of land use and production within Brazilian territory (at a micro-regional level) for a given supply and demand scenarios.
c. Economic effects on agricultural production, prices and profitability
d. Feedback Effect of Climate Change induced changes distribution of land use, and economic effects on Brazil's GHG Mitigation Targets to 2020

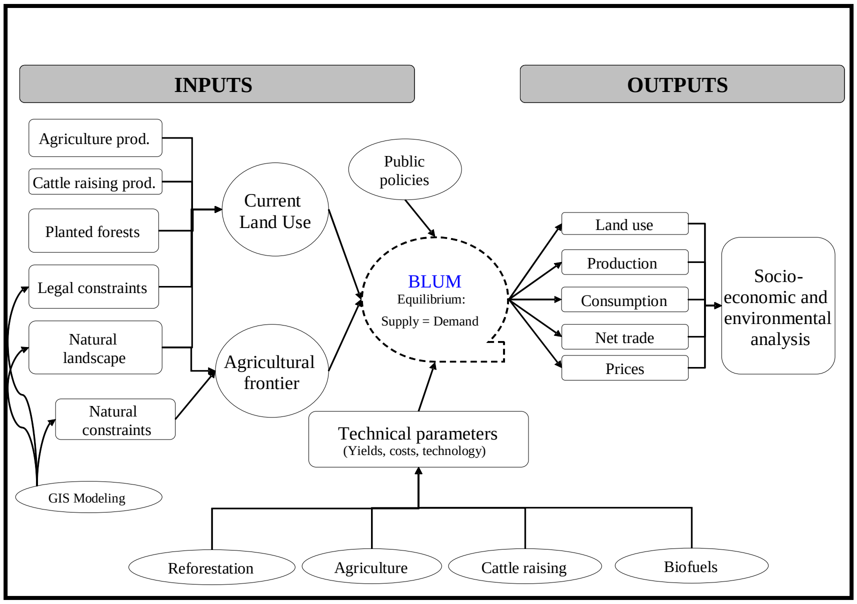


Figure 6. Conceptual Framework of the Brazilian Land Use Model (BLUM)

Source: ICONE.

Coupling a Climate-Smart Agro Zoning approach with BLUM

As depicted in Figure 6, the key outputs of BLUM include land allocation (hectares) and production (tons) for soybean, corn, cotton, dry beans, sugarcane, rice, wheat, barley and pastures distributed by the 550 IBGE micro-regions. The EMBRAPA/UNICAMP Agro Zoning model generates information on potential production (by crop and rainfall risk) that serves as an input driver for BLUM, in conjunction with other physical and economic variables, to generate the distribution of land demand. BLUM can provide changes in the distribution of future production and planted area (or allocated area in the case of pastures) as a function of the Ago Zone model's projections of crop suitability potential (or maximum crop production) for all micro-regions (municipalities). Crop models that derive future yield scenarios based on current yields and current agro (suitability) zones can be adjusted to integrate technological advances (e.g. new adapted varieties, land and water management) and to generate updated scenarios for assessing adaptation options and responses.

Climate change induced changes in supply and demand of agricultural products at a national level

Changes in prices and profitability will promote changes in supply and demand, thus affecting also the decision of the consumers, and in the economic result of each sector, which will be evaluated through changes in the value of production (production multiplied by prices). Changes in climate and its consequences in yields and costs will induce to shifts of the supply curve of the agricultural products, promoting new market equilibriums and, consequently, establishing new levels of prices and consumption.

Economic effects on agricultural production and profitability

Agricultural profitability will be affected by changes in yields and production costs and, consequently, that will determine different choices set for agricultural products (crops and livestock) under new climate scenarios. The interaction between BLUM and the Agro Climatic Model is that the information for potential production (or suitability potential by crop) will be input onto BLUM as constraints that will drive, in conjunction with other physical and economic variables, the distribution of land demand. BLUM will provide changes in the distribution of production and planted area (or allocated area in the case of pastures) in the future according to the information provided by the agricultural model and suitability potential. In addition, the established climate scenarios will be translated into changes on potential yields and production costs that will be exogenously inserted in BLUM in order to assess how the agricultural production will respond to changes in profitability.

Changes in the distribution of land use and production within Brazilian territory for given supply and demand scenarios.

Given that impacts of climate change will not be homogenous within the Brazilian territory, the distribution of land use and production will also be affected under changing climate. The allocation of land and production (given that production is a function of land multiplied by yields) will be established for the 550 IBGE micro-regions, considering the potential production and yields impacts constraints using the Agro Climatic Model results for different climate change scenarios.

Analysis of the Feedback Effect of Climate Change on Brazil's GHG Mitigation Targets

The climate change projections and agricultural production impacts will plausibly result in a different level of carbon sequestration and emissions than the baseline scenario for Brazil. The proposed opportunities for enhanced climate change impact and agricultural productivity assessments at regional to local levels can provide inputs for a partial assessment of how the shifts in productivity and land use allocation between livestock/pasture, crop agriculture and forests, would affect the feasibility of meeting Brazil's stated GHG mitigation targets. The changes in carbon flows could be assessed using the outputs generated by the BLUM model in the previous stage: the projected changes in crop yields, crop production patterns, livestock production, and the incremental land use change that may occur as a result of the additional pressures on the cerrado and forest areas under nationally accepted climate scenarios as informed by the on-going CREAS efforts or regional scale modeling.

7. Conclusions

This report highlights the work required to provide more robust and quantitative information on how and where the drivers of agricultural production growth are more likely to be impacted by changing climate. The goal is to empower policy makers to ensure that the farming sector has access to the knowledge and resources to undertake the adaptation that will be necessary to cope with unavoidable climate changes while simultaneously contributing to mitigating GHG emissions.

<u>Four key integrated and linked</u> interventions that are needed in the short term to significantly improve currently available assessments of climate change impact on Brazilian agriculture and to guide policy makers with the priorities and phasing of needed investments.

1. **Reduce the "climate data deficiency" in all the sub-regions in Brazil** (see map on pg 27) as well as at a regional scale. The lack of data or access to long term data that is currently not in digital form is a MAJOR constraint to (a) developing robust and accurate

modeling projections, and (b) calibrating and validating new generation models. On-going and emerging data assembly, data security, and data access efforts need support.

2. **Refine climate change projections via coupling global, regional and local scale modeling**.
   a. Harness the emerging Global and Regional (GCM + 3 RCM) climate modeling platforms being developed and tested in Brazil
   b. Integrate the best GCM and RCMs that are available, the state of the art Brazilian developments in Regional Atmospheric Model (BRAMS) that incorporates aerosol and land cover/land use feedbacks for much improved local weather and climate (especially rainfall) projections.
3. **Couple the Enhanced GCM and RCM suite of models described above with the EMBRAPA /UNICAMP Agro Zoning model and** recently available highly disaggregated land (soil) quality data at municipal level and the meteorological data from all calibrated and validated ground stations of the Brazilian Water Agency (ANA) for a **Climate-Smart Agro Zoning Model** that can be readily updated as more refined climate projections become available.
4. **Couple the Brazilian Land Use Model (BLUM) with state of the art outputs from 1, 2, and 3 (above)** for an improved **Climate-Sensitive BLUM** to assess:
   a. Climate change induced changes in supply and demand of agricultural products at a national level
   b. Changes on the distribution of land use and production within Brazilian territory for given supply and demand scenarios.
   c. Economic effects on agricultural production and profitability

The need for improved and integrated climate change impact assessments is especially urgent for the agricultural sector. A recent survey carried out by the Brazilian Enterprise for Agriculture and Animal Research (EMBRAPA), revealed that even with advanced breeding techniques, it takes approximately 10 years of R&D and costs between six to seven million US dollars to obtain a new heat and/or drought tolerant cultivar. The literature review synthesis from this report suggests that within the next decade, Brazilian agriculture will already be dealing with a significant level of climate induced crop and livestock productivity stresses.

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9. Appendix 1 - The Brazilian Land Use Model (BLUM)

The Institute for International Trade Negotiations (ICONE) in partnership with the Food and Agricultural Policy Research Institute (FAPRI)[1] developed an economic model named Brazilian Land Use Model (BLUM) that aims to analyze and project the dynamic of the main agricultural sectors in Brazil. The model comprises the following products: soybeans, corn (first and second crop), cotton, rice, dry beans (first and second crop), sugarcane, wheat, barley, dairy, and livestock sectors (beef, broiler, eggs and pork). Commercial forests are considered as exogenous projections. In conjunction, these activities were responsible for 95 percent of total area used for agricultural production in 2008.[2] Although second and winter crops, such as corn, dry beans and wheat do not generate additional need for land (they are smaller and planted in the same place of first season crops), their production is accounted in the national supply.

Land allocation for agricultural and livestock is calculated for six regions,[3] as showed in Figure 1 below:

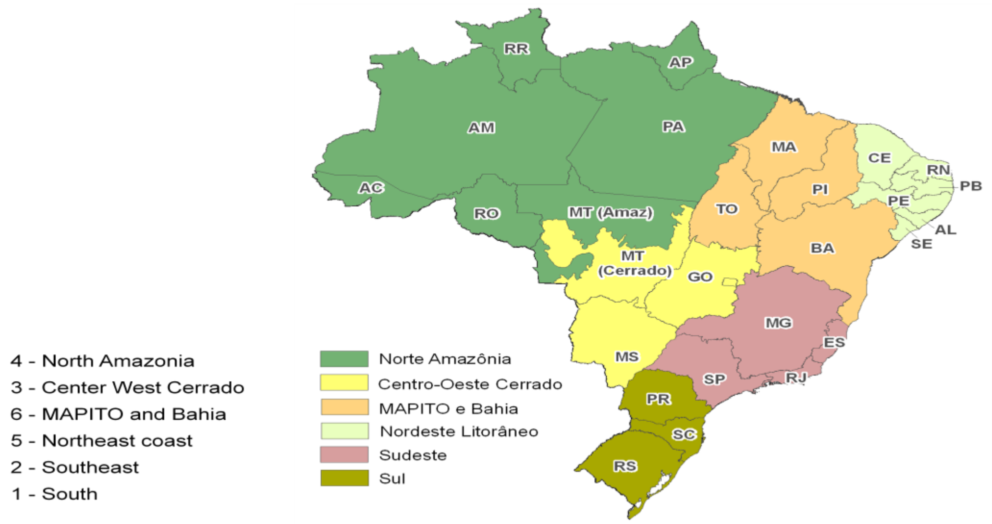
- Region 1: South (states of Paraná, Santa Catarina, Rio Grande do Sul);
- Region 2: Southeast (states of São Paulo, Rio de Janeiro, Espírito Santo, Minas Gerais);
- Region 3: Center-West Cerrado (states of Mato Grosso do Sul, Goiás and part of the state of Mato Grosso inside the biomes Cerrado and Pantanal);
- Region 4: North Amazon (part of the state of Mato Grosso inside the Amazon biome, Amazonas, Pará, Acre, Amapá, Rondônia, and Roraima);
- Region 5: Northeast Coast (Alagoas, Ceará, Paraíba, Pernambuco, Rio Grande do Norte, and Sergipe);
- Region 6: MAPITO and Bahia (Maranhão, Piauí, Tocantins, and Bahia).

[1] FAPRI is a joint effort of Iowa State University's Center for Agricultural and Rural Development (CARD) and the University of Missouri-Columbia. For purposes of the work in this report, ICONE worked with the CARD/FAPRI team at Iowa State University.

[2] When we refer to agricultural area, we consider crops and livestock.

[3] The main criteria to divide the regions were agricultural production homogeneity and individualization of biomes with especial relevance for conservation.

Figure 1 – Map of the *Brazilian Land Use Model* – BLUM regions



Source: Based on Instituto Brasileiro de Geografia e Estatística (IBGE)'s analysis. Developed by ICONE and the Federal University of Minas Gerais (UFMG).

(a) MODEL STRUCTURE

BLUM is a multi-market, partial equilibrium economic model and comprises two general sections*: supply and demand* and *land use*. These sections are interdependent through national production of each activity and are described on the two following sub-sections. The third sub-section explains how the model is solved and what kind of results is generated.

In the supply and demand section, the demand is projected in a national level and is formed by domestic demand, net trade (exports minus imports) and final stocks (which is not considered for dairy and livestock sectors and sugarcane),[4] which respond to prices and to exogenous variables such as gross domestic product (GDP), population and exchange rate. The supply is formed by national production (which is regionally projected) and initial stocks (again considered only for grains and final products of sugarcane) and responds to expected profitability of each commodity, which depends on costs, prices and yields.

[4] In the case of sugarcane, stocks are only for its final products, sugar and ethanol. The model does not include, as a source of income for the sugarcane, other various byproducts of sugarcane production such as bagasse (whether used for electricity generation or animal feed).

Annual productions in each region, comes from the product of land allocated and yields. The national production is the sum of all regions production, in addition with initial stocks. This relationship guarantees the interaction between the sections of *land use* and *supply and demand* in the model, considering that the following identity must be satisfied:

Beginning stock + *Production* + *Imports* = *Ending Stock* + *Domestic Consumption* + *Exports*

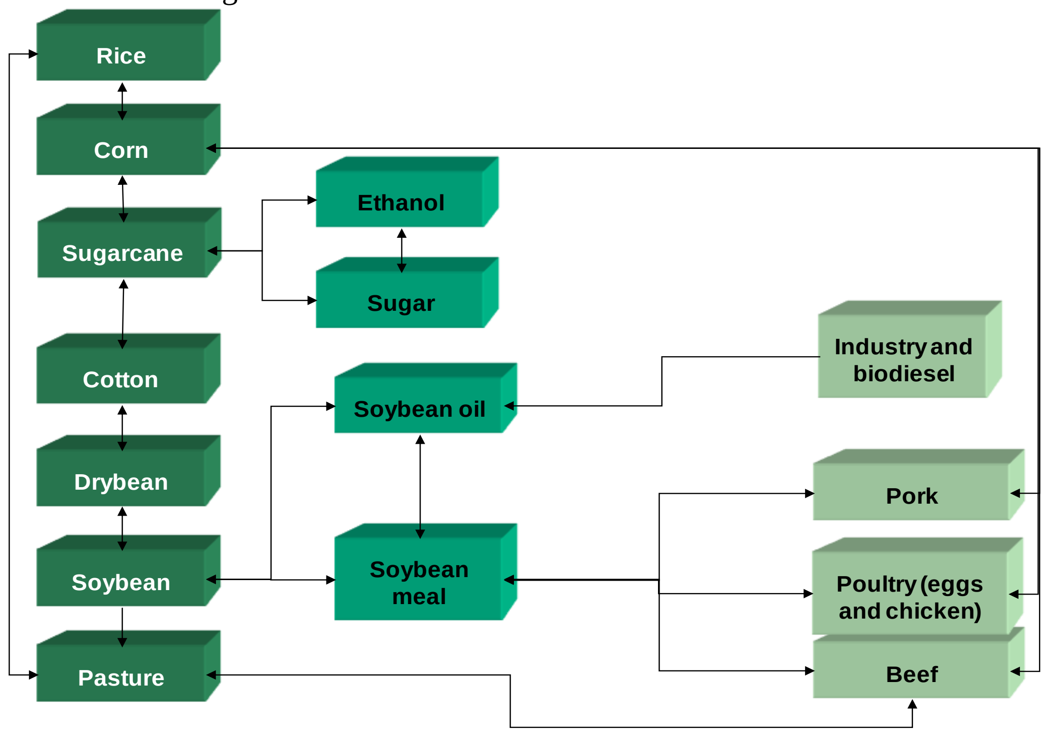
or, considering that *Net Trade* = *Exports* - *Imports:*

Beginning stock + *Production* = *Ending Stock* + *Domestic Consumption* + *Net Trade*

BLUM also takes into account interactions among the analyzed sectors (Figure 2 below), and among one product and its sub-products. For example, the interaction between grains and livestock sectors is the feed consumption (basically corn and soybean meal) that comes from the supply of meat, milk and eggs, which is one component of the domestic demand of corn and soybeans. In the case of soybean complex, soybean meal and soybean oil are components of the domestic demand of soybeans and are determined by crush demand. Similarly, ethanol and sugar are the components of sugarcane demand.

The land use dynamics is divided in two effects: *competition* and *scale*. Intuitively, competition effect represents how the different activities compete for land for a given amount of available land, and the scale effect refers to the way that the competition among different activities generates the need for additional land allocation. This need is accommodated by the expansion of total agricultural area over natural vegetation.

Figure 2 – Interactions among BLUM sectors



Source: ICONE

The competition effect follows the methodology proposed by Holt (1999), and consists on a system of equations that allocates a share of agricultural area to each crop and pasture in each region as a function of its own and cross price-profitability. It establishes that, for a given amount of agricultural land, an increase of the own profitability of one activity will increase the share of area dedicated to this activity. On the other hand, an increase on profitability of a competing activity reduces the share of area of the first activity. In Holt (1999), total agricultural area is exogenously determined, while in the BLUM it is endogenously determined in the scale effect, as will be explored later on. The regularity conditions (homogeneity, symmetry and adding up) are imposed so that the elasticity matrices (and associated coefficients) are theoretically consistent. For any set of these coefficients we calculate own and cross impacts and competition among activities. Results of BLUM then allow us to calculate not only land allocation but also land use changes. In other words, the conditions allow the identification of the area exchanged, activity by activity, considering the amount of allocated total agricultural area.[5]

In order to guarantee coherence on the cited conditions, pasture area is regionally and endogenously determined but modeled as the residual of total agricultural area minus crops area. In the context of the Brazilian agriculture, it is particularly relevant to project pasture both endogenously and regionally.

Although the competition among activities may represent the situation of regions where agricultural area is stable and near to its available potential, this is an insufficient analysis for Brazil. Recent Brazilian agricultural history showed that crops, commercial forests and pasture in conjunction respond to market incentives by contributing to an expansion of total area allocated to agriculture. This effect is captured in the scale section in the BLUM. This methodological improvement is essential to adjust the model skills to the specific reality of Brazilian agricultural land use dynamics.

The *scale effect* refers to equations that define how the returns of agricultural activities determine the total land allocated to agricultural production. More precisely, total land allocated to agriculture is a share of total area available to agriculture, and this share responds to changes in average return of agriculture. For each region, total land allocated to agricultural production is projected as:

$$Agland = f(Avg\,\mathrm{Re}\,turn) * A,$$

where $Agland$ is total land allocated to agricultural production, $Avg\,\mathrm{Re}\,turn$ is the average agricultural return of the region, A is the total available land (that was estimated geospatial information), $f(.)$ is a constant elasticity function with results in the interval [0,1] for reasonable values of average return.

Scale and competition effects are not independent, though. In conjunction, they are the two components of the own return elasticities of each activity. Considering a *ceteris paribus* condition, the increase on profitability of one activity has three effects: increases total

[5] Section 2.2.2.1 explores total land availability in Brazil used in the BLUM.

agricultural area (through average return), increases its own share of agricultural area and, thereby, reduces the share of agricultural area of other activities. For competing crops, cross effects of profitability on area are negative.

As mentioned, the own elasticities of each crop are the sum of competition and scale elasticities. At the same time, regional elasticity of land use with respect to total agricultural returns (total *Agland* elasticity) is the sum of scale elasticities of each activity. So, competition elasticities can be directly calculated after total *Agland* elasticity and total own elasticities were obtained through econometric analysis and literature review. The option to estimate area response to return, instead of price, is supported by several studies.[6] The process to obtain proper elasticities was comprehensively discussed between ICONE and CARD/FAPRI staffs until the final values were agreed.

Own return elasticity was mainly estimated by time series econometric analysis, using official data for area, namely from Brazil's Agriculture Ministry's National Supply Agency (CONAB) and the Brazilian Institute of Geography and Statistics (IBGE), and annual profitability calculated by ICONE. Literature review and experts were also consulted for qualitative ranking of elasticities. Table 1 reports the own area-return elasticities (averaged by area) used in BLUM for this paper for crops and pasture. In the second row of the table, the elasticities used for Brazil in FAPRI international model are also reported, for comparison.[7]

[6] See BRIDGES & TENKORANG (2009).
[7] Elasticities used in FAPRI international model are available at: http://www.fapri.iastate.edu/tools/elasticity.aspx

Table 1: Average own return elasticities for Brazil used for first crops and pasture

Activity	Corn 1st crop	Soybeans	Cotton	Rice	Dry beans 1st crop	Sugarcane	Pasture
BLUM elasticities	0.20	0.45	0.24	0.14	0.10	0.40	0.11
FAPRI elasticities	0.42	0.34	NA	0.07*	NA	0.20*	NA

(*) indicates production elasticity instead of area elasticity

Source: ICONE, based on ICONE and CARD/FAPRI joint work

The inference of regional total *Agland* elasticity was based on 1996 and 2006 Census data (with corrections on pasture area) for area allocated to agriculture; geospatial data for land available, and estimated average return estimated by ICONE. Values of regional *Agland* elasticities are presented in Table 2 below.

Table 2: Estimated regional elasticity of land allocated to agriculture with respect to total agricultural returns

Region	South	Southeast	Center-West Cerrado	North Amazon	Northeast	MAPITO and Bahia	Brazil
Agland elasticity	0.06	0.07	0.18	0.25	0.01	0.10	0.13

Source: ICONE, based on ICONE and FAPRI joint work

Specific geospatial analysis was conducted in order to estimate total potential land available for agricultural production for each BLUM region, which enters as an input for the scale effect section in the model. Two databases are available: (i) one developed by UFMG in the context of the Brazil Low Carbon Study and integrated to SIMBRASIL model [8] and (ii) a second one

[8] *Using the SIM Brazil to allocate land use changes, projected by the BLUM, to smaller georgaphic areas and by year*. SIM Brazil, applied to the estimates generated by the BLUM model, can be used to create favorability maps

provided by the Agricultural Land Use and Expansion Model – Brazil (AgLUE-BR).[9] For restricting agricultural land use expansion physical (soil, climate and slope) and legal (environmental legislation applicable to private farmland and public conservation parks) were also spatially considered. The incorporation of land availability as a build-in constraint in the BLUM indicates how the model will be adapted for the objectives of this project. Potential production and yields to be provided by EMBRAPA-CNPTIA models will also be incorporated as constraints, following procedures similar to the ones used to incorporate land availability. Given that BLUM will generate land allocation and production at the micro-regional level, data from EMBRAPA-CNPTIA will be provided on the same regional unit.

(b) MODEL SOLUTION AND ITS RESULTS

As explained earlier, national supply and demand and regional land use of each product respond to price. Consequently, for a given year, equilibrium is obtained by finding a vector of prices that solves all markets simultaneously. Year by year, a sequence of price vectors are found, which allows following the market trajectory along time. The outputs of the model are: regional land use and change, national production, prices, consumption and net trade. A synthesis of the model is described in Figure 3,

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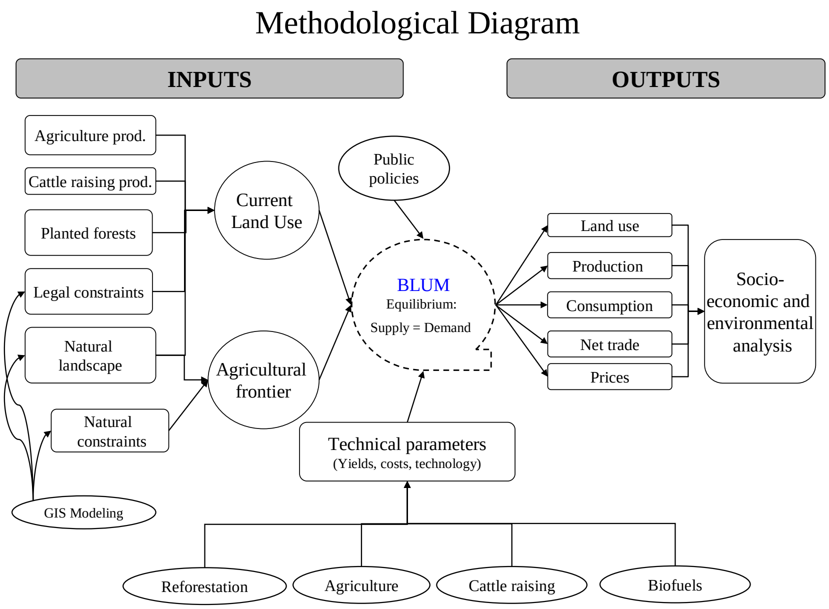
for crop allocation on the basis of the following criteria: agricultural aptitude, distance to roads, urban attraction, cost of trasport to ports, declivity, and distance to converted areas. These estimates can be generated by the SIM Brazil model for the IBGE micro-regions, and at an even higher level of resolution—for 1 km2 pixels. When available land in a given micro-region is insufficient, SIM Brazil reallocates the distribution of agricultural production to neighboring regions, thereby creating a spillover effect and providing estimates of agricultural expansion and land land use change.

[9] AgLUE-BR is in final stage of revision for publication. After publication the original databases used in the model will be made available for public access.

Figure 3. Methodological diagram of the Brazilian Land Use Model (BLUM)



Source: ICONE