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Climate Change Impacts and Efficient Adaptation Options in the Bolivian Agriculture:

From Crop Models to Integrated Assessments.

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“Choose a job you love,

and you will never have to work a day in your life”

Confucius

Contents

Tables

General Introduction

The agricultural sector could be one of the most vulnerable economic sectors to climate change impacts during the coming decades. Climate change impacts are related to change in the growth period, agricultural yields, extreme weather events, change in temperature and precipitation patterns, among others. All these impacts will have consequences on the agricultural production (Bates et al., 2008). Given the lack of substantial studies for climate change impacts on agriculture in Bolivia, this thesis dissertation develops an analysis and quantification of climatic change impacts and adaptation options using different model techniques, both, bottom-up and top-down, and in the last chapter an integrated assessment is developed. Agricultural models simulate crop behavior and production systems allowing for an ex-ante evaluation of policy intervention. The use of agricultural models varies at different scales, from studies at farm level, to studies of the whole agricultural sector and the economy. Top-down models evaluate the system from aggregate economic variables, whereas bottom-up models consider more detailed technological options or project-specific characteristics, both having advantages and drawbacks.

The thesis consists of 4 main research chapters using different techniques to quantify Climate Change impacts and adaptation in agriculture, which will be submitted as independent papers in peer reviewed journals (Environmental Modeling and Software, Global Environmental Change and Ecological Economics). The presented work is the result of research activities and field work developed at different Institutions, including Ca'Foscari University of Venice in Italy, Yale University in the United States, and the Fundación Amigos de la Naturaleza in Bolivia.

In the first chapter, *"Understanding Climate Change and* CO_2 *Fertilization Effects in the Bolivian Agriculture"*, a literature review of the scientific basis behind the relation between climate, soil and crops is developed. After that, a Bottom-Up approach is applied by calibrating and validating the CERES and CROPGRO models for soybeans, maize and rice in the Bolivian conditions. Then, the impacts of climate change are introduced in the baseline daily data 2001-2007 (A2 and B2 SRES Scenarios generated and downscaled for the main production areas, for the short "2030" and long "2070" terms), and finally, the impacts of isolated Climate Change and Climate Change plus CO_2 fertilization effect in the Bolivian agriculture are quantified. Simulation results show very close results to those observed in studies for Latin America with a lower spatial resolution.

In the second chapter, *"Crop Yields in Bolivia: From Crop Models to Response Functions for Impact Analysis"*, a Top-Down approach is applied by using the techniques of the Ricardian Analysis (Mendelsohn, et al., 1994), and taking into account cross-sectional data. The main objective of the chapter is to extrapolate crop yield results from specific sites to the whole Santa Cruz Department by developing response functions. Historical crop yields per unit area, disaggregated by Municipality are not available for Bolivia. For this reason, the data for this indicator is obtained by running the calibrated and validated CERES and CROPGRO crop models (soybeans, maize and rice) for several locations, years and planting dates (a database of 1260 simulations). Following that, the chapter develops a rigorous statistical and regression analysis to determine the most accurate "response functions", having soybeans, maize and rice crop yields as dependent variables, and maximum temperature, minimum temperature, rainfall, solar radiation and soil characteristics as independent variables. The extrapolation from site results to national results is sometimes a challenging enterprise. However, in this case, correlation results between crop model yields and response function yields show a very high level of accuracy.

In the third chapter, *"Efficient Adaptation in the Bolivian Agriculture from a Bottom-Up Approach"*, an adaptation analysis is developed. Several adaptation options are available to be applied for reducing the impacts of Climate Change on agriculture. In this section, the calibrated and validated models for soybeans, maize and rice of chapter 1, are re-run for different planting dates in 10-day intervals, testing the "change of the planting date" as an experimental efficient adaptation measure for rainfed conditions. The analysis is done for the observed daily weather data "baseline" in order to check whether the producers are planting in the most appropriate dates or not. And in the second step, the models are re-run for the A2 and B2 SRES scenarios (short and long terms, 2030 and 2070, respectively), for identifying the most efficient planting date for each crop (the highest average yield with the lowest inter-annual variance). To conclude, a Cost-Benefit Analysis at the micro level is done. The simulation results show that crop models are sensitive enough to detect optimal changes for different scenarios, and the Cost-Benefit analysis results confirm that changing the planting date is a very feasible and low-cost adaptation measure to face climate change effects.

Finally, in the fourth chapter, *"Climate Change Impacts and Adaptation in Bolivia: Linking Micro and Macro Economic Policies for Sustainable Development"*, an integrated assessment is developed. Currently, the observed crop yields per hectare in Bolivia are low compared to neighboring countries. Furthermore, with Climate Change the temperature is expected to increase in the coming years, further reducing these yields. With lower yields and a rising demand for foods (expected increase in population growth rates), an expansion of the agricultural frontier is expected. To slow down the deforestation rate, to increase farmers' welfare and to ensure food security, a much more efficient agriculture is needed, implementing adaptation measures at the micro level to increase crop yields per hectare, linked with macroeconomic policies of natural resources protection, for achieving sustainable development. In this chapter, adaptation options are further developed using the change of the planting date, application of irrigation, application of fertilization and overall technology improvement (which includes all the 3 previous single adaptation options) as experimental examples, using the CERES and CROPGRO crop models. All these results are linked and introduced into a Recursive Dynamic Computable General Equilibrium Model (CGE) for Bolivia, coded in the GAMS Programming Tool. This step implies the modification, calibration, validation and linkage of the CGE and the Social Accounting Matrix (SAM) of Bolivia for the year 2000 to be coherent with soil and weather data. After the model is validated, some macroeconomic policies are tested in order to achieve food security and sustainable development at the same time; in other words, higher GDP levels accompanied by lower deforestation rates. With the microeconomic policies, increases in crop yields (and GDP also) are observed, but an increase in deforestation (demand for new land) is also observed. For maintaining these new higher crop yields, and reducing the deforestation rates, some macroeconomic policies in the agriculture sector are applied, such as: Commodity Taxes, Activity Taxes and Commodity Export Prices. Finally, a social cost for forest conservation is estimated by using the scenario results. Integrated model results show that microeconomic and macroeconomic policies applied together can lead to sustainable development, thus increasing Gross Domestic Product (GDP) and per capita income and reducing deforestation rates at the same time.

Objectives and Contribution of the Thesis

The main objective of the thesis is to explore and compare bottom-up and top-down approaches for quantifying the impacts of climate change on agriculture and adaptation options. For this purpose, 3 models are applied for Bolivian local conditions: First, the CERES and CROPGRO crop models for soybeans, maize and rice (bottom-up); second, econometric response functions of soybeans, maize and rice yields (top-down); and finally, an integrated Recursive Dynamic Computable General Equilibrium Model for the Bolivian economy (bottom-up and top-down linked together).

On one hand, crop models have been calibrated, validated and implemented in many parts of the world for the analysis of climate change scenarios. However, there is a lack of studies in Bolivia with the detailed spatial distribution for the main production zones as presented in the first chapter of this thesis. What is more, the use of crop models as tools for assessing adaptation options is much less common in the literature than its use on impact assessments. In the third chapter, these models use an in-depth methodology to test the change of the planting date as an adaptation option for the whole year in 10-day intervals, including a Cost-Benefit analysis of climate change impacts with and without adaptation for different scenarios.

On the other hand, top-down models have also been used in different regions of the planet for quantifying the impacts of climate change on agriculture by using the Ricardian Analysis and regression techniques. However, this kind of analysis was not previously done for Bolivia. After a very detailed econometric and statistical analysis, 3 response functions are created for soybeans, maize and rice, with linear, quadratic, cubic and interaction terms of maximum temperature, minimum temperature, precipitation, solar radiation and soil characteristics. The most efficient planting dates identified by the response functions, are very closely fitted to those observed in the fieldwork, and their yield estimates are highly correlated with the yield estimations of crop models, showing their high level of accuracy. These response functions can be quite useful for the development of bio-economic models and Geographic Information Systems (GIS) for the whole Santa Cruz Department.

Finally, in chapter four, an integrated assessment is developed by linking crop models with a Dynamic Recursive General Equilibrium Model for the Bolivian Economy. This kind of linked - models are found in the literature for some regions of the world for quantifying the impacts of climate change in different sectors of the economy. However, there is a lack of substantial studies concerning their use for sustainable development analysis (GDP growth and forests conservation). The modification, calibration and validation of the CGE and the Social Accounting Matrix, is made for quantifying the relation between agriculture expansion and deforestation in Bolivia, analysis which has not been previously done before. When applying microeconomic and macroeconomic measures in an anticipatory and coordinated manner, a country can achieve higher GDP levels, per capita income and lower deforestation rates than the ceteris paribus scenario, as showed in chapter 4, proving that climate policy mainstreaming is a key issue to counteract climate change effects. Additionally, a conservation social cost range is identified for the short and long runs, which estimates the approximate cost of conserving natural forests per hectare, a very important starting point for Payment for Ecosystem Services (PES) and/or Reducing Emissions from Deforestation and Degradation (REDD+) schemes for Bolivia, work which has never been done before.

Chapter 1: Understanding Climate Change and Carbon Dioxide Effects in Agriculture: Soybeans and Maize in the Bolivian Lowlands

Abstract

Increases in both mean and extreme temperatures are expected for many places of the globe accompanied by a rise of CO_2 concentration in the atmosphere. The combined effects plus the increased probability of extreme events (droughts, floods), will have serious effects in the agricultural sector. Climate influences crop growth and yields directly through impacts on phenology, photosynthesis, and other physiological processes. Temperature and water availability are key determinants in the evaporative and transpiration demand of crops, which might change the time from planting to maturity, ultimately reducing their yields. High concentrations of CO_2 in the atmosphere also have a direct effect on plant growth (mostly positive because of higher quantities of carbon nutrients), known as the fertilization effect. The net effect of climate change comes from a balance of these positive and negative effects. Several studies are found in the literature describing the impacts of climatic change in agriculture at a world, regional and country level using crop models. However, studies at a finer scale for Bolivia are not available yet. In this sense, this paper explains the scientific basis behind the relation of crop production, climate change and CO_2 fertilization specifically for yields of soybeans and maize (C_3 and C_4 family of plants, respectively) in the most important production zones of Bolivia, comparing the effects of climate change (isolated) and the effects of climate change plus the CO_2 fertilization effect using the CERES – Maize and CROPGRO – Soybeans Models of the DSSAT v.4 software. The model results agree with the scientific basis and are inside the range of results from previous studies. Just temperature and precipitation changes alter soybeans yields between -18% to +2%, and maize yields from -25% to +9%. When including CO_2 fertilization, the yield variations for soybeans range from +25% to +42% and for maize from -10% to +19%. The range of variation is high, especially for maize, given the different agro-ecological production areas. C_3 plants will likely be more positively affected by CO_2 concentrations than C_4 plants and soybeans are more resilient to warming than maize.

Keywords

Climate Change, CO_2 fertilization effect, Crop Model, Soybeans, Maize, Crop Yields, Bolivia, DSSAT.

1. Introduction

Climate influences crop growth and yields directly through impacts on phenology, photosynthesis, and other physiological processes. Temperature and moisture availability affect the time from planting to maturity and yields. Temperature and moisture availability are intrinsically linked as temperature affects evaporative and transpiration demand of crops. Indirect effects relate to nutrient availability, weeds, pests and diseases, and ability of farmers to work in the field. Therefore, temperature and precipitation changes will affect plant growth and plant characteristics both directly and indirectly. In some instances warming will be beneficial for plant growth, while in other, it will be harmful. The same applies to changes in precipitations. On the other hand, carbon dioxide (CO_2) concentrations in the atmosphere also have a direct effect on plant growth. The higher is the concentration of CO_2; the more efficient is the plant photosynthesis. High concentrations of CO_2 increase plant growth because the plant can absorb more easily higher quantities of carbon nutrients. With enough water and nutrients, rising CO_2 concentrations will be beneficial for crops. This is known as the fertilization effect. To estimate the net effect of climate change on plant growth it is necessary to run experiments that modify the climatic and atmospheric conditions under which the crop is grown, in a controlled environment. This is sometimes difficult to reproduce; however, some attempts have been made as the work done by Ainsworth and

Long (2005) showing some interesting results. On the other hand, the use of crop models is a very convenient option for quantifying the impacts of changing climatic and atmospheric conditions in crop yields. Several studies are found in the literature describing the impacts of climatic change at a world, regional and country level using crop models, such as the work done by Parry, et al., (1999) and (2004) and Gerald, et al., (2009). However, the majority of these studies give only mean country level results in terms of yields on one hand (mean crop yields for a group of cereals); and on the other hand, mean regional results in terms of yields (for example for the whole Latin America). Nevertheless in reality, most of the countries vary in terms of agro-ecological and climatic conditions. For this reason, there is the need to have individual crop yield results at a finer scale in order to take the appropriate responses. In this sense, the present paper testes the effects of climate change scenarios on soybeans and maize yields after calibrating and validating the CERES – Maize and CROPGRO – Soybeans models in the most important agricultural zones of Bolivia in terms of production. The effects of isolated climatic factors are first quantified; and then, the combined effects of climatic and atmospheric CO_2 concentration are tested for each of the crops and production areas.

1.1 Climate – Crop Interactions

The Guide to Agricultural Meteorological Practices, elaborated by the World Meteorological Organization (WMO) in 2010, serves as a good starting point and very detailed literature review of the interactions between climate indicators and crop yields. Each of the key climate indicators is analyzed in points 1.1.1 to 1.1.5, beginning with temperature effects and ending with CO_2 fertilization effects on crop yields.

1.1.1 Temperature Effects

Climate change disturbs both average and extreme temperatures. If mean monthly temperatures increase due to increases in minimum temperature (e.g. at night-time) the consequences for a crop may be very different to the same change being caused by an increase in day-time temperature. As Kukla and Karl, 1993 mention, rising night-time temperature can lead to decreases in yield, while increasing day-time temperature might increase yields in northern latitudes (by increasing growing season length) but decrease yields in middle latitudes (due to earlier ripening) (Droogers et al., 2004). For most crops elevated temperature causes a reduction in yield as there is less time for the capture of light, water and nutrients by the plant (Lawlor and Mitchell, 2000), but also in lower latitudes because of the maximum temperature threshold, which has already been achieved. Elevated temperature during early growth stages will often be beneficial, but during the time of maximum growth can be detrimental due to shortening this period. Where cold limitations are removed in temperate areas (upper latitudes) productivity might even increase. In general, higher temperatures during the growing season will be associated with higher radiation and a demand for more water, which along with elevated CO_2 are major interactions that have to be considered.

1.1.2 Water Availability

The availability of water is crucial for agriculture. As stated on WMO, 2010, the impact of climate change can occur through three major routes: drought – a lack of water for a period of time causing severe physiological stress to plants; flooding – an excess of water for a period of time causing physiological and direct physical stress to plants; and timing of water availability – when severe lack or excess of water does not occur but its availability through the year changes so as to no longer be suitable for current agricultural practices and crops. When evaluating climate change impacts in areas typically using irrigation, the analysis of water availability must also consider how the supply is buffered and/or stored for irrigation use. Irrigation demand is likely to rise in most regions with temperature increases due to increased evapotranspiration and possibly related decreases in rainfall at critical times during the growing season. Theoretically C_4 crops should require less water per gram of carbon assimilated than C_3 crops (Young and Long, 2000) and this means that crops like sorghum and maize should be more tolerant to water stress than other cereal crops. However, in reality maize suffers irreparable damage due to water stress compared to sorghum (Doggett, 1988) and is less suited to drought conditions due to its morphology and physiology. Interestingly, sorghum is also more tolerant of temporary water-logged conditions than maize. There is evidence that soybeans yields suffer with both early and late water stress in the growing season (e.g. Jones et al., 1985) and therefore timing of water availability might be important.

1.1.3 Wind Effects

Following WMO, 2010, wind can affect crops, forests, animals and the soil, in each case having a direct impact on the productivity and perhaps sustainability of a system of production. For most field crops wind is important as a regulator of evapotranspiration and as a modifier of canopy structure. The occurrence of a relatively continuous moderate wind is beneficial for the control of virus diseases in crops such as potato (Mercer et al., 2004), but such issues are very difficult to capture in a meaningful way by most models, like this case where the wind and pest effects are not considered. However, in areas with cold stress wind amplifies the problem. The impact of occasional and quite short-term storm events will be quite different to long-term continuous wind. Short-term high wind speeds cause wind-throw while long-term continuous wind (of between 7-15 m/s) can cause deformation and stunted growth. In areas where soil is poorly structured and dominated by silt or fine sand, continuous wind of >10 m/s can cause erosion to occur. In summary, the two types of impacts are: short-term high winds (e.g. hurricanes, tropical storms, tornadoes); and long-term changes in the wind climate (e.g. progressive but slight increase or decrease in mean wind speed or a change in wind direction distribution). For situations where wind will affect drying rates and soil water content, which in turn will influence crop production and demand for water, then wind climate must be considered, but might be captured in terms of a change in evapotranspiration rates. In areas where wind might have a devastating effect (e.g. Monsoon regions and the Caribbean), it is necessary to at least interpret the results of crop models in terms of the likelihood of a complete loss of crop output.

1.1.4 Photosynthetically Active Radiation

According to WMO, 2010, photosynthetically active radiation (PAR) is the proportion of solar radiation (about 50%) that actively drives photosynthesis (wavelengths between 0.4 and 0.7 μm). Monteith (1977) established that biomass growth could be expressed as a function of PAR, the fraction of PAR intercepted by foliage (fPAR), the radiation use efficiency of the plant (RUE) and time. In terms of photosynthesis it is actually the number of photons per unit area per unit time that is important because all photons in PAR have a similar ability to drive light reactions in photosynthesis (Finkele et al., 2004). Similar definitions and formulas have been defined in the DSSAT series of crop models to simulate crop behavior. The main issue to consider when simulating climate change effects causing changes in PAR is whether the plant is growing in conditions of saturated irradiance. If the plant remains in saturated conditions then a change in PAR will not have any effect, however if PAR decreases to the point that the plant photosynthesis becomes related to photon flux density it will be necessary to capture this in the simulation model. The nature of the relationship between photon flux density, photosynthesis, and the amount of energy required for photosynthesis, is plant type (particularly C_3 vs. C_4) and cultivar specific. For intensively managed monoculture crops and forages there is little need to consider plant competition for light with climate change, but for agriculture that is currently sustained by (semi) natural ecosystems, changing plant competition for PAR may be very important, as might interactions with CO_2, nutrient and water availability.

1.1.5 Elevated CO_2 Effects

Following WMO, 2010, it is widely recognized that elevated atmospheric CO_2 will have a “fertilization” effect increasing crop biomass, possibly crop yield, but not necessarily crop quality. The direct effects of increased atmospheric CO_2 concentrations on plant productivity are substantial. In ideal conditions photosynthesis can increase by 30-50% for C_3 plants and 10-25% for C_4 plants (Ainsworth and Long, 2005). However, such increases are not readily translated into crop productivity. In the real world, soil conditions, nutrient availability, pests and diseases, and competition from weeds and other crops render yields much reduced from these figures. Experiments with food crops growing in enriched CO_2 chambers suggest that doubled CO_2 concentrations enhance wheat and rice yields by 10-15% and potatoes by 30% (Derner et al., 2003). Grasslands show an increase of 15-20% in productivity (Nowak et al., 2004). Similarly, positive results are obtained for many forest crops, especially many commercial species, if fertilizers are used (Wittig et al, 2005). Interestingly, many potential bio-fuel crops such as miscanthus and willow also increase under enhanced CO_2 concentrations (Veteli et al, 2002). Less confidence exists that any increases in crop yields will automatically be translated into increases in nutrient quality and some experiments suggest reductions in mineral nutrients and protein content may occur (Wu et al, 2003). By the period 2010-2030 it is estimated that yields will increase for many crops (CSCDGC, 2002): rice: 15%; cotton: 19%; wheat: 15%; maize: 8%; beet: 8%; and tomato: 12%. On average a 17% increase in yield across all crops might be expected when atmospheric CO_2 reaches 550 ppm (Long et al., 2004) which is possible before 2050. Such a simplistic approach to impact modeling is however unacceptable for situations where the resources are not intensively managed, most specifically for open and rangeland grazing. In these situations the elevation of atmospheric CO_2 is likely to cause changes in the quality of food available to grazers (e.g. protein content) and the types of food (changes in plant communities) (Ehleringer et al., 2002). As a matter of fact, The CO_2 fertilization factors used in the past models to project future yields were derived from enclosure studies conducted approximately 20 years ago. More recent studies using free-air concentration enrichment (FACE) technology have facilitated large-scale trials of the major grain crops at elevated CO_2 concentrations under fully open-air field conditions. In those trials, elevated CO_2 enhanced yields by - 50% less than in enclosure studies. This casts serious doubts on projections that rising CO_2 will fully offset losses due to climate change; therefore crop models could be overestimating the positive effects of CO_2. A review of CO_2 effects on plants, especially on photosynthesis can be found in Long et al., 2006, Tubiello et al., 2007, Ainsworth et al., 2007 and 2008. On the other hand, while major impacts such as thermal stress and drought are likely to offset a CO_2 influence on plant communities in tropical, semi-arid and Mediterranean climates, a change in plant communities and food quality may need to be captured when modeling extensively managed grazing systems in temperate situations. Changing plant community interactions will probably extend to pests and diseases and the interaction of elevated CO_2 and warmer temperatures will probably result in greater crop loss due to these factors (e.g. Stacey and Fellows, 2002). Irrespective of the theoretical benefits of CO_2 on agriculture and bio-resources, the secondary influences of climate change, namely temperature and precipitation change, will frequently be counterproductive. However, the extent to which these secondary influences will counteract the positive direct influences of CO_2 fertilization is not at all clear, and further research is necessary to establish which influence dominates yield outcomes. The result is also likely to vary spatially as well as for specific crops and management practices. Certainly, higher temperatures will extend the growing season in mid-latitudes, signs of which are already apparent (Sweeney et al, 2002), and increase substantially the potential crop yields in high mid latitude locations and permit the agricultural margin to move to higher altitudes. Frost damage will be substantially reduced at some locations (Howden, 2003). Greater warmth in summer may also induce greater heat stress.

2. Material and Methods

2.1 CERES and CROPGRO series of crop models

Several studies on climate change impacts on agriculture have been completed using different models from top-down to bottom-up methods. They provide a first indication of the impact types to expect, and thus the most effective analysis methods to implement. Potential impacts on world food supply have been estimated for several climate change and socioeconomic scenarios. As the work done by Mendelsohn, et. al., 2006, which uses the top-down Ricardian method, which shows that some regions may improve their agricultural production whereas others will suffer from yield losses, causing distributional effects among poor and rich countries, and so a reorganization of the agricultural production areas may be required.

On the other hand, some bottom-up studies have also been developed, like the work done by IFPRI, 2009 using the CERES and CROPGRO series of crop models, showing similar results, though in a higher scale (Continent level). This study quantified the impacts of climate change coming from the A2 scenario with and without fertilization effects developed by 2 General Circulation Models: the National Center for Atmospheric Research, US (NCAR) model and the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO) model. The NCAR model shows temperature increases of 2 to 3.5 degrees Celsius for the period 2000-2050, while the increases in the CSIRO model are higher (3 to 5 degrees Celsius) for Bolivia. The precipitation patterns for Latin America are quite similar for both models, with increases from 10 to 100 mm per year. In this sense, the expected impacts for rainfed soybeans in the region may vary from -2.6 to +4.2% for the A2 scenario without CO_2 effect and +19.1% for the same scenario plus the fertilization effect. On the other hand, for rainfed maize, yield reductions from -0.4 to -1.9% are expected in the isolated A2 scenario, while for the A2 plus the fertilization effect, increases from 0.4 to 2.2% are expected. Other studies, like the one made by Parry et al., 2004 using the same series of crop models (CERES and CROPGRO), quantify the impacts of climate change in the world cereal production (maize, rice, wheat and soybeans) at a Country level. The percentage change in average cereal crop yields for the HadCM2 climate change scenario for Bolivia is around -10%. In such study, with climate change isolated (without CO_2 Fertilization Effect), a yield reduction from -2 to -30% is expected in Bolivia for the short and long runs, respectively, for Scenarios A2 and B2. When the CO_2 fertilization effect is introduced, the variations of cereal yields range from -2.5% in the short run to +2.5% in the long run for the A2 scenario; while for the B2 scenario a decrease of -2.5% is expected. However these results are still too broad and a finer scale analysis is needed given the diverse agro-ecological areas inside Bolivia (from the Andes to the Amazon).

The crop models used in this study are the CROPGRO - Soybeans and the CERES – Maize which are calibrated and validated for local conditions prior the impact assessment. The choice is made considering that these have been relatively well tested at a range of different environments. The series of CROPGRO and CERES models are included in the DSSAT v.4 modeling system (Tsuji et al., 1994, Hoogenboom et al., 1999) developed by the International Consortium for Agricultural Systems Applications (ICASA). These are simulation models for soybeans and maize crops, respectively, which describe the daily phenological development and growth in response to environmental factors (soil, climate and management). The modeled processes include phenological development, such as the duration of growth stages, growth of vegetative and reproductive parts of the plant, growth of leaves and stems, senescence of leaves, biomass production and partition between the plant parts and root system dynamics. The models include sub - modules to simulate the water and nitrogen balance in soil and plants, and these have the ability to simulate the effects of nitrogen deficiency and water deficit on photosynthesis and soil pathways movement of carbohydrates in the plant.

As a first step, isolated impacts are quantified in the different zones, introducing variations on each of the weather inputs. After that, combined effects are introduced in the DSSAT series of models using the IPCC A2 and B2 SRES scenarios, for the short and long runs, with and without CO_2 fertilization effect.

2.2 CERES and CROPGRO Models Applied for Bolivian Conditions

Many crop models have been developed to explore the impact of climate change on food production and potential adaptation options at a global, national and regional level. However, there are many sources of uncertainty in such studies, including possible Green House Gas emissions (GHG), and differences between climate scenarios generated by various General Circulation Models (GCM's). There is also uncertainty regarding the application of plot specific crop models to estimate production over large areas. This arises from scale mismatches between plot specific crop models, GCM's and Regional Circulation Models' outputs (RCM's), and regional agricultural production. Most of crop models are designed to represent the plot scale production as the case of CERES and CROPGRO, and this makes it difficult to predict the impacts of climate change at a regional level, unless some assumptions are made to enlarge the scale of results. The conventional approach for climate change impact studies has being either running the model for different sites and then enlarge the scale of results at regional level, or, to model regional yields using representative and region – specific soil types, crop varieties and management practices, which is also applied in this study. As Xiong et al., 2008, mentions, all crop models should be validated and calibrated in the environment of interest if the results are to be robust. The model calibration involves: the minimization of the error between model outputs and observed data. In addition, it also involves the determination of model parameters for a particular purpose. The validation of models assesses the ability of a calibrated model to simulate the characteristics of a separate database. The regional impact of climate change assessment, the geographic area and the limited observed data, usually confines the calibration to use the results of yield trials from: whether agricultural experiment stations, or the most commonly varieties sown. The selection of calibration sites can be rather arbitrary, driven by data availability, rather than a true representation of regional practices or spatial heterogeneity. For this study, the calibration and validation recommendations mentioned above were considered. Therefore the 5 most productive areas of the Santa Cruz Department in Bolivia were analyzed, using the crop varieties and management techniques most widely used. In this sense, the calibration and validation process is summarized in the following 3 sections[1]:

2.2.1 Calibration

For the calibration process of CROPGRO-Soybeans, the CIAT-Bolivia field experiments for the 2001/2002 Campaign in Okinawa 1 and Saavedra were used. From the variety M GROUP 9, available in the CROPGRO crop model and following the methodology mentioned in the DSSAT manuals (Hoogenboom et al., 1999), genetic parameters were calibrated (vegetative and reproductive) of that variety to create the new specific variety of UIRAPURU, which is the most widely used in Bolivia.

On the other hand, for the calibration process of CERES-Maize, the field experiments conducted by CIAT-Bolivia in the 2001/2002 Campaign for Mairana and Gutierrez were used. From the variety SUWAN-1, available in the CERES crop model and following the methodology mentioned in the DSSAT manuals (Hoogenboom et al., 1999), genetic parameters were calibrated (vegetative and reproductive) of that variety to create the new specific variety of SUWAN-Saavedra, which is the most widely used in Bolivia.

With these field data, plus the daily weather data from Servicio Nacional de Meteorologia e Hidrologia, SENAMHI Meteorological Stations' (maximum temperature, minimum temperature, precipitation and solar radiation) and soil physic-chemical data obtained from CIAT-Bolivia database, the following results are observed:

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[1] A full review of the calibration and validation process for rice, maize and soybeans can be found in Viscarra, 2010.

Table 1: Yield Simulation after Calibration for UIRAPURU in Okinawa 1 and Saavedra

UIRAPURU Variety for Soybeans					
Production Zone		Okinawa 1		Saavedra	
		Observed	Simulated	Observed	Simulated
2001/2002 Campaign	Anthesis (Days After Planting)	49	48	47	47
	Physiological Maturity (Days After Planting)	126	118	127	123
	100 Grain Weight (gr)	12,4	14,22	13	15,47
	Yield (kg/ha)	2890	3331	2270	2516

Table 2: Yield Simulation after Calibration for SUWAN-Saavedra in San Pedro and Mairana

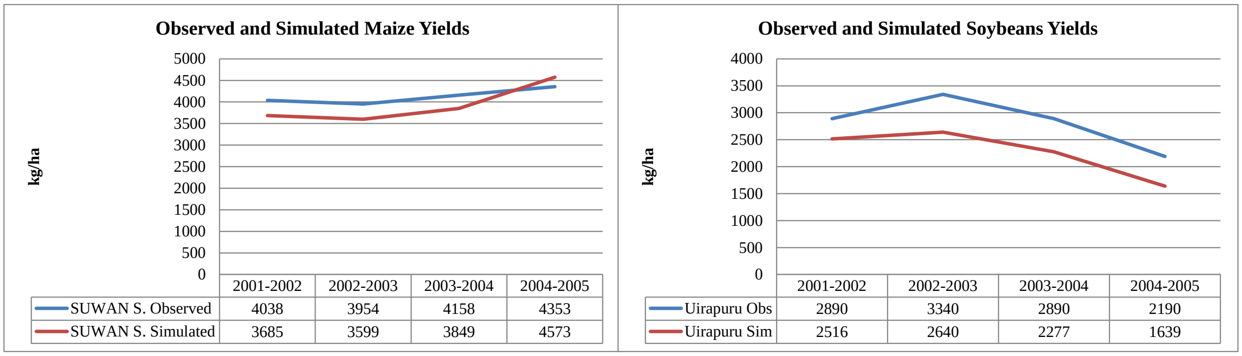
SUWAN-Saavedra Variety for Maize					
Production Zone		San Pedro		Mairana	
		Observed	Simulated	Observed	Simulated
2001/2002 Campaign	Male Anthesis (Days After Planting)	57	62	72	66
	Female Anthesis (Days After Planting)	59	64	74	68
	Corncobs per 100 plants	117	139	120	155
	Yield (kg/ha)	4038	3685	4806	3775

The simulated data is very close to the observed field data in CIAT-Bolivia's work, which means that the CROPGRO-Soybeans and CERES-Maize models behave very well for Bolivian local conditions with the new specific varieties calibrated.

2.2.2 Validation

To validate the models, field experiments conducted by CIAT-Bolivia in Okinawa 1 for soybeans and in San Pedro for maize were used, these data were obtained from the Annual Technical Reports for 2001/2002, 2002/2003, 2003/2004 and 2004/2005 campaigns, for the varieties UIRAPURU and SUWAN-Saavedra, considering all the management data, such as: planting date, fertilizer application, soil conditions, climate, among others. The results are as follows:

Figure 1: Observed and Simulated Yield for Soybeans and Maize



	2001-2002	2002-2003	2003-2004	2004-2005
SUWAN S. Observed	4038	3954	4158	4353
SUWAN S. Simulated	3685	3599	3849	4573

	2001-2002	2002-2003	2003-2004	2004-2005
Uirapuru Obs	2890	3340	2890	2190
Uirapuru Sim	2516	2640	2277	1639

In Figure 1, it can be seen that all simulated yields with the calibrated varieties follow the same trend as the observed varieties in the field work done by CIAT-Bolivia for different campaigns than the calibration year. Nevertheless, for more robust validation purposes, Jones and Kiniry, 1986, used linear regression techniques of the form $y = a + bx$, with simulated results as the independent variable. In this sense, good performance was obtained when the model intercept ***(a)*** is approaching 0 and the slope of the regression ***(b)*** approaching 1, indicating an almost perfect relation between simulated and observed values. The regression results for the observed and simulated Soybeans and Maize varieties are the following:

Figure 2: Soybeans and Maize Linear Regression

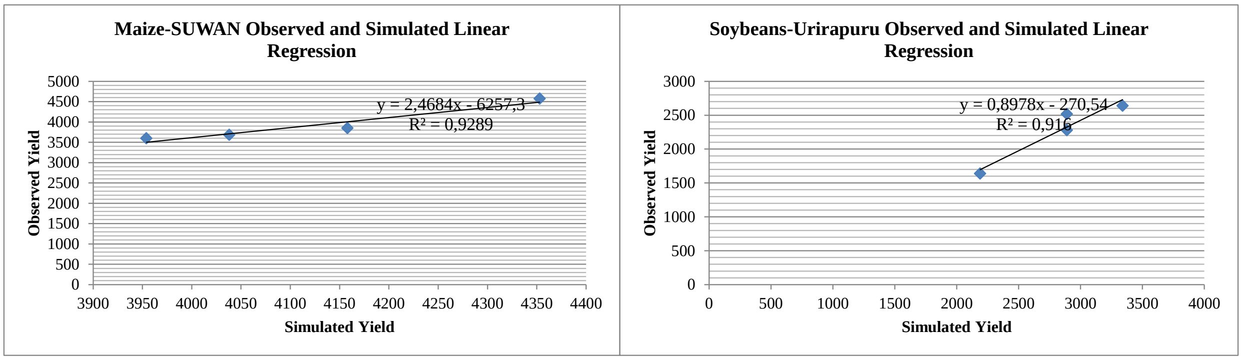
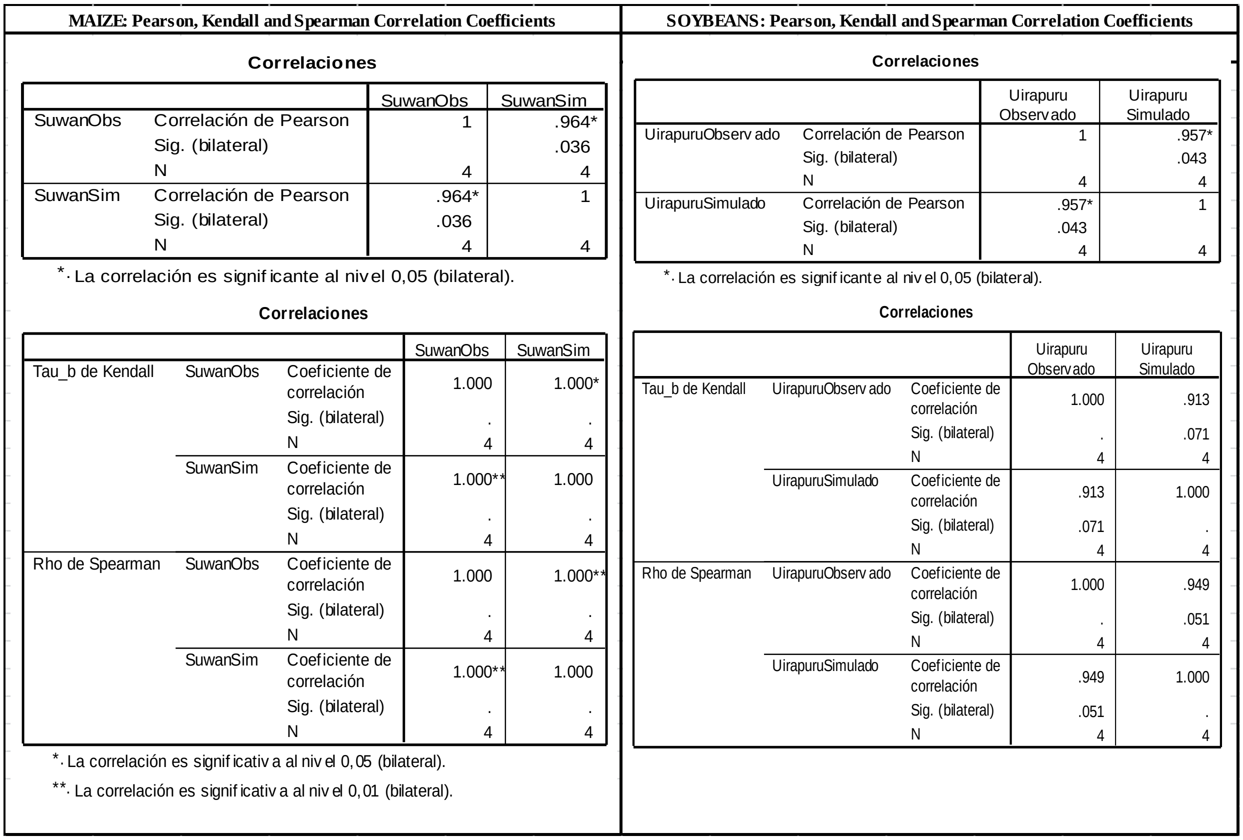


Figure 2 shows the regression for maize with an intercept of -6257 (less than 0), and a slope of 2.46 which is close to 1 and an R^2 of 0.93 (the percentage of variation which is accounted by the model), this shows a good performance of the model's prediction capacity. On the other hand, the regression for soybeans shows an intercept of -270 (less than 0), and a slope of 0.89 which is close to 1 and a R^2 of 0.92, this results also show the good performance of the model's prediction capacity.

Complementary to this regression analysis, according to Jones and Kiniry, 1986, the Pearson, Kendall and/or Spearman correlation coefficient can be applied to observed and simulated yields, indicating the similarity or inverse similarity of a response in ***y*** for a response in ***x***. The results are shown in the following Table:

Table 3: Soybeans and Maize Correlation Coefficients



MAIZE: Pearson, Kendall and Spearman Correlation Coefficients

Correlaciones

		SuwanObs	SuwanSim
SuwanObs	Correlación de Pearson	1	.964*
	Sig. (bilateral)		.036
	N	4	4
SuwanSim	Correlación de Pearson	.964*	1
	Sig. (bilateral)	.036	
	N	4	4

*· La correlación es significante al nivel 0,05 (bilateral).

Correlaciones

			SuwanObs	SuwanSim
Tau_b de Kendall	SuwanObs	Coeficiente de correlación	1.000	1.000*
		Sig. (bilateral)	.	.
		N	4	4
	SuwanSim	Coeficiente de correlación	1.000**	1.000
		Sig. (bilateral)	.	.
		N	4	4
Rho de Spearman	SuwanObs	Coeficiente de correlación	1.000	1.000**
		Sig. (bilateral)	.	.
		N	4	4
	SuwanSim	Coeficiente de correlación	1.000**	1.000
		Sig. (bilateral)	.	.
		N	4	4

*· La correlación es significativa al nivel 0,05 (bilateral).

**· La correlación es significativa al nivel 0,01 (bilateral).

SOYBEANS: Pearson, Kendall and Spearman Correlation Coefficients

Correlaciones

		Uirapuru Observado	Uirapuru Simulado
UirapuruObservado	Correlación de Pearson	1	.957*
	Sig. (bilateral)		.043
	N	4	4
UirapuruSimulado	Correlación de Pearson	.957*	1
	Sig. (bilateral)	.043	
	N	4	4

*· La correlación es significante al nivel 0,05 (bilateral).

Correlaciones

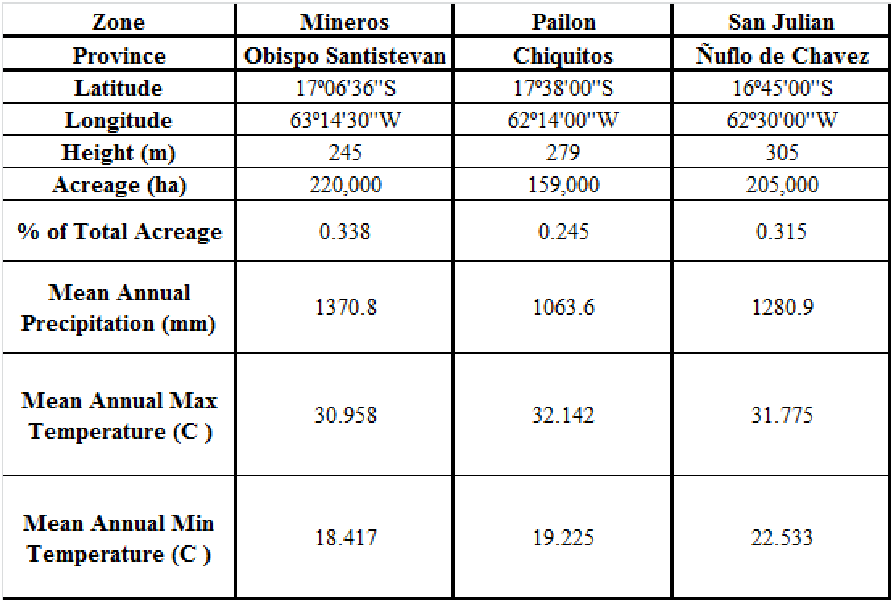
			Uirapuru Observado	Uirapuru Simulado
Tau_b de Kendall	UirapuruObservado	Coeficiente de correlación	1.000	.913
		Sig. (bilateral)	.	.071
		N	4	4
	UirapuruSimulado	Coeficiente de correlación	.913	1.000
		Sig. (bilateral)	.071	.
		N	4	4
Rho de Spearman	UirapuruObservado	Coeficiente de correlación	1.000	.949
		Sig. (bilateral)	.	.051
		N	4	4
	UirapuruSimulado	Coeficiente de correlación	.949	1.000
		Sig. (bilateral)	.051	.
		N	4	4

Table 3, shows that the observed and simulated Suwan-Saavedra and Uirapuru varieties for maize and soybeans respectively, are highly correlated, which means that the models are very closely fitted with the observations, and can be applied for impacts or adaptation analysis in local conditions.

2.3 Study Zones for Impact Analysis

After having the scientific basis of the plant-environment interrelationships and the soybeans and maize models calibrated and validated, 3 agricultural zones of Bolivia located in the Santa Cruz Department are selected for quantifying the impacts of climate change and the CO_2 fertilization effect on crop yields in a finer scale. The 3 most important zones in terms of production are chosen, differentiated on climate and soils, catching the effects of different agro-ecological environments. These zones are the following: Mineros, Pailón and San Julián.

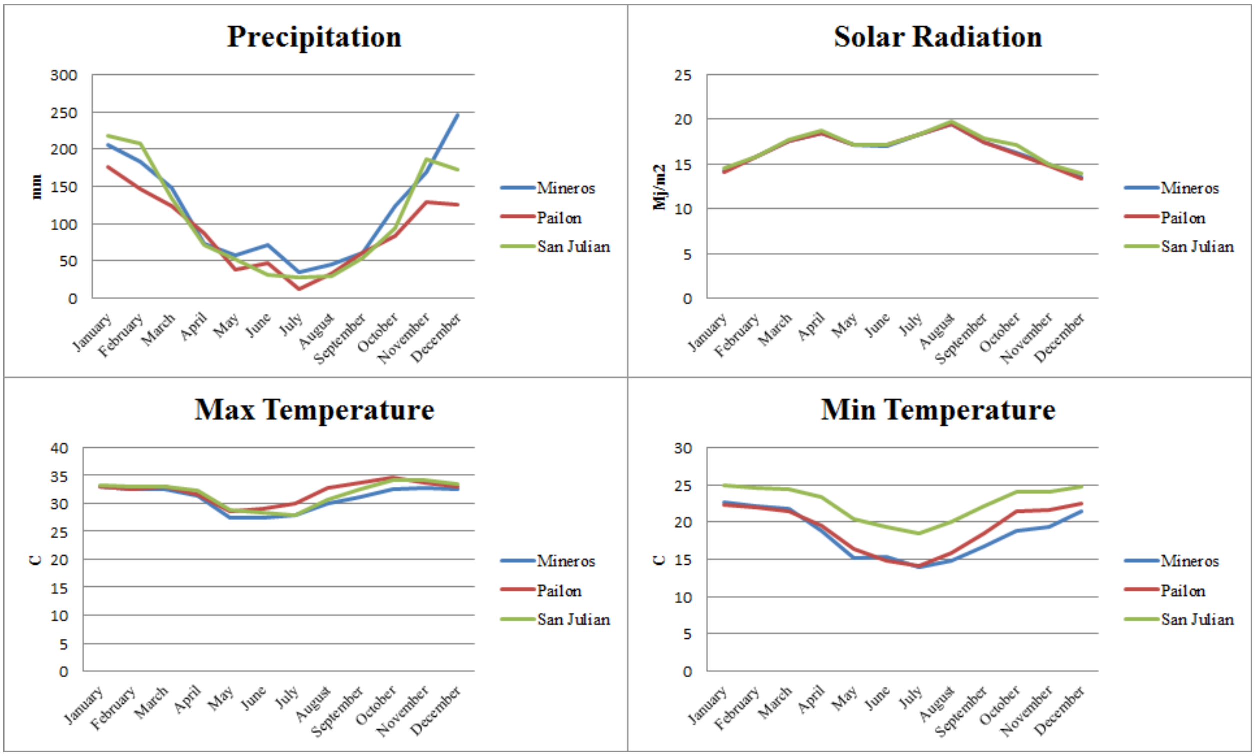
Table 4: Main Soybeans and Maize Production Zones in the Bolivian Lowlands



Zone	Mineros	Pailon	San Julian
Province	**Obispo Santistevan**	**Chiquitos**	**Ñuflo de Chavez**
Latitude	17º06'36''S	17º38'00''S	16º45'00''S
Longitude	63º14'30''W	62º14'00''W	62º30'00''W
Height (m)	245	279	305
Acreage (ha)	220,000	159,000	205,000
% of Total Acreage	0.338	0.245	0.315
Mean Annual Precipitation (mm)	1370.8	1063.6	1280.9
Mean Annual Max Temperature (C)	30.958	32.142	31.775
Mean Annual Min Temperature (C)	18.417	19.225	22.533

Based on the Servicio Nacional de Meteorologia e Hidrologia (SENAMHI) Meteorological Station's observed daily data from 2001 to 2007, Mineros is the most humid zone with a mean annual precipitation of 1370.8 mm, but also showed the lowest mean maximum temperature (30.9 degrees Celsius). San Julián is the intermediate zone in terms of humidity, showing the second highest rainfall (1280.9 mm per year) and the second lowest maximum temperature (31.7 degrees Celsius). Finally, Pailón is the driest zone with 1063.6 mm of mean annual rainfall, but also with the highest mean maximum temperature (32.1 degrees Celsius). The mean monthly distribution of precipitation, solar radiation, maximum and minimum temperature in the 3 different meteorological stations is showed in Figure 3. Precipitation, maximum and minimum temperature are quantified using the data from SENAMHI's meteorological stations (2001 to 2007), while daily incoming solar radiation is estimated according to Allen et al., (1998); the necessary input variables are location, day of the year and hours of direct sunshine.

Figure 3: Mean Monthly Distribution of Key Meteorological Indicators

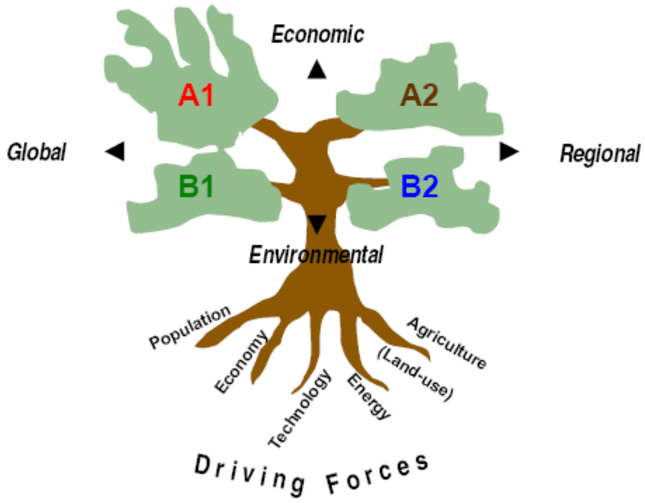


As it is observed in Figure 3, the rainy months begin in October and finish in March, reaching the peak in December and January with different quantities among the 3 different zones. The temperatures are almost constant during the whole year, but it is warmer from September to March, and the minimum temperatures are reached in the months from April to August.

2.4 IPCC's Emission Scenarios

The scenarios differ from the estimates and projections, as the latest extrapolate past patterns into the future. The scenario descriptions are intended to be internally consistent, coherent and plausible possible future states of the world (IPCC, 2001). They usually cover a range of alternative futures. The main causes can be economic, social, institutional, managerial and cultural (Nakicenovic et al., 2000). In this sense, the IPCC developed a series of GHG emission scenarios. These provide high resolution changes in climate variables, such as: temperature, solar radiation and precipitation, resulting from these alternative scenarios. The scenarios are based on different backgrounds of the world's future socio-economic development, in terms of governance and orientation towards social and environmental concerns, as well as other prevailing values. These were subsequently revised and updated, to consider changes in methodologies and the understanding of the emission causes, including changes in the understanding of the carbon intensity or energy supply, the income gap between developed and underdeveloped countries, and future rates of sulfur emissions (Nakicenovic et al., 2000). However, recently some other scenarios are in the process of development the so called Representative Concentration Pathways (RCPs) (Moss et al., 2010), which rather than starting with socio-economic scenarios that give rise to alternative greenhouse gas emissions, these new scenarios take alternative futures in global greenhouse gas and aerosol concentrations as their starting point. The RCPs scenarios can be used in parallel with the SRES Scenarios, but in the present study, only SRES scenarios are used due to their availability and for comparative purposes with previous studies.

Figure 4: IPCC's SRES Scenarios



Source: Extracted from Nakicenovic et al., 2000

This set of emission scenarios, are known as the IPCC's SRES emission scenarios, and have been widely used for assessing climate change, its impacts and the mitigation options. These can be summarized as follows:

- **A1 Scenario Family:** A materialistic and consumerist world, in which there is increasing globalization and convergence, fast economic development and uniform technological innovation.
- **A2 Scenario Family:** A very heterogeneous world, with a continuously growing population and economic world regionally oriented, which is fragmented and slower than the previous scenario.
- **B1 Scenario Family:** A convergent world, with rapid changes in economic structure towards service and information economy, with reductions in material intensity, and the introduction of clean and resource - efficient technologies.
- **B2 Scenario Family:** A prosperous and fair world, in which as a result of general orientation towards sustainable development, shows relatively low GHG emissions.

In this analysis, two climate change emission scenarios are used: the pessimistic A2, and the optimistic B2, for the time periods 2001-2030 (20's) → ***Short Term***, and for 2071-2100 (70's) → ***Long Term***. The main socio-economic characteristics are shown below:

Table 5: Characteristics of the SRES A2 and B2 Scenarios

Characteristic	A2	B2
Population Growth	High	Mid
GDP Growth	Mid	Mid
Energy Use	High	Mid
Land Use Change	Mid/High	Mid
Resources Availability	Low	Mid
Velocity and Direction of Technological Change	Slow	Mid
Change Towards:	Regional	"Always Dynamics"

Source: Nakicenovic et al., 2000

Table 6: Main Economic and Environmental Indicators

Emissions Scenario	Global Population (Billions)	Global GDP[1]	Per Capita Income Ratio[2]	CO2 Concentration (ppm)	Global Δ Temperature (ºC)	Global Sea - Level Rise (cm)
1990	5.3	21	16.1	354	0	0
2000	6.1 - 6.2 [3]	25 -28 [3]	12.3 - 14.2 [3]	367 [4]	0.2	2
2050						
SRES A2	11.3	82	6.6	536	1.4	16
SRES B2	9.3	110	4	478	1.4	16
2100						
SRES A2	15.1	243	4.2	857	3.8	42
SRES B2	10.4	235	3	615	2.7	36

[1] Gross Domestic Product (trillion 1990 US$ per year)

[2] Ratio of development countries and economies in transition (UNFCCC - defined Annex I) to developing countries (Non - Annex I)

[3] Modeled range across the six illustrative SRES scenarios

[4] Observed 1999 value (Prentice et al., 2001)

Source: IPCC, 2007.

The 2 scenarios were chosen, given the high resolution of available data for Bolivia. This data comes from a downscaled Regional Circulation Model (RCM) named PRECIS (Providing REgional Climates for Impacts Studies).

PRECIS is a RCM, based in the regional climate modeling system of the Hadley Center, which is used to generate high resolution information of climate change for any region in the world. The Bolivian Adaptation to Climate Change Departmental Pilot Program, using the climate change SRES scenarios (A2 and B2), generated regional climate scenarios for the whole country in the following time periods: (1961-1990), (2001-2030) and (2071-2100), using the methodology done by Seiler, 2009. The methodology uses a nested climate model, with outputs from a Global Circulation Model (GCM), (ocean – atmosphere), named ECHAM4 (grid range 250 km approximately), which is used to create a high resolution RCM (grid range 25 km approximately) for Bolivia. PRECIS takes the outputs of ECHAM4 as lateral boundaries, thus inherits the large scale characteristics of ECHAM4, but has a finer resolution, both spatially (typically 25 km), and temporally (in a daily basis), a better spatial detail (topography), and better simulation capability for extreme weather events.

As explained before, climate change impacts on agriculture come from a combination of positive and negative effects; these effects are quantified by using the downscaled IPCC SRES scenarios developed for Bolivia by Seiler, C. 2009. The A2 and B2 scenarios are used, A2 meaning a "business as usual" scenario with high emissions; and on the other hand, B2 with lower emissions considering a "greener society", which gives as a plausible range of climate change impacts in the future, thus, reducing the uncertainty. The monthly variations on maximum and minimum temperature, precipitation and solar radiation are introduced in the baseline observed meteorological data (2001 – 2007), for the short run (2000 – 2030) and also for the long run (2070 – 2100). Finally the CO_2 concentrations are kept constant at 330 parts per million (ppm) for the analysis of isolated climate change impacts. While for quantifying the impacts of climate change plus the CO_2 fertilization effect, different CO_2 concentration quantities are considered following Nakicenovic, et al., 2000:

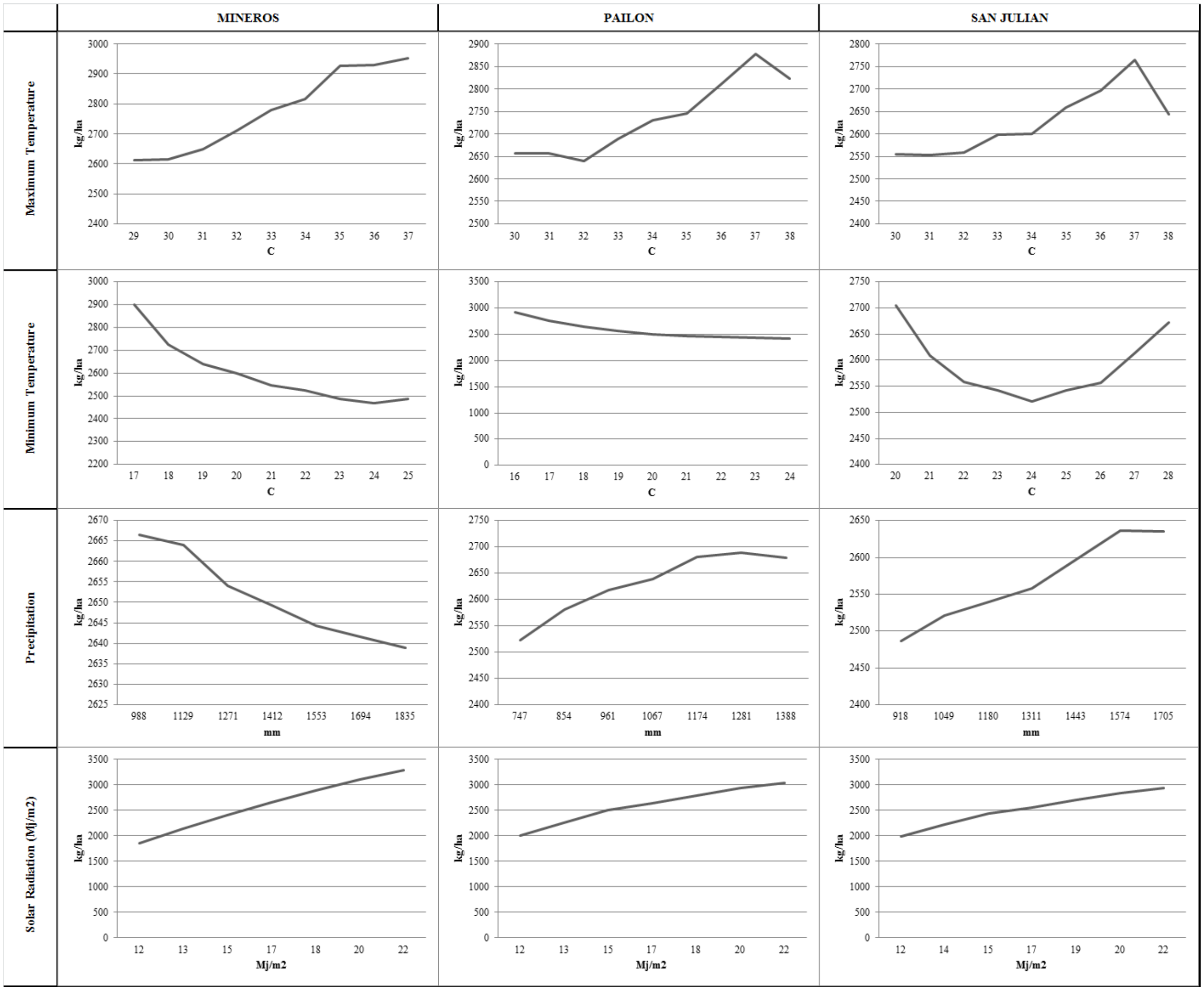
- Baseline → 330 ppm
- A2 20s → 536 ppm
- A2 70s → 857 ppm
- B2 20s → 478 ppm
- B2 70s → 615 ppm

Finally the results obtained in this step are compared with the results of other studies made in larger scales.

3. Results and Discussion

3.1 Temperature, precipitation and solar radiation impacts

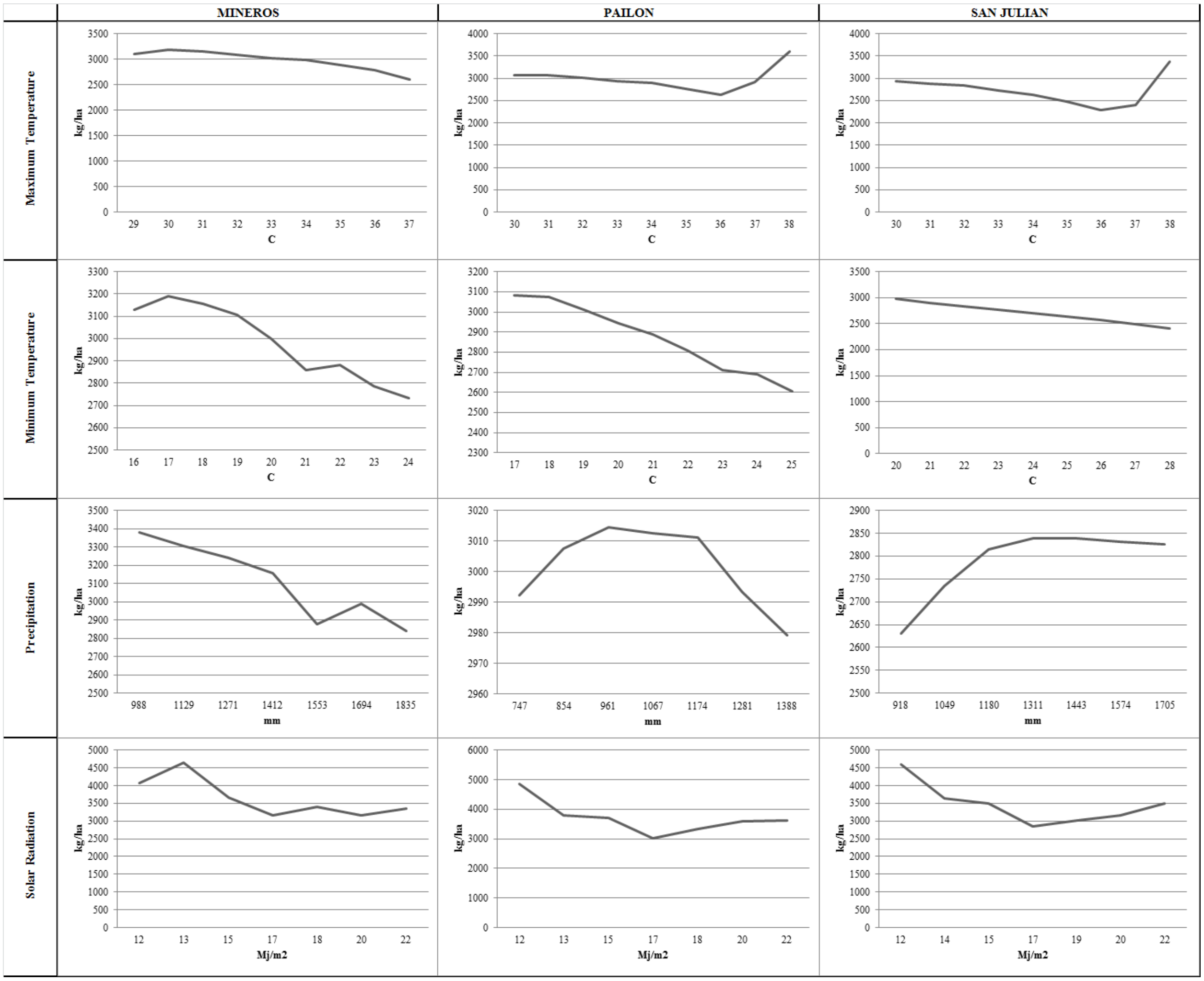
Figure 5: Climate Change Isolated Impacts on SOYBEANS (C_3)



- ***Max Temperature:*** Increases in Maximum Temperature are positive for all production areas and only when enough water is available, but in the hottest places (Pailón and San Julián), the benefits turns into losses when the 37 degrees Celsius are reached, therefore according to the model results, maximum temperatures higher than 37 degrees Celsius are counterproductive for soybeans yields.
- ***Min Temperature:*** Increases in Minimum Temperature, are counterproductive for soybeans yields in all the areas, given that these temperatures are reached at night. However, when minimum temperatures reach 24 degrees Celsius, the slope of the curve changes. As expected rising night-time temperature can lead to decreases in yields.

- ***Precipitation:*** Increases in precipitation are detrimental for the more humid zones (Mineros), but for the dryer areas they are positive until the area becomes too humid (1200 to 1500 mm per year).
- ***Solar Radiation:*** Increases in solar radiation have a positive effect on soybeans yields for all the production zones as expected, given that this crop belongs to the C_3 family of plants.

Figure 6: Climate Change Isolated Impacts on MAIZE (C_4)

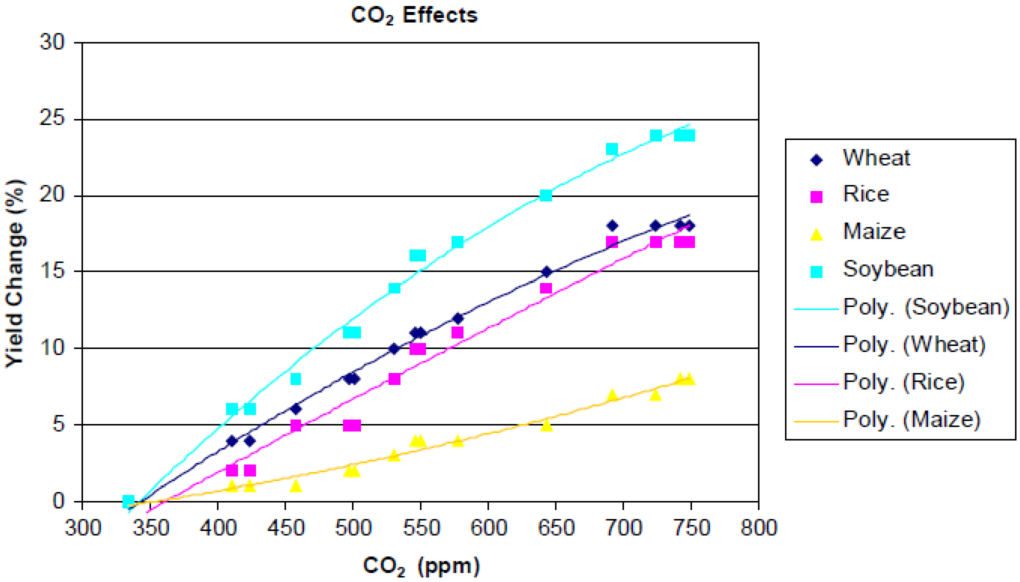


- ***Max Temperature:*** Increases are detrimental for all the areas. However, when maximum temperatures are higher than 37 degrees Celsius, the model results show a slight increase on maize yields.
- ***Min Temperature:*** Increases in minimum temperature are counterproductive for all of the areas; the highest minimum temperature that maize can tolerate is 17 degrees Celsius; with higher min temperatures, the crop suffers from heat stress.
- ***Precipitation:*** Increases of precipitation in the humid areas are detrimental to maize (Mineros). But they have a positive effect in dryer areas like Pailón and San Julián. The optimal rainfall for

this crop is around 1000 mm per year. But also according to model results, maize is less resilient to water stress than soybeans.

- ***Solar Radiation:*** Increases in solar radiation have a negative effect on maize yields for all the areas in contrast to soybeans (given that maize belongs to the C_4 group of plants).

Figure 7: Summary of Likely CO_2 effects on Different Crop Yields



Source: Extracted from Parry et.al, 2003, the potential increases in yield exhibited by wheat, rice, maize and soybeans under elevated levels of CO_2.

- ***CO_2 Fertilization:*** Increases in CO_2 concentrations are positive for all crop yields, but as observed in Figure 7, within the observed crops, wheat, rice and soybeans belong to the C_3 group of crops, while maize to the C_4. As expected C_3 plants are benefited the most from the fertilization effect. Figure 7 is obtained from Godard Institute for Space Studies (GISS) analysis, from multiple citations using the CERES and CROPGRO series of crop models. However, as explained before, these impacts can be overestimated and CO_2 net benefits in reality can be much more modest.

3.2 Carbon Fertilization and Climate Impacts

The results obtained from the A2 and B2 IPCC's SRES Scenarios introduced in the CROPGRO and CERES models for soybeans and maize, respectively, are showed in Table 7 and Figure 8:

Table 7: Climate Change Mean Variations and Impacts

Mean Climate Change Effects in Mineros					Soybean Yield in Mineros				Maize Yield in Mineros			
Mineros	**Solar Radiation**	**Max Temp**	**Min Temp**	**Precipitation**	**CC**	**CO2**	**CC %**	**CO2 %**	**CC**	**CO2**	**CC %**	**CO2 %**
Baseline	16.7	31.0	18.4	1419.3	2601.4	2601.4	0.00	0.00	3361.7	3361.7	0.00	0.00
A220s	17.3	30.7	22.2	1478.2	2670.3	3603.0	0.03	0.39	3593.7	3859.9	0.07	0.15
A2 70s	17.3	34.7	25.8	1763.5	2440.9	3688.3	-0.06	0.42	3138.7	3562.7	-0.07	0.06
B2 20s	17.4	30.6	22.1	1434.7	2662.6	3456.3	0.02	0.33	3677.9	3938.9	0.09	0.17
B2 70s	17.4	33.2	24.5	1631.3	2631.0	3697.9	0.01	0.42	3667.7	3883.6	0.09	0.16

Mean Climate Change Effects in Pailon					Soybean Yield in Pailon				Maize Yield in Pailon			
Pailon	**Solar Radiation**	**Max Temp**	**Min Temp**	**Precipitation**	**CC**	**CO2**	**CC %**	**CO2 %**	**CC**	**CO2**	**CC %**	**CO2 %**
Baseline	16.6	32.1	19.2	1063.6	2464.6	2464.6	0.00	0.00	3273.0	3273.0	0.00	0.00
A220s	17.1	30.5	22.1	1468.0	2463.9	3475.1	0.00	0.41	3342.9	3881.4	0.02	0.19
A2 70s	17.5	34.7	25.8	1675.1	2029.3	3372.7	-0.18	0.37	2454.7	3071.6	-0.25	-0.06
B2 20s	17.2	30.5	21.9	1454.7	2444.1	3251.4	-0.01	0.32	3041.4	3431.4	-0.07	0.05
B2 70s	17.4	33.0	24.3	1600.5	2250.6	3385.4	-0.09	0.37	2636.7	3186.9	-0.19	-0.03

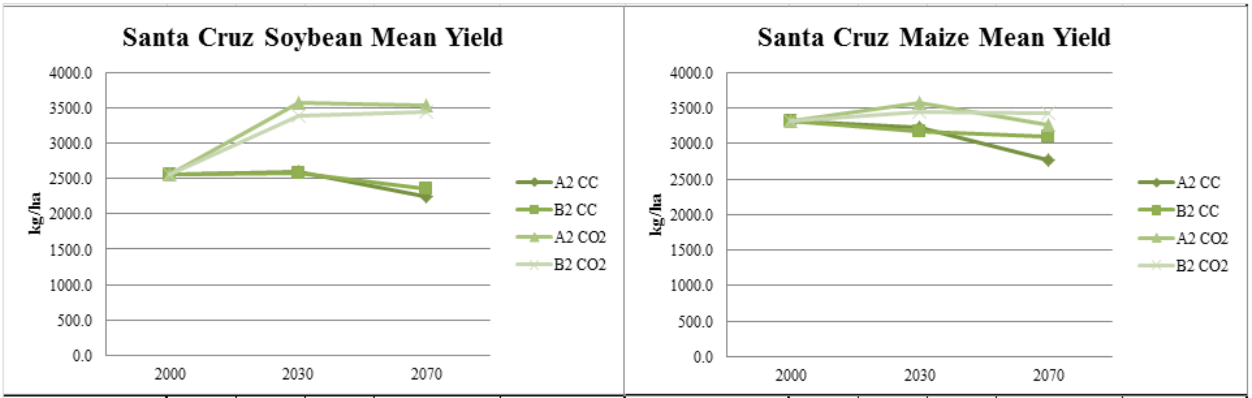
Mean Climate Change Effects in San Julian					Soybean Yield in San Julian				Maize Yield in San Julian			
Pailon	**Solar Radiation**	**Max Temp**	**Min Temp**	**Precipitation**	**CC**	**CO2**	**CC %**	**CO2 %**	**CC**	**CO2**	**CC %**	**CO2 %**
Baseline	16.9	31.8	22.5	1280.9	2588.3	2588.3	0.00	0.00	3309.4	3309.4	0.00	0.00
A220s	18.1	31.1	22.4	1317.7	2646.4	3610.6	0.02	0.39	2710.3	2998.4	-0.18	-0.09
A2 70s	18.3	35.3	26.0	1552.1	2260.6	3536.4	-0.13	0.37	2731.1	3145.6	-0.17	-0.05
B2 20s	18.1	31.0	22.2	1301.4	2644.4	3437.9	0.02	0.33	2800.9	2984.9	-0.15	-0.10
B2 70s	18.3	33.7	24.6	1426.8	2197.6	3247.7	-0.15	0.25	2974.6	3219.4	-0.10	-0.03

- ***Mineros:*** An increase of 1 to 3 % is expected for A2 and B2 Scenarios, and a reduction of 6% in the A2 scenario for the long run. This can be explained because in the short run, maximum temperature will be constant and there will be an increase of only 3 degrees for B2 and 4 degrees for A2. What is more, precipitation and solar radiation will also increase, increasing yields. Finally when considering the CO_2 fertilization effect, the increase in yields is much higher (33 to 42%). Maize will experience an increase for all scenarios, excluding the A2 70s where too much rain and too much solar radiation are observed.

- ***Pailón:*** For this site, the results are quite similar for soybeans, keeping the yields almost constant for both scenarios in the short run, but decreasing in the long run from -18 to -9%. This can be explained because Pailón is drier than Mineros. On the other hand when applying the CO_2 fertilization effects, an increase for all scenarios is observed, in a lower magnitude than Mineros (from 32 to 41%). While for maize, a reduction is observed for all scenarios (from -25 to -7%), only the A2 20s scenario shows a small increase (2%), this is explained by the increase in solar radiation and precipitation.

- ***San Julián:*** In the short run a small increase is observed for soybeans for A2 and B2 scenarios (2%), given that the temperature will remain constant and there will be a little increase in precipitation. In the long run the temperatures are increasing up to 5 degrees Celsius and a small increase of precipitation, causing a decrease of around 15% on soybeans yields. On the other hand, maize experience the highest yield loses (from -18 to -10%), given that there is a very large increase of solar radiation (the largest from the 3 production areas), the impacts are lower in the long run because there is a little yield increase coming form an increase in temperatures, which is beneficial for maize up to a certain threshold.

Figure 8: Climate Change Mean Impacts on Departmental Crop Yields



Soybean Mean	2000	2030	2070	%Change 2030	%Change 2070
A2 CC	2551.4	2593.5	2243.6	0.02	-0.12
B2 CC	2551.4	2583.7	2359.7	0.01	-0.08
A2 CO2	2551.4	3562.9	3532.5	0.40	0.38
B2 CO2	2551.4	3381.9	3443.7	0.33	0.35

Maize Mean	2000	2030	2070	%Change 2030	%Change 2070
A2 CC	3314.7	3215.6	2774.9	-0.03	-0.16
B2 CC	3314.7	3173.4	3093.0	-0.04	-0.07
A2 CO2	3314.7	3579.9	3260.0	0.08	-0.02
B2 CO2	3314.7	3451.7	3430.0	0.04	0.03

As it is observed some crops and places will benefit from climate change while other will lose; but in general, the net impact of climate change in the Santa Cruz's agriculture as a whole without considering CO_2 effects, will be slightly positive for soybeans in the short run (increases from 1 to 2%), but negative in the long run (decreases from -12 to -8%). While considering CO_2 effects, the observed impacts are positive with increases between 33 to 40%. On the other hand, maize production will be severely affected in the scenario without CO_2 effects, with reductions ranging from -16 to -3%, the higher impacts are expected for the long run. Finally when including the CO_2 effect, a slight increase in yields is observed for all scenarios (from 3 to 8%), but the A2 70s scenario, which shows a reduction of 2% on maize yields.

Table 8: Simulated Yield Variations Compared to Other Studies

Crop	Soybean				Maize			
Source	A2 CC	A2 CO2	B2 CC	B2 CO2	A2 CC	A2 CO2	B2 CC	B2 CO2
DSSAT Bolivia	(-12, +2)	(+38, +40)	(-8, +1)	(+33, +35)	(-16, -3)	(-2, +8)	(-7, -4)	(+3, +4)
Parry, et al., 2004	(-30, -2)	(-2.5, +2.5)	(-30, -2)	(-2.5, +2.5)	(-30, -2)	(-2.5, +2.5)	(-30, -2)	(-2.5, +2.5)
Gerald, et al., 2009	(-2.6, +4.2)	(+19)	-	-	(-1.9, -0.4)	(+0.4, +2.2)	-	-

In Table 8, the results of the simulations in the present study (DSSAT Bolivia) are compared with the results obtained by other studies with lower spatial resolution. These simulations are inside the range of results of the other studies, but it has to be noticed that the study done by Parry, et al., 2004, shows a mean yield of a group of cereals (maize, wheat, rice and soybeans), which introduces some additional uncertainty in the results. While the results by Gerald, et al., 2009, are obtained by crop, but the spatial resolution is too general, with results showing the expected yield variation for different crops grown in the whole Latin America and the Caribbean considered as a region, also adding some additional level of uncertainty.

4. Conclusions

After running the model for isolated impacts and combined impacts for the different crops, it can be established that soybeans in Bolivia are more resilient to increases in maximum temperature and decreases of precipitation, while they are more reactive to CO_2 concentrations. On the other hand, maize seems to be more sensitive to increases in solar radiation and precipitation, less resilient to heat stress and less reactive to CO_2 concentrations. These results can be extended to the crops belonging to the same family, C_3 crops for soybeans and C_4 for maize, given their similar characteristics on photosynthesis and evapotranspiration. To compare such differences, an impact assessment of soybeans and maize yields is made considering climate change plus the CO_2 fertilization effect. As soybeans belong to the C_3 group of plants, it is observed that the positive fertilization effect exceeded climate change negative impacts for all of the study locations. The increases in yield range from 30 to 40 % compared to the isolated climate change scenario. While for maize, as a C_4 plant, the benefits are much more modest, 7 to 15% higher than the isolated climate change scenario. The positive fertilization effects are higher in the short run because of more water (and less temperature) availability. However, the positive fertilization effects can be overestimated, as field FACE experiments show. The combination of higher temperatures with lower availability of water is devastating, as observed in the drier areas (Pailón and San Julián). On the other hand, with higher temperatures and higher water availability, some benefits coming from climate change can be seen, therefore water management and timing is quite important for increasing yields and as an adaptation measure.

Finally, the crop-environment relations and the theoretical climate change and fertilization effects on crops are confirmed by the results obtained in the CROPGRO and CERES simulations. These results are inside the range of results of other studies done for Bolivia and Latin America, with the extra benefit that these are obtained in a finer scale, given the downscaled SRES scenarios (higher spatial resolution), and the individual analysis for the different crops and areas of production. This is quite important for quantifying the impacts of climate change and bridging the gap between science and policy making in a regional scale, where the applicability of results is needed.

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Chapter 2: Crop Yields in Bolivia: From Crop Models to Response Functions for Impact Analysis

Abstract

Empirical Estimates of climate response functions basically come from 2 sources: laboratory experiments coupled with process-based simulation models; and, cross-sectional studies; both having advantages and disadvantages. The objective of the paper is to develop response functions which can include as much advantages and as low drawbacks as possible from both approaches, in order to have results that can be used for extrapolating the results from specific sites to the Santa Cruz Region as a whole. The study uses the simulation CERES and CROPGRO simulation models included in the DSSAT software, calibrated and validated for the 5 most important production zones of Santa Cruz, Bolivia (Guarayos, Mineros, Pailon, San Julian and Yapacani) for obtaining response functions of soybeans, maize and rice yields to changes in maximum temperature, minimum temperature, precipitation, solar radiation and soil characteristics. A database of 1260 yield simulations for each crop is created from observed weather indicators and by running the crop models. After that, a statistical analysis is developed to choose the best model by regressing crop yields (as dependent variable) with observed maximum temperature, minimum temperature, precipitation, solar radiation and soils in different forms (linear, quadratic, cubic and interaction), as independent variables. From the maximum models, reduced form models are created using the forward and backward stepwise regression technique. Then, different evaluation criteria are used to choose the best regressions. The results show that the adjusted R^2, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), coincide in choosing the reduced form models only containing significant linear, quadratic, cubic and interaction terms for soybeans, maize and rice, respectively. Finally, for validating the selected models, a correlation analysis is done to analyze the mean yields of soybeans, maize and rice in the different production zones at different planting dates obtained by the CERES and CROPGRO simulation models compared to the same results obtained by the regressed best response functions. The results exhibit very high correlation coefficients between simulated and regressed results: 97, 93 and 94% for soybeans, maize and rice, respectively, which support the hypotheis that the simulation outputs can be reproduced with adequate care and within explored environmental and cultivation conditions by means of response functions and thus allowing to bridge agronomic and economic modelling.

Keywords

CERES, CROPGRO, Crop Yields, Soybeans, Maize, Rice, Response Functions, Bolivia.

1. Introduction

Empirical Estimates of climate response functions basically come from 2 sources: laboratory experiments coupled with process-based simulation models; and, statistical models using time series, panel and cross-sectional data; both having advantages and drawbacks. For instance, experimental evidence can isolate the effect of climate from other factors in the environment, which is good, but on the other hand, one must model all responses by the organism or system to make accurate predictions, adaptation is a key issue for not overestimating climate change damages.

On one hand, studies of statistical regression techniques coupled with process-based models, have been applied in the past for quantifying the impacts of climatic change at the regional and the global scales. Parry et al., 1999, made a global assessment of climate change impacts on food security by using the IBSNAT-ICASA dynamic crop growth models for the major grain cereals and soybeans, which were specified and validated in 124 sites in 18 countries representing major agricultural regions of the world, and then statistical analyses were used to derive regional yield response functions from the site results. First, relationships between crop yield and temperature and precipitation anomalies over the entire growing period and atmospheric CO_2 levels were analyzed independently using the Pearson product moment correlation coefficient. This exploratory analysis served to identify those variables, which explained a significant proportion of the observed yield variance. The yield response to combined changes in temperature, precipitation and CO_2 concentration (between 10 and 200 simulations per crop and agro-climatic region) was then statistically analyzed. The multiple linear and quadratic regression models were tested as possible yield functions. For each function, the agreement between simulated and observed yields (the term observed is used here to designate the results of the crop model simulations) and yields predicted by the functions was measured using the adjusted R^2, representing the fraction of variation in simulated yield explained by the fitted yield values. The significance of the estimated models was also assessed by screening the values obtained using the F-test criteria of F values being less than 0.0001 at the 95% significance level. Function parameters, their significance, and predicted yields were calculated using the SPSS statistical program. What is more, Iglesias et al., 1999, made a regional assessment on agricultural impacts of climate change in Spain by calibrating and validating the CERES-Wheat crop model and then applying a multiple regression analysis (linear and quadratic) to derive regional response functions, having crop yield as the dependent variable and temperature, precipitation and CO_2 concentration as independent variables. These response functions were then used for spatial analysis. Also, Parry, et al., 2004, analyses the global consequences to crop yields, production, and risk of hunger of linked socio-economic and climate scenarios. In the study, projected changes in yield are calculated using transfer and/or response functions derived from CERES and CROPGRO model simulations with observed climate data and projected climate change scenarios. The production functions incorporate: crop responses to changes in temperature, precipitation, carbon dioxide and some adaptation measures around the linear relation fitted to the aggregated data. In the same way, Lobell and Field, 2007 fitted a regression of crop yield on temperature and precipitation for a number of crops, by using average global yields data provided by the Food and Agriculture Organization and temperature and precipitation observations, registered to a global grid by the Climate Research Unit of the University of East Anglia. The climate data was aggregated into weighted-area averages and growing-season averages, both crop-specific. However, it has been shown (Hu and Buyanovsky, 2003; Schlenker, 2006) how intra-seasonal variability may affect crop yields in important ways, and this method does not explicitly account for its possibly significant effects, which would contribute to the scatter. More recent work (Lobell et al., 2008, Quiroga and Iglesias, 2009; Lobell and Burke, 2010; and Iglesias et al., 2011), derive response functions following the same rationale and including more independent variables for developing response functions (like different sowing dates and application of fertilizer, among others), but all of the efforts in the process of deriving response functions were done to be able to: (1) expand the results over large areas (crop models have a limited application over wide areas due to limitations in the datasets); (2) include conditions that are without the range of historical observations; and (3) simulate optimal management and therefore estimate possible adaptation.

On the other hand, given that climate change which has occurred over the past century has sometimes been too subtle to serve as the basis for impact experiments, there exists the observational opportunities to use cross sectional experiments. By comparing the outcomes in systems in different locations that face different climates, one can measure the long-term consequences of climate change. However data quality and availability is very important for different periods of time and this approach cannot reveal the effect of variables that are uniform throughout the sample (such as CO_2 and price). Several studies have been done in the past using this technique such as the Ricardian approach, which assumes that the producers maximize profits based on a vector of climate and socio-economic parameters. Therefore, under perfect competition, the value of the land equals the present value of the profits. Under these assumptions, the model also estimates a series of response functions, such as the work done by Mendelsohn et al., 1994, who estimate the effects of climate change on farm values and revenues on the United States economy. They develop a quadratic form for the farm value function for the years 1978 and 1982. The authors use temperature and precipitation for the months of January, April, July and October as independent variables; each representing one season. Massetti and Mendelsohn, 2011, repeat the cross section regressions for the years of the census from 1978 to 2002. They use the log value of farmlands as the dependent variable and a quadratic form equation for the climate variables. However, they use new control variables in addition to Mendelsohn et al., 1994 and also more accurate measures of climate variables, as well as expand the number of United States counties. Besides the United States, this approach was implemented in many other regions such as Europe, Asia, Africa and Latin America.

After having a very detailed literature review of the available techniques for deriving crop response functions to climatic factors, the objective of the paper is to develop response functions which can include as much advantages and as low drawbacks as possible from both approaches, for having results that can be extrapolated for the whole Santa Cruz Department and used for finer scale impact and adaptation assessments. In this sense, the paper studies the calibrated and validated CERES and CROPGRO simulation crop models included in the DSSAT software on the 5 most important production areas of Santa Cruz, Bolivia (Guarayos, Mineros, Pailon, San Julian and Yapacani) for obtaining response functions of soybeans, maize and rice yields to changes in maximum temperature, minimum temperature, precipitation and solar radiation. A full review of the calibration and validation process for Bolivian local conditions can be found in Viscarra, 2010. However a summary can be found previous chapter. The regressions include more independent variables than the previous work done in the field (maximum temperature, minimum temperature, precipitation, solar radiation and soil characteristics) in linear, quadratic, cubic and interaction forms. What is more, the database includes different planting dates (in 10 day intervals) for representing the growth period of crops and interaction between climate indicators in a more accurate way, improving some of the drawbacks of past efforts. Finally, the statistical analysis for determining the best response function is quite rigorous and applies different evaluation criteria instead of only correlation and significance test analysis as done in other analysis. However, CO_2 fertilization effects are not considered in the functions due to the high uncertainty of the outcomes (Long et al., 2006), this can be considered either a drawback or advantage.

2. Methods

First, the yields are estimated for each of the crops and production areas for the whole year in 10-day intervals by using the calibrated and validated CERES and CROPGRO models included in the DSSAT v. 4. Software (Decision Support System for Agrotechnology Transfer), obtaining a total number of

1260 values (252 for each area). The main inputs for the series of models are: observed daily maximum temperature, minimum temperature, precipitation, solar radiation, and soil physic and chemical characteristics; while the main outputs are the crop yields per unit area (kg/ha). The data from SENAMHI meteorological stations (2001-2007) and soil physic-chemical analysis form CIAT-Bolivia and ANAPO are used. This daily data is converted into monthly means and then used to run the models for avoiding noise, outliers, measurement errors and chaotic responses, of data obtained from meteorological stations.

After having obtained the soybeans, maize and rice yields from the empirical models, a database of 1260 "observations"[2] is created for each of the crops. Every "observation" consists of the 3 simulated crop yields as dependent variables, and as independent variables: the 150-days mean observed weather indicators (around 5 months)[3] for maximum temperature, minimum temperature and solar radiation; on the other hand, precipitation as the sum of daily rainfall in 150 days (from the planting date to maturity) for each observation. This exercise (which has never been done in previous studies), gives the response functions more accuracy and the ability to project crop yields during the whole year in a more precisely manner. After that, with the elaborated database, a vigorous statistical analysis is done to choose the best model by regressing yields (dependent variable) with observed maximum temperature, minimum temperature, precipitation, solar radiation and soil characteristics as independent variables. 4 maximum models are defined for each of the crops, that is, the models containing all explanatory variables which could possibly be present in the final model.:

a) Models with 19 explanatory variables plus the intercept including: 12 regressors in linear, quadratic and cubic forms of the 4 main inputs, 6 interaction terms between the main 4 inputs, and a dummy variable to account for the differences in the 5 production areas (especially soil characteristics).

b) Models with 15 explanatory variables plus the intercept including: 8 regressors in linear and quadratic forms of the 4 main inputs, 6 interaction terms, and a dummy variable to account for the differences in the 5 production areas.

c) Models with 13 explanatory variables plus the intercept including: 12 regressors in linear, quadratic and cubic forms of the 4 main inputs, and a dummy variable to account for the differences in the 5 production areas.

d) Models with 9 explanatory variables plus the intercept including: 8 regressors in linear and quadratic forms of the 4 main inputs, and a dummy variable to account for the differences in the 5 production areas.

From these 4 maximum models for each crop, reduced models are obtained using the Forward and Backward Stepwise Regression Procedure in the R software.

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[2] Given the lack of standardized crop yield observations in Bolivia by Municipalities, a crop yield "observation" in this paper is obtained by running the CERES and CROPGRO series of crop models, calibrated and validated for local conditions.

[3] This length is chosen given that in Bolivian latitudes the timing from crop planting to maturity takes between 4 to 5 months in normal conditions.

And finally the best fitted model is chosen for each of the crops using the $\boldsymbol{R^2}$, ***adjusted*** $\boldsymbol{R^2}$, ***AIC***, ***BIC*** criterions[4], and the ***Spearman*** correlation coefficient.

2.1 Selection Criteria

First of all, the maximum model must be defined, that is, the model containing all explanatory variables which could possibly be present in the final model. Note that these include linear, quadratic, cubic and interaction terms (maximum temperature, minimum temperature, precipitation and solar radiation) that might affect the response variable (soybeans, maize and rice yields). Thus, any possible model for the data is a restriction of the maximum model, in the sense that it can be achieved by omitting a number of the explanatory variables from the maximum model.

When defining the maximum model, it is important to include all explanatory variables which might have an effect on the response variable; however, one has to be careful not to include too many unimportant explanatory variables. If the model contains many explanatory variables compared to the number of observations, the variation in the estimators of the regression parameters can be very large, and thus lead to inaccurate parameter estimates. Further, the more explanatory variables in a model, the greater the risk of confounding or collinearity (that is, two or more variables are linearly dependent). Confounding and collinearity can lead to omitting the "wrong" explanatory variables. In the present study, as the "observations" come from crop models, its main inputs were considered (maximum temperature, minimum temperature, precipitation, solar radiation and soil characteristics), in contrast to other studies where only mean temperature, precipitation and CO_2 are considered.

Finally, there is the issue of parsimony: if two models are equally good, one should prefer the simpler. There are several reasons for this: firstly, complex models often confuse interpretations of the results from the analysis; secondly, the larger the model, the less precise the parameter estimates will be; and thirdly, if the model is very large, analyzing the data can take a very long time and not necessarily lead to more useful results. In general, the number of explanatory variables in the maximum model should take into account the sample size of the data set that is to be analyzed: the smaller the sample size, the smaller the maximum model should be. There are various rules for defining the sample. The most common ones are that the error degrees of freedom should be at least ten, that is $n - k - 1 >= 10$, or, that there should be at least 5 observations for each explanatory variable, that is $n >= 5k$. Note that the second rule is much stronger than the first, e.g. if $k = 5$, the first rule requires $n >= 16$, while the second rule requires $n >= 25$. By using the stronger rule in the present analysis, the largest maximum model includes 19 regressors plus the intercept, so the sample must be higher than 100 observations; fortunately, the sample size seems not to be a problem (1260 observations).

Once the maximum model has been defined, the next point to consider is how to determine whether one model is "better" than the others. A selection criterion is a principle, which will order all possible models from "best" to "worst". Many different criteria have been suggested through time, but there is no single criterion which is overall preferred. Essentially, the purpose of selection criteria is to compare the maximum model with a reduced model which is a restriction of the maximum model. If the reduced model provides (almost) as good a fit to the data as the maximum model, then the reduced model is preferred. For these reasons, 4 maximum models are defined for each of the crops (soybeans, maize and

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[4] The Akaike Information Criterion and the Bayesian Information Criterion, respectively.

rice), and from these models, a Forward and Backward Stepwise Regression Procedure analysis is done for getting reduced models, and finally compare all the resulting possible models with different selection criteria.

Stepwise Regression Procedure

This procedure is used to obtain reduced form models from maximum models. It is based in a systematic use of the forward selection and backward elimination procedures. The backward elimination procedure is basically a sequence of tests for significance of explanatory variables. Starting out with the maximum model, then variable with the lowest ***p-value*** for the test of significance is removed, conditioned on the ***p-value*** being bigger than some pre-determined level (for example, 0.10). Next, the new reduced model is fitted (having removed the variable from the maximum model), and remove from the reduced model the variable with the highest ***p-value*** for the test of significance of that variable (if $p > 0.10$). And so on, the process runs iteratively. The procedure ends when no more variables can be removed from the model at significance level of 10%. On the other hand, the forward selection procedure is a reversed version of the backward elimination procedure. Instead of starting with the maximum model, and eliminating variables one by one; an "empty" model with no explanatory variables is the starting point, and adding variables one by one until the model cannot be improved significantly by adding another variable. Note that in the present study the Akaike Information Criterion (***AIC***) is used in each step, so the procedure will end when no more variables can be removed and/or added in order to get a lower ***AIC.***

The performances of the forward and backward procedures can be really improved by introducing the modification Stepwise Regression Procedure, which modifies them in the following way: for the forward selection procedure, each time a new variable is added to the model, the significance of each of the variables already in the model is re-examined. That is, at each step in the forward selection procedure, each variable currently in the model is tested for significance, and the one with the highest ***p-value*** is removed. The model is then re-fitted without this variable, before going to the next step in the forward selection procedure. The stepwise regression procedure continues until no more variables can be added and/or removed. The procedure is applied for the data base in the R programming tool.

R^2, R^2_a, AIC, BIC and Spearman Correlation Criterions

The statistic selection criterions are used for comparing and choose the "best" fitted model from both maximum and reduced form models. The simplest and most known is the R^2, which is the proportion of the total amount of variation in the data which can be explained by the fitted model. The closer the model fits the data, the larger R^2 will be. Thus, an intuitive method to compare the two models would be to compare the R^2s corresponding to the models; the model with the highest R^2 provides the closest fit. However, the method has a number of drawbacks. The most important being that, due to the way R^2 is defined, the largest model (the one with most explanatory variables) will always have the largest R^2 (whether the extra variables provide any important information about the response variable or not). A common way to avoid this problem is to use an ***adjusted*** version of R^2 instead of R^2 itself. The ***adjusted*** R^2 ***statistic*** does not necessarily increase when the number of explanatory variables increases.

On the other hand, another technique for selecting a model is the ***Akaike Information Criterion (AIC)*** which is the measure of the relative goodness of fit of a statistical model. It is grounded in the concept of information entropy, in effect offering a relative measure of the information lost when a given model is used to describe reality. It can be said to describe the tradeoff between bias and variance in model construction, or loosely speaking between accuracy and complexity of the model. ***AIC*** does not provide a test of a model in the sense of testing a null hypothesis; i.e. ***AIC*** can tell nothing about how well a model fits the data in an absolute sense. If all of the candidate models fit poorly, ***AIC*** will not give any warning of that in contrast to ***R^2*** indicators. Given a set of candidate models for the data, the preferred model is the one with the minimum ***AIC*** value. Hence ***AIC*** not only rewards goodness of fit, but also includes a penalty that is an increasing function of the number of estimated parameters. This penalty discourages over fitting (increasing the number of free parameters in the model improves the goodness of the fit, regardless of the number of free parameters in the data-generating process). However, the ***AIC*** penalizes the number of parameters less strongly than does the ***Bayesian Information Criterion*** (***BIC***) which is a special case of ***AIC***. A comparison of ***AIC*** and ***BIC*** is given by Burnham and Anderson, 2002. The "best" model is the one with the lower ***AIC*** and ***BIC*** statistics.

Finally and complementary to the mentioned selection criteria, according to Jones and Kiniry, 1986, the ***Spearman*** correlation coefficient (***rho***), is also a very conservative indicator to evaluate a model; representing the similarity or inverse similarity of a response in ***y*** (observed crop yield) for a response in ***x*** (fitted crop yield). It assesses how well the relationship between two variables can be described using a monotonic function. If there are no repeated data values, a perfect ***Spearman*** correlation of +1 or −1 occurs when each of the variables is a perfect monotone function of the other. The closer the correlation is to 1, the better the model prediction power would be.

3. Results

First, the largest maximum models "***a***" are run for soybeans, maize and rice to get the reduced form models.

Table 9: Linear, Quadratic, Cubic and Interaction Maximum Models (a)

Table 1: Linear, Quadratic, Cubic and Interaction Maximum Models

Estimator	Soybean					Maize					Rice				
	Estimate	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**	
(Intercept)	-7.93E+02	1.04E+04	-0.076	9.39E-01		-8.86E+04	1.96E+04	-4.512	0.00000675	***	-2.11E+05	2.32E+04	-9.127	<2.00E-16	***
Precip	8.71E+00	7.49E-01	11.632	<2.00E-16	***	6.23E+00	1.41E+00	4.423	0.0000102	***	-6.72E-01	1.66E+00	-0.404	0.686038	
p2	-7.44E-03	3.75E-04	-19.855	<2.00E-16	***	-8.48E-03	7.04E-04	-12.045	<2.00E-16	***	3.13E-03	8.31E-04	3.772	0.000166	***
p3	2.00E-06	1.36E-07	14.737	<2.00E-16	***	3.10E-06	2.55E-07	12.146	<2.00E-16	***	-1.94E-06	3.01E-07	-6.454	1.33E-10	***
Max.Temp	-2.03E+03	8.58E+02	-2.364	1.82E-02	*	9.80E+03	1.61E+03	6.076	1.44E-09	***	1.60E+04	1.90E+03	8.4	<2.00E-16	***
maxt2	6.66E+01	2.49E+01	2.679	7.44E-03	**	-3.07E+02	4.68E+01	-6.555	6.84E-11	***	-4.50E+02	5.52E+01	-8.153	5.8E-16	***
maxt3	-6.55E-01	2.41E-01	-2.715	6.69E-03	**	3.08E+00	4.54E-01	6.799	1.34E-11	***	3.94E+00	5.35E-01	7.373	2.32E-13	***
Min.Temp	1.84E+03	3.20E+02	5.727	1.16E-08	***	2.20E+03	6.02E+02	3.652	0.000266	***	-2.63E+03	7.11E+02	-3.701	2.20E-04	***
mint2	-4.79E+01	1.35E+01	-3.548	3.97E-04	***	-6.39E+01	2.54E+01	-2.515	0.011955	*	1.35E+02	3.00E+01	4.51	6.82E-06	***
mint3	6.79E-01	1.95E-01	3.48	5.10E-04	***	6.63E-01	3.67E-01	1.807	0.070875	.	-2.80E+00	4.33E-01	-6.46	1.27E-10	***
Sol.Rad	7.23E+02	4.99E+02	1.451	1.47E-01		-5.89E+03	9.37E+02	-6.28	4.03E-10	***	6.79E+03	1.11E+03	6.144	9.47E-10	***
solr2	-4.55E+01	3.16E+01	-1.441	1.50E-01		2.76E+02	5.94E+01	4.649	0.00000352	***	-4.43E+02	7.00E+01	-6.317	3.19E-10	***
solr3	9.27E-01	6.69E-01	1.386	1.66E-01		-4.85E+00	1.26E+00	-3.856	0.000119	***	9.25E+00	1.48E+00	6.234	5.41E-10	***
SiteMineros	2.09E+01	2.77E+01	0.753	4.52E-01		1.19E+02	5.21E+01	2.28	0.022727	*	7.79E+02	6.15E+01	12.671	<2.00E-16	***
SitePailon	1.21E+02	2.80E+01	4.302	0.0000176	***	3.37E+02	5.27E+01	6.401	1.86E-10	***	7.49E+02	6.21E+01	12.053	<2.00E-16	***
SiteSanJulian	-3.16E+02	3.01E+01	-10.509	<2.00E-16	***	-2.14E+02	5.66E+01	-3.775	0.000164	***	-4.85E+02	6.68E+01	-7.268	4.97E-13	***
SiteYapacani	8.99E+01	2.60E+01	3.453	0.000564	***	-4.95E+01	4.89E+01	-1.011	0.311889		6.66E+02	5.77E+01	11.543	<2.00E-16	***
Precip:Max.Temp	-1.36E-02	1.51E-02	-0.899	0.368625		7.33E-02	2.84E-02	2.582	0.00989	**	-1.12E-01	3.35E-02	-3.35	0.000821	***
Precip:Min.Temp	-1.69E-01	1.88E-02	-9.015	<2.00E-16	***	-5.77E-02	3.53E-02	-1.635	1.02E-01		3.07E-03	4.16E-02	0.074	9.41E-01	
Precip:Sol.Rad	2.51E-01	2.37E-02	10.615	<2.00E-16	***	3.23E-02	4.45E-02	0.726	0.468107		3.08E-01	5.25E-02	5.865	5.13E-09	***
Max.Temp:Min.Temp	-1.16E+01	2.53E+00	-4.588	0.00000472	***	-6.56E+00	4.76E+00	-1.38	0.167829		3.29E+01	5.61E+00	5.867	5.07E-09	***
Max.Temp:Sol.Rad	5.11E+00	5.20E+00	0.983	0.3257		2.42E+01	9.78E+00	2.473	0.013473	*	3.02E-01	1.15E+01	0.026	0.979096	
Min.Temp:Sol.Rad	-1.16E+01	4.46E+00	-2.61	0.009101	**	-1.01E+00	8.38E+00	-0.12	0.904246		-3.63E+00	9.88E+00	-0.367	0.713337	

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 9, shows the significance of the climate variables in the last column for soybeans, maize and rice, respectively. Almost all variables are significant for the models, excluding solar radiation in all of its forms and the interaction terms (cross products) of precipitation multiplied by maximum temperature and maximum temperature multiplied by minimum temperature for soybeans. For maize, all variables are significant except for some interaction terms: precipitation multiplied by minimum temperature, precipitation multiplied by solar radiation, maximum temperature multiplied by minimum temperature and minimum temperature multiplied by solar radiation. Finally, rice shows significant values for most of the variables, excluding linear precipitation and the interaction terms: precipitation multiplied by minimum temperature, maximum temperature multiplied by solar radiation and minimum temperature multiplied by solar radiation.

Table 10: Linear, Quadratic, Cubic and Interaction Reduced Models (a)

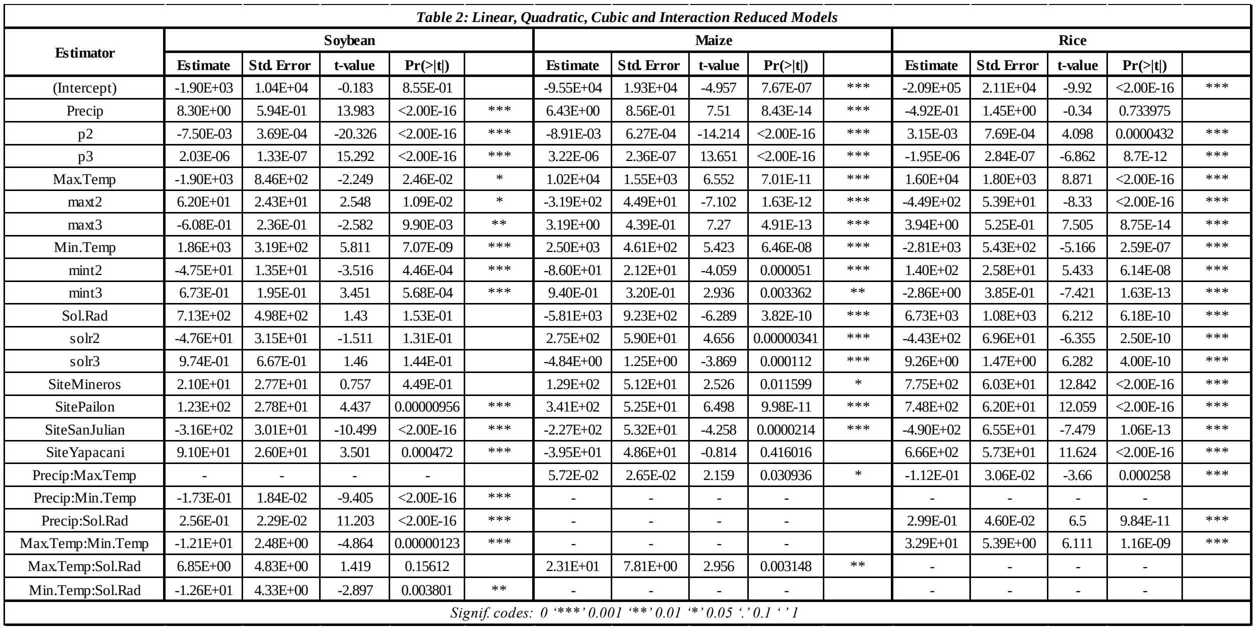

Table 2: Linear, Quadratic, Cubic and Interaction Reduced Models

Estimator	**Soybean**					**Maize**					**Rice**				
	Estimate	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**	
(Intercept)	-1.90E+03	1.04E+04	-0.183	8.55E-01		-9.55E+04	1.93E+04	-4.957	7.67E-07	***	-2.09E+05	2.11E+04	-9.92	<2.00E-16	***
Precip	8.30E+00	5.94E-01	13.983	<2.00E-16	***	6.43E+00	8.56E-01	7.51	8.43E-14	***	-4.92E-01	1.45E+00	-0.34	0.733975	
p2	-7.50E-03	3.69E-04	-20.326	<2.00E-16	***	-8.91E-03	6.27E-04	-14.214	<2.00E-16	***	3.15E-03	7.69E-04	4.098	0.0000432	***
p3	2.03E-06	1.33E-07	15.292	<2.00E-16	***	3.22E-06	2.36E-07	13.651	<2.00E-16	***	-1.95E-06	2.84E-07	-6.862	8.7E-12	***
Max.Temp	-1.90E+03	8.46E+02	-2.249	2.46E-02	*	1.02E+04	1.55E+03	6.552	7.01E-11	***	1.60E+04	1.80E+03	8.871	<2.00E-16	***
maxt2	6.20E+01	2.43E+01	2.548	1.09E-02	*	-3.19E+02	4.49E+01	-7.102	1.63E-12	***	-4.49E+02	5.39E+01	-8.33	<2.00E-16	***
maxt3	-6.08E-01	2.36E-01	-2.582	9.90E-03	**	3.19E+00	4.39E-01	7.27	4.91E-13	***	3.94E+00	5.25E-01	7.505	8.75E-14	***
Min.Temp	1.86E+03	3.19E+02	5.811	7.07E-09	***	2.50E+03	4.61E+02	5.423	6.46E-08	***	-2.81E+03	5.43E+02	-5.166	2.59E-07	***
mint2	-4.75E+01	1.35E+01	-3.516	4.46E-04	***	-8.60E+01	2.12E+01	-4.059	0.000051	***	1.40E+02	2.58E+01	5.433	6.14E-08	***
mint3	6.73E-01	1.95E-01	3.451	5.68E-04	***	9.40E-01	3.20E-01	2.936	0.003362	**	-2.86E+00	3.85E-01	-7.421	1.63E-13	***
Sol.Rad	7.13E+02	4.98E+02	1.43	1.53E-01		-5.81E+03	9.23E+02	-6.289	3.82E-10	***	6.73E+03	1.08E+03	6.212	6.18E-10	***
solr2	-4.76E+01	3.15E+01	-1.511	1.31E-01		2.75E+02	5.90E+01	4.656	0.00000341	***	-4.43E+02	6.96E+01	-6.355	2.50E-10	***
solr3	9.74E-01	6.67E-01	1.46	1.44E-01		-4.84E+00	1.25E+00	-3.869	0.000112	***	9.26E+00	1.47E+00	6.282	4.00E-10	***
SiteMineros	2.10E+01	2.77E+01	0.757	4.49E-01		1.29E+02	5.12E+01	2.526	0.011599	*	7.75E+02	6.03E+01	12.842	<2.00E-16	***
SitePailon	1.23E+02	2.78E+01	4.437	0.00000956	***	3.41E+02	5.25E+01	6.498	9.98E-11	***	7.48E+02	6.20E+01	12.059	<2.00E-16	***
SiteSanJulian	-3.16E+02	3.01E+01	-10.499	<2.00E-16	***	-2.27E+02	5.32E+01	-4.258	0.0000214	***	-4.90E+02	6.55E+01	-7.479	1.06E-13	***
SiteYapacani	9.10E+01	2.60E+01	3.501	0.000472	***	-3.95E+01	4.86E+01	-0.814	0.416016		6.66E+02	5.73E+01	11.624	<2.00E-16	***
Precip:Max.Temp	-	-	-	-		5.72E-02	2.65E-02	2.159	0.030936	*	-1.12E-01	3.06E-02	-3.66	0.000258	***
Precip:Min.Temp	-1.73E-01	1.84E-02	-9.405	<2.00E-16	***	-	-	-	-		-	-	-	-	
Precip:Sol.Rad	2.56E-01	2.29E-02	11.203	<2.00E-16	***	-	-	-	-		2.99E-01	4.60E-02	6.5	9.84E-11	***
Max.Temp:Min.Temp	-1.21E+01	2.48E+00	-4.864	0.00000123	***	-	-	-	-		3.29E+01	5.39E+00	6.111	1.16E-09	***
Max.Temp:Sol.Rad	6.85E+00	4.83E+00	1.419	0.15612		2.31E+01	7.81E+00	2.956	0.003148	**	-	-	-	-	
Min.Temp:Sol.Rad	-1.26E+01	4.33E+00	-2.897	0.003801	**	-	-	-	-		-	-	-	-	

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 10, reproduces the results after applying the Stepwise Regression Procedure and gets rid of the non- significant variables for all the “***a***” maximum models for soybeans, maize and rice, respectively.

Table 11: Linear, Quadratic and Interaction Maximum Models (b)

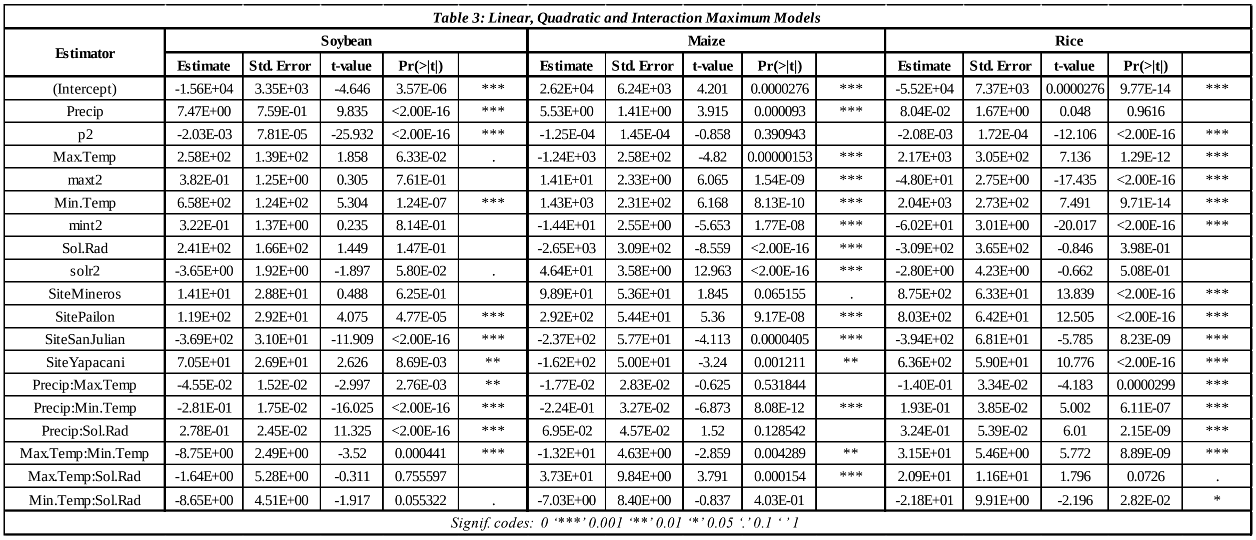

Table 3: Linear, Quadratic and Interaction Maximum Models

Estimator	Soybean					Maize					Rice				
	Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept)	-1.56E+04	3.35E+03	-4.646	3.57E-06	***	2.62E+04	6.24E+03	4.201	0.0000276	***	-5.52E+04	7.37E+03	0.0000276	9.77E-14	***
Precip	7.47E+00	7.59E-01	9.835	<2.00E-16	***	5.53E+00	1.41E+00	3.915	0.000093	***	8.04E-02	1.67E+00	0.048	0.9616	
p2	-2.03E-03	7.81E-05	-25.932	<2.00E-16	***	-1.25E-04	1.45E-04	-0.858	0.390943		-2.08E-03	1.72E-04	-12.106	<2.00E-16	***
Max.Temp	2.58E+02	1.39E+02	1.858	6.33E-02	.	-1.24E+03	2.58E+02	-4.82	0.00000153	***	2.17E+03	3.05E+02	7.136	1.29E-12	***
maxt2	3.82E-01	1.25E+00	0.305	7.61E-01		1.41E+01	2.33E+00	6.065	1.54E-09	***	-4.80E+01	2.75E+00	-17.435	<2.00E-16	***
Min.Temp	6.58E+02	1.24E+02	5.304	1.24E-07	***	1.43E+03	2.31E+02	6.168	8.13E-10	***	2.04E+03	2.73E+02	7.491	9.71E-14	***
mint2	3.22E-01	1.37E+00	0.235	8.14E-01		-1.44E+01	2.55E+00	-5.653	1.77E-08	***	-6.02E+01	3.01E+00	-20.017	<2.00E-16	***
Sol.Rad	2.41E+02	1.66E+02	1.449	1.47E-01		-2.65E+03	3.09E+02	-8.559	<2.00E-16	***	-3.09E+02	3.65E+02	-0.846	3.98E-01	
solr2	-3.65E+00	1.92E+00	-1.897	5.80E-02	.	4.64E+01	3.58E+00	12.963	<2.00E-16	***	-2.80E+00	4.23E+00	-0.662	5.08E-01	
SiteMineros	1.41E+01	2.88E+01	0.488	6.25E-01		9.89E+01	5.36E+01	1.845	0.065155	.	8.75E+02	6.33E+01	13.839	<2.00E-16	***
SitePailon	1.19E+02	2.92E+01	4.075	4.77E-05	***	2.92E+02	5.44E+01	5.36	9.17E-08	***	8.03E+02	6.42E+01	12.505	<2.00E-16	***
SiteSanJulian	-3.69E+02	3.10E+01	-11.909	<2.00E-16	***	-2.37E+02	5.77E+01	-4.113	0.0000405	***	-3.94E+02	6.81E+01	-5.785	8.23E-09	***
SiteYapacani	7.05E+01	2.69E+01	2.626	8.69E-03	**	-1.62E+02	5.00E+01	-3.24	0.001211	**	6.36E+02	5.90E+01	10.776	<2.00E-16	***
Precip:Max.Temp	-4.55E-02	1.52E-02	-2.997	2.76E-03	**	-1.77E-02	2.83E-02	-0.625	0.531844		-1.40E-01	3.34E-02	-4.183	0.0000299	***
Precip:Min.Temp	-2.81E-01	1.75E-02	-16.025	<2.00E-16	***	-2.24E-01	3.27E-02	-6.873	8.08E-12	***	1.93E-01	3.85E-02	5.002	6.11E-07	***
Precip:Sol.Rad	2.78E-01	2.45E-02	11.325	<2.00E-16	***	6.95E-02	4.57E-02	1.52	0.128542		3.24E-01	5.39E-02	6.01	2.15E-09	***
Max.Temp:Min.Temp	-8.75E+00	2.49E+00	-3.52	0.000441	***	-1.32E+01	4.63E+00	-2.859	0.004289	**	3.15E+01	5.46E+00	5.772	8.89E-09	***
Max.Temp:Sol.Rad	-1.64E+00	5.28E+00	-0.311	0.755597		3.73E+01	9.84E+00	3.791	0.000154	***	2.09E+01	1.16E+01	1.796	0.0726	.
Min.Temp:Sol.Rad	-8.65E+00	4.51E+00	-1.917	0.055322	.	-7.03E+00	8.40E+00	-0.837	4.03E-01		-2.18E+01	9.91E+00	-2.196	2.82E-02	*

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 11, shows the significance of the climate variables in the last column for the "***b***" models. In this case the cubic variables are omitted. Soybeans model indicates that squared maximum temperature, squared minimum temperature, solar radiation in quadratic and linear forms and the interaction term, maximum temperature multiplied by solar radiation, are not significant. Maize model shows that precipitation squared, precipitation multiplied by maximum temperature, precipitation multiplied by solar radiation, and minimum temperature multiplied by maximum temperature are not significant. Finally, in the rice model, linear precipitation and solar radiation (linear and quadratic), are not significant.

Table 12: Linear, Quadratic and Interaction Reduced Models (b)

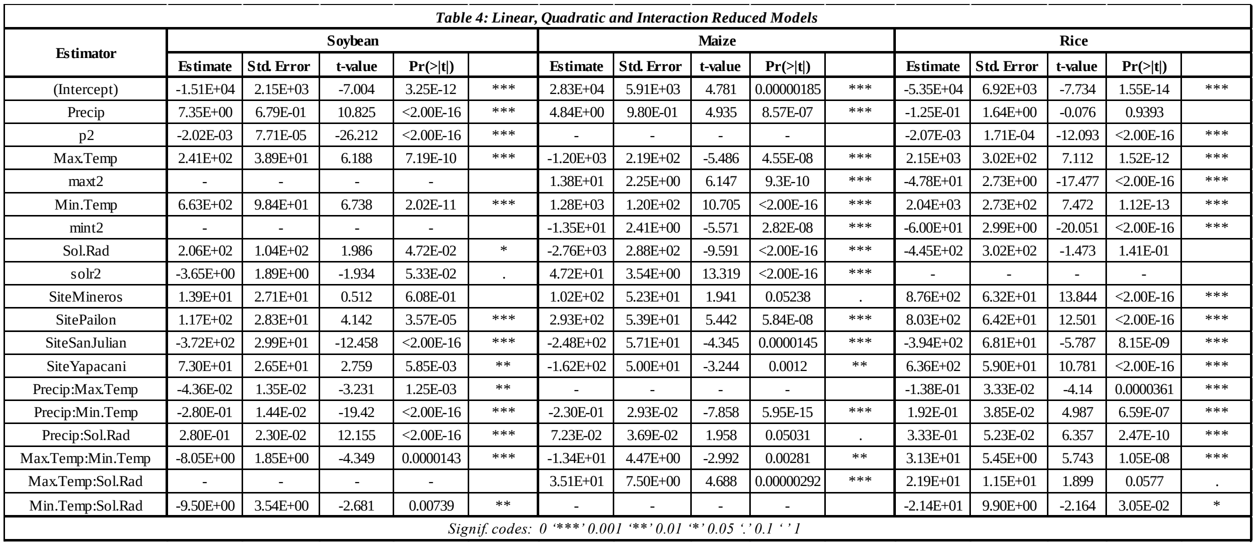

Table 4: Linear, Quadratic and Interaction Reduced Models

Estimator	Soybean					Maize					Rice				
	Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept)	-1.51E+04	2.15E+03	-7.004	3.25E-12	***	2.83E+04	5.91E+03	4.781	0.00000185	***	-5.35E+04	6.92E+03	-7.734	1.55E-14	***
Precip	7.35E+00	6.79E-01	10.825	<2.00E-16	***	4.84E+00	9.80E-01	4.935	8.57E-07	***	-1.25E-01	1.64E+00	-0.076	0.9393	
p2	-2.02E-03	7.71E-05	-26.212	<2.00E-16	***	-	-	-	-		-2.07E-03	1.71E-04	-12.093	<2.00E-16	***
Max.Temp	2.41E+02	3.89E+01	6.188	7.19E-10	***	-1.20E+03	2.19E+02	-5.486	4.55E-08	***	2.15E+03	3.02E+02	7.112	1.52E-12	***
maxt2	-	-	-	-		1.38E+01	2.25E+00	6.147	9.3E-10	***	-4.78E+01	2.73E+00	-17.477	<2.00E-16	***
Min.Temp	6.63E+02	9.84E+01	6.738	2.02E-11	***	1.28E+03	1.20E+02	10.705	<2.00E-16	***	2.04E+03	2.73E+02	7.472	1.12E-13	***
mint2	-	-	-	-		-1.35E+01	2.41E+00	-5.571	2.82E-08	***	-6.00E+01	2.99E+00	-20.051	<2.00E-16	***
Sol.Rad	2.06E+02	1.04E+02	1.986	4.72E-02	*	-2.76E+03	2.88E+02	-9.591	<2.00E-16	***	-4.45E+02	3.02E+02	-1.473	1.41E-01	
solr2	-3.65E+00	1.89E+00	-1.934	5.33E-02	.	4.72E+01	3.54E+00	13.319	<2.00E-16	***	-	-	-	-	
SiteMineros	1.39E+01	2.71E+01	0.512	6.08E-01		1.02E+02	5.23E+01	1.941	0.05238	.	8.76E+02	6.32E+01	13.844	<2.00E-16	***
SitePailon	1.17E+02	2.83E+01	4.142	3.57E-05	***	2.93E+02	5.39E+01	5.442	5.84E-08	***	8.03E+02	6.42E+01	12.501	<2.00E-16	***
SiteSanJulian	-3.72E+02	2.99E+01	-12.458	<2.00E-16	***	-2.48E+02	5.71E+01	-4.345	0.0000145	***	-3.94E+02	6.81E+01	-5.787	8.15E-09	***
SiteYapacani	7.30E+01	2.65E+01	2.759	5.85E-03	**	-1.62E+02	5.00E+01	-3.244	0.0012	**	6.36E+02	5.90E+01	10.781	<2.00E-16	***
Precip:Max.Temp	-4.36E-02	1.35E-02	-3.231	1.25E-03	**	-	-	-	-		-1.38E-01	3.33E-02	-4.14	0.0000361	***
Precip:Min.Temp	-2.80E-01	1.44E-02	-19.42	<2.00E-16	***	-2.30E-01	2.93E-02	-7.858	5.95E-15	***	1.92E-01	3.85E-02	4.987	6.59E-07	***
Precip:Sol.Rad	2.80E-01	2.30E-02	12.155	<2.00E-16	***	7.23E-02	3.69E-02	1.958	0.05031	.	3.33E-01	5.23E-02	6.357	2.47E-10	***
Max.Temp:Min.Temp	-8.05E+00	1.85E+00	-4.349	0.0000143	***	-1.34E+01	4.47E+00	-2.992	0.00281	**	3.13E+01	5.45E+00	5.743	1.05E-08	***
Max.Temp:Sol.Rad	-	-	-	-		3.51E+01	7.50E+00	4.688	0.00000292	***	2.19E+01	1.15E+01	1.899	0.0577	.
Min.Temp:Sol.Rad	-9.50E+00	3.54E+00	-2.681	0.00739	**	-	-	-	-		-2.14E+01	9.90E+00	-2.164	3.05E-02	*

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 12, represents the results of "***b***" reduced models eliminating the non-significant variables. Most of the linear and quadratic terms are significant in the models, except the quadratic term of maximum temperature in soybeans, precipitation squared in maize and precipitation linear in rice; while most of the interaction terms are significant for all models.

Table 13: Linear, Quadratic and Cubic Maximum Models (c)

Table 5: Linear, Quadratic and Cubic Maximum Models

Estimator	**Soybean**					**Maize**					**Rice**				
	Estimate	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**	
(Intercept)	-2.95E+04	9.16E+03	-3.217	1.31E-03	**	-1.11E+05	1.65E+04	-6.714	2.39E-11	***	-2.15E+05	1.98E+04	-10.874	<2.00E-16	***
Precip	1.10E+01	2.73E-01	40.494	<2.00E-16	***	8.04E+00	4.90E-01	16.418	<2.00E-16	***	3.39E+00	5.88E-01	5.763	9.36E-09	***
p2	-9.96E-03	3.31E-04	-30.075	<2.00E-16	***	-8.57E-03	5.95E-04	-14.404	<2.00E-16	***	2.73E-04	7.15E-04	0.382	0.702	
p3	2.75E-06	1.24E-07	22.105	<2.00E-16	***	3.09E-06	2.24E-07	13.825	<2.00E-16	***	-1.07E-06	2.69E-07	-3.996	0.0000665	***
Max.Temp	-3.43E+02	7.67E+02	-0.447	6.55E-01		1.08E+04	1.38E+03	7.837	7.02E-15	***	1.51E+04	1.66E+03	9.119	<2.00E-16	***
maxt2	1.63E+01	2.27E+01	0.716	4.74E-01		-3.24E+02	4.08E+01	-7.927	3.48E-15	***	-4.11E+02	4.90E+01	-8.378	<2.00E-16	***
maxt3	-2.08E-01	2.23E-01	-0.929	3.53E-01		3.22E+00	4.01E-01	8.016	1.73E-15	***	3.62E+00	4.82E-01	7.516	8.07E-14	***
Min.Temp	2.38E+03	2.57E+02	9.252	<2.00E-16	***	2.50E+03	4.62E+02	5.418	6.65E-08	***	-2.70E+03	5.55E+02	-4.87	1.19E-06	***
mint2	-9.42E+01	1.18E+01	-7.968	2.51E-15	***	-8.62E+01	2.12E+01	-4.06	0.0000507	***	1.79E+02	2.55E+01	7.005	3.24E-12	***
mint3	1.24E+00	1.79E-01	6.946	4.87E-12	***	9.43E-01	3.21E-01	2.94	0.00332	**	-3.36E+00	3.85E-01	-8.723	<2.00E-16	***
Sol.Rad	1.53E+03	5.05E+02	3.017	2.58E-03	**	-5.36E+03	9.08E+02	-5.902	4.14E-09	***	8.40E+03	1.09E+03	7.703	1.97E-14	***
solr2	-8.43E+01	3.27E+01	-2.58	9.96E-03	**	2.95E+02	5.87E+01	5.032	5.23E-07	***	-5.30E+02	7.05E+01	-7.509	8.51E-14	***
solr3	1.63E+00	6.93E-01	2.36	1.84E-02	*	-5.32E+00	1.24E+00	-4.278	0.0000196	***	1.10E+01	1.49E+00	7.347	2.80E-13	***
SiteMineros	3.76E+01	2.85E+01	1.319	1.87E-01		1.27E+02	5.12E+01	2.482	0.01313	*	7.58E+02	6.16E+01	12.311	<2.00E-16	***
SitePailon	1.55E+02	2.90E+01	5.355	9.41E-08	***	3.30E+02	5.21E+01	6.323	3.06E-10	***	7.85E+02	6.26E+01	12.538	<2.00E-16	***
SiteSanJulian	-3.72E+02	2.96E+01	-12.603	<2.00E-16	***	-2.24E+02	5.31E+01	-4.226	0.0000247	***	-4.50E+02	6.38E+01	-7.064	2.14E-12	***
SiteYapacani	1.31E+02	2.70E+01	4.856	0.00000128	***	-4.74E+01	4.85E+01	-0.978	0.32837		6.89E+02	5.83E+01	11.815	<2.00E-16	***

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 13, shows the significance of the climate variables in the last column for the "***c***" models. In this case the interaction (cross product) variables are omitted. For soybeans all the variables are significant but maximum temperature in all of its forms. Maize shows that all the variables are significant. Finally, rice shows that only precipitation in quadratic form is not significant.

Table 14: Linear, Quadratic and Cubic Reduced Models (c)

Table 6: Linear, Quadratic and Cubic Reduced Models

Estimator	**Soybean**					**Maize**					**Rice**				
	Estimate	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**		**Estimate**	**Std. Error**	**t-value**	**Pr(>|t|)**	
(Intercept)	-3.33E+04	3.14E+03	-10.606	<2.00E-16	***	-1.11E+05	1.65E+04	-6.714	2.39E-11	***	-2.16E+05	1.97E+04	-10.975	<2.00E-16	***
Precip	1.11E+01	2.71E-01	40.81	<2.00E-16	***	8.04E+00	4.90E-01	16.418	<2.00E-16	***	3.61E+00	1.59E-01	22.641	<2.00E-16	***
p2	-9.98E-03	3.29E-04	-30.339	<2.00E-16	***	-8.57E-03	5.95E-04	-14.404	<2.00E-16	***	-	-	-	-	
p3	2.76E-06	1.24E-07	22.277	<2.00E-16	***	3.09E-06	2.24E-07	13.825	<2.00E-16	***	-9.72E-07	5.32E-08	-18.276	<2.00E-16	***
Max.Temp	-	-	-	-		1.08E+04	1.38E+03	7.837	7.02E-15	***	1.52E+04	1.64E+03	9.228	<2.00E-16	***
maxt2	6.11E+00	1.01E+00	6.065	1.54E-09	***	-3.24E+02	4.08E+01	-7.927	3.48E-15	***	-4.13E+02	4.87E+01	-8.478	<2.00E-16	***
maxt3	-1.08E-01	1.93E-02	-5.605	2.33E-08	***	3.22E+00	4.01E-01	8.016	1.73E-15	***	3.64E+00	4.79E-01	7.606	4.1E-14	***
Min.Temp	2.37E+03	2.57E+02	9.243	<2.00E-16	***	2.50E+03	4.62E+02	5.418	6.65E-08	***	-2.73E+03	5.49E+02	-4.972	7.12E-07	***
mint2	-9.40E+01	1.18E+01	-7.959	2.70E-15	***	-8.62E+01	2.12E+01	-4.06	0.0000507	***	1.80E+02	2.53E+01	7.103	1.62E-12	***
mint3	1.24E+00	1.78E-01	6.938	5.14E-12	***	9.43E-01	3.21E-01	2.94	0.00332	**	-3.38E+00	3.83E-01	-8.813	<2.00E-16	***
Sol.Rad	1.54E+03	5.05E+02	3.046	2.35E-03	**	-5.36E+03	9.08E+02	-5.902	4.14E-09	***	8.43E+03	1.09E+03	7.752	1.35E-14	***
solr2	-8.51E+01	3.26E+01	-2.608	9.18E-03	**	2.95E+02	5.87E+01	5.032	5.23E-07	***	-5.32E+02	7.03E+01	-7.563	5.68E-14	***
solr3	1.65E+00	6.91E-01	2.387	1.71E-02	*	-5.32E+00	1.24E+00	-4.278	0.0000196	***	1.10E+01	1.49E+00	7.405	1.83E-13	***
SiteMineros	3.72E+01	2.85E+01	1.306	1.92E-01		1.27E+02	5.12E+01	2.482	0.01313	*	7.56E+02	6.13E+01	12.335	<2.00E-16	***
SitePailon	1.55E+02	2.90E+01	5.344	9.99E-08	***	3.30E+02	5.21E+01	6.323	3.06E-10	***	7.84E+02	6.26E+01	12.536	<2.00E-16	***
SiteSanJulian	-3.72E+02	2.95E+01	-12.604	<2.00E-16	***	-2.24E+02	5.31E+01	-4.226	0.0000247	***	-4.49E+02	6.36E+01	-7.056	2.27E-12	***
SiteYapacani	1.34E+02	2.65E+01	5.037	0.000000509	***	-4.74E+01	4.85E+01	-0.978	0.32837		6.90E+02	5.83E+01	11.838	<2.00E-16	***

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 14, represents the results for the "***c***" reduced models, eliminating the non-significant variables. The soybeans eliminate linear maximum temperature; rice eliminates precipitation squared, while maize is the same as the maximum model.

Table 15: Linear and Quadratic Maximum Models (d)

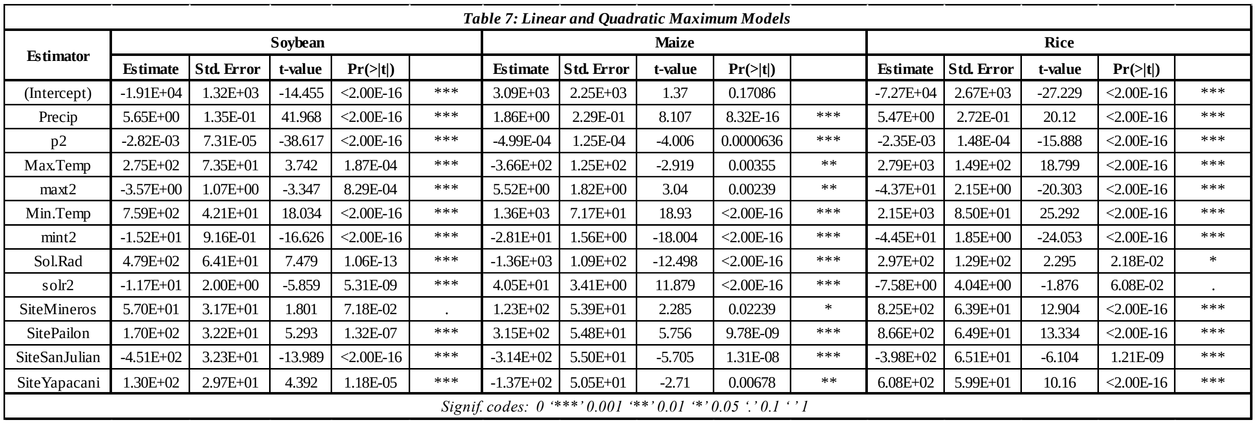

Table 7: Linear and Quadratic Maximum Models

Estimator	Soybean					Maize					Rice				
	Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept)	-1.91E+04	1.32E+03	-14.455	<2.00E-16	***	3.09E+03	2.25E+03	1.37	0.17086		-7.27E+04	2.67E+03	-27.229	<2.00E-16	***
Precip	5.65E+00	1.35E-01	41.968	<2.00E-16	***	1.86E+00	2.29E-01	8.107	8.32E-16	***	5.47E+00	2.72E-01	20.12	<2.00E-16	***
p2	-2.82E-03	7.31E-05	-38.617	<2.00E-16	***	-4.99E-04	1.25E-04	-4.006	0.0000636	***	-2.35E-03	1.48E-04	-15.888	<2.00E-16	***
Max.Temp	2.75E+02	7.35E+01	3.742	1.87E-04	***	-3.66E+02	1.25E+02	-2.919	0.00355	**	2.79E+03	1.49E+02	18.799	<2.00E-16	***
maxt2	-3.57E+00	1.07E+00	-3.347	8.29E-04	***	5.52E+00	1.82E+00	3.04	0.00239	**	-4.37E+01	2.15E+00	-20.303	<2.00E-16	***
Min.Temp	7.59E+02	4.21E+01	18.034	<2.00E-16	***	1.36E+03	7.17E+01	18.93	<2.00E-16	***	2.15E+03	8.50E+01	25.292	<2.00E-16	***
mint2	-1.52E+01	9.16E-01	-16.626	<2.00E-16	***	-2.81E+01	1.56E+00	-18.004	<2.00E-16	***	-4.45E+01	1.85E+00	-24.053	<2.00E-16	***
Sol.Rad	4.79E+02	6.41E+01	7.479	1.06E-13	***	-1.36E+03	1.09E+02	-12.498	<2.00E-16	***	2.97E+02	1.29E+02	2.295	2.18E-02	*
solr2	-1.17E+01	2.00E+00	-5.859	5.31E-09	***	4.05E+01	3.41E+00	11.879	<2.00E-16	***	-7.58E+00	4.04E+00	-1.876	6.08E-02	.
SiteMineros	5.70E+01	3.17E+01	1.801	7.18E-02	.	1.23E+02	5.39E+01	2.285	0.02239	*	8.25E+02	6.39E+01	12.904	<2.00E-16	***
SitePailon	1.70E+02	3.22E+01	5.293	1.32E-07	***	3.15E+02	5.48E+01	5.756	9.78E-09	***	8.66E+02	6.49E+01	13.334	<2.00E-16	***
SiteSanJulian	-4.51E+02	3.23E+01	-13.989	<2.00E-16	***	-3.14E+02	5.50E+01	-5.705	1.31E-08	***	-3.98E+02	6.51E+01	-6.104	1.21E-09	***
SiteYapacani	1.30E+02	2.97E+01	4.392	1.18E-05	***	-1.37E+02	5.05E+01	-2.71	0.00678	**	6.08E+02	5.99E+01	10.16	<2.00E-16	***

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 15, shows the significance of the climate variables in the last column for the "***d***" models. In this case the interaction (cross product) and the cubic variables are omitted. For soybeans, maize and rice all the linear and quadratic variables are significant.

Table 16: Linear and Quadratic Reduced Models (d)

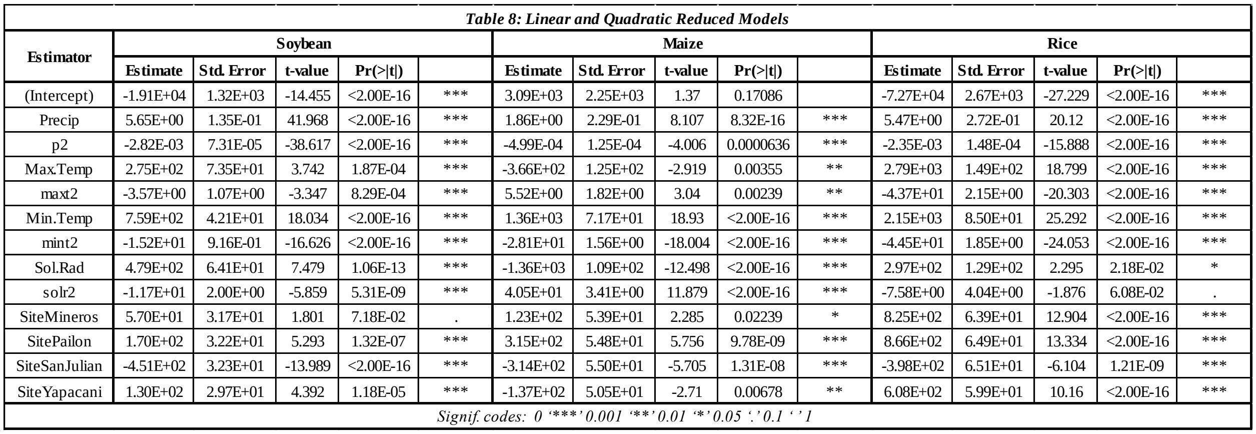

Table 8: Linear and Quadratic Reduced Models

Estimator	Soybean					Maize					Rice				
	Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)		Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept)	-1.91E+04	1.32E+03	-14.455	<2.00E-16	***	3.09E+03	2.25E+03	1.37	0.17086		-7.27E+04	2.67E+03	-27.229	<2.00E-16	***
Precip	5.65E+00	1.35E-01	41.968	<2.00E-16	***	1.86E+00	2.29E-01	8.107	8.32E-16	***	5.47E+00	2.72E-01	20.12	<2.00E-16	***
p2	-2.82E-03	7.31E-05	-38.617	<2.00E-16	***	-4.99E-04	1.25E-04	-4.006	0.0000636	***	-2.35E-03	1.48E-04	-15.888	<2.00E-16	***
Max.Temp	2.75E+02	7.35E+01	3.742	1.87E-04	***	-3.66E+02	1.25E+02	-2.919	0.00355	**	2.79E+03	1.49E+02	18.799	<2.00E-16	***
maxt2	-3.57E+00	1.07E+00	-3.347	8.29E-04	***	5.52E+00	1.82E+00	3.04	0.00239	**	-4.37E+01	2.15E+00	-20.303	<2.00E-16	***
Min.Temp	7.59E+02	4.21E+01	18.034	<2.00E-16	***	1.36E+03	7.17E+01	18.93	<2.00E-16	***	2.15E+03	8.50E+01	25.292	<2.00E-16	***
mint2	-1.52E+01	9.16E-01	-16.626	<2.00E-16	***	-2.81E+01	1.56E+00	-18.004	<2.00E-16	***	-4.45E+01	1.85E+00	-24.053	<2.00E-16	***
Sol.Rad	4.79E+02	6.41E+01	7.479	1.06E-13	***	-1.36E+03	1.09E+02	-12.498	<2.00E-16	***	2.97E+02	1.29E+02	2.295	2.18E-02	*
solr2	-1.17E+01	2.00E+00	-5.859	5.31E-09	***	4.05E+01	3.41E+00	11.879	<2.00E-16	***	-7.58E+00	4.04E+00	-1.876	6.08E-02	.
SiteMineros	5.70E+01	3.17E+01	1.801	7.18E-02	.	1.23E+02	5.39E+01	2.285	0.02239	*	8.25E+02	6.39E+01	12.904	<2.00E-16	***
SitePailon	1.70E+02	3.22E+01	5.293	1.32E-07	***	3.15E+02	5.48E+01	5.756	9.78E-09	***	8.66E+02	6.49E+01	13.334	<2.00E-16	***
SiteSanJulian	-4.51E+02	3.23E+01	-13.989	<2.00E-16	***	-3.14E+02	5.50E+01	-5.705	1.31E-08	***	-3.98E+02	6.51E+01	-6.104	1.21E-09	***
SiteYapacani	1.30E+02	2.97E+01	4.392	1.18E-05	***	-1.37E+02	5.05E+01	-2.71	0.00678	**	6.08E+02	5.99E+01	10.16	<2.00E-16	***

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1*

Table 16, shows the results of the reduced models where soybeans, maize and rice are the same as the maximum models.

After having all the 8 maximum and reduced form candidate models, the best fitted models are selected using the different evaluation criteria mentioned in the previous lines. The summary of results is presented in Table 17:

Table 17: Model Selection with Different Criteria

Table 9: Model Selection with Different Criteria

Crop		Model	R2	R2a	AIC	BIC	CorrSpear
Soybean	*a*	Linear, Quadratic, Cubic and Interaction Maximum Model	0.8514	0.8499	33842.0000	33979.8800	0.8147
	a	Linear, Quadratic, Cubic and Interaction Reduced Model	0.8513	0.8499	33840.8200	33972.9500	0.8143
	b	Linear, Quadratic and Interaction Maximum Model	0.8349	0.8336	34076.4800	34191.3800	0.7936
	b	Linear, Quadratic and Interaction Reduced Model	0.8349	0.8338	34070.8000	34168.4600	0.7936
	c	Linear, Quadratic and Cubic Maximum Model	0.8361	0.8349	34056.0300	34159.4400	0.7827
	c	Linear, Quadratic and Cubic Reduced Model	0.8361	0.8350	34054.2300	34151.9000	0.7824
	d	Linear and Quadratic Maximum Model	0.7945	0.7934	34570.4000	34650.8300	0.7438
	d	Linear and Quadratic Reduced Model	0.7945	0.7934	34570.4000	34650.8300	0.7438
Maize	*a*	Linear, Quadratic, Cubic and Interaction Maximum Model	0.6283	0.6247	36758.9700	36896.8500	0.5607
	a	Linear, Quadratic, Cubic and Interaction Reduced Model	0.6276	0.6247	36755.2500	36870.1600	0.5555
	b	Linear, Quadratic and Interaction Maximum Model	0.5950	0.5919	36948.8600	37063.7600	0.5617
	b	Linear, Quadratic and Interaction Reduced Model	0.5946	0.5920	36945.2000	37042.8600	0.5616
	c	Linear, Quadratic and Cubic Maximum Model	0.6259	0.6233	36761.8200	36865.2300	0.5558
	c	Linear, Quadratic and Cubic Reduced Model	0.6259	0.6233	36761.8200	36865.2300	0.5558
	d	Linear and Quadratic Maximum Model	0.5783	0.5761	37030.2500	37110.6800	0.5387
	d	Linear and Quadratic Reduced Model	0.5783	0.5761	37030.2500	37110.6800	0.5387
Rice	*a*	Linear, Quadratic, Cubic and Interaction Maximum Model	0.7778	0.7757	37522.2700	37660.1500	0.5529
	a	Linear, Quadratic, Cubic and Interaction Reduced Model	0.7778	0.7759	37516.4900	37637.1300	0.5531
	b	Linear, Quadratic and Interaction Maximum Model	0.7577	0.7558	37714.2600	37829.1600	0.5591
	b	Linear, Quadratic and Interaction ReducedModel	0.7577	0.7559	37712.7000	37821.8500	0.5585
	c	Linear, Quadratic and Cubic Maximum Model	0.7681	0.7664	37609.3800	37712.7900	0.5447
	c	Linear, Quadratic and Cubic Reduced Model	0.7681	0.7665	37607.5300	37705.1900	0.5450
	d	Linear and Quadratic Maximum Model	0.7454	0.7441	37816.3900	37896.8200	0.5594
	d	Linear and Quadratic Reduced Model	0.7454	0.7441	37816.3900	37896.8200	0.5594

The ***adjusted R***^{2}, ***AIC*** and ***BIC*** criteria, coincide in choosing ***a*** reduced form models for soybeans, maize and rice, respectively. These models include only significant linear, quadratic, cubic and interaction terms. On the other hand, the ***Spearman*** correlation coefficient chooses the maximum model ***a*** for soybeans (linear, quadratic, cubic and interaction regressors), the maximum model ***b*** for maize, and the maximum model ***d*** (linear and quadratic) for rice. For these reasons, the chosen regressions are the "***a***" reduced form models which include only significant linear, quadratic, cubic and interaction terms for all crops.

1)

$$\textbf{Soybeans Yield} = -1899 + 8.31\, Precip - 0.007\, Precip^2 + 0.000002026\, Precip^3 - 1904\, MaxTemp + 61.98\, MaxTemp^2 - 0.61\, MaxTemp^3 + 1856\, MinTemp - 47.45\, MinTemp^2 + 0.67\, MinTemp^3 + 712.7\, SolRad - 47.58\, SolRad^2 + 0.97\, SolRad^3 + SoilDummy_i - 0.17\, Precip*MinTemp + 0.25\, Precip*SolRad - 12.06\, MaxTemp*MinTemp + 6.85\, MaxTemp*SolRad - 12.56\, MinTemp*SolRad$$

2)

$$\textbf{Maize Yield} = -95510 + 6.43\, Precip - 0.009\, Precip^2 + 0.000003222\, Precip^3 - 10170\, MaxTemp - 319.2\, MaxTemp^2 + 3.189\, MaxTemp^3 + 2500\, MinTemp - 85.99\, MinTemp^2 + 0.9397\, MinTemp^3 - 5805\, SolRad + 274.5\, SolRad^2 - 4.838\, SolRad^3 + SoilDummy_i + 0.05724\, Precip*MaxTemp + 23.09\, MaxTemp*SolRad$$

3)

$$\textbf{Rice Yield} = -209100 - 0.4916\, Precip + 0.003151\, Precip^2 - 0.000001949\, Precip^3 + 15960\, MaxTemp - 449.2\, MaxTemp^2 + 3.939\, MaxTemp^3 - 2807\, MinTemp + 139.9\, MinTemp^2 - 2.857\, MinTemp^3 + 6726\, SolRad - 442.5\, SolRad^2 + 9.257\, SolRad^3 + SoilDummy_i - 0.1119\, Precip*MaxTemp + 0.2991\, Precip*SolRad + 32.94\, MaxTemp*MinTemp$$

For validating the selected models, a correlation analysis is done to analyze the mean yields of soybeans, maize and rice in the different production zones and different planting dates obtained by the DSSAT simulation models compared to the same results obtained by the best regression models (***a***) which are the ***Response Functions***.

Figure 9: DSSAT and Response Function Mean Crop Yields at Different Planting Dates

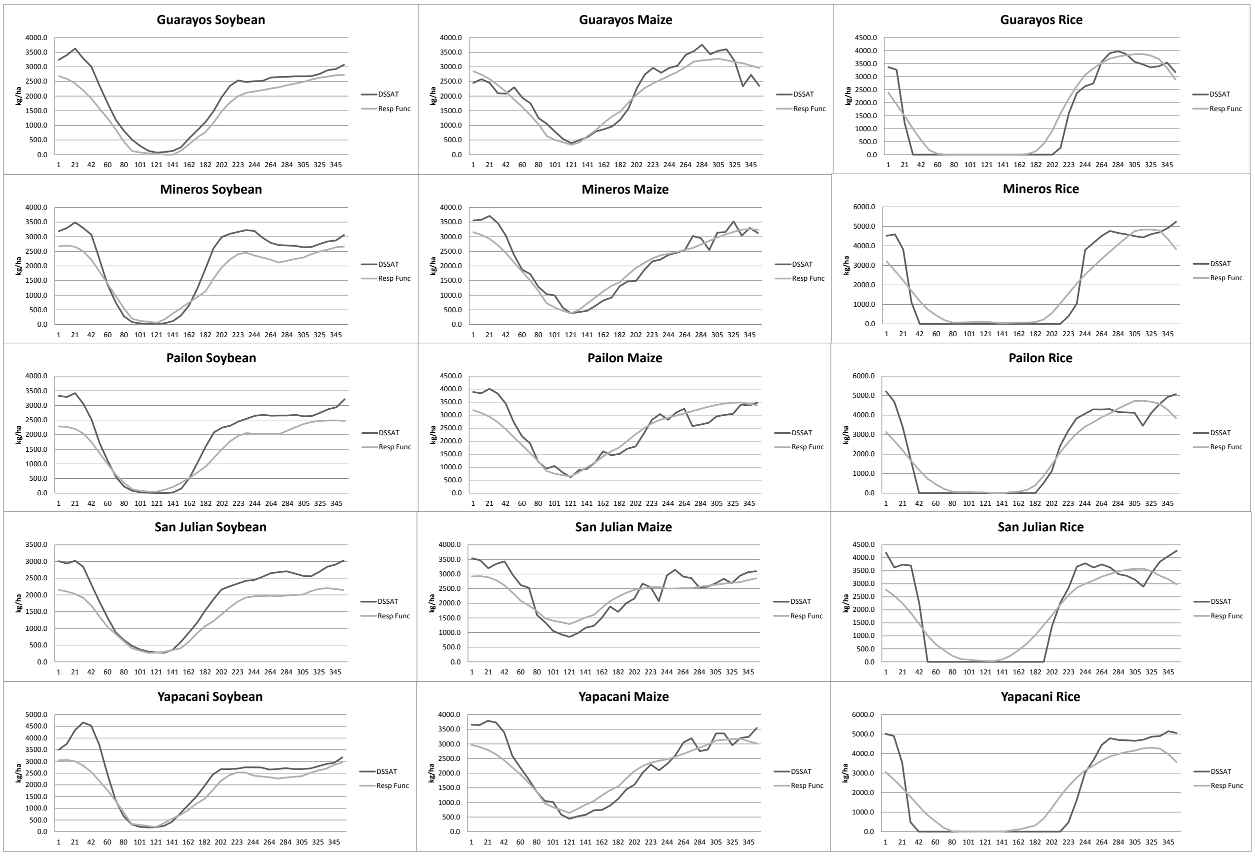

Figure 9, illustrates the mean yields for the 3 crop models for all the 5 production areas in the vertical axis, while the horizontal axis shows the different planting days (days of the year, from 1 to 365). As it is observed the response functions are very closely fitted to mean simulated yields during the whole year.

Table 18: Correlation between DSSAT and Response Functions Mean Yields

Production Zone	Soybean	Maize	Rice
Guarayos	0.97	0.95	0.96
Mineros	0.97	0.96	0.94
Pailon	0.97	0.90	0.94
San Julian	0.99	0.92	0.92
Yapacani	0.94	0.94	0.92

When doing an assessment of mean yields (2001-2007) for each of the crops and planting dates, the correlation between the results obtained from DSSAT series of crop models and the Response Functions developed in the previous steps is very high, 97% for soybeans, 93% for maize and 94% for rice on average.

4. Conclusions

This paper has studied the yields of soybeans, maize and rice in the 5 most important production areas of Santa Cruz, Bolivia with focus on their relationships with observed meteorological data. First the calibrated and validated CERES and CROPGRO series of crop models included in the DSSAT software are run for 7 years in 10-day time intervals for the 5 production areas (1260 simulations), in order to create robust Response Functions from these results. After that, a vigorous statistical analysis has been implemented for choosing the best models for the 3 mentioned crops to fit the simulations of the empirical crop models. Linear, quadratic, cubic and interaction terms have been introduced to test for the individual and general significances. The best models according to all the selection criteria are the reduced forms of the maximum model which includes linear, quadratic, cubic and interaction regressors. After choosing the model, they are used to quantify the average yields (2001-2007) for all of the different planting dates and production zones (1260 different yields), which then are compared with the results of the DSSAT series of crop models. During the time horizon the results of the correlation coefficients between yields from crop models and yields from the derived response functions are very high, 97, 93 and 94% for soybeans, maize and rice, respectively, which validate the prediction power of the response functions. The used estimation technique has not been implemented so far for other previous studies; the weather variables included are: precipitation, solar radiation, minimum temperature, maximum temperature and soil characteristics in contrast to other studies which only mean temperature, CO_2 concentration and precipitation are included. On the other hand, as these response functions come from very detailed and sophisticated crop models, the predictions can be more accurate than using census or survey data from cross-sectional analysis. What is more, it is quite interesting and novel for the sample size and the intrinsic adaptation measure of planting date. When running the model, one can determine the planting date with the highest mean yield, and/or the lowest variance, which can be very useful for impact analysis extrapolation in the whole Santa Cruz Department.

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Chapter 3: Efficient Adaptation in the Bolivian Agriculture from a Bottom – Up Approach

Abstract

There are many adaptation options that can be undertaken in response to climate change in every sector. Adaptation is one of the most important links between an initial environmental change and the final consequences to society. As a consequence, adaptation (including its costs and benefits) must be taken into account in order to design efficient climate change policies. This paper analyses the change of the planting date and crop choice as a first experimental example of the variety of adaptation measures that can be applied in the Bolivian agriculture sector. The study is developed in 3 of the most important production Provinces of Bolivia for soybeans, maize and rice grown under rainfed conditions. After the most efficient planting date has been identified for each of the crops, a Cost-Benefit Analysis is developed for the IPCC's A2 and B2 SRES Scenarios with and without adaptation for illustrating the final consequences of climate change and adaptation on producer's net income in the Region. For quantifying those impacts and adaptation options, the calibrated and validated CERES and CROPGRO crop models are used. The crop model simulations replicate farmer's behavior very well, showing that the best planting dates (with higher yields and lower variability from year to year) are between the months of October and December (days of the year 274 to 365) for the baseline, consistent with the observations of fieldwork. When introducing the climate change impact scenarios, it is observed that climate change without adaptation is counterproductive for most of the areas and crops with yield reductions ranging from -3 to -8% for soybeans, -3 to -31% for maize and -2 to -73% for rice. While, when applying the adaptation measure, the counterproductive effects of climate change can be reduced and/or exceeded for most of the scenarios and production zones with increases ranging from 3 to 22% for soybeans, 4 to 25% for maize and 3 to 15% for rice. However, some losses are still observed for the long run in both scenarios, though these losses are smaller when compared to the scenarios without adaptation. Finally, with these results, a Cost-Benefit analysis is developed to compare farmer's net incomes with and without adaptation. The results demonstrate that climate change without adaptation can reduce soybeans, maize and rice net incomes but if efficient planting date is used, increases are observed for the short run, and the losses in the long run are much reduced. The most efficient planting dates and most profitable crops are identified for all production Provinces, but in general with the observed trend and climate change scenarios, the planting dates are expected to be slightly delayed in the short run (10 to 40 days) and even more delayed in the long run (up to 70 days). Only rice seems to react better to early sowing, due to the fact of more temperature and rainfall in the winter time.

Keywords

Climate Change, Adaptation, Crop Model, Soybeans, Maize, Rice, Planting Date, Cost-Benefit, Bolivia**.**

1. Introduction

As Mendelsohn, R., 2000 mentions: *"Firms and individuals will likely engage in substantial private adaptation with respect to climate change in such sectors as farming, energy, timber, and recreation because it is in their interest to do so. Whether the world's governments settle on strict abatement policies or no policies at all, one issue every country in the world must face is how to adapt to the future changes in climate that will occur".* There are many adaptations that can be undertaken in response to climate change. Damages from climate change in virtually every sector, both market and nonmarket, can be reduced by taking the appropriate responses. Adaptation is consequently one of the important links between environmental change and the final consequences to society. Adaptation (including its costs and benefits) must consequently be taken into account for designing efficient climate change policies. Agricultural systems have shown considerable capacity to adapt to the climate changes in land management practices, crop and cultivar choice and selection of animal species and technologies to increase efficiency of water use have all been used to change the geographic and climate spread of our agricultural activities. A good source of available adaptation measures for agriculture activities is found in Smit and Skinner, 2002. The paper systematically classifies and characterizes agricultural adaptation options to climate change according to the involvement of different agents (producers, industries and governments); the intent, timing and duration of employment of the adaptation; the form and type of the adaptive measure; and the relationship to processes already in place to cope with risks associated with climate stresses. The results reveal that most adaptation options are modifications to on-going farm practices and public policy decision-making processes with respect to a suite of changing climatic (including variability and extremes) and non-climatic conditions (political, economic and social). All of the adaptation options could and will be deployed by farmers to respond to climate change, although as the degree of climate change increases the limits of this adaptive capacity may be challenged. There might be gains in some regions emerging from low levels of climate change as a result of longer growing seasons, less cold waves, higher precipitation and CO_2 fertilization effects. However, if only losses are seen, there are always some actions which can be taken for reducing and/or exceeding the negative effects. The objective of this paper is to explore the potentials of changes of the planting date and crop choice as an efficient adaptation measure in Bolivia for soybeans, maize and rice grown under rainfed conditions as a first experimental example of the variety of adaptation measures that can be applied in the Bolivian agriculture sector. After the most efficient planting dates have been identified, a Cost-Benefit Analysis is developed for the different IPCC's A2 and B2 SRES Scenarios with and without adaptation to show the final consequences of climate change and adaptation on producer's net income in the Region.

2. Methods

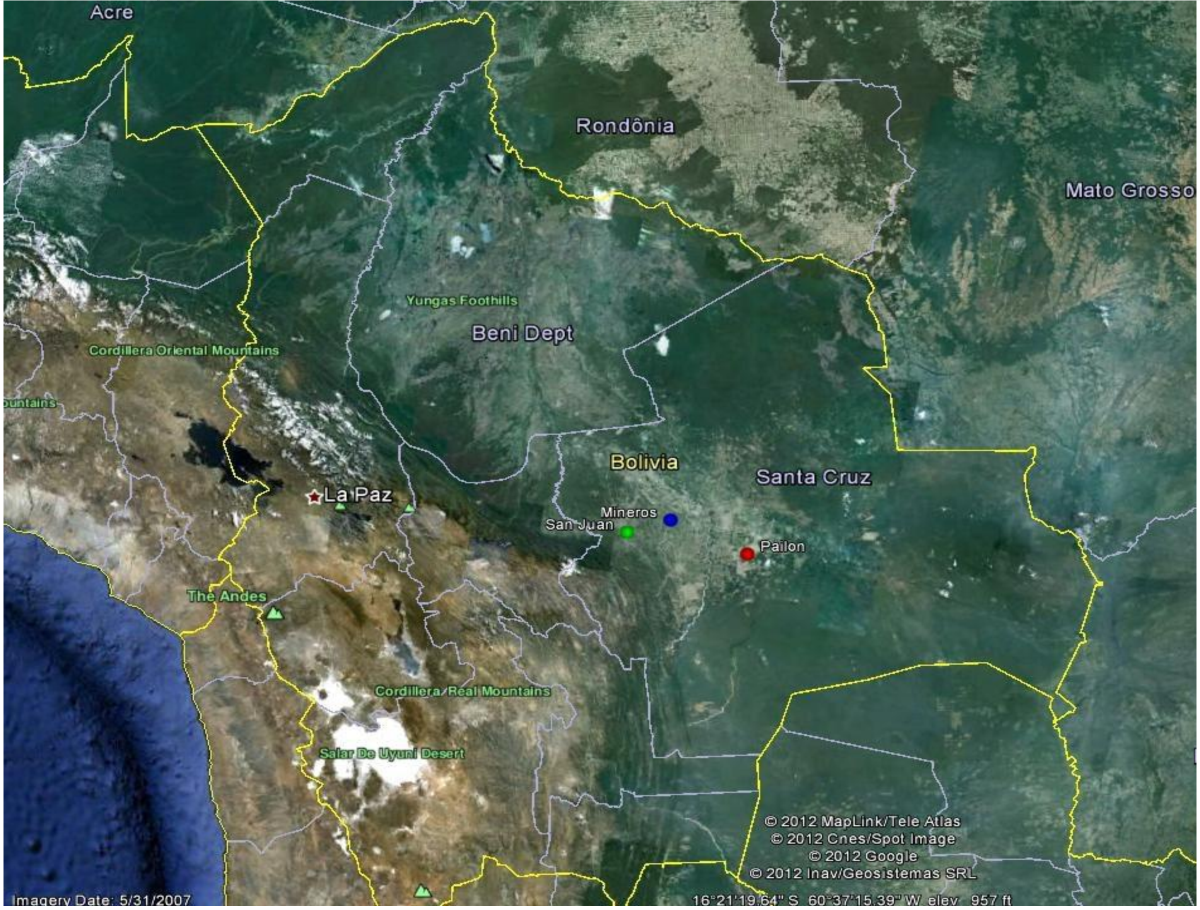
For quantifying the efficient adaptation options, first, the Baseline soybeans, maize and rice yields are computed using the CERES and CROPGRO models included in the DSSAT v.4 version for the whole year in different planting dates in 10-day intervals. The calibration and validation process for CERES and CROPGRO models for Bolivian local conditions is found in Viscarra, 2010. These results show how the different crops behave through the year and whether the model reproduces actual farmer's behavior or not with observed fieldwork data. The Baseline Scenario is the simulation of the calibrated models coming from observed daily weather data from 2001 to 2007. This time horizon is used for all the analysis to account for inter-annual variability of weather. As a second step, the effects of climate change from the different IPCC's Scenarios (changes in maximum temperature, minimum temperature, precipitation and solar radiation) are introduced in the Baseline weather data. The IPCC's A2 and B2 SRES Scenarios for the short term (2001-2030) and for the long term (2071-2100) are considered, assuming a "Business as Usual" and a "Greener Economy" for A2 and B2, respectively. CO_2 fertilization effects are not considered. The purpose of the analysis is to see if the different crop yields change their behavior throughout the year, and if so, identify the most efficient planting date (the one with the highest average yield and the lowest variability). After having the yields for the Baseline and the SRES Scenarios quantified for the different crops using traditional planting dates, the net incomes per hectare are quantified using the FAO's crop prices from 2000-2007 and the mean production cost extracted from CAO, 2007 statistics. Afterwards, with the highest mean yield identified for each of the crops and production areas, the net revenues are also quantified for the different scenarios, this time including the cost of adaptation. Finally, the net incomes coming from Status Quo (without adaptation) and with efficient adaptation cases are compared.

2.1 Production Zones

In order to have a broad impact assessment for Santa Cruz – Bolivia, 3 of the most important production provinces are chosen for soybeans, maize and rice, grown under rainfed conditions.

Figure 10: Production Zones

Zone	Province	Latitude	Longitude	Height (m)	Acreage (ha)	% of Total Acreage	Mean Annual Precipitation (mm)	Mean Annual Max Temperature (C)	Mean Annual Min Temperature (C)
Mineros	**Obispo Santistevan**	17º06'36"S	63º14'30"W	245	220,000	0.338	1370.8	30.958	18.417
San Julian	**Ñuflo de Chavez**	16º45'00"S	62º30'00"W	305	205,000	0.315	1280.9	31.775	22.533
Pailon	**Chiquitos**	17º38'00"S	62º14'00"W	279	159,000	0.245	1063.6	32.142	19.225



The locations are well distributed around the agricultural frontier of Santa Cruz Department and the distance between each of the different spatial points ranges from 70 to 180 km. The humidity of each place depends not only in the amount of rain they receive, but also on the maximum and minimum temperatures. In these terms, the most humid zone is Mineros followed by San Julian, and finally Pailon.

2.2 Baseline and Climate Change Weather Indicators

The following Figures show the weather patterns of the different production areas in the whole year, for 7 different periods (2001-2007):

Figure 11: Baseline Weather Indicators in Mineros

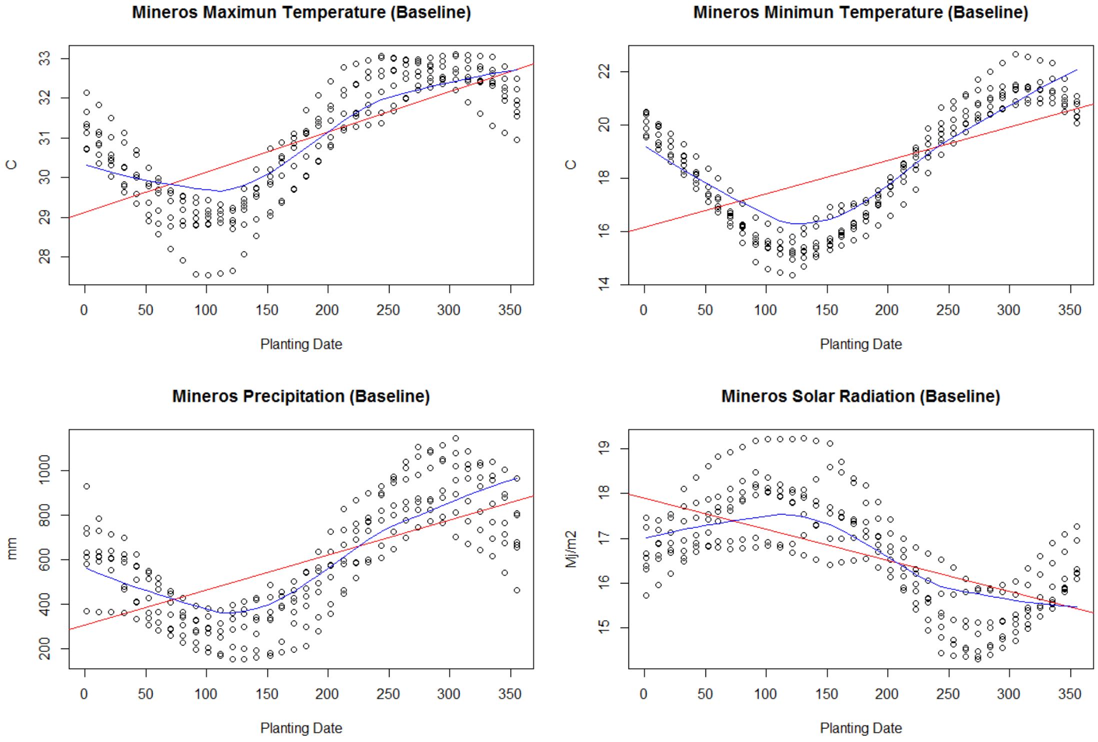


Figure 12: Baseline Weather Indicators in Pailon

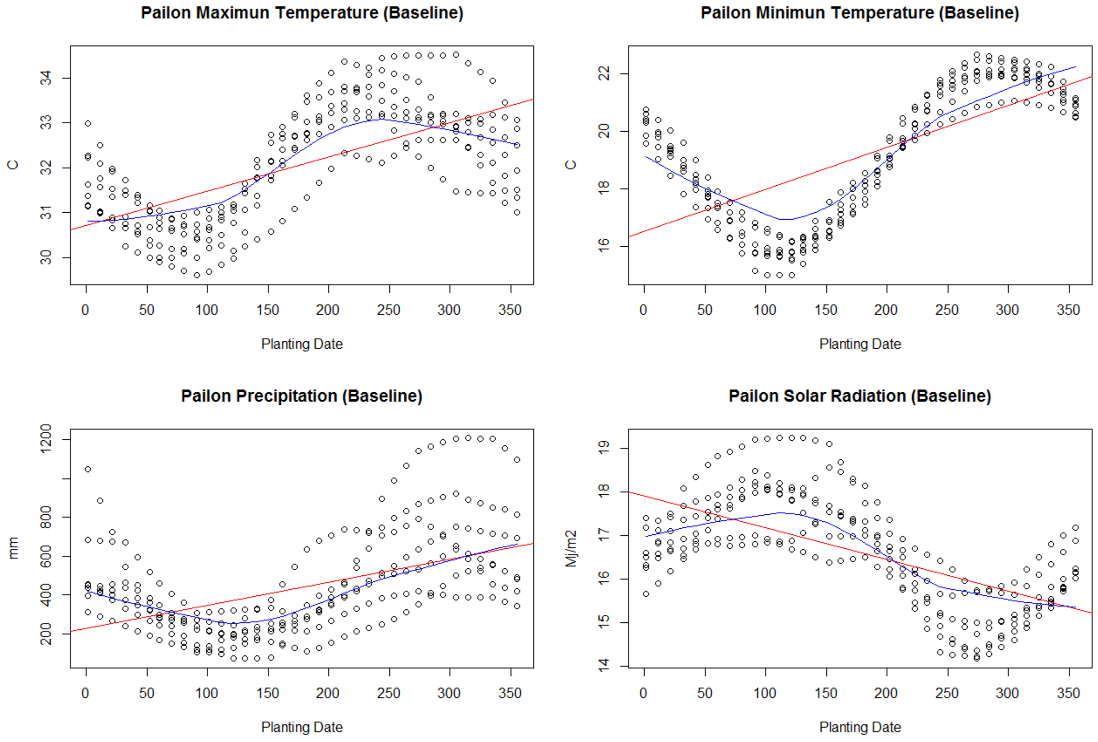
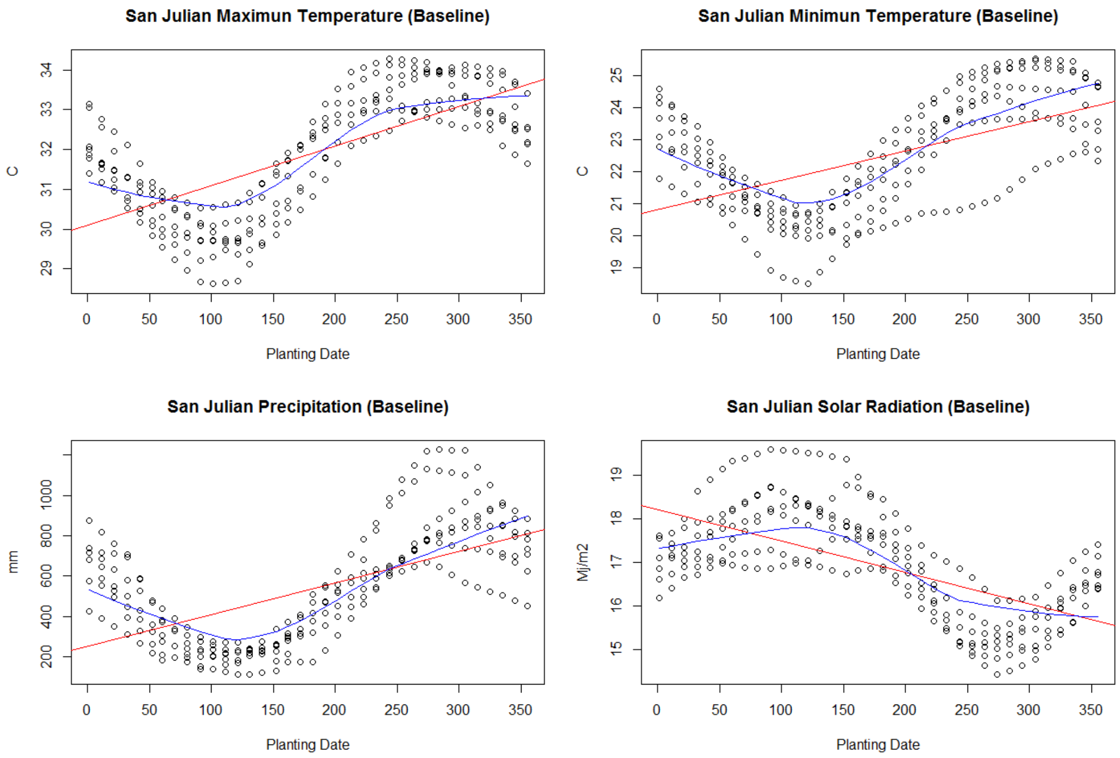


Figure 13: Baseline Weather Indicators in San Julian



Each circle in Figures 11 to 13 displays an individual weather observation in the Baseline Scenario, the red line is the linear trend and the blue curve is the best fitted nonlinear trend.

For the climate change impacts analysis, the downscaled A2 and B2 SRES Scenarios from IPCC developed by Seiler, 2009 for Bolivia are used. The impacts introduced in the Baseline observed weather data are summarized in Figure 14, where, temperatures are expressed in degrees Celsius, precipitation in mm/year and solar radiation in Mj/m^2:

Figure 14: A2 and B2 Average Climate Change Impacts

	Weather Indicator	Baseline	A2 20s	A2 70s	B2 20s	B2 70s
Mineros	**Maximum Temperature**	**31.0**	-0.3	3.8	-0.4	2.3
	Minimum Temperature	**18.4**	3.8	7.4	3.6	6.1
	Precipitation	**1419.3**	51%	74%	49%	-8%
	Solar Radiation	**16.7**	0.6	0.7	0.8	0.8
Pailon	**Maximum Temperature**	**32.1**	-1.6	2.5	-1.7	0.8
	Minimum Temperature	**19.2**	2.9	6.6	2.7	5.1
	Precipitation	**1063.6**	35%	67%	42%	-5%
	Solar Radiation	**16.6**	0.5	0.8	0.6	0.8
San Julian	**Maximum Temperature**	**31.8**	-0.6	3.6	-0.8	1.9
	Minimum Temperature	**22.5**	-0.2	3.4	-0.3	2.1
	Precipitation	**1280.9**	-2%	10%	-2%	-6%
	Solar Radiation	**16.9**	1.1	1.4	1.2	0.6

As it is observed, A2 and B2 scenarios in the short term (20s) show around half degree reduction in maximum temperature and an increase from 2 to 4 degrees Celsius for the long run (70s). Minimum temperature is increased in most of the scenarios excepting the A2 and B2 in the short run for San Julian.

Finally precipitation increases from 10 to 74% in the different scenarios and areas, and a reduction for the long run in Mineros and San Julian. Precipitation reductions are observed only for the B2 70s Scenario, ranging from -5 to -8%.

The physic and chemical soil characteristics are shown in the following Figure:

Figure 15: Physic and Chemical Soil Characteristics

Area	Sand (%)	Loam (%)	Clay (%)	pH (mol/L)	Organic Matter (%)	Nitrogen %	P (ppm)
Mineros	48	32	20	6.5	2	0.13	15.5
Pailon	12	56	32	6.6	2.8	0.2	39
San Julian	14	59	27	6.4	2.9	0.18	35

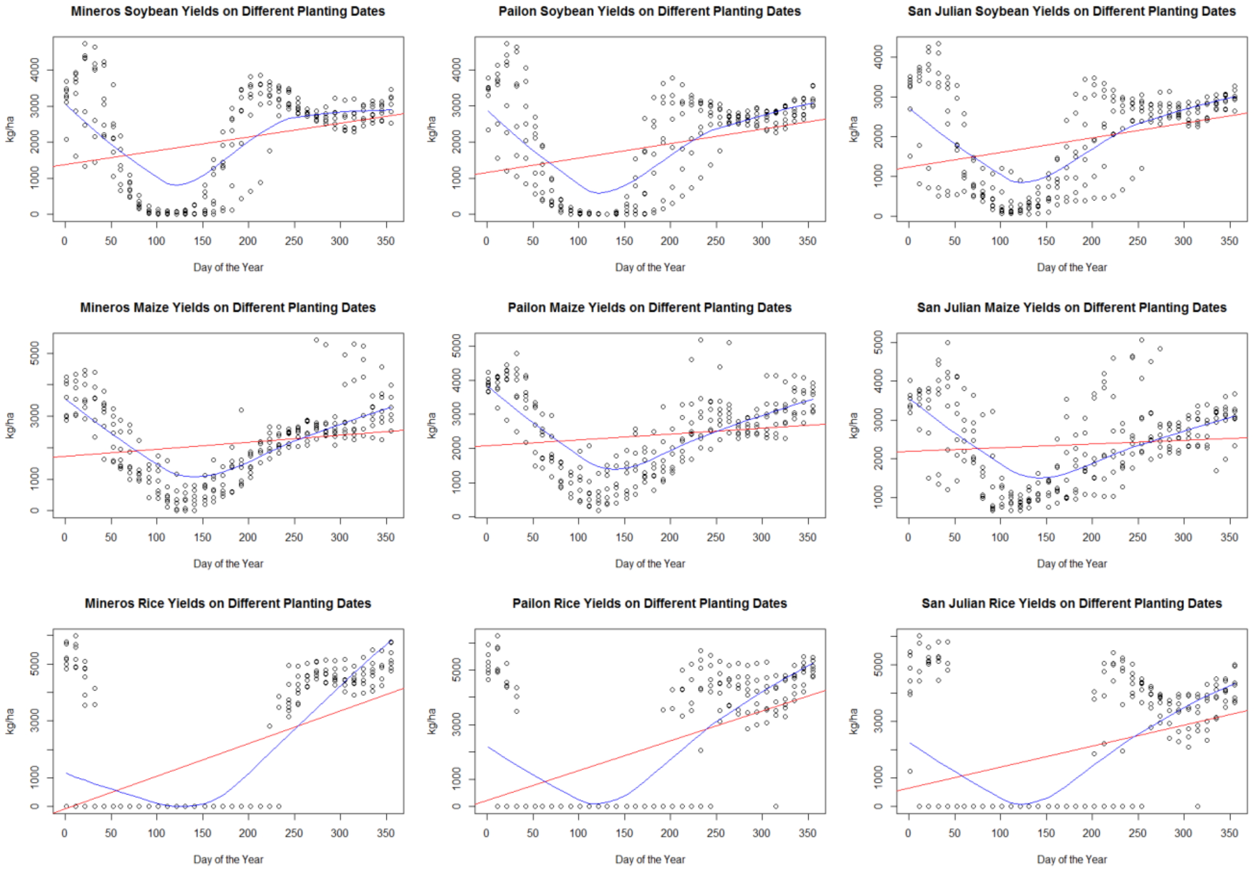
These characteristics are also introduced in the crop models and they have an impact on crop yields, especially because of the water holding capacity, albedo and availability of macro and micro nutrients found in the different soil types.

3. Results

3.1 Baseline Yields

In this section, the yields of crops are quantified considering the traditional practices (sowing date and crop choice) for each of the Production Provinces for the Baseline and for the different climate change scenarios. According to Mauricio Roca (president of CAO Agricultural Chamber), the planting dates for the summer campaign begin in the second half of October and extend until late December. Most farmers rationale (soybeans, maize, rice and wheat producers), is based on rainfall availability, as the majority of crops are grown under rainfed conditions. In this sense, the farmer begins planting after the soil accumulates at least 200 mm of rainfall to obtain appropriate crop yields. Figure 16 shows the yield behavior obtained from the simulations for the different crops and production areas in the years 2001 to 2007.

Figure 16: Soybeans, Maize and Rice Yields at Different Planting Dates


Mineros Soybean Yields on Different Planting Dates

Pailon Soybean Yields on Different Planting Dates

San Julian Soybean Yields on Different Planting Dates

Mineros Maize Yields on Different Planting Dates

Pailon Maize Yields on Different Planting Dates

San Julian Maize Yields on Different Planting Dates

Mineros Rice Yields on Different Planting Dates

Pailon Rice Yields on Different Planting Dates

San Julian Rice Yields on Different Planting Dates

As it is observed, the crop model simulations replicate farmer’s behavior very well, showing that the best planting dates (with higher yields and lower variability from year to year) are between the months of October and December (days of the year 274 to 365) for the baseline. However, it has to be noticed that, soybeans and maize are planted in Santa Cruz – Bolivia during both, the summer and winter campaigns; while rice only in the summer campaign. From these simulations, the planting date with the highest average yield inside the mentioned range is chosen for the baseline, thus eliminating the “dumb farmer”[5] assumption.

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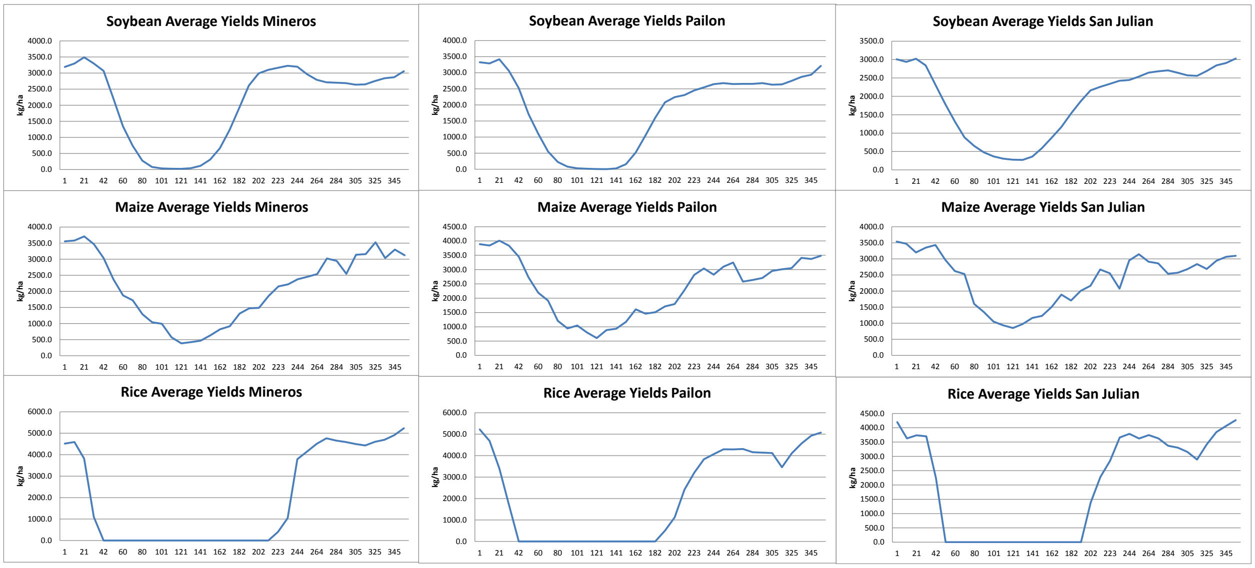
[5] The "dumb farmer" assumption - which is not unique to agriculture - is a metaphor for any impacted agent that is assumed not to anticipate or respond to changed climate conditions but continues to act as if nothing has changed (Rosenberg, 1992; Easterling et al., 1993; Smit et al., 1996).

Figure 17: Average Crop Yields (2001-2007) at Different Planting Dates


Soybean Average Yields Mineros
Soybean Average Yields Pailon
Soybean Average Yields San Julian
Maize Average Yields Mineros
Maize Average Yields Pailon
Maize Average Yields San Julian
Rice Average Yields Mineros
Rice Average Yields Pailon
Rice Average Yields San Julian

Following the farmers rationale, the best planting dates are chosen for each of the crops and production areas. All crops report the highest average yield at planting date 355, in other words December 21st. The only crop that has a better performance at planting date 325 (November 21st) is Maize in Mineros. Thus, these dates will be used as planting dates for the baseline and also for the climate change scenarios without adaptation.

Figure 18: Observed Yields in the Baseline

Year	SOYBEAN			MAIZE			RICE		
	Mineros	Pailon	San Julian	Mineros	Pailon	San Julian	Mineros	Pailon	San Julian
2001	3250	3561	3175	4252	3239	2335	5753	5470	3664
2002	3058	3144	3021	2374	3799	3277	4838	5142	4995
2003	3455	3546	3282	3016	3578	3228	5398	4756	3846
2004	2538	3196	2643	2603	3925	3681	5776	5043	3747
2005	2838	3031	3178	2387	3109	3042	5100	5348	4958
2006	3044	2989	2967	4807	3068	3077	4761	4810	4365
2007	3220	3021	2932	5225	3652	3039	5001	4950	4303
Mean	**3057.6**	**3212.6**	**3028.3**	**3523.4**	**3481.4**	**3097.0**	**5232.4**	**5074.1**	**4268.3**

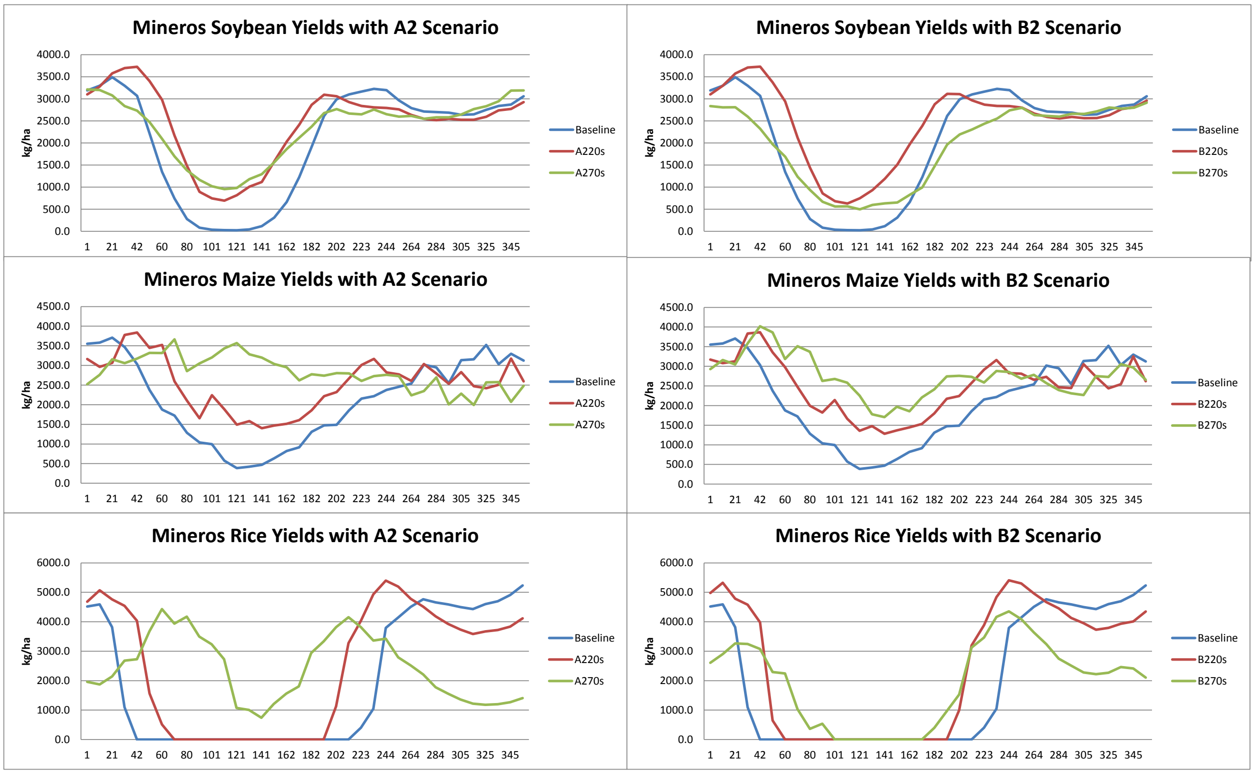
Figure 18, shows that Mineros has better mean yields for maize and rice, while Pailon does for soybeans. These results are perfectly reflected in the crop choices observed for Bolivia, having Mineros as one of the main rice production areas and Pailon as one of the main soybeans production areas.

After having the yields for the Baseline, the A2 and B2 climate change impacts are introduced into the Baseline, for quantifying the expected yields with and without adaptation.

3.2 A2 and B2 Climate Change Yields

Figures 19 to 21, illustrate the average yield of crops for the whole year; the blue line is the Baseline (average crop yields for 2001-2007, quantified for the different planting dates), the red lines are the A2 and B2 climate change scenarios in the short run (20s) and the green lines are the A2 and B2 climate change scenarios for the long run (70s), quantified by introducing the climate variations of temperature, precipitation and solar radiation in the baseline scenario.

Figure 19: Mineros Average Crop Yields for Different Climate Change Scenarios



Mineros Soybean Yields with A2 Scenario

Mineros Soybean Yields with B2 Scenario

Mineros Maize Yields with A2 Scenario

Mineros Maize Yields with B2 Scenario

Mineros Rice Yields with A2 Scenario

Mineros Rice Yields with B2 Scenario

Figure 20: Pailon Average Crop Yields for Different Climate Change Scenarios

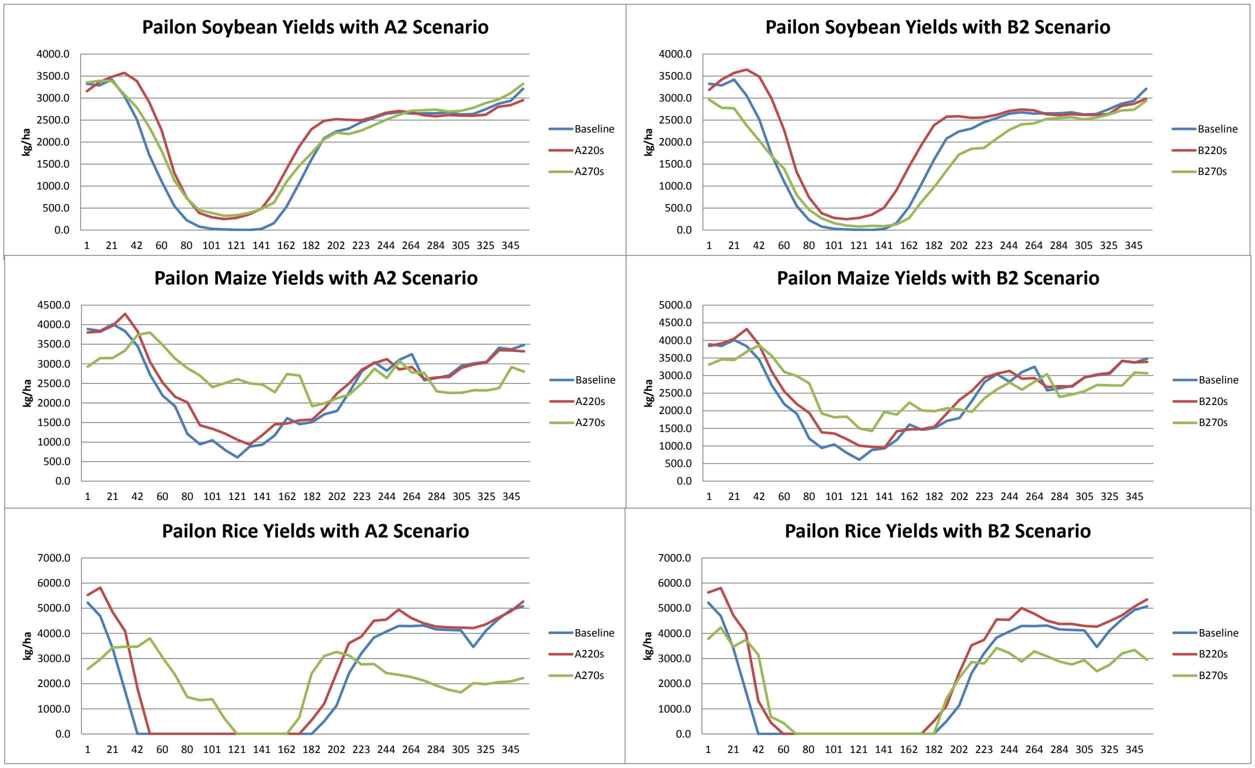
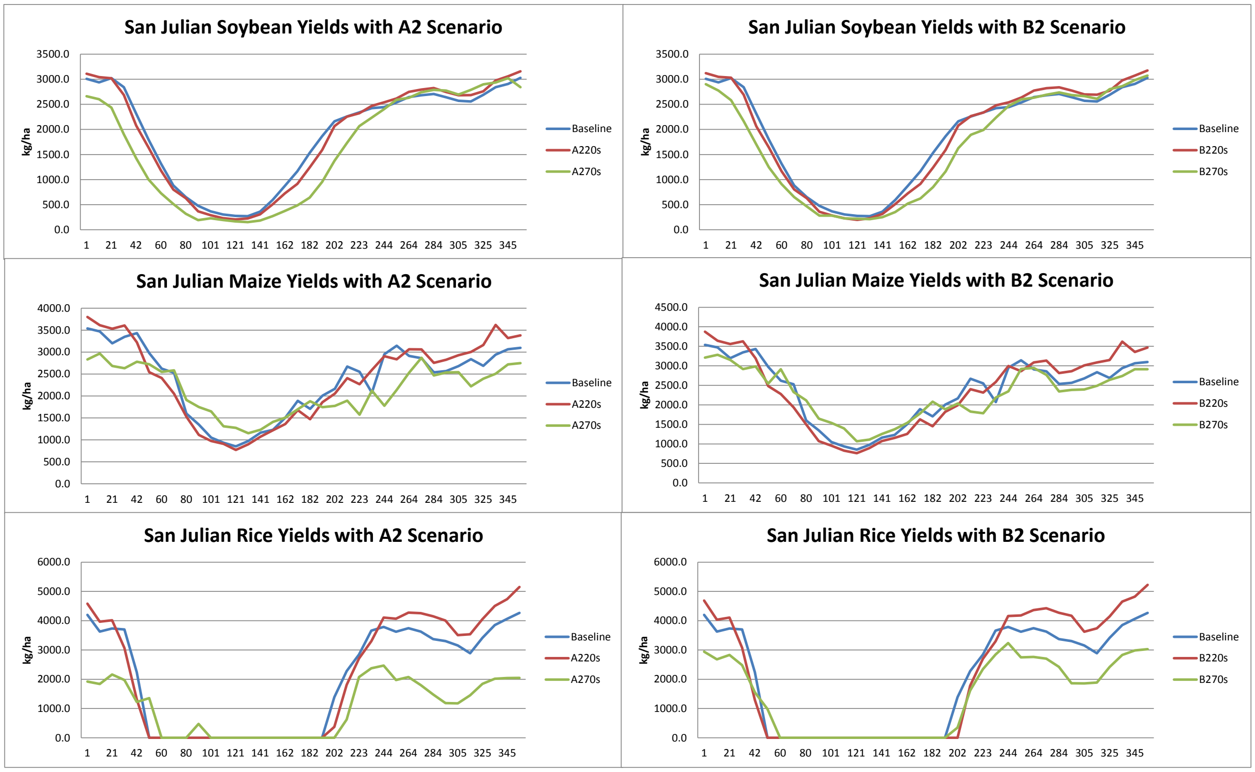


Figure 21: San Julian Average Crop Yields for Different Climate Change Scenarios



From these Figures, 2 groups of result can be extracted: crop yields without adaptation (planted on the same dates as the Baseline), and crop yields with adaptation (changing the planting date to the one with the highest average yields).

Table 19: Crop Yields in the A2 and B2 Scenarios without Adaptation (kg/ha)

							MINEROS								
Year	**SOYBEAN**					**MAIZE**					**RICE**				
	Baseline	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**	**Baseline**	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**	**Baseline**	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**
2001	3250	3064	3451	3101	3377	4252	3195	2324	3178	3271	5753	4668	1619	5105	2700
2002	3058	2912	3249	2947	3063	2374	2424	1825	2357	2106	4838	4462	1966	4484	2916
2003	3455	3101	3414	3145	3465	3016	2481	3903	2509	2240	5398	4173	1180	4311	2226
2004	2538	3008	2296	3037	1233	2603	2249	4084	2316	2431	5776	4672	1339	4903	0
2005	2838	2697	3024	2722	3110	2387	2237	1909	2298	2288	5100	3963	1323	4162	2463
2006	3044	2774	3427	2807	2784	4807	2368	2533	2357	2085	4761	3438	1434	3730	2432
2007	3220	2917	3474	2954	3354	5225	1989	1399	2058	4677	5001	3437	994	3764	1993
Mean	**3057,6**	**2924,7**	**3190,7**	**2959,0**	**2912,3**	**3523,4**	**2420,4**	**2568,1**	**2439,0**	**2728,3**	**5232,4**	**4116,1**	**1407,9**	**4351,3**	**2104,3**
							PAILON								
Year	**SOYBEAN**					**MAIZE**					**RICE**				
	Baseline	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**	**Baseline**	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**	**Baseline**	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**
2001	3561	3105	3405	3167	3082	3239	3042	2502	3073	2603	5470	5665	2258	5706	3523
2002	3144	2924	3241	2976	3013	3799	3621	3064	3770	3210	5142	5335	2186	5496	3364
2003	3546	3161	3549	3182	3497	3578	3418	3067	3529	3404	4756	5005	1574	5053	3022
2004	3196	3142	3475	3166	2163	3925	4114	3310	3965	3576	5043	5586	2537	5653	0
2005	3031	2755	3081	2774	2881	3109	2929	2450	3050	2805	5348	5343	2460	5521	3816
2006	2989	2769	3315	2790	3027	3068	2850	2427	2840	2767	4810	4347	1831	4429	3037
2007	3021	2832	3204	2850	2914	3652	3257	2800	3515	3077	4950	5588	2712	5591	3866
Mean	**3212,6**	**2955,4**	**3324,3**	**2986,4**	**2939,6**	**3481,4**	**3318,7**	**2802,9**	**3391,7**	**3063,1**	**5074,1**	**5267,0**	**2222,6**	**5349,9**	**2946,9**
							SAN JULIAN								
Year	**SOYBEAN**					**MAIZE**					**RICE**				
	Baseline	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**	**Baseline**	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**	**Baseline**	**A2 20s**	**A2 70s**	**B2 20s**	**B2 70s**
2001	3175	3304	3309	3276	3485	2335	2589	2169	2597	2249	3664	4751	1494	4683	2500
2002	3021	3185	3415	3209	3151	3277	3599	3016	3787	3151	4995	5776	2553	5605	3487
2003	3282	3373	3550	3377	3671	3228	3464	2755	3471	2904	3846	4530	1570	4934	2474
2004	2643	2771	772	2844	1777	3681	3918	2620	4073	3277	3747	4783	1530	5029	2653
2005	3178	3257	3603	3257	3377	3042	3611	3025	3627	2964	4958	5922	2403	5837	3424
2006	2967	3117	2374	3143	2883	3077	3273	2852	3398	2994	4365	5118	2374	5346	3413
2007	2932	3096	2878	3118	3162	3039	3197	2809	3324	2868	4303	5178	2403	5137	3258
Mean	**3028,3**	**3157,6**	**2843,0**	**3174,9**	**3072,3**	**3097,0**	**3378,7**	**2749,4**	**3468,1**	**2915,3**	**4268,3**	**5151,1**	**2046,7**	**5224,4**	**3029,9**

Climate change without adaptation is counterproductive for most of the areas and crops with yield reductions ranging from -3 to -8% for soybeans, -3 to -31% for maize and -2 to -73% for rice. Some production areas show increases in the short run such as San Julian (3 to 4% and 9 to 12% for soybeans and maize, respectively).

Table 20: Crop Yields in the A2 and B2 Scenarios with Adaptation

MINEROS															
Year	SOYBEAN					MAIZE					RICE				
	Baseline	A2 20s	A2 70s	B2 20s	B2 70s	Baseline	A2 20s	A2 70s	B2 20s	B2 70s	Baseline	A2 20s	A2 70s	B2 20s	B2 70s
2001	3250	4400	3760	4474	3377	4252	3206	5666	3211	4736	5753	5901	5436	5631	3988
2002	3058	4713	3579	4768	3063	2374	4002	3296	4027	4041	4838	4657	4970	4653	4206
2003	3455	2721	3378	2795	3465	3016	2759	3667	2820	3978	5398	5303	5629	5244	4569
2004	2538	4182	3451	4159	1233	2603	3802	3090	3854	4058	5776	6280	4861	6347	3603
2005	2838	3576	2392	3483	3110	2387	4203	2731	4066	3749	5100	5151	5223	5202	0
2006	3044	2535	2690	2512	2784	4807	4062	4013	4121	4177	4761	5159	0	5246	3031
2007	3220	3940	3230	3904	3354	5225	4843	3186	4984	3412	5001	5339	4898	5547	3459
Mean	**3057,6**	**3723,9**	**3211,4**	**3727,9**	**2912,3**	**3523,4**	**3839,6**	**3664,1**	**3869,0**	**4021,6**	**5232,4**	**5398,6**	**4431,0**	**5410,0**	**3265,1**
PAILON															
Year	SOYBEAN					MAIZE					RICE				
	Baseline	A2 20s	A2 70s	B2 20s	B2 70s	Baseline	A2 20s	A2 70s	B2 20s	B2 70s	Baseline	A2 20s	A2 70s	B2 20s	B2 70s
2001	3561	4817	4085	4859	3082	3239	5094	4700	5094	4962	5470	5744	5895	5835	4037
2002	3144	2863	3616	3128	3013	3799	4098	2867	4108	2117	5142	6399	4520	6250	4873
2003	3546	4253	3664	4186	3497	3578	3845	3605	3825	4139	4756	5764	5592	5774	4717
2004	3196	2569	2846	2451	2163	3925	4171	3968	4301	3795	5043	5807	0	5692	4017
2005	3031	1736	1961	1940	2881	3109	4273	3198	4501	3003	5348	5648	0	5973	3426
2006	2989	4407	3601	4519	3027	3068	4061	4019	4046	4485	4810	5553	5196	5311	4172
2007	3021	4377	3980	4440	2914	3652	4395	4243	4362	4544	4950	5827	5413	5797	4405
Mean	**3212,6**	**3574,6**	**3393,3**	**3646,1**	**2939,6**	**3481,4**	**4276,7**	**3800,0**	**4319,6**	**3863,6**	**5074,1**	**5820,3**	**3802,3**	**5804,6**	**4235,3**
SAN JULIAN															
Year	SOYBEAN					MAIZE					RICE				
	Baseline	A2 20s	A2 70s	B2 20s	B2 70s	Baseline	A2 20s	A2 70s	B2 20s	B2 70s	Baseline	A2 20s	A2 70s	B2 20s	B2 70s
2001	3175	3304	3134	3276	3485	2335	3682	2967	3795	3183	3664	4751	3693	4683	4255
2002	3021	3185	3306	3209	3151	3277	3512	2809	3527	3125	4995	5776	0	5605	0
2003	3282	3373	3653	3377	3671	3228	3903	3332	4042	3476	3846	4530	2292	4934	3843
2004	2643	2771	1428	2844	1777	3681	3974	2984	3987	3555	3747	4783	2485	5029	2906
2005	3178	3257	3369	3257	3377	3042	3521	2154	3527	2549	4958	5922	2903	5837	4093
2006	2967	3117	3053	3143	2883	3077	3890	3270	4038	3568	4365	5118	2489	5346	3645
2007	2932	3096	3221	3118	3162	3039	4102	3264	4202	3521	4303	5178	3407	5137	3899
Mean	**3028,3**	**3157,6**	**3023,4**	**3174,9**	**3072,3**	**3097,0**	**3797,7**	**2968,6**	**3874,0**	**3282,4**	**4268,3**	**5151,1**	**2467,0**	**5224,4**	**3234,4**

When applying the adaptation measure (changing the planting date), the counterproductive effects of climate change can be reduced and/or exceeded for most of the scenarios and production zones with increases ranging from 3 to 22% for soybeans, 4 to 25% for maize and 3 to 15% for rice. However, some losses are still observed for the long run in both scenarios, though these losses are smaller when compared to the scenario without adaptation. The identified efficient planting dates for the different scenarios are detailed in Table 21:

Table 21: Efficient Planting Dates in Different Zones and Scenarios (Day of the Year)

Scenario	SOYBEAN			MAIZE			RICE		
	Mineros	Pailon	San Julian	Mineros	Pailon	San Julian	Mineros	Pailon	San Julian
Baseline	355	355	355	325	355	355	355	355	355
A220s	42	32	355	42	32	1	244	11	355
A270s	1	11	345	70	52	11	60	52	244
B220s	42	32	355	42	32	1	244	11	355
B270s	355	355	355	42	42	11	21	11	244

The planting dates are expressed in Julian days ("day of the year"), where 1 represents January 1st and 365 December 31st. In Table 21, it is observed that with climate change (increases in temperature and increases/decreases in precipitation), the crops should be planted later, in the months of January and even February for soybeans and maize. While for rice, the efficient planting dates are either earlier or later than usual, depending on the production area.

3.3 Cost – Benefit Analysis

As any utility maximizer agent, a farmer must maximize its net returns by making an efficient use of its inputs. The main inputs in agriculture come from weather and soils and the outputs are the crop yields. Crops grow better in certain conditions where water, heat and/or nutrient stresses are minimized. This is especially important in regions where the rainfed technology is applied; in order to achieve the efficient results the traditional sowing date can be changed but also the crop choice. The Cost – Benefit analysis consists in quantifying the mean net income generated by the activity, considering the inter-annual climate and price variability. On the other hand, the costs are assumed to be constant.

$$I = P*Y - C - AC \qquad (1)$$

Where:

I: Net income generated by the crop activity ($/ha)
P: Price of crop in terms of volume ($/kg)
Y: Yield of crop considering the Adaptation Measure Taken (kg/ha)
C: Production cost of each cultivar (sowing, irrigation, fertilization, harvesting) ($/ha)
AC: Adaptation Cost (cost of changing planting date or cost of changing crop) ($/ha)

The prices for soybeans, maize and rice for 2001 to 2007 are extracted from FAOSTATS, and the production costs from CAO, 2007 statistics. As mentioned before, the latter are kept constant for 2001 to 2007.

Table 22: Soybeans, Maize and Rice Prices and Costs

Year	Soybean Price ($/Ton)	Maize Price ($/Ton)	Rice Price ($/Ton)	Soybean Cost ($/ha)	Maize Cost ($/ha)	Rice Cost ($/ha)
2001	142.30	149.50	145.70	259.49	236.43	339.00
2002	137.20	138.40	155.50	259.49	236.43	339.00
2003	138.00	142.40	186.20	259.49	236.43	339.00
2004	139.90	135.60	165.60	259.49	236.43	339.00
2005	134.60	138.00	162.00	259.49	236.43	339.00
2006	166.90	148.30	213.90	259.49	236.43	339.00
2007	188.20	163.60	331.50	259.49	236.43	339.00

Rice is the commodity with the highest mean price (194.3 $/Ton), followed by soybeans (149.5 $/Ton) and finally by maize (145.11 $/Ton). Rice is also the most expensive crop to grow, followed by soybeans and the least expensive is maize. The cost of adaptation (changing the planting date) is assumed to be from 0 to 30 $/ha, given that only some soil analysis and climate data analysis has to be acquired. However, this kind of early warning policy is usually done by public agencies for free; therefore, the cost of adaptation could be nil. To be conservative, the cost of adaptation in this analysis is equal to 0.

Table 23: Mineros Mean Net Revenue in Different Scenarios with and without Adaptation

Soybean	Mean Income (2001-2007)	Mean Costs	Adaptation Costs	Mean Net Revenue	% Variation
Baseline	598.7	259.5	0.0	**339.2**	**0**
A2 20s W/O	567.4	259.5	0.0	**307.9**	**-9**
A2 70s W/O	628.4	259.5	0.0	**368.9**	**9**
B2 20s W/O	574.2	259.5	0.0	**314.7**	**-7**
B2 70s W/O	314.9	259.5	0.0	**55.4**	**-84**
A2 20s Adap	714.4	259.5	0.0	**454.9**	**34**
A2 70s Adap	619.8	259.5	0.0	**360.3**	**6**
B2 20s Adap	714.0	259.5	0.0	**454.5**	**34**
B2 70s Adap	575.6	259.5	0.0	**316.1**	**-7**
Maize	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	520.5	236.4	0.0	**284.1**	**0**
A2 20s W/O	351.0	236.4	0.0	**114.5**	**-60**
A2 70s W/O	368.2	236.4	0.0	**131.8**	**-54**
B2 20s W/O	353.7	236.4	0.0	**117.3**	**-59**
B2 70s W/O	402.7	236.4	0.0	**166.3**	**-41**
A2 20s Adap	559.5	236.4	0.0	**323.0**	**14**
A2 70s Adap	534.0	236.4	0.0	**297.5**	**5**
B2 20s Adap	564.2	236.4	0.0	**327.7**	**15**
B2 70s Adap	582.7	236.4	0.0	**346.3**	**22**
Rice	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	779.7	339.0	0.0	**440.7**	**0**
A2 20s W/O	608.6	339.0	0.0	**269.6**	**-39**
A2 70s W/O	207.8	339.0	0.0	**-131.2**	**-130**
B2 20s W/O	644.8	339.0	0.0	**305.8**	**-31**
B2 70s W/O	314.9	339.0	0.0	**-24.1**	**-105**
A2 20s Adap	806.9	339.0	0.0	**467.9**	**6**
A2 70s Adap	648.2	339.0	0.0	**309.2**	**-30**
B2 20s Adap	810.1	339.0	0.0	**471.1**	**7**
B2 70s Adap	490.9	339.0	0.0	**151.9**	**-66**

Mineros shows reductions from -9 to -84% for soybeans producers without adaptation for the short and the long runs, respectively. Only an increase of 9% is observed for the A2 70s Scenario (this comes from an increase in temperatures accompanied by 74% increase of precipitation); and increases of 34% in the short run, while the increase are much more modest in the long run if using the efficient planting date approach (around 4%). Maize shows reductions between -41 and -60% with no adaptation, and a small increase of 14% in the short run if adaptation is applied, while in the long run the increases can be as high as 22%. Rice exhibits decreases from -39 to -130% for the short and long runs in absence of adaptation, what is more rice can't be sown anymore for the A2 and B2 70s Scenarios. The only scenarios which show better results than the baseline are the A2 and B2 in the short runs.

Table 24: Pailon Mean Net Revenue in Different Scenarios with and without Adaptation

Soybean	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	618.4	259.5	0.0	**359.0**	**0**
A2 20s W/O	570.5	259.5	0.0	**311.0**	**-13**
A2 70s W/O	643.8	259.5	0.0	**384.3**	**7**
B2 20s W/O	576.0	259.5	0.0	**316.5**	**-12**
B2 70s W/O	572.4	259.5	0.0	**313.0**	**-13**
A2 20s Adap	719.9	259.5	0.0	**460.4**	**28**
A2 70s Adap	674.0	259.5	0.0	**414.6**	**15**
B2 20s Adap	733.2	259.5	0.0	**473.7**	**32**
B2 70s Adap	572.4	259.5	0.0	**313.0**	**-13**
Maize	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	504.7	236.4	0.0	**268.3**	**0**
A2 20s W/O	480.0	236.4	0.0	**243.6**	**-9**
A2 70s W/O	405.7	236.4	0.0	**169.3**	**-37**
B2 20s W/O	491.2	236.4	0.0	**254.8**	**-5**
B2 70s W/O	443.4	236.4	0.0	**207.0**	**-23**
A2 20s Adap	621.8	236.4	0.0	**385.4**	**44**
A2 70s Adap	554.6	236.4	0.0	**318.2**	**19**
B2 20s Adap	627.5	236.4	0.0	**391.1**	**46**
B2 70s Adap	566.0	236.4	0.0	**329.5**	**23**
Rice	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	757.1	339.0	0.0	**418.1**	**0**
A2 20s W/O	786.7	339.0	0.0	**447.7**	**7**
A2 70s W/O	334.4	339.0	0.0	**-4.6**	**-101**
B2 20s W/O	798.4	339.0	0.0	**459.4**	**10**
B2 70s W/O	446.9	339.0	0.0	**107.9**	**-74**
A2 20s Adap	869.5	339.0	0.0	**530.5**	**27**
A2 70s Adap	588.1	339.0	0.0	**249.1**	**-40**
B2 20s Adap	866.0	339.0	0.0	**527.0**	**26**
B2 70s Adap	634.6	339.0	0.0	**295.6**	**-29**

When no adaptation measures are taken, Pailon soybeans net incomes show reductions of around -12%, but when applying the efficient adaptation, yields can increase up to 32%. Maize producers reduce their incomes in as much as -37% with no adaptation; while when applying adaptation yields can increase from 19 to 46%. Rice yields are positively affected in the short run for both scenarios showing increases from 7 to 10%, but rice production is not profitable in the long run according to the scenarios even when efficient adaptation is applied (reductions from -29 to -101%).

Table 25: San Julian Mean Net Revenue in Different Scenarios with and without Adaptation

Soybean	Mean Income (2001-2007)	Mean Costs	Adaptation Costs	Mean Net Revenue	% Variation
Baseline	586.1	259.5	0.0	326.6	0
A2 20s W/O	612.0	259.5	0.0	352.5	8
A2 70s W/O	549.6	259.5	0.0	290.2	-11
B2 20s W/O	615.7	259.5	0.0	356.2	9
B2 70s W/O	598.2	259.5	0.0	338.7	4
A2 20s Adap	612.0	259.5	0.0	352.5	8
A2 70s Adap	593.4	259.5	0.0	333.9	2
B2 20s Adap	615.7	259.5	0.0	356.2	9
B2 70s Adap	598.2	259.5	0.0	338.7	4
Maize	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	447.8	236.4	0.0	211.4	0
A2 20s W/O	488.1	236.4	0.0	251.6	19
A2 70s W/O	398.5	236.4	0.0	162.0	-23
B2 20s W/O	501.0	236.4	0.0	264.6	25
B2 70s W/O	421.8	236.4	0.0	185.4	-12
A2 20s Adap	552.2	236.4	0.0	315.7	49
A2 70s Adap	432.5	236.4	0.0	196.1	-7
B2 20s Adap	563.5	236.4	0.0	327.1	55
B2 70s Adap	477.5	236.4	0.0	241.0	14
Rice	**Mean Income (2001-2007)**	**Mean Costs**	**Adaptation Costs**	**Mean Net Revenue**	**% Variation**
Baseline	638.2	339.0	0.0	299.2	0
A2 20s W/O	769.8	339.0	0.0	430.8	44
A2 70s W/O	309.4	339.0	0.0	-29.6	-110
B2 20s W/O	780.6	339.0	0.0	441.6	48
B2 70s W/O	455.8	339.0	0.0	116.8	-61
A2 20s Adap	769.8	339.0	0.0	430.8	44
A2 70s Adap	376.7	339.0	0.0	37.7	-87
B2 20s Adap	780.6	339.0	0.0	441.6	48
B2 70s Adap	490.8	339.0	0.0	151.8	-49

San Julian soybeans incomes are positively affected in the short and long runs (around 8% increases), only the A2 70s show -11% reductions (coming from an increase in temperatures accompanied by only 10% increase in precipitation). However, when applying adaptation, the net incomes cannot be increased further, given that the most efficient planting dates are already used. Maize exhibits reductions in the long runs ranging from -12 to -23%, without adaptation. When applying the adaptation measure increases from 14 to 55% are observed. Finally, rice shows that it is not profitable in the long runs, but in the short run it will have increases from 44 to 48%. However, when applying adaptation the net incomes cannot be further increased given that the most efficient planting dates have already been used.

Table 26: Summary of Recommended Efficient Planting Dates and Crop Choice by Production Province

Province	Baseline	Expected Net Income	A220s Adap	Expected Net Income Variation	A270s Adap	Expected Net Income Variation	B220s Adap	Expected Net Income Variation	B270s Adap	Expected Net Income Variation
Mineros	1. Rice (December 21st)	440.7	1. Rice (September 1st)	6%	1. Soybean (January 1st)	6%	1. Rice (September 1st)	7%	1. Maize (February 11th)	22%
	2. Soybean (December 21st)	339.2	2. Soybean (February 11th)	34%	2. Rice (March 1st)	-30%	2. Soybean (February 11th)	34%	2. Soybean (December 21st)	-7%
	3. Maize (November 21st)	284.1	3. Maize (February 11th)	14%	3. Maize (March 11th)	5%	3. Maize (February 11th)	15%	3. Rice (January 21st)	-66%
Pailon	1. Rice (December 21st)	418.1	1. Rice (January 11th)	27%	1. Soybean (January 11th)	15%	1. Rice (January 11th)	26%	1. Maize (February 11th)	23%
	2. Soybean (December 21st)	359	2. Soybean (February 1st)	28%	2. Maize (February 21st)	19%	2. Soybean (February 1st)	32%	2. Soybean (December 21st)	-13%
	3. Maize (December 21st)	268.3	3. Maize (February 1st)	44%	3. Rice (February 21st)	-40%	3. Maize (February 1st)	46%	3.Rice (January 11th)	-29%
San Julian	1. Soybean (December 21st)	326.6	1. Rice (December 21st)	44%	1. Soybean (December 11th)	2%	1. Rice (December 21st)	48%	1. Soybean (December 21st)	4%
	2. Rice (December 21st)	299.2	2. Soybean (December 31st)	8%	2. Maize (February 21st)	-7%	2. Soybean (December 21st)	9%	2. Maize (January 11th)	14%
	3. Maize (December 21st)	211.4	3. Maize (January 1st)	49%	3. Rice (February 21st)	-87%	3. Maize (January 1st)	55%	3. Rice (September 1st)	-49%

Figure 29 exhibits the efficient planting dates for each of the crops and production zones. The options are numbered from 1 to 3, meaning 1 as the "first best option", 2 as the "second best option" and 3 as the "third best option". The third column shows the expected mean net incomes in the baseline for the different crops, and in the adaptation scenarios, the red and green numbers, represent percentual reductions and/or increases of net incomes with respect to the baseline, respectively. It has to be noticed that in some scenarios like the A220s in Mineros for instance, eventhough there is a reduction of 1% in rice net income, this activity is still more profitable than producing soybeans with a 25% increase of net income, or maize with 3% increase of net income, thus showing another effective adaptation measure (crop choice). In summary, in the short run (A2 20s and B2 20s scenarios), it is more profitable to plant rice, while in the long run (A2 70s and B2 70s) soybeans and maize become more profitable.

4. Conclusions

Soybeans yields will be likely benefited from climate change if this comes from a combination of increased precipitation (around 70%) and slight temperature increase (up to 37 degrees Celcius) as the A2 70s Scenario for Mineros and Pailon shows. If the temperature is increased and the precipitation is also increased but in a lesser magnitude (only by 10%), the yields will tend to reduce as the Scenario A270s for San Julian shows. On the other hand if temperatures are slightly increased (up to 2 and 5 degrees Celsius for min and max temperature, respectively), and precipitation is slightly reduced (5 to 8%) as the Scenario B270s for all the production areas, yields are likely to be reduced.

Maize yields on the other hand, show more inter-annual variation than soybeans. However the scenario results exhibit that this crop will be more profitable in the winter campaign in the long run for Mineros and Pailon, due to more water availability and warmer temperatures at that season, but current planting dates become too hot. Therefore, from these results one can infer that maize is less resilient to heat stress than soybeans when enough water is available. San Julian is a special case because Scenarios A220s and B220s show reductions in temperatures, which are actually beneficial for maize yields; what is more, the planting dates do not become more profitable in winter campaign because of water availability (only a 10% increase).

Rice yields are reduced in current planting dates due to increases in maximum and minimum temperatures. But in some regions (Mineros and Pailon), higher temperatures combined with more water availability will make the winter time more suitable to plant; although the increases of water availability should be quite high (from 40 to 70%). If temperatures increases and precipitation decreases, rice yields decrease through the year for all the planting dates.

When analyzing the impacts of climate change on farmer's net incomes, climate change without adaptation can reduce soybeans, maize and rice net incomes but if efficient planting date is used, increases are observed for the short run, and the losses in the long run are much reduced. The most efficient planting dates and most profitable crops are identified for all production provinces, but in general with the observed trend and climate change scenarios, the planting dates will be slightly delayed in the short run and even more delayed in the long run. Only rice seems to react better to early sowing, due to the fact of more temperature and rainfall in the winter time. In summary, soybeans is the more tolerant crop to increases in maximum and minimum temperatures and less responsive to water stress; while maize and rice suffer stress from both indicators. Minimum temperature increase is as damaging as maximum temperature increase; this can be exhibited in San Julian's crop yields which are reduced in a lesser magnitude than the other areas even though less water is available. Finally, the results confirm that water availability is a key input for determining crop yields, especially in tropical regions, where season shift can be applied with warmer temperatures; therefore, irrigation as an adaptation measure should be considered and studied in more detail to face climate change impacts.

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Chapter 4: Climate Change Impacts and Adaptation in the Bolivian Agriculture: Linking Micro and Macroeconomic Policies for Sustainable Development

Abstract

The expansion of the agricultural frontier in Bolivia has increased considerably, with observed deforestation rates of about 270,000 ha/year in the whole country (FAO, 2006), of which around 200,000 ha/year occurred in the Santa Cruz Department. One of the drivers of the extensive agriculture expansion has been soybeans production under rainfed conditions, with very low observed crop yields per hectare compared to neighboring countries. Furthermore, with climate change the temperature is expected to increase in the coming years, further reducing these yields. With lower yields and a rising demand for food (increase in population growth rates), an expansion of the agricultural frontier is expected. To slow down the deforestation rate, to increase farmers' welfare and to ensure food security, a much more efficient agriculture is needed, implementing adaptation measures at the microeconomic level to increase crop yields per hectare, linked with macroeconomic policies of natural resources protection, to achieve sustainable development. For quantifying the impact of such policies, a linked Recursive Dynamic Crop-CGE Model is used. 4 microeconomic adaptation measures are tested for counteracting climate change adverse effects and increasing crop yields per unit area: fertilization, irrigation, change in the planting date and overall technology improvement. Model results show that overall technology improvement is the most efficient measure for increasing crop yields, GDP and average household per capita income. However, the increases in crop yields are accompanied with the adverse effects of higher demand for land given the new crop profitability. For reducing these adverse effects, some macroeconomic policies are coupled with the most efficient policy at the micro level (Commodity Tax, Activity Tax and Export Price), simulating a climate policy mainstreaming scenario. The best macroeconomic policy in terms of sustainability is the reduction of export price, which reduces the deforestation rate of the overall technology improvement micro policy. After identifying the best combination, an estimated social cost of forest protection for the short and long runs is estimated from the policy scenario results. These costs are a good starting point for REDD schemes negotiation processes in the context of Global Climate Change Agreements.

Keywords

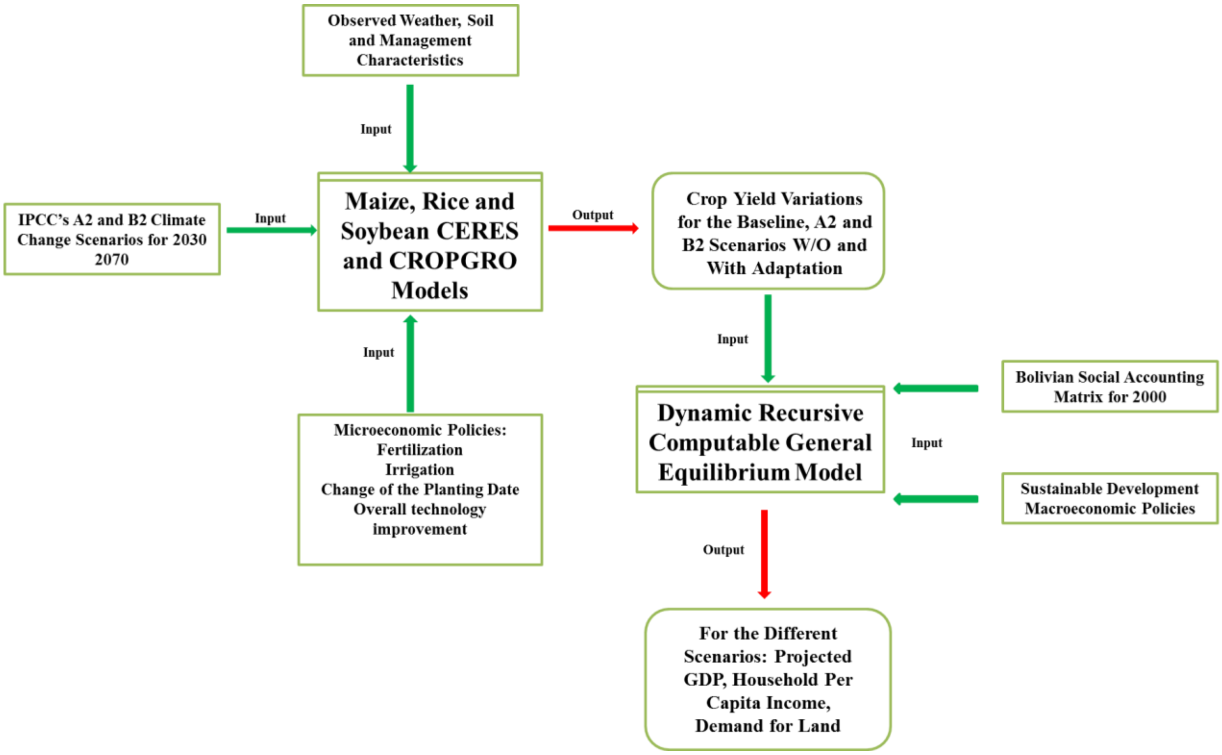
Climate Change, Agriculture, Adaptation, Climate Policy Mainstreaming, Sustainable Development, Deforestation, Bolivia, CGE.

1. Introduction

In Bolivia the expansion of the agricultural frontier has increased considerably, with observed deforestation rates of about 270,000 ha/year in the whole country (FAO, 2006), of which around 200,000 ha/year occurred in the Santa Cruz Department. The Santa Cruz Department, besides being one of the biggest in Bolivia, is the one with the largest amount of land suitable for agriculture, thanks to its climate and location next to the Amazonian lowlands. Indeed, the observed evolution of the agriculture land has increased at an average rate of 7.9%, in other words, from 0.48 million hectares in 1990 to 1.95 million hectares in 2009 (CAO, 2010). The Department's agricultural production in terms of volume represents approximately 75% of total national production. Its main production areas can be classified into: Integrated Zone (which includes: Warnes, Mineros, Yapacani Municipalities); and Expansion Zone: (which includes: Pailón, San Julián, Gutierrez and Guarayos Municipalities), while the main crops grown are: soybeans, sugarcane, maize and rice. Producers range from small to large scale, but most of them are settlers who continue to expand the agricultural frontier by implementing the inefficient method of slash and burn under rainfed conditions, making them much more vulnerable to changes in weather patterns and getting low yields per unit area. In fact, the national average yields are much lower than those observed in neighboring countries (especially Brazil and Argentina), which have a better planned agriculture and access to irrigation. Moreover, in recent years there were reductions in crop yields even higher, due to increases in temperature, droughts and floods. In this regard, as the IPCC, 2001 reported: "Under climate change, increases in both mean and extreme temperatures are expected in many parts of the globe". These changes may impact the growth, development and yield of crops in a number of ways. Temperature and water are key determinants of the evaporative demand and transpiration, particularly in tropical regions (Priestley and Taylor, 1972). With this situation plus the increasing rate of national and global population, more planted hectares of crops will be required for meeting the demand for food in the coming decades, thereby increasing the deforestation rate, which cannot be extended indefinitely given that forests are scarce and provide environmental services, without which agriculture would not be further possible (water cycle, CO_2 fixation and wind protection among others). In fact, there is global agreement on the literature concerning the relation of the local land use change phenomena with ecosystem services, water cycle, albedo and wind, among others. In this sense, in order to maintain the ecosystem's balance, according to Turner, 2003, appears the "sustainability science", which comes from the understanding of the human relationship with the environment, with the dual objective of meeting the needs of society and to maintain life support systems of the planet. These objectives, in turn, require more dialogue between science and decision making. In other words, each ecosystem has its natural resources, determined by ecological and climatic characteristics (forest), but also pressures on them, determined by socio-economic characteristics of the area (agriculture). Sustainability is only possible if the balance is in equilibrium. The ability to achieve balance or not, depends on a good management of natural resources, i.e. planning policy, legal and institutional framework that is selected to be defined and implemented. Therefore, to counteract climate change effects, guarantee food security and also to slow down the deforestation rate in Bolivia, some adaptation measures should be applied at the micro level to increase crop yields per hectare (fertilization, irrigation, change in the planting date and overall technology improvement), accompanied by policies to protect natural resources at the macro level (Commodity Taxes, Activity Taxes, Export Prices, Management of Protected Areas and Forest Reserves, among others), to counteract the adverse incentives of agricultural expansion coming from an increased demand and higher crop yields. As a matter of fact, in the last decades, crops and livestock demand for new additional land, has led to alarming deforestation rates, especially in Permanent Forest Production

Lands (Tierras de Producción Forestal Permanente TPFPs), not suitable for agriculture activities. As a result of this inappropriate use of forest resources, the country is suffering huge economic losses and a series of negative social and environmental impacts, most of which are irreversible (Wachholtz et al., 2006). Historically, market forces and government policies have encouraged agricultural expansion to achieve economic development at the expense of forested land. Only since the 1990s successive governments have begun promoting sustainable development policies related to forest and natural resource use. However, despite the many political and multilateral assistance programs designed to reduce the high rates of deforestation, the deterioration in forest cover still continues. Given this context, the present study's main objective is to quantify and compare the impacts of climate change in the Bolivian agriculture with and without adaptation at different levels: At the micro level, in the per capita income; and at the macro level, in total welfare of the Bolivian Economy as a whole (GDP), and the demand of Land from Modern Agriculture (as a proxy variable of deforestation). For the research two modeling tools are linked: the CERES and CROPGRO crop models for maize, rice and soybeans, for quantifying the impacts of different climate change scenarios on crop yields per hectare; and on the other hand, the Dynamic Recursive Computable General Equilibrium Model (CGE) developed by Thurlow, 2004, which is adapted, calibrated and validated for the Bolivian economy in order to specifically evaluate the performance of the agricultural sector.

Figure 22: Methodology Flowchart



As observed in Figure 22, first, the CERES and CROPGRO crop models are calibrated and validated with observed daily meteorological data, soil physic and chemical analysis and field work for soybeans, maize and rice in the 5 most important production zones of Santa Cruz, Bolivia. A full review of the calibration and validation process is found in Viscarra, 2010. After that, the impacts of the A2 and B2 IPCC's SRES climate change scenarios are introduced in the crop models for quantifying the variations in crop yields per hectare. Next, some microeconomic adaptation measures are introduced in the crop models to counteract the negative effects of climate change. In parallel, the Dynamic Recursive General Equilibrium model is modified, calibrated and validated to for the Bolivian economy using a Social Accounting Matrix for 2000 to be coherent with available data for crop models. Once the CGE model is validated for the baseline, the crop yield variations from the A2 and B2 scenarios W/O and with adaptation are introduced in the CGE for quantifying the GDP, the household per capita income and the demand for land from Modern Agriculture Activity as a proxy of deforestation. Finally, when the most appropriate adaptation measure is identified, some macroeconomic policies are implemented in the CGE for reaching sustainable development (the highest welfare with the lowest depletion of natural resources).

This document focuses on the CGE modeling part of the methodology and it is broken down into 6 sections. The first section reveals the background and introduction of the study. The second presents the historical and institutional framework related to agriculture and deforestation in Bolivia. Section 3, details the methodology and explains the main features of CGE modeling and the conceptual and mathematical specification of the model applied to the Bolivian economy. Section 4, provides the database, calibration and validation of the CGE for the Baseline. Following that, the results of the simulations for the different climate change and policy scenarios are presented in section 5. And finally, section 6 shows the main conclusions and recommendations.

2. Agriculture and Deforestation in Bolivia: Historic and Institutional Framework

Forests in Bolivia cover an area of 46 million hectares, which represents 42% of the country (Killeen et al, 2007). Most of these resources are natural and cover most of the lowlands and the Amazon from the center to the eastern part of the country. Much of this region is located at less than 500 above the sea level, which is why it is commonly known as “lowlands” and includes the whole administrative boundaries of Santa Cruz, Beni and Pando and parts of La Paz, Cochabamba, Chuquisaca and Tarija Departments. For several decades, the reduction of forest areas in the country has been below the rates shown in other tropical forest countries. However, deforestation in recent years has reached alarming levels, since observed deforestation rates in the last decade have almost doubled those recorded in the previous decade. This increase is attributed to the expansion of the agricultural frontier mainly in the Santa Cruz Department, region with the best soils suitable for agriculture in the country.

2.1 Bolivian Forest Cover Variation in the Global Context

One of the latest FAO assessments on forest resources in the world (2006), suggests that deforestation continues at a shocking rate. According to the study, between 2000 and 2005, approximately 13 million hectares of forest have been lost each year, making South America the region with the highest net losses of forests - about 4.2 million ha/year - followed by Africa, which lost 4.0 million ha/year (Table 27).

Table 27: Regions and Countries with the Largest Areas of Deforestation Between 2000 and 2005 (thousands of hectares)

Region	Country	Forest Cover[a]		Annual Change	Annual Percentage Change (%)[b]
		2000	2005		
Africa		**655613**	**635412**	**-4040**	**-0.62**
	Sudan	70491	67546	-589	-0.8
	Zambia	44676	42452	-445	-1
Asia*		**566562**	**571577**	**1003**	**0.18**
	Indonesia	97852	88495	-1871	-2
	Myannmar	34554	32222	-466	-1.4
North and Central America		**707514**	**705849**	**-333**	**-0.05**
	Mexico	65540	64238	-260	-0.4
South America		**852796**	**831540**	**-4251**	**-0.5**
	Brazil	493213	477698	-3103	-0.6
	Bolivia	60091	58740	-270	-0.5
	Venezuela	49151	47713	-288	-0.6
a Total Forest Cover includes forest plantations					
b Rate of change in the percentage of remaining forest area each year within the given period					
** Increase in forest cover in Asia is largely because in China more than four million hectares per year during the period 2000-2005 were reforested*					

Source: Own elaboration with FAO, 2006 data.

Bolivia has a relatively low level of deforestation compared to other countries. However, in the South American region the country has the third highest forest loss in the last five years after Brazil and Venezuela. Currently, Bolivian forest losses are around 270,000 ha/year; while Venezuelan are 288,000 ha/year and Brazilian 3.1 million ha/year (FAO, 2006). The latter represents the most severe case worldwide. The forest cover loss in Bolivia is especially troubling because this is concentrated in semi-deciduous old growth tropical forests, which has been almost completely eliminated in the rest of South America (Hecht, 2005). It is also alarming that over 40% of deforestation takes place in Permanent Forest Production Lands (TPFPs), which is not suitable for agricultural use and degrades quickly once the forests are cut down and burned. Indeed, few forest lands in the tropics still retain the ability to allow sustainable agriculture (Wachholtz et al., 2006).

2.2 Historical evolution of deforestation in Bolivia

In Bolivia there are few studies on the historical changes in forest cover. In addition, the information available is very fragmented in time and it covers different geographical areas. The main weaknesses of deforestation estimates have been: (i) the absence of a continuous and systematic monitoring, (ii) the lack of disaggregated information for each agro-ecological zone, and (iii) the use of different calculation methods, geographical units of reference and confusing definitions of deforestation (Pacheco, 1998). All of these elements prevent the comparison of the results of the various estimates. However, Table 28 summarizes the main deforestation estimates available nationwide:

Table 28: Estimates of Historical Deforestation in Bolivia (thousands of hectares)

Source	Methodology *	Period	Final Forest Cover	Deforestation		Deforestation Rate (%)
				Period	Annual	
MDSMA a	60 LANDSAT 5-TM Images with 30m of resolution	1975-1993	53444	3024	168	-0.3
UMD b	44 LANDSAT - TM and MSS Images with 60m of resolution	1986-1992	43790	917	153	-0.34
BOLFOR c	39 LANDSAT 7-TM Images with 15m of resolution	1993-2000	51552	1892	270	-0.5
MHNNKM d	45 LANDSAT - TM Images with 30m of resolution	1992-2000	46744	1205	151	-0.32
	18 LANDSAT - TM Images with 30m of resolution	2001-2004	46070	674	225	-0.49
SF e	145 MOD13Q1 Images with 231m of resolution	2004-2005	53745	556	278	-0.51
	115 MOD13Q1 Images with 231m of resolution	2006	53437	307	307	-0.57

* The smaller is the number of meters per pixel in the image, the higher the level of resolution. So resolutions of 15 and 231 meters represent observable minimal surfaces of 0.02 and 5.3 hectares, respectively

Source: Own elaboration with different sources data: ***(a)*** *Pacheco, 1998,* ***(b)*** *Steininger et al., 2001,* ***(c)*** *Rojas et al., 2003,* ***(d)*** *Killeen et al., 2007 and* ***(e)*** *Wachholtz et al., 2006 and 2007.*

According to the Forest Map of 1993 published by the Ministry of Sustainable Development and Environment (Ministerio de Desarrollo Sostenible y Medio Ambiente, MDSMA), forest cover for that year was 53.4 million hectares. Comparing this data with the 1975 forest area estimated by the Geological Survey of Bolivia (GEOBOL), the MDSMA estimated that over a period of 18 years (1975-1993), 3.02 million hectares of forest cover have been removed at a rate of 168,000 ha/year, giving an average annual deforestation rate of -0.3% (Pacheco, 1998).

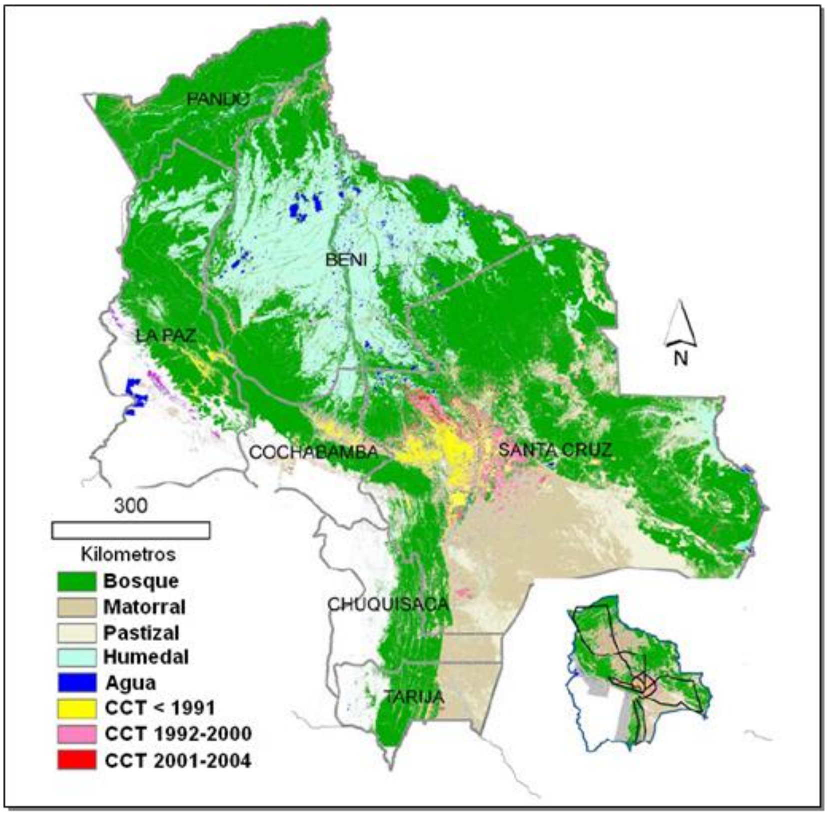
Another important estimate on the change of the Bolivian forest cover was submitted by the Department of Geography at the University of Maryland (UMD) that identified a cumulative deforestation of 917,100 ha between 1986 and 1992, in other words 152,850 ha/year. The most affected area in this period was located in the department of Santa Cruz with 68.5% of the total cumulative national deforestation, followed by Beni with 10%, then Cochabamba with 9.1%, La Paz with 6.9% and Pando with 5.5% (Steininger et al., 2001).

According to the study presented by the BOLFOR project, since the 1990s deforestation has increased significantly in the country. This work is based on a comparison between the coverage of the 1993 Forest Map and satellite images of 2000. The study found that the average deforestation rate in this period was 270,000 ha/year. Again, most of the deforestation between 1993 and 2000 was concentrated in the Santa Cruz Department whose cleared areas were three times higher (75.3%) than those estimated for the departments of Cochabamba (8.2%), Beni (4.7%), La Paz (4.1%), Pando (2.6%), Chuquisaca (2.6%) and Tarija (2.5%) (Rojas et al., 2003).

More recent efforts to measure changes in forest cover include investigations of the Natural History Museum Noel Kempff Mercado (Museo de Historia Natural Noel Kempff Mercado, MHNNKM) and the Forestry Superintendence (Superintendencia Forestal, SF). For the former, the estimated rates of deforestation were 151,000 ha/year and 225,000 ha/year for the periods 1992-2000 and 2001-2004 respectively (see Map 1) (Killeen et al., 2007). On the other hand, the SF estimated for the period 2004-2005 a deforestation of 278,000 ha/year, while for 2006 a deforestation of 307,000 hectares (Wachholtz et al., 2006 and 2007). Both studies show that deforestation concentration was similar to that found in the 1990s studies, in other words: *in recent years about 75% of deforestation occurred in Santa Cruz and the rest in the other Departments.*

Although it is not possible to accurately compare the different results, the mentioned reference data suggest that deforestation rates remained relatively low until the late 1980s, and then rose sharply since the early 1990s especially in Santa Cruz where the agricultural frontier expansion was taking place.

Figure 23: Geographical Distribution and Temporal Changes in Land Cover (CCT) in Bolivia, with Flight Path Validation

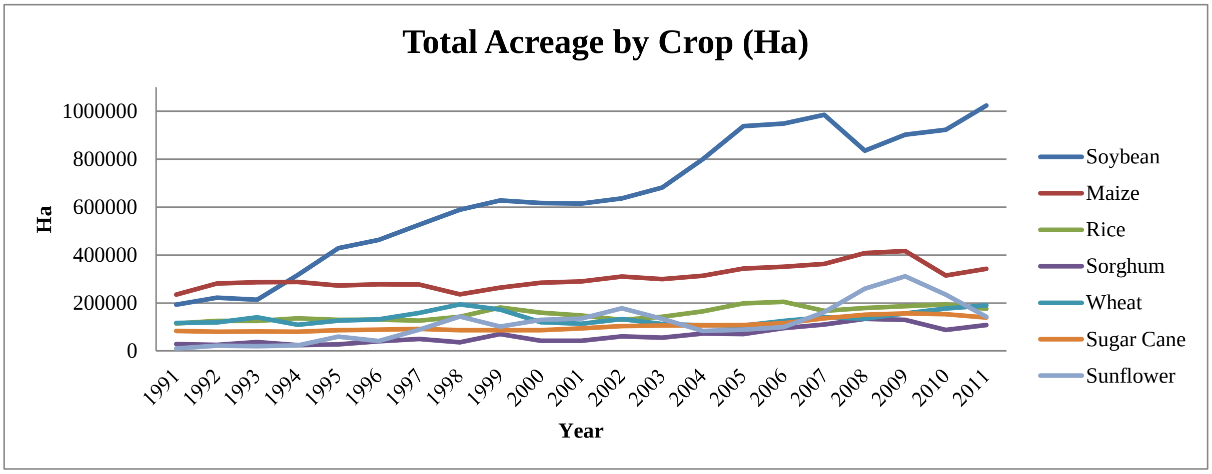


Source: Killen et al., 2007.

2.3 Economic Policies, Markets and Deforestation

Government policies play a decisive role on deforestation, given that they influence the evolution of the agricultural frontier and the expansion of the market for goods produced at such borders (Pacheco, 2006, Kaimowitz et al., 1999). In Bolivia, two critical changes in the political and economic structure of the country have marked the historical development of the agricultural frontier. The first began in 1952 and was characterized by protectionist policies that sought to diversify the economy through import substitution based on strengthening the agriculture, mining and industry sectors; and the second, since 1985, policy which was based on the growth of the economy with a neo-liberal approach towards market opening (Pacheco, 2006). Although in both periods policies promoted the agricultural expansion to achieve economic development at the expense of forest land, from the 1990s successive government's policies began promoting sustainable use of natural resources and forest land. However, problems related to weak institutional capacity, insecure land tenure and the pressure of agricultural product markets have prevented these initiatives to have the desired impact. It was not until late 1990 that the agricultural expansion was halted for a few years due to a recessive crisis that faced the Bolivian economy, however, with the economic recovery and new policies to promote the sector, the demand for new land for agriculture and livestock continued. During this period and after overcoming the crisis and having achieved economic stabilization, the Bolivian government with technical and financial support from the World Bank implemented the "Eastern Lowlands Project", which implemented a program to promote the cultivation of soybeans in the eastern part of the Santa Cruz Department, commonly known as “Expansion Zone”. The program included working capital financing and investment for farmers, agricultural extension support and improvement of roads. All these factors contributed greatly to the increase of deforestation related to large-scale agricultural production especially soybeans. Figure 24 shows the historical evolution of the cultivated area of the products with the highest requirement of land in Bolivia between 1991 and 2006, which clearly highlights the expanding soybeans acreage during this period (INE, 2013).

Figure 24: Total Acreage by Crop in Hectares



Source: Own elaboration using National Statistics Institute (INE), 2013 data.

Other crops that experienced growth were: wheat, sorghum and sunflower, which are generally grown as rotation crops on land previously enabled for soybeans in the summer campaign. Similarly, the extension of mechanized crops such as maize and rice had less impact on deforestation because they are grown mostly in agricultural areas and not TPFPs (Pacheco, 1998).

On the other hand, livestock has had a relatively minor impact on deforestation in the lowlands in relation to the impact of agriculture. This is because most of expanding herds were in natural pastures in the Beni, Department which is the main supplier of meat for decades in the domestic market (Pacheco, 1998), thus, currently livestock expansion seems not to be a trigger for deforestation. This situation has changed in recent years due to increased livestock production in the Chiquitania area of Santa Cruz and in the northern part of Pando to supply the growing market of meat mainly from the cities of Santa Cruz and La Paz (Pacheco, 2006), but in a much lesser magnitude than soybeans expansion.

2.4 Complementary Policies on Natural Resources

In view of the growing process of natural resources exploitation related to models of economic development, sustainable development policies began to be promoted in the 1990s in Bolivia. Among these policies are: the 1333 Environmental Law, the creation of the National System of Protected Areas, the development of the Land Use Plan (Plan de Uso de Suelo, PLUS), the INRA Law (Instituto Nacional de Reforma Agraria, INRA) and the Forestry Law. These last two laws have a special relationship with the subject under study; therefore, a more detailed explanation is given in the following sections.

2.4.1 INRA Law

The INRA Law, 1996 substantially modified the legal and institutional framework of agricultural land use in Bolivia that existed since the early 1950s. The main challenges to be solved by the law were the unequal distribution of the country's rural land, tenure security and the historical rights claim over the land of indigenous people (Muñoz, 1999). For this purpose, the Agrarian Reform Institute was created as coordinator and executor of policies, and the Agrarian Superintendence (Superintendencia Agraria , SA) as the regulator of the agricultural sector.

However, after more than 10 years of rule, the law challenges were not met. Approximately 80% of the land is not reclaimed by indigenous people, which constantly generates overlapping conflicts of properties that in most cases do not encourage rational use of land; besides, these conflicts impair productive investments, implementation of management policies and natural resource management.

Similarly, although the INRA Law establishes as a Social Economic Function (Función Económico Social, FES) to the sustainable land use made by agricultural, forest and other activities according to the major capacity of land (Art.2), the market conditions for agricultural products and the land tenure insecurity have influenced in the agricultural use of land, recognizing it as the main reason to meet the FES requirements, which has encouraged farmers to deforest lands that clearly had forest productive capacity only, and then claim for property rights and obtain short-term income.

2.4.2 Forestry Law

In order to regulate the sustainable use and protection of forest resources, in 1996, the 1700 Forestry Law was established, from which an institutional framework was structured with three main actors: the Ministry of Sustainable Development and Environment as the national body, the Forestry Superintendence (SF) as a regulatory body and the National Forest Development Fund (FONABOSQUE) as a financial institution. Also, the law fostered decentralized participation of Prefectures and Municipalities for strengthening the Forestry Regime (Art. 19).

According to regulations, the lands subject to authorization for clearing are those that are defined in Article 16 of the Forestry Law and Article 49 of the General Regulations as forested land suitable for various uses, according to the Predial Management Plan (Plan de Ordenamiento Predial, POP). Moreover, the process of land conversion for agriculture, livestock or other uses must comply with the technical and legal limitations set forth in the "Special Regulations Controlled Burn and Forest Clearing" (Ministerial Resolution No. 131/97).

Despite the establishment of rules and institutions to regulate the forestry sector in Bolivia, the relative political instability and institutional weakness in recent years has led to a mistreatment of the forestry sector mainly reflected in the increase in the rate of illegal land clearing. Between 2004 and 2005, over

88% of deforestation was illegal, i.e. without the authorization of the SF, and over 40% of deforestation occurred in land unsuitable for agricultural use (TPFPs), (Wachholtz et al., 2006).

Forestry Regulation establishes a system of progressive and cumulative fines to prevent illegal deforestation; however, in many cases the complex administrative process for offenders has prevented effective sanctions. Similarly, the lack of coordination between the Agrarian Superintendence, the Forestry Superintendence and the INRA Institute increases the likelihood of erroneous authorizations to clear land unsuitable for agriculture.

As observed, the institutions, laws and policy implemented in the Forest and Agriculture sectors in Bolivia during the last couple of decades were not enough in order to meet sustainable development objectives. A set of complementary policies has to be developed, which is the final objective of the paper and will be analyzed in the next sections, but first the methodology has to be defined.

3. Methodology

The paper uses 2 different kinds of models, one bottom-up and the other top-down. The bottom-up are the calibrated and validated CERES and CROPGRO models for soybeans, maize and rice in the 5 most important production zones in Santa Cruz – Bolivia. Only the results are used, given that the full methodological implementation is detailed in Viscarra, 2010. On the other hand, the top-down model is a Recursive Dynamic Computable General Equilibrium Model modified, calibrated and validated for the Bolivian Economy. The main features are presented in the following sections.

3.1 Computable General Equilibrium Models (CGE)

The Computable General Equilibrium Models (CGE), try to represent the main features of the functioning of an economy by the joint application of microeconomic principles and key macroeconomic balances. This approach is based on the neoclassical structure of Walras, where equilibrium is characterized by a set of prices for goods and factors, and levels of production and use of inputs that vary endogenously to match supply and demand in competitive markets (Abdullah 2006).

The main advantage of CGE models is that they allow quantitative assessment of the effects of changes in domestic policies and market conditions on relative prices by simulating the inter-sectorial relations (van der Werf and Peterson, 2007)[6]. Model results show what would have happened, or may happen in a given period if a policy of interest had been implemented and all the other internal and external conditions would have been held constant (ceteris paribus). Thus, CGE models are important tools for the analysis of resource allocation in a given country.

The first and simplest numerical application of a CGE model was developed by Johansen, 1960 who used market equilibrium assumptions to determine the prices of many sectors in the economy of Norway endogenously. For this work, Johansen used the logarithmic derivatives in specifying the nonlinear general equilibrium model to generate a linearized model and solve it using matrix inversion techniques. Subsequently, Dixon et al., 1982 continued to develop this approach in a multi-sectorial model for Australia called ORANI, which was used by Hertel, 1990 and 1997, and Darwin et al., 1995 for various investigations in the U.S. and globally.

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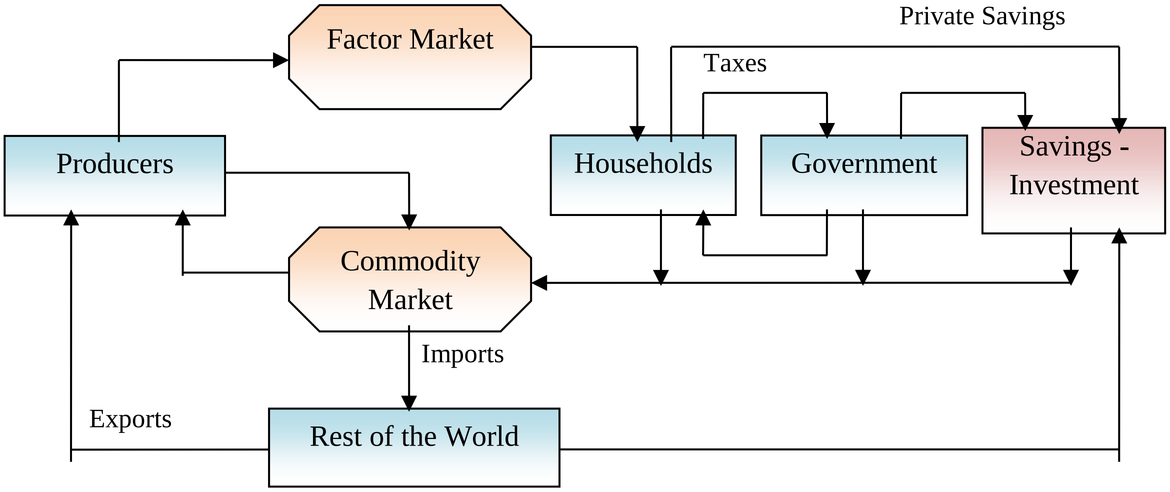
[6] The main criticism of the Marshallian partial equilibrium models lies in its limitations to model the impacts of policies on all sectors of the economy. Generally economic activities are connected through primary input markets, trade of goods and, in this way, changes in prices (or other market conditions) simultaneously affect aggregate welfare of consumers and producers from various sectors.

The applications of CGE models have been diverse and cover a range of countries and regions, issues related to factor markets, macroeconomic variables, specification and sectorial disaggregation of agents. Moreover, the policies considered were related to domestic taxes, foreign trade, labor market, production technologies and environment.

3.1.1 General Characteristics of a CGE Model

The basic structure of a model is summarized in the CGE circular flow diagram shown in Figure 25. The main actors in the economy are households, firms, government and the rest of the world, whose activities are associated with the goods and factor markets.

Figure 25: Circular Flow of Payments in CGE Models

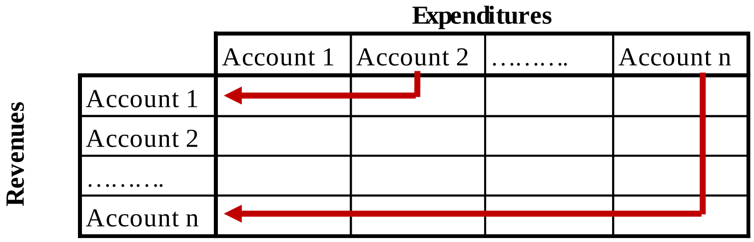


Source: Own elaboration, based on San, Löfgren and Robinson, 2000.

Households receive income from the sale of production factors and some transfers from other agents; in turn these revenues are used for consumption, savings, tax payments and other transfers. Companies can also receive payments for some factors and transfers from other agents, which are allocated to savings, investments, taxes and transfers to other institutions. The government collects taxes and receives transfers from other institutions, these revenues are directed to the purchase of consumer goods, savings and some transfers. Finally, the rest of the world makes payments between domestic and foreign institutions, whose balance is represented by a foreign savings account (or current account deficit), which is the difference between income and expenditure in foreign currency (Löfgren et al. 2002).

Economic data representing these circular flows are contained in a balanced Social Accounting Matrix (SAM), which provides a characterization based on all transactions in an economy over a given time period (Ross, Depo and Pattanayak, 2007). The SAM is a square matrix in which each account is represented by a row and a column. Each cell shows the payment from the account of its column to the account of its row and a revenue account appear along its row and its expenditures along its column as shown in Figure 26. The principle of double entry in this array requires that for each account the total revenue (row total) equals total expenditure (total column).

Figure 26: Expenditure and income flows on a Social Accounting Matrix



	Account 1	Account 2	………	Account n
Account 1				
Account 2				
………				
Account n				

The CGE model explains all payments recorded in the SAM, where the economic structure and the estimated variables determine how the production and consumption may change in response to new policies. The agent's behavior is modeled based on the fundamentals of microeconomic theory, where producers maximize profits subject to prices and technology and households maximize utility subject to budget constraints. In the aggregate, the equilibrium is modeled by prices, quantities, and payment flows to which supply and demand are equal in competitive markets (San, Löfgren and Robinson, 2000).

3.1.2 Applications of CGE Models to Land Use Change and Forestry Sectors

In recent decades, various attempts have been made to extend CGE models to include issues related to land use change activities. The first attempts to develop CGE models to analyze these issues were focused on forestry applications with inter-temporal considerations and differences between land uses, but in many cases the biophysical aspects of land were weakly represented[7]. For this reason, recent efforts have incorporated aspects aimed at improving the treatment of the transition between different land uses - particularly among crops, livestock, forest, and also to differentiate between different types of soils (van der Werf and Peterson, 2007).

Among the most important studies is that of Burniaux and Lee, 2003, who extend the static standard GTAP model to evaluate the inter-sectorial transition of land and in this way evaluate the emissions of Methane, CO_2 and NO_2 due to changes in land use change[8]. In this approach, the land factor owners' (considered as a homogeneous factor), assign its uses to activities that generate higher returns under the restriction on the Constant Elasticity Transformation (CET) which determines the degree of mobility between different uses.

On the other hand, Abdullah, 2006 and Ignaciuk, 2006, propose land as an heterogeneous factor, which means that certain types of soil are not suitable for certain group of crops and/or activities. Abdullah develops a static CGE model for the Philippines and incorporates a bio-energy sector to study the conflict between food production and biofuels. While the Ignaciuk's model considers a certain amount of contaminated soil by mining and industrial activities that can only be used for the production of bio-fuels and not for agricultural activities.

Another similar attempt to represent land use in a more detailed manner using CGE models is the Future Agricultural Resources Model (FARM) developed to assess climate change impacts on global agricultural system (Darwin et al., 1996). The FARM model is composed of a Geographic Information System (GIS) and an extension of the GTAP model, where the world is divided into 12 regions in which

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[7] See Xie, Vincent and Panayoutou, 1996 and Kaimowitz and Angelsen, 1998 for a detailed review of the first related articles.

[8] The standard GTAP model is a multi-region, multi-sector CGE model under perfect competition with constant returns to scale. For details see Hertel, 1997.

there are six types of land differentiated by the length of growth periods. An important aspect is that the GIS data provide regional water supply for different sectors. There is also a dynamic version called D-FARM, which considers property rights and investment theory to create a recursive model based on estimated growth rates of regional GDP, domestic investment, population and labor (Ianchivichina et al., 2001; Alavalapati and Wong, 2003).

Finally, Lee et al., 2005b, advance more the question on heterogeneity of land through the application of GTAP model globally based on integrated information that includes data land cover and use, forest carbon storage and GHG emissions. The quality of land is differentiated in 18 agro-ecological zones (AEZ, 6 growth periods combined with 3 climatic zones) within which there exists similar characteristics of soil, slope and climate that affect productivity levels. In addition, land can move between sectors if it is suitable for the required use, but not between AEZs. This model continues under construction in search of greater biophysical realism when using CGE models, and thus achieving adequate agricultural and natural resources policy analysis, especially strategies to reduce Global GHG emissions (Hertel et al., 2006; Golub, Hertel and Sohngen, 2007).

3.2 Agriculture Dynamics and Deforestation in the CGE

Given the lack of substantial research concerning the impacts of climate change and sustainable development in the Bolivian Economy focused in the land use change sector, this study proposes the use and link of crop model results with a Recursive Dynamic CGE Model to measure the shocks of different climate change scenarios and adaptation policies in the agriculture and demand for land sectors, with their collateral effects to the economy as a whole, and after that to test macroeconomic policies together with efficient and plausible microeconomic adaptation measures for achieving sustainable development ("climate policy mainstreaming"[9]).

The model used is a modification, calibration and validation of the CGE Model originally developed by Thurlow, 2004, through extensions to the standard static CGE Model of the International Food Policy Research Institute (IFPRI) (Lofgren et al., 2002). The general features of the model are as follows:

- **Geographical Aggregation:** The information contained in the SAM is aggregated at a country level; therefore, the analysis is performed on this scale. Better assessment and analysis of results could be achieved by using a more disaggregated SAM (e.g. by region, assets, size of farmer), but by the time this information is not available.
- **Time Specification:** The model is recursive dynamic, thus, it simulates the behavior of economic agents given its previous decisions and changes in external factors specified in the time horizon. For this purpose, a time horizon of 11 years is considered (2000-2010), in which every year is a period of time where the overall equilibrium must be resolved.
- **Financial vs. Real Economy:** The model does not consider the financial sector; this limitation is evident by the absence of variables such as the interest rate and the money supply. Simulations in this paper have implicitly assumed that the monetary sector adjusts passively to facilitate the observed changes in the real economy. It should be noted that in this type of model, only fiscal macroeconomic policies can be assessed.

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[9] Climate policy mainstreaming, understood as: "the integration of policies and measures to address climate change in ongoing sectorial and development planning and decision-making, aimed at ensuring the sustainability of investments and at reducing the sensitivity of development activities to current and future climatic conditions"), (Klein et al., 2005).

Also, given the recursive nature of the CGE model used, this is divided into two components: the component of each period and the component between periods, where the latter contains the model dynamics. The differences in the Conceptual Structure and Mathematical Specification of both are presented in this section.

3.3 Conceptual Structure

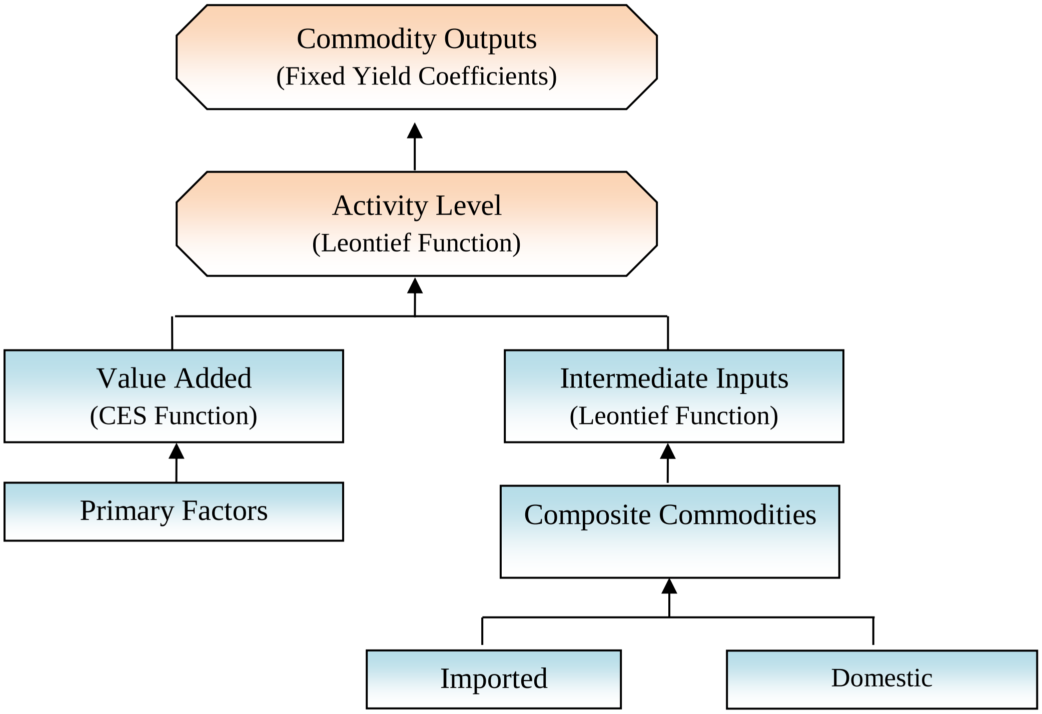
3.3.1 Component of Each Period

The component of each period represents the static CGE model of a single period. The description of this component consists of the production and trade structure, land use and deforestation factor, market closures and finally the mathematical specification.

3.3.1.1 Production and Trade Structure

On the supply side we assume that each producer (represented by an activity) maximizes its profits subject to a production technology represented in Figure 27. At the highest level, the technology is specified by a Leontief function between the amounts of value added and aggregate intermediate input. At the lowest level, the value added is a Constant Elasticity of Substitution function (CES) of the primary factors of production; while aggregate intermediate input is a Leontief function of disaggregated domestic and imported inputs, where shares of domestic and imported commodities can be changed.

Figure 27: Production Technology



Source: Own elaboration, based on Löfgren et al., 2002.

The model differences between activities and products, which allow that the same product can be produced by more than one sector and also that one sector, can produce one or more products. The modified calibrated and validated model for Bolivia represents an economic region distributed in nine activities: 1) Traditional Agriculture, 2) Modern Agriculture, 3) Forestry, Hunting and Fishing, 4) Food Processing, 5) Hydrocarbons and Mining, 6) Industry, 7) Construction, 8) Trade and Transport, and 9) Services; and twelve products: 1) Traditional Farming, 2) Industrial Agriculture, 3) Coca, 4) Cattle, 5) Forestry, Hunting and Fishing, 6) Processed Food, 7) Oil, Gas and Minerals, 8) Industrial Products, 9) Construction, 10) Transport, 11) Services and 12) Trade. These activities use a combination of intermediate inputs with six factors of production: skilled and unskilled labor, informal and formal capital, land and natural resources, extracted from INE's National Data. Table 29 shows the activities, goods produced and factors used for these activities.

Table 29: Economic activities, Produced Goods and Factors Used in the CGE Model for Bolivia

Activities	Products	Primary Factors Used
Traditional Agriculture	Traditional farming, cattle and processed food	Unskilled labor and land
Modern Agriculture	Traditional farming, industrial agriculture, coca, cattle, forestry, hunting and fishing and processed food	Unskilled and skilled labor, formal capital and land
Forestry, Hunting and Fishing	Forestry, hunting and fishing	Unskilled and skilled labor, formal capital and natural resources
Food Processing	Processed food	Unskilled and skilled labor, formal and informal capital
Hydrocarbons and Mining	Oil, gas, minerals and related industrial products	Unskilled and skilled labor, formal capital and natural resources
Industry	Industrial products	Unskilled and skilled labor, formal and informal capital
Construction	Construction	Unskilled and skilled labor, formal and informal capital
Trade and Transport	Transport, related services and trade	Unskilled and skilled labor, formal and informal capital
Services	Construction, transport, related services and trade	Unskilled and skilled labor, formal and informal capital

Source: Own elaboration, based on the SAM developed in Lay et al., 2006.

Table 29 shows that there are 2 main Activities in the Agriculture sector (Traditional Agriculture and Modern Agriculture), which have some products in common, such as: Traditional Farming, Cattle and Processed food. The main difference between these 2 activities is that Traditional Agriculture is done in a smaller scale and is labor intensive, while Modern Agriculture is done in a larger scale and applies capital and machinery in its production process. On the other hand, the sectorial allocation of factors is determined endogenously in a market where wages are flexible. Each activity pays a specific wage which comes from the product of wages throughout the economy and the distortion wage fixed term of the specific activity. This specification, in which the returns of the factors are sector specific, is preferable to using simple average wages, since observed average wages in Bolivia vary both between occupations and sectors. The income factor also includes remittances received from the rest of the world.

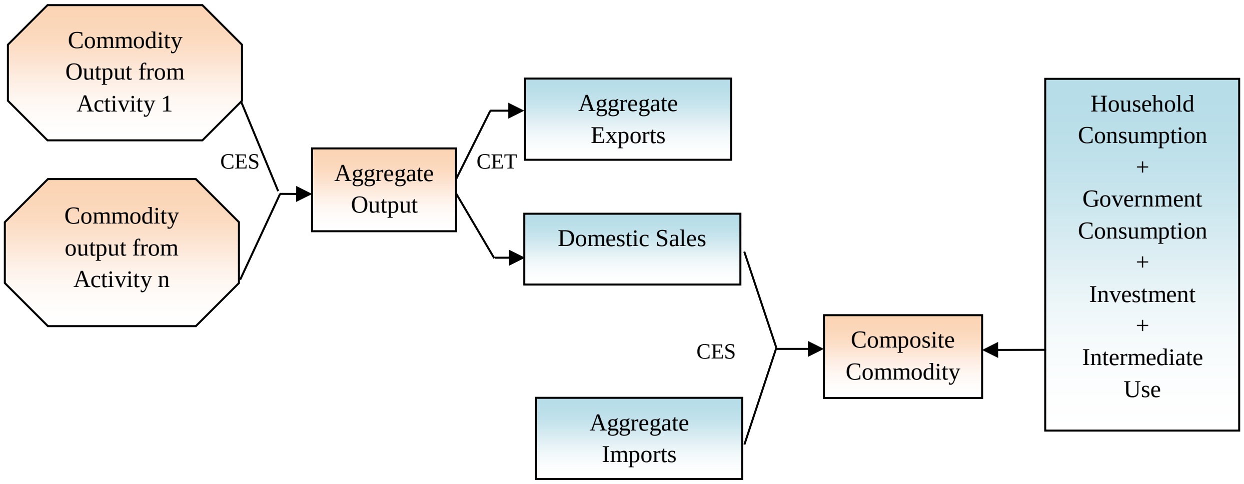
Payments to factors generated in the production process are distributed to four different groups of households, differentiated according to their income level (poor or rich) and its location (rural or urban). According to Lay et al., 2006, this distinction allows the examination of the channels through which certain shocks in the agricultural sector can have negative impacts on income distribution.

All domestically produced goods enter the market which generates different trade flows as represented in Figure 28[10]. To model business relationships, initially all similar produced goods are added by different activities through a CES function reflecting imperfect substitutability between them, this is to represent the fact that commonly similar products have differences in quality and maturity among others. Subsequently, the added product goes to for domestic consumption or export under the assumption that producers maximize profits subject to imperfect transformability between these two alternatives, expressed as a Constant Elasticity of Transformation (CET) function.

On the other hand, domestic market demands an aggregated product are comprised by domestically produced goods and imported products. For this purpose, generally the Armington assumption is used, under which, consumers minimize their costs subject to imperfect substitutability between these two types of goods, characteristic represented by a CES function. Final demand depends on institution incomes and composite aggregated demand, which is the sum of household consumption, government consumption, investment and intermediate goods.

The transformability and substitutability assumptions for international trade guarantee that the national price system has a certain degree of independence from foreign prices, and also prevent from unrealistic effects in the exports and imports due to changes in the national productive environment (Cattaneo, 2002).

Figure 28: Flows of Marketed Commodities



Source: Own elaboration, based on Löfgren et al., 2002.

For the analysis, it is assumed that Bolivia is a "price taker" small economy in the global markets of products for export and import, as it produces a very small percentage of total sector products in South America. For this reason, perfectly elastic exportable demand and importable supply functions to existing prices are used.

Transaction costs are incurred only in domestic sales. These costs are treated as a fixed portion per unit of output, and generate demand for trade and transport services.

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[10] The CGE model does not consider production for self-consumption.

3.3.1.2 Demand for Land Factor and Deforestation

Since this study focuses on the demand for land as a factor of production, it is necessary to make a more detailed specification of this factor in the analysis. The Agro-Ecological Zones approach (AEZ), is quite useful for defining the demand for land as a factor of production for different uses (Hertel, et al., 2009). However, disaggregated spatial and input/output data for different AEZ is not available for Bolivia. For this reason, some assumptions had to be made in the model: land is considered as a homogeneous and perfectly mobile factor that is only used by Traditional and Modern Agriculture activities (see Table 29). Therefore, climate change, micro and macro policy shocks affect the employment of land between these two competing sectors. All the shocks in the Modern Agriculture activities come from changes in productivity of soybeans modeled in CROPGRO crop models. While, shocks to Traditional Agriculture activities come from an averaged productivity change of maize and rice modeled in CERES crop models.

Deforestation is estimated by increasing demand for new land in time only from Modern Agriculture activities, which in Bolivia is the main cause of deforestation as evidenced by the literature review in previous sections. It has to be noticed that heterogeneous supply and transformation of land constraints are not considered in the CGE model, this can be considered a drawback of the model and further research is needed for the Bolivian Economy. However, the homogeneous and perfectly mobility of land as a production function assumption, is very plausible given that agriculture in Bolivia is spatially centered in the Santa Cruz Department (almost 80% of the production).

3.3.1.3 Macroeconomic Constraints

The balance between supply and demand for both product and factor is obtained by including a set of macroeconomic closure rules that indicate how the aggregate accounts are adjusted to achieve equilibrium in response to changes in economic activities. The selection of these restrictions is strongly related to the context of the analysis and the general characteristics of CGE model applied. For this study, the rules of "neoclassical market close" commonly used in dynamic CGE models are used, where constraints are as follows:

- **Factor Market:** The factor market equilibrium depends on how the relationship between supply and wages of each factor is defined. The following Table shows the summary of this relationship, as well as the level of employment and mobility of each factor:

Table 30: CGE Market Factor Characteristics

Factors	Supply	Mobility	Utilization
Unskilled Labor	Flexible	Yes	Full Employment
Skilled Labor	Flexible	Yes	Full Employment
Land	Flexible	Yes	Full Employment
Natural Resources	Flexible	Yes	Full Employment
Informal Capital	Fixed	No	Full Employment
Formal Capital	Fixed	No	Full Employment

In the model, labor, land and natural resources supply are flexible and mobile between sectors, and face positive slope supply curves where their elasticity determine the adjustments in supply caused by changes in real wages. On the other hand, the supply of capital is fixed in each period and specific activity, this implies that capital is not mobile and gets industry-specific returns. Finally, all factors are used to full employment.

- **Current Account with the Rest of the World:** A flexible exchange rate balances the current account with the rest of the world; this implies that foreign savings are fixed. This closure is appropriate for Bolivia because the exchange rate system in the country is flexible.
- **Government Balance:** Flexible savings balances the savings account of government, while tax rates (both, direct and indirect) and government consumption levels remain constant.
- **Savings-Investment Balance:** Investment (private and public) is determined by savings, thus, the model assumes that saving rates for domestic institutions are exogenous.
- **Cash Price:** The Price Index for Domestic goods is defined as cash price, and then the exchange rate corresponds to the real exchange rate of the neoclassical trade theory (Robinson et al, 1999)[11].

3.3.2 Component Between Periods

The component between periods describes how certain variables are updated based on the results of previous periods, i.e., it explains the Recursive Dynamic behavior of the CGE model. In this regard, the dynamic features of the model are:

- **Population Growth:** It is exogenously given and based on growth projections calculated separately. It is assumed that the growing population generates a higher level of consumer demand, and therefore increases supernumerary income level of household consumption. Moreover there is no change in the marginal rate of consumption of goods, which means that new users have exactly the same preferences as existing consumers.
- **Growth of Factors:** The specific factor productivities are imposed exogenously to the model, based on historical trends of labor and capital, and it is the linkage between crop model results and the CGE model. Therefore the shocks of climate change and microeconomic policies (adaptation measures) are introduced in the model through these factors.
- **Capital Accumulation:** The process of capital accumulation is modeled endogenously, where previous investment periods generate new capital stock for the next period. While the allocation of new capital across sectors depends on the initial portion of each sector in aggregate capital income, the final allocation depends on the rate of depreciation and the benefit differential rate between sectors benefits in the new period.
- **Government Consumption Growth:** Since government spending in each period is fixed in real terms, government consumption and transfers are exogenously determined between periods.

3.4 Mathematical Specification

In its mathematical form, the CGE model is a system of simultaneous, nonlinear equations. The model is square that is, the number of equations is equal to the number of variables. In this class of models, this is a necessary (but not a sufficient) condition for the existence of a unique solution (Löfgren et al., 2002).

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[11] Since the model is homogeneous of degree zero in prices, a cash price required. When doubling the value of cash, prices are doubled but all real numbers will not change. All simulations of changes in prices and income should be interpreted in relation to the cash price index, in this case the Consumer Price Index.

The full model specification requires that all market relations, behaviors and system equations are built and described in each account of the Social Accounting Matrix.

The presentation of the equations in the model follows the pattern of income generation. First the equations defining the price system are defined, followed by equations describing the production and the generation of value added. The following equations show the value added step of institutional income. Finally, there are system constraints that the economic model must satisfy; these include market equilibrium conditions and the choice of macroeconomic closure rules. Appendix A describes and enumerates the full equation system used in the CGE model, which includes major additions made by Thurlow, 2004 to the original equation system of Löfgren et al., 2002. Also, Table 31 shows the differences in the size of both systems.

Table 31: Characteristics of reference equations systems

Complete Model	Löfgren (2002)	Thurlow (2004)
Variables Block	43	49
Equations Block	48	57
Number of Variables	433	474
Number of Equations	433	474
Parameters	2189	2260

The mathematical additions considered for each component of the study are discussed below.

3.4.1 Component of Each Period

Two main additions to the component of each period are considered: 1) specific productivity of factors and 2) the positively sloped factor supply curve. Thurlow, 2004, also added to this component, mathematical specifications for regional disaggregation of international trade; however, these additions are not considered because for the purpose of this study these aspects are not relevant, there is only one account for international trade named Rest of the World.

3.4.1.1 Specific Productivity of Factors

Value added (Equation 13) and factors demand (Equation 14) functions, include a term of specific productivity adjustment factor ($\alpha_{f}^{vaf}{}_{a}$). In the initial equilibrium or base year, the value of this term is set to 1, while for the other periods this value is determined exogenously.

$$QVA_a = \alpha_a^{va} . \left(\sum_{f \in F} \delta_{f\,a}^{va} \cdot \left(\alpha_{f\,a}^{va\,f} \cdot QF_{f\,a} \right)^{-\rho_a^{va}} \right)^{-\frac{1}{\rho_a^{va}}} \qquad a \in A \qquad \textbf{(13)}$$

(Quantity of Aggregated Value Added) = CES (Factor Inputs)

$$W_{f} \cdot WFDIST_{f\,a} = PVA_{a} \cdot (1 - tva_{a}) \cdot QVA \cdot \left(\sum_{f \in ''F'} \delta^{va}_{f\,a} \cdot \left(\alpha^{vaf}_{f\,a} \cdot QF_{f\,a} \right)^{-\rho^{va}_{a}} \right)^{-1} \cdot$$

$$\delta^{va}_{f\,a} \cdot \left(\alpha^{va\,f}_{f\,a} \cdot QF_{f\,a} \right)^{-\rho^{va}_{a} - 1} \qquad a \in A \quad f \in F \qquad \textit{(14)}$$

(Marginal Cost of Factor f in activity a) = (Marginal Incomes Produced by Factor f in Activity a)

3.4.1.2 Positively Sloped Factor Supply Curve

Two new equations are included in the model to allow a factor closure in which both, supply and real wages, to be endogenously determined. Equation 28 allows that factors supply adjusts to its original level (QFS^{0}_{f}) according to changes on the average real wage (RWF_{f}), response that is governed by the factor supply elasticity ($etals_{f}$). The average wage is defined in equation 29.

$$\frac{QFS_{f}}{QFS^{0}_{f}} = \left(\frac{RWF_{f}}{RWF^{0}_{f}} \right)^{etals_{f}} \qquad f \in F \qquad \textit{(28)}$$

(Factor f supply ratio) = f (real wage ratio)

$$RWF_{f} = \left(\frac{YF_{f}}{QFS_{f}} \right) \Big/ \left(\frac{CPI}{CPI^{0}} \right) \qquad f \in F \qquad \textit{(29)}$$

(average real wage per factor unit) = (average wage per factor unit) / (consumer price index ratio)

3.4.2 Component Between Periods

To generate the dynamic process in the component between periods, the following conceptual aspects are considered: population, labor, land and natural resources growth; capital accumulation; government consumption; and transfers.

3.4.2.1 Population Growth

Each representative household consumes commodities under a Linear Expenditure System (*LES*) of demand. Equation 33 from the IFPRI model is shown below. This system allows for an income-independent level of consumption ($PQ_{c} \cdot \gamma^{m}_{ch}$) measured as the market value of each household's consumption of each commodity that is unaffected by changes in disposable income. The remaining terms in Equation 33 determine the level of additional consumption demand that adjusts with changes in income.

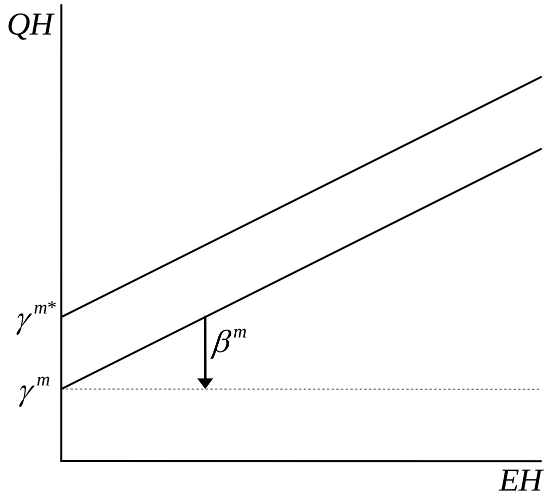
$$PQ_c \cdot QH_{c\,h} = PQ_c \cdot \gamma^m_{ch} + \beta^m_{ch} \cdot \left(EH_h - \sum_{c' \in C} PQ_{c'} \cdot \gamma^m_{c'\,h} \right) \qquad c \in C \quad h \in H \tag{33}$$

(household consumption spending on market commodity c) = f (total household consumption spending, market price of c, other commodity prices (market and home))

According to Thurlow, 2004, population growth is assumed to enter the model through its direct and positive affect on the level of private consumption spending. During the dynamic updating process and as the population grows, the level of each household's consumption of a particular commodity is adjusted upwards to account for greater consumption demand. This is achieved by increasing the quantity of income-independent demand ($\gamma^m{}_{ch}$) at the same rate as population growth.

Equation 33 is represented graphically in Figure 8 for a single representative household's consumption of a particular commodity (QH_{ch}). This is then related to the household's level of total consumption spending (EH_h). The upward-sloping consumption demand curve reflects the positive relationship between the household's disposable income and the level of consumption. Initially the level of income-independent consumption is given by γ^m. Under the *LES* specification there is a linear relationship between income and consumption, and this is reflected in the constant slope (β^m) of the consumption curve. In the dynamic model, population growth increases the value of γ^m proportionately and causes the consumption curve to shift upwards to reflect the higher level of minimum consumption (γ^{m*}). As seen in the Figure 29, it is assumed that the slope of the consumption curve (β^m) remains unchanged. Therefore population growth is assumed to affect only average, and not marginal, consumption demand. Accordingly, new consumers are assumed to share the same consumption preferences as existing consumers.

Figure 29: Household Consumption Demands and Population Growth



Source: Own elaboration, based on Thurlow, 2004.

3.4.2.2 Labor, Land and Natural Resources Growth

The supply of labor, land and natural resources is flexible between periods but is restricted in its ability to adjust by the real wage elasticity of labor supply (*etalsf*). Therefore, it is not necessary that these factors update with exogenous parameters, given that their supply adjusts endogenously to determine the level of employment and final wages.

3.4.2.3 Capital Accumulation

All changes in the total capital supply are endogenous in the recursive dynamic model. In a given time period the total available capital is determined by the previous period's capital stock and investment spending. The model allocates investment in different proportions to each sector. These proportions are adjusted by the ratio of each sector's profit rate to the average profit rate for the economy as a whole. Sectors with a higher-than-average profit rate receive a larger share of investment than their share in aggregate profits. This updating process involves four steps:

Equation 49 describes the first step at which the average economy-wide rental rate of capital (AWF^{a}_{ft}) is calculated for time period *t*. This is equal to the sum of the rental rates of each sector weighted by the sector's share of total capital factor demand.

$$AWF^{a}_{f\,t} = \sum_{a}\left[\left(\frac{QF_{f\,at}}{\sum_{a'} QF_{f\,a't}}\right)\cdot WF_{f\,t}\cdot WFDIST_{f\,at}\right] \qquad \begin{array}{c} f \text{ is capital} \\ a \in A \\ a' \in A \\ t \in T \end{array} \qquad (49)$$

(average capital rental rate) = (weighted sum of sectors' capital rental rates)

In the second step each sector's share of the new capital investment ($\eta^{a}_{f\,a\,t}$) is calculated by comparing its rental rate to the economy-wide average. For those sectors with above average rental rates, the second term on the right-hand side of Equation 50 will be greater than one. The converse would be true for sectors with rental rates that are below average. This term is then multiplied by the existing share of capital stock to arrive at a sectorial distribution for new capital. The inter-sectorial mobility of investment is indicated by β^{a}. In the extreme case where β^{a} is zero there is no inter-sectorial mobility of investment funds, and all investment can be thought of as being funded by retained profits.

$$\eta^{a}_{f\,at} = \left(\frac{QF_{f\,at}}{\sum_{\ddot{a}'} QF_{f\,a't}}\right) = \left(\beta^{a}\cdot\left(\frac{WF_{f\,t}\cdot WFDIST_{f\,at}}{AWF^{a}_{f\,t}} - 1\right) + 1\right) \qquad \begin{array}{c} f \text{ is capital} \\ a \in A \\ a' \in A \\ t \in T \end{array} \qquad (50)$$

(share of new capital) = (share of existing capital) · (capital rental rate ratio)

Equation 51 shows the third step of the updating procedure in which the quantity of new capital is calculated as the value of gross fixed capital formation divided by the price of capital (PK_{ft}). This is then multiplied by each sector's share of new capital ($\eta\ ^{a}_{f\,a\,t}$) to arrive at a final quantity allocated to each sector ($\Delta K^{a}_{\ f\,a\,t}$). The determination of the unit capital price is shown in Equation 52.

$$\Delta K^{a}_{f\,a\,t} = \eta^{a}_{f\,a\,t} \cdot \left(\frac{\sum_{c} PQ_{c\,t} \cdot QINV_{c\,t}}{PK_{f\,t}} \right)$$

(quantity of new capital by sector) = (share of new capital) · (total quantity of new capital)

f *is capital*
$a \in A$
$c \in C$
$t \in T$

(51)

$$PK_{f\,t} = \sum_{c} PQ_{c\,t} \cdot \frac{QINV_{c\,t}}{\sum_{c'} QINV_{c'\,t}}$$

(unit Price of capital) = (weighted market price of investment commodities)

f *is capital*
$a \in A$
$c \in C$
$c' \in C$
$t \in T$

(52)

In the final step the new aggregate quantity of capital (QFS_{ft+1}) and the sectorial quantities of capital ($QF_{f\,a\,t\,+1}$) are adjusted from their previous levels to include new additions to the capital stock. Over and above these changes there is also a loss of capital to account for depreciation (υ_f).

$$QF_{f\,a\,t+1} = QF_{f\,a\,t} \cdot \left(1 + \frac{\Delta K^{a}_{f\,a\,t}}{QF_{f\,a\,t}} \right) - \upsilon_{f}$$

(average capital rental rate) = (weighted sum of sectors' capital rental rates)

f *is capital*
$a \in A$
$t \in T$

(53)

$$QFS_{f\,t+1} = QFS_{f\,t} \cdot \left(1 + \frac{\sum_{a} \Delta K_{f\,a\,t}}{QFS_{f\,t}} - \upsilon_{f} \right)$$

(average capital rental rate) = (weighted sum of sectors' capital rental rates)

f *is capital*
$a \in A$
$t \in T$

(54)

The above specification of capital accumulation and allocation is not fully inter-temporal. It is assumed that any expectations that influence the level and distribution of investment are based on past experience. While this is an assumption, it does greatly simplify the dynamics of the model and avoids the specification of inter-temporal optimization.

3.4.2.4 Government Consumption and Transfers Spending

According to Thurlow, 2004, since government consumption spending and transfers to households are fixed in real terms within a particular period it is necessary to exogenously increase these payments between periods. This is done by increasing the value of qg_c in Equation 36 in the IFPRI original model in the case of government consumption spending, and $trnsfr_{igov}$ in Equation 38 in the case of government transfers to households.

4. CGE Data, Calibration and Validation

4.1 Social Accounting Matrix (SAM)

As the main database for the calibration of the CGE, a SAM of the Bolivian economy at current prices for the year 2000 is used. This matrix was originally used and developed by Lay, et al., 2006. For the present study, the matrix is modified so that the main structure follows the format required by the IFPRI standard CGE model. Appendix B shows the values of the macroeconomic accounts of the mentioned SAM. The currency in the SAM is Thousands of Bs. (Bolivian local currency), where 7 Bs., is equivalent to almost 1 US$. This SAM does not include detailed information on agriculture, livestock and forestry, including disaggregated data by region, farm size, produced goods and land heterogeneity (arable, pasture, forest).

The structure of the Bolivian economy is represented by the level of disaggregation in the SAM accounts. Table 32 shows that in 2000, Agriculture (Traditional and Modern) contributed with 13% to the generation of value added; while the forestry, hunting and fishing sector contributed only with 1%. This is a clear signal of the relatively large importance of agriculture in total national income[12]. Other important sectors in the Bolivian economy are trade and transport (18.5%) and services (42.5%).

Table 32: Structure of Value Added in Bolivia for the Year 2000

Activities	Value Added (Thousands of Bs.)	GDP Participation (%)
Traditional Agriculture	3,598,864	8
Modern Agriculture	2,174,985	5
Forestry, Hunting and Fishing	449,005	1
Food Processing	3,003,973	7
Hydrocarbons and Mining	4,760,217	11
Industry	1,961,373	4
Construction	1,516,102	3
Trade and Transport	8,288,258	19
Services	19,007,751	43
Total Value Added	**44,760,528**	**100**

Source: Own calculation, based on Lay, et al., 2006 SAM.

Regarding international trade, industrial agricultural products, coca, hydrocarbons, minerals and some industrial products are the most exported, about 30% in all cases. On the other hand, most of imported goods are the industrial and industrial agriculture products (especially processed food), 58% and 25% respectively (Table 33).

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[12] The agricultural sector is also important as a source of intermediate inputs to non-agricultural sectors; various agricultural products are used in food processing, manufacturing and certain services.

Table 33: Trade Orientation in the Year 2000

Products	Sectorial Values (Millions of Bs.)				Proportion (%)	
	Production	Exports	Imports	Sales	Exports/Production	Imports/Sales
Traditional Farming	3,655	63	412	4,004	2	10
Industrial Agriculture	1,531	540	330	1,320	35	25
Coca	450	145	-	305	32	
Livestock	2,543	114	19	2,447	4	1
Forestry, hunting and fishing	694	77	10	626	11	2
Processed Food	11,975	2,311	883	10,547	19	8
Oil, gas and minerals	9,061	2,484	727	7,304	27	10
Industrial	7,669	2,299	7,420	12,790	30	58
Construction	4,370	-	-	4,370		
Transport	9,351	550	572	9,373	6	6
Services	30,803	583	729	30,948	2	2
Trade	6,543	-	-	6,543		

Source: Own calculation, based on Lay, et al., 2006 SAM.

Every economic activity handles different combination of productive factors, which directly affects the distribution of income among the various "institutions"[13] that own these factors. The unskilled labor is concentrated in poor urban and rural households (92.8%) and it is used by all sectors mainly in traditional agriculture, forestry, hunting and fishing, industry, trade and transport. The skilled labor belongs mainly to rich urban families (75.5%) and it is used in almost every activity except for traditional agriculture. The informal capital belongs only to poor urban households, while the formal capital is mainly concentrated in companies. Only agriculture activities use land as a production factor, which mainly belongs to poor rural households. Finally, natural resources are used by specific sectors (oil and gas industry in the case of hydrocarbons, and forests and wildlife in the case of forestry, hunting and fishing), these resources belong to rich rural and urban households. The summary of factor use is shown in Table 34.

Table 34: Factor Allocation between Activities and Income Distribution between Domestic Institutions (%)

Activities	Unskilled Labor	Skilled Labor	Informal Capital	Formal Capital	Land	Natural Resources
Traditional Agriculture	67	-	-	-	33	-
Modern Agriculture	20	27	-	25	28	-
Forestry, Hunting and Fishing	55	33	-	3	-	10
Food Processing	35	22	11	32	-	-
Hydrocarbons and Mining	9	10	-	70	-	12
Industry	43	23	12	22	-	-
Construction	40	20	15	25	-	-
Trade and Transport	41	24	21	15	-	-
Services	8	45	2	45	-	-
Domestic Institutions	**Unskilled Labor**	**Skilled Labor**	**Informal Capital**	**Formal Capital**	**Land**	**Natural Resources**
Companies	-	-	-	72	-	-
Poor Rural Households	28	-	-	-	66	-
Rich Rural Households	-	6	-	4	34	7
Poor Urban Households	64	19	100	-	-	-
Rich Urban Households	7	76	-	25	-	93

Source: Own calculation, based on Lay, et al., 2006 SAM.

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[13] Where "Institution" is defined as a differentiated group of households with common characteristics.

4.2 Elasticities

The specification of the model requires the determination of exogenous elasticities for trade, production and consumption. Most of these values are adopted from the study developed by Andersen and Faris, 2006. On the other hand, due to lack of information on the elasticity of factor supply for Bolivia, this data is taken from Thurlow, 2004. Table 35 shows a summary of this information.

Table 35: Adopted Elasticities for the CGE in Bolivia

TRADE	Value
Elasticity of Substitution (CES)	4.00
Elasticity of Transformation (CET)	1.30
PRODUCTION	
Elasticity of Factor Substitution (CES)	1.30
Elasticity of Substitution Aggregate Factors and Intermediate Inputs (CES)	1.30
Elasticity of Production Aggregation (CES)	1.30
Elasticity of Factor Supply (etals)	0.40
CONSUMPTION	
Elasticity of Market Demand	1.00

Source: Own elaboration, based on Andersen and Faris, 2006, and Thurlow, 2004.

4.3 Factor Employment

To estimate the change in the use of factors in the face of an economic shock, it is necessary to determine the level of employment in the base year. This quantity is related to the value added generated by each factor in each activity. The following Table identifies these initial quantities.

Table 36: Factor Quantity Used in 2000

Activity	FACTOR					
	Unskilled Labor (people)	Skilled Labor (people)	Informal Capital (Value)	Formal Capital (Value)	Land (Hectares)	Natural Resources (Value)
Traditional Agriculture	1,589,116	-	-	-	15,584,615	-
Modern Agriculture	77,791	37,099	-	542,640	10,874,048	-
Forestry, Hunting and Fishing	10,000	2,500	-	9,107	-	40,992
Food Processing	61,433	21,794	329,931	951,671	-	-
Hydrocarbons and Mining	61,369	19,797	-	3,317,005	-	575,430
Industry	126,889	55,968	235,292	430,287	-	-
Construction	149,041	37,317	224,612	382,268	-	-
Trade and Transport	632,100	244,107	1,767,605	1,201,432	-	-
Services	259,983	438,219	426,632	8,544,285	-	-

Source: Own calculation, based on Lay, et al., 2006 SAM.

The amount of labor, capital and natural resources assigned to each sector in the baseline was estimated by Lay, et al., 2006. However, the number of hectares of land allocated to Traditional Agriculture and Modern Agriculture Activities are quantified based on the land use of each product generated by these activities in the year 2000 as summarized in Table 37:

Table 37: Land Use by Product and Activity in 2000 (hectares)

Products	Activity	
	Traditional Agriculture	Modern Agriculture
Traditional Farming (a)	1,034,815	100,000
Industrial Agriculture (a)	-	749,368
Coca (b)	-	24,680
Cattle (c)	14,549,800	10,000,000
Forestry, Hunting and Fishing	-	-
Total	**15,584,615**	**10,874,048**

Source: Own elaboration, based on: (a) INE, 2008; (b) Rojas, 2002; and (c) MACA, 2002.

4.4 Dynamic Simulation Data

The solution of the CGE's dynamic component is obtained from exogenous data updates. Tables 38 and 39 show growth rates data introduced in the simulations.

Table 38: Population Growth Rates by Institution (%/year)

Institution	Population Growth Rate
Households (Aggregated)	**2.74**
Poor Rural Households	1.42
Rich Rural Households	1.42
Poor Urban Households	3.62
Rich Urban Households	3.62

Source: Own elaboration, based on INE, 2008.

Table 39: Annual Growth Rates for Independent Variables (%/year)

Account	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Government Consumption	12.0	7.0	13.0	10.7	8.7	7.0	10.0	10.6	10.9	11.2	11.2	11.2	11.2
Transfers from Governmet to Households	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Activity Tax	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Imports Tax	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Exports Tax	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Sales Tax	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Direct Tax	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Households Marginal Propensity to Save	12.2	13.3	16.0	19.2	21.5	15.7	15.7	13.4	10.5	5.0	5.0	5.0	5.0
Companies Marginal Propensity to Save	6.1	6.6	8.0	9.6	8.6	6.3	5.5	4.7	3.2	1.0	1.0	1.0	1.0
External Saves	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Government Saves	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Exchange Rate	7.0	8.5	6.8	3.7	1.8	-0.4	-1.4	-9.2	-10.0	-7.9	1.0	1.0	1.0
International Price of Exports	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
International Price of Imports	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps	eps
Capital Depreciation Rate	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0

Source: INE, 2008 and own estimations.

It is important to note that information on marginal propensity rates is very important to simulate the accumulation of capital and investment in the model. The data used are calculated from information about the gross national disposable income and its allocation during the period 2000-2005 (INE, 2008), for the period 2006-2010 these values are estimated and kept constant in other case to be plausible. On the other hand, the "*eps*" value is a very small number close to 0 and means that the growth rates are almost kept constant from year to year.

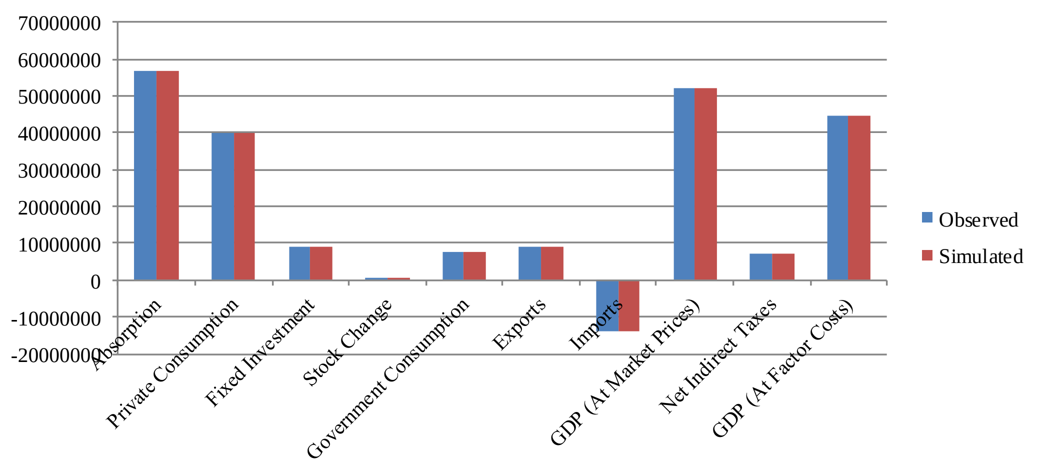
4.5 CGE Model Calibration

According to Robinson, et al., 1999, CGE model calibration involves determining the set of parameters and exogenous variables in order to exactly replicate the economy represented in the SAM database. The main test to calibrate the model is to verify that the observed and simulated national aggregate accounts are approximately equal for the base year.

In this sense, the CGE model is represented as a Mixed Complementary Problem and solved using the PATH solver of the General Algebraic Modeling System (GAMS) programming system (see on Appendix C). Table 40 shows the summary of the observed and simulated macroeconomic accounts compared in the calibration process. The solution is calculated for one period (2000), in which the structure of the economy in question is adjusted to find the balance.

Table 40: Summary of Observed and Simulated Macroeconomic Accounts for the Year 2000 (in Thousands of Bs.)

Macroeconomic Accounts	Observed		Simulated	
	Value	GDP Participation (%)	Value	GDP Participation (%)
Absorption	56,819,177	109.51	56,819,180	109.56
Private Consumption	39,706,364	76.53	39,706,360	76.56
Fixed Investment	9,248,209	17.82	9,248,210	17.83
Stock Change	213,082	0.41	213,080	0.41
Government Consumption	7,651,521	14.75	7,651,520	14.75
Exports	9,168,860	17.67	9,168,860	17.68
Imports	-14,104,173	-27.18	-14,104,170	-27.20
GDP (At Market Prices)	51,883,864	100.00	51,883,870	100.05
Net Indirect Taxes	7,080,943	13.65	7,080,940	13.65
GDP (At Factor Costs)	44,802,921	86.35	44,802,920	86.39



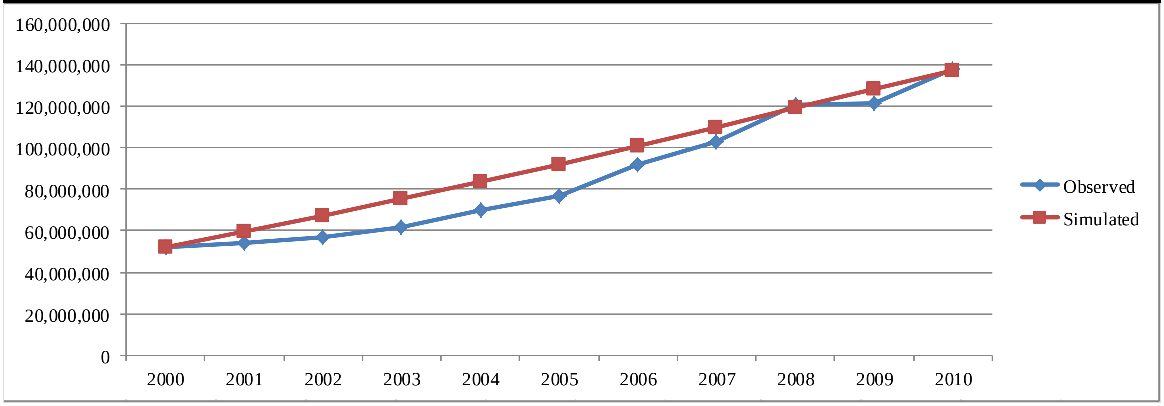
As it is observed, simulated results are equal to observed results for the main macroeconomic accounts which mean that the selected parameters and the model are properly chosen and calibrated, respectively. From the results for the initial year, dynamic simulations are performed to project the behavior of the economy in the whole study period (2000-2010). But first the model has to be validated. For this purpose, the simulated GDP is compared with the existing data of observed GDP from 2001 to 2010.

4.6 CGE Model Validation for the Baseline

For model validation, the simulated baseline scenario is compared with observed data (INE) for the whole study horizon (2000-2010).

Table 41: Observed and Simulated Gross Domestic Product for the Baseline (Bs.)

GDP	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Observed	51,928,490	53,790,330	56,682,330	61,904,450	69,626,110	77,023,820	91,747,790	103,009,180	120,693,760	121,726,740	137,875,570
Simulated	51,883,870	59,636,330	67,119,170	75,263,490	83,507,890	92,043,260	100,831,100	110,012,550	119,220,970	128,393,760	137,420,700

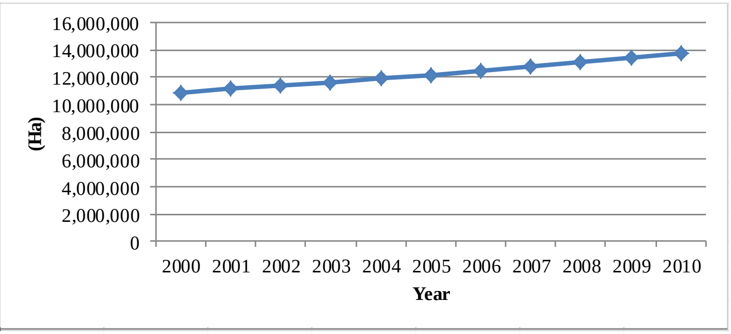


As it is observed in Table 41, observed and simulated GDP are very close and follow the same trend with a correlation factor of 1 (which means perfect direct correlation). The fastest growing sectors are *Services*, *Trade and Transportation*, and *Oil and Mining*, whose production values for 2010 would reach 41, 22 and 14 billion Bs., respectively. *Modern Agriculture* activity would reach 6.4 billion Bs. by then (see the Appendix D for macroeconomic and activity full results).

Under the Baseline scenario, the demand for land in *Modern Agriculture* increases from 10.9 to 13.8 million hectares in 10 years. This result comes with increasing annual variations, where demand for new land in the first year is 293,116 hectares and in the last year is 327,852 hectares (Table 42), deforestation rates are very close to those observed in previous studies, given that annual increases in the demand for land are proxy variables of deforestation rates in the country.

Table 42: Modern Agriculture Activity Simulated Demand for Land

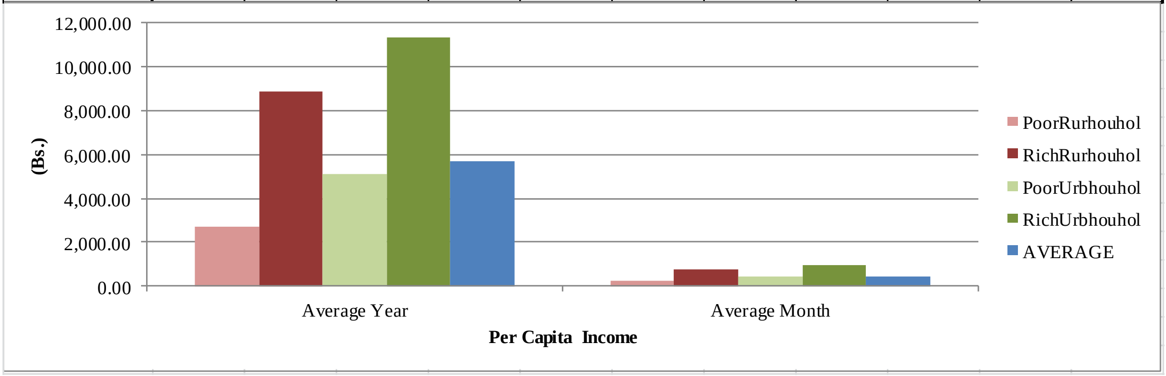
Year	Demand for New Land (ha)
2001	293,116
2002	217,796
2003	251,983
2004	266,145
2005	284,378
2006	312,237
2007	318,560
2008	322,953
2009	326,009
2010	327,852



As regards income distribution, all types of households are benefiting from economic growth in the Baseline scenario, as per capita income levels of urban households mainly continuously increase over time. Also, in aggregated terms, consumption (private and government), investment, exports and imports are increased generating higher levels of domestic production.

Table 43: Per Capita Income by Institution and Average for the Baseline (Bs.)

Institution	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
PoorRurhouhol	1,799.95	2,010.17	2,196.22	2,374.17	2,550.85	2,722.76	2,889.42	3,042.75	3,185.38	3,312.43	3,421.24
RichRurhouhol	6,961.50	7,675.57	8,220.39	8,702.80	8,957.30	9,123.24	9,303.76	9,454.41	9,558.22	9,713.93	10,032.69
PoorUrbhouhol	3,738.65	4,096.70	4,399.86	4,690.90	4,965.25	5,221.31	5,461.62	5,674.67	5,859.44	6,009.30	6,123.28
RichUrbhouhol	11,368.77	11,903.55	12,178.41	12,331.78	12,073.49	11,669.68	11,305.58	10,926.02	10,498.62	10,186.25	10,156.90
AVERAGE	**4,633.05**	**5,006.97**	**5,294.32**	**5,548.67**	**5,707.72**	**5,824.71**	**5,939.92**	**6,033.21**	**6,097.77**	**6,164.71**	**6,270.60**



The richest households are located on urban areas and they earn 11,327 Bs/year, and the poorest are in rural areas earning 2,682 Bs/year on average. The mean per capita income is 5,683 Bs/year, in other words 474 Bs/month.

5. Scenarios Results

Alternative scenarios constitute different shocks in the economy that would impact the outcome of the baseline scenario (2000 to 2010, decade). Thus, the model is solved for new equilibriums and changes in the simulated results are compared with those of the baseline scenario. Three kind of shocks will be analyzed in the present study: 1) Climate Change Impacts coming from different Scenarios affecting the Agricultural Production Yields, in the short and long runs; 2) Microeconomic policies taken as adaptation measures to counteract climate change impacts on agriculture; and 3) Macroeconomic policies for achieving sustainable development in the economy (higher GDP and income, accompanied by lower and sustained deforestation rates), as an illustrative example of "climate policy mainstreaming".

5.1 Climate Change Impacts

Climate Change is going to affect Agriculture and all the other sectors of the Economy in different ways in the whole world. However, in this study, the impacts of climate change are only introduced in the productivity changes of Agriculture Activities for Bolivia. On the other hand, the impacts of climate change in the Rest of the World are kept constant given that Bolivia is a small market in a World Economy where some countries will increase their productivity, while others will reduce their productivities due to climatic change (Mendelsohn, et al., 2006), having always more exports than imports in agriculture activities. In this section the downscaled impacts of climate change for the A2 and

B2 SRES Scenarios from the IPCC are quantified in the CERES and CROPGRO crop models[14]; the downscaling methodology and description of these Scenarios are summarized in Chapter 1. The impacts in soybeans yields are introduced in the CGE as factor productivity variations for Modern Agriculture activity; while the average impacts in maize and rice yields are introduced in the CGE as factor productivity variations in the Traditional Agriculture Account. The A2 scenarios is a "business as usual" or pessimistic, while the B2 is a "greener economy" or optimistic. Both scenarios are considered to narrow the uncertainty of possible climate change impacts in the short and long runs. The summary of climate change impacts and average results from crop models are detailed in Table 44:

Table 44: Climate Change Impacts and Average Yields in Bolivia for the Different Scenarios (kg/ha)

Weather Indicator		Baseline	A2 20s	A2 70s	B2 20s	B2 70s
Mineros	**Maximum Temperature**	**31,0**	-0,3	3,8	-0,4	2,3
	Minimum Temperature	**18,4**	3,8	7,4	3,6	6,1
	Precipitation	**1419,3**	51%	74%	49%	-8%
	Solar Radiation	**16,7**	0,6	0,7	0,8	0,8
Pailon	**Maximum Temperature**	**32,1**	-1,6	2,5	-1,7	0,8
	Minimum Temperature	**19,2**	2,9	6,6	2,7	5,1
	Precipitation	**1063,6**	35%	67%	42%	-5%
	Solar Radiation	**16,6**	0,5	0,8	0,6	0,8
San Julian	**Maximum Temperature**	**31,8**	-0,6	3,6	-0,8	1,9
	Minimum Temperature	**22,5**	-0,2	3,4	-0,3	2,1
	Precipitation	**1280,9**	-2%	10%	-2%	-6%
	Solar Radiation	**16,9**	1,1	1,4	1,2	0,6
Yapacani	**Maximum Temperature**	**29,5**	1,1	5,1	1,0	3,6
	Minimum Temperature	**19,5**	2,7	6,4	2,6	5,1
	Precipitation	**1707,7**	1%	16%	-4%	-10%
	Solar Radiation	**16,9**	-0,5	-0,8	-0,4	-0,6
Guarayos	**Maximum Temperature**	**30,5**	0,6	4,3	0,5	3,0
	Minimum Temperature	**19,6**	3,1	5,3	2,9	4,5
	Precipitation	**1370,8**	45%	22%	40%	-5%
	Solar Radiation	**17,0**	-0,1	-0,1	0,1	-1,1

Soybean Average Yields in Bolivia (Modern Agriculture)		
Impacts	**Yield (kg/ha)**	**Variation**
Baseline	**3108,11**	**%**
A220	2953,66	-5
A270	3141,23	1
B220	2982,43	-4
B270	2951,14	-5

Maize and Rice Average Yields in Bolivia (Modern Agriculture)		
Impacts	**Yield (kg/ha)**	**Variation**
Baseline	**4194,39**	**%**
A220	3708,59	-12
A270	2216,20	-47
B220	3706,10	-12
B270	2698,13	-36

Source: Own elaboration, based on CERES and CROPGRO crop model results.

The numbers in green represent increases while the red ones are reductions. As it is observed, climate change will increase maximum and minimum temperatures in different quantities depending on the location; while precipitation is going to increase in the short run (2020) for both Scenarios and in the long run is going to have increases even higher for the A2 Scenario. The only Scenario that shows precipitation reductions is the B270s. Finally, solar radiation is going to remain almost constant for all the Scenarios. Soybeans yields are the average of the results from the 5 production zones; in all the scenarios there are reductions from -4 to -5%. The only scenario that shows increases is the A270s (1%). On the other hand, maize and rice yields are obtained by quantifying the average yields of these two crops in the 5 production areas. All the scenarios show reductions ranging from -12 to -47% in the short and long runs, respectively. These yield variations are introduced in the CGE as Productivity Variations, for Modern and Traditional Agriculture, respectively (*parameter* ***TFPGR (A, SIM, YR)***, *total factor productivity growth rate*). The same parameter is used to quantify for impacts of microeconomic and

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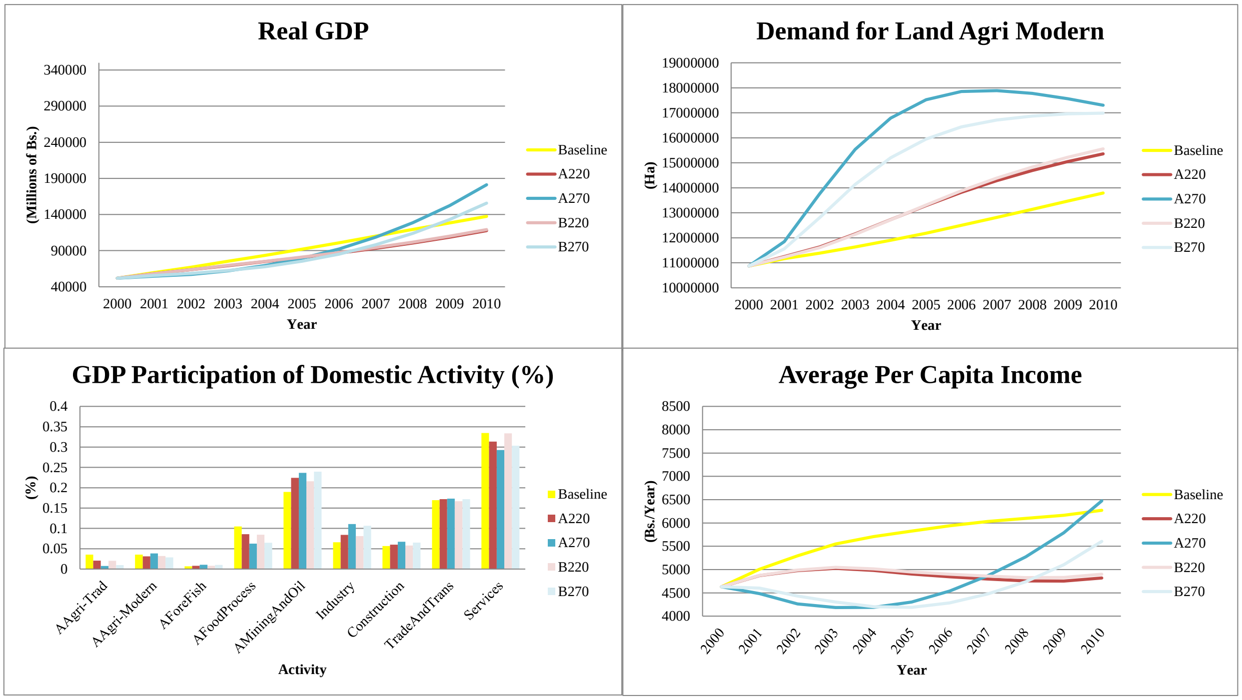
[14] The downscaled climate variations in Bolivia for the A2 and B2 IPCC SRES Scenarios in the short and long runs (2030 and 2070, respectively) are detailed in Seiler, 2009.

macroeconomic policies. The summary of results is presented in Figure 30, having the yellow line as the baseline (2000 – 2010, a decade), the red lines as the climate change impacts in the short run, and the blue lines the impacts of climate change in the long run.

Figure 30: Climate Change Impacts on GDP, Deforestation and Per Capita Income for Different Scenarios



Real GDP

Demand for Land Agri Modern

GDP Participation of Domestic Activity (%)

Average Per Capita Income

Source: Own Elaboration, based on CGE Model Simulations.

- ***Short Run (2020s):*** As it is observed, the impacts of climate change are going to reduce real GDP in the short run (A220s and B220s), in about -10%. This can be explained by the GDP participation of domestic activity, in the short run the participation of traditional and modern agriculture are going to be reduced, so this unemployed factors will move towards mining and oil and industry activities. On the other hand, with lower yields per hectare, the demand for land (deforestation) is going to be increased by 7 to 8% (around 85,000 ha/year of additional deforestation). Finally, the average per capita income is also going to be reduced by -14% on average.
- ***Long Rung (2070s):*** In the long run, GDP seems to be higher in the last 3 years, but on average there is a reduction in the range of -2 to -8% for the whole period. This smaller reduction can be explained by the higher participation of modern agriculture in the A270 Scenario (coming for an increase of 1% in productivity), and also higher participation and/or factor substitution towards mining and oil, industry, construction and services. The demand for land in the Modern Agriculture Activity is much higher (21 to 29%), in other words, 240,000 to 320,000 hectares of additional deforestation per year. Finally, the per capita income is reduced by -15 to -19% on average in the whole period, with very high decreases in the first half and increases in the second half. The increase on average per capita income in the last half of the period is due to factor production shift into a more industrialized economy.

5.2 Microeconomic Policies (Adaptation Measures)

To counteract the adverse effects of climate change in crop yields, agriculture sector and the whole Bolivian economy, some adaptation options at the micro level are applied: 1) Fertilization (no macro and micro nutrient stresses); 2) Irrigation (no water stress), 3) Change of the planting date; and 4) Overall Technology Improvement (which includes fertilization, irrigation and change of the planting date). Table 45 shows the details of the parameters modified in the CERES and CROPGRO models:

Table 45: Adaptation Options and Parameter Modifications in the CERES and CROPGRO Crop Models

Adaptation Option	Parameter	Label	Description	Details
1) Fertilization	**NICM**	Tot N app kg/ha	Inorganic N applied (kg [N]/ha)	The crop models have the option to apply nitrogen fertilization automatically when needed, We will use this option assuming that we know crop needs and demand fro this macronutrient in the different development and growth periods.
	NI#M	N apps #	Number of Nitrogen applications	
2) Irrigation	**IRRD**	IRRIG mm/d	Irrigation (mm/day)	The crop models have the option to apply irrigation automatically when needed, We will use this option assuming that we know crop ET and water demand needs in the different development and growth periods.
	IR#M	Irri apps #	Number of Irrigation applications	
3) Change of the Planting Date	**PDAT**	Planting Date (YrDoy)	Planting date (Day of the Year)	An experiment of changing the planting date from January the 1st to December the 21st has been done in 10-day intervals in order to identify the "most efficient planting date" the one with the highest mean yield and lowest variance from year to year.
4) Overall Technology Improvement	**IRRD**	IRRIG mm/d	Irrigation (mm/day)	The crop models have the option to apply irrigation automatically when needed, We will use this option assuming that we know crop ET and water demand needs in the different development and growth periods.
	IR#M	Irri apps #	Number of Irrigation applications	
	PDAT	Planting Date (YrDoy)	Planting date (Day of the Year)	An experiment of changing the planting date from January the 1st to December the 21st has been done in 10-day intervals in order to identify the "most efficient planting date" the one with the highest mean yield and lowest variance from year to year.
	NICM	Tot N app kg/ha	Inorganic N applied (kg [N]/ha)	The crop models have the option to apply nitrogen fertilization automatically when needed, We will use this option assuming that we know crop needs and demand fro this macronutrient in the different development and growth periods.
	NI#M	N apps #	Number of Nitrogen applications	

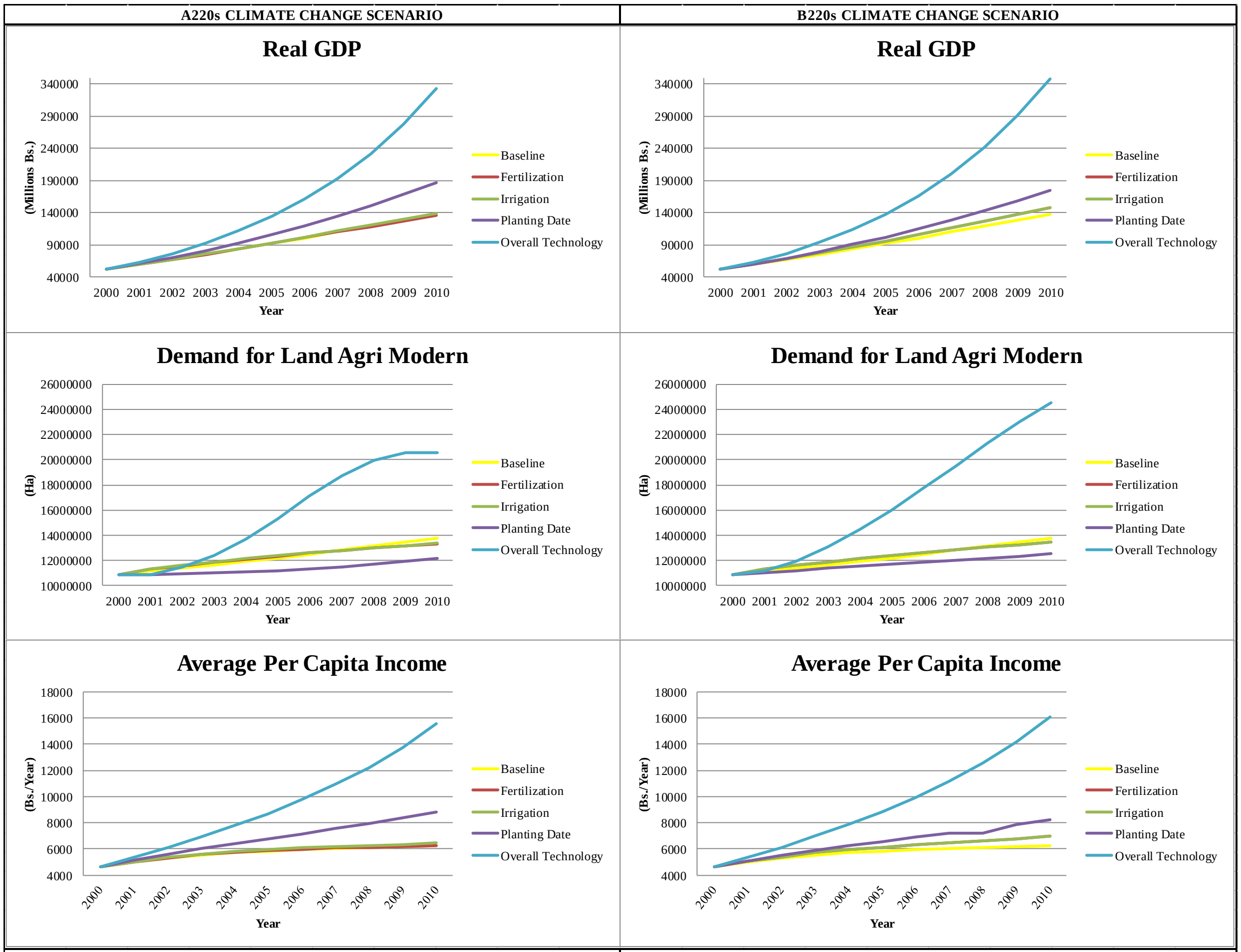
These adaptation options are applied for all the 5 most important production areas of Santa Cruz Bolivia and then the averages are introduced in the CGE. Again, average results for soybeans are introduced in the Modern Agriculture Activity, and average results of maize and rice in the Traditional Agriculture Activity. On the other hand, the costs of Adaptation can be high for some of these measures, especially irrigation investments. However, in this study, adaptation costs are considered to be 0, given the diversity of projects and funding on adaptation programs granted by international cooperation.

Table 46: Average Productivity Changes from Adaptation Options in Bolivia Introduced in the CGE Model

SOYBEAN AVERAGE YIELDS IN BOLIVIA (Modern Agriculture)										
	Impacts		**Fertilization**		**Irrigation**		**Planting Date**		**Overall Technology**	
Baseline	**3108**	**%**	**3108**	**%**	**3108**	**%**	**3108**	**%**	**3108**	**%**
A220	2954	-5	2962	-5	2954	-5	3650	17	4198	35
A270	3141	1	3152	1	3457	11	3419	10	3894	25
B220	2982	-4	2969	-4	2980	-4	3354	8	3826	23
B270	2951	-5	2952	-5	3124	1	2967	-5	3471	12
MAIZE AND RICE AVERAGE YIELDS IN BOLIVIA (Traditional Agriculture)										
	Impacts		**Fertilization**		**Irrigation**		**Planting Date**		**Overall Technology**	
Baseline	**4194**	**%**	**4194**	**%**	**4194**	**%**	**4194**	**%**	**4194**	**%**
A220	3709	-12	4382	4	4391	5	4408	5	5332	27
A270	2216	-47	2438	-42	2454	-41	3120	-26	3820	-9
B220	3706	-12	4493	7	4490	7	4449	6	5628	34
B270	2698	-36	3077	-27	3070	-27	3328	-21	4263	2

As shown in Table 46, the red numbers represent reductions in productivity of Modern and Traditional Agriculture, while the green numbers are increases in productivity. These results are introduced in the CGE model to quantify the impacts on GDP, deforestation and per capita income. The productivity variations are introduced in the CGE for Traditional and Modern Agriculture Activities through the parameter ***TFPGR (A,SIM,YR)***, named: “Total Factor Productivity Growth Rates”. The summary of results is presented on Figures 31 and 32, for the short and long runs, respectively.

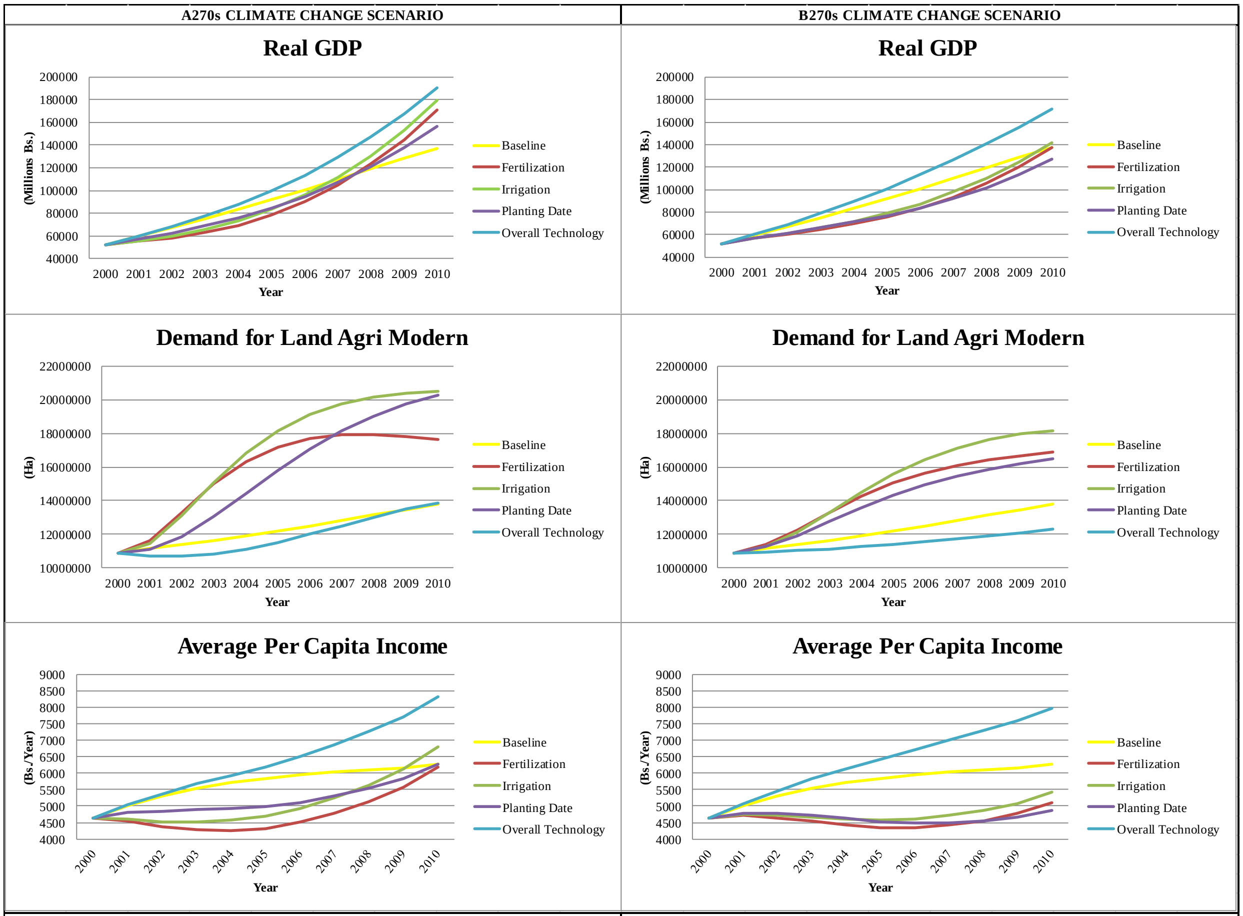
Figure 31: Adaptation Options Impacts in GDP, Deforestation and Per Capita Income for the Short Run (2020s)



A220s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)				B220s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)			
A220s Scenario	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**	**B220s Scenario**	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**
Climate Change Impacts	-10	7	-14	**Climate Change Impacts**	-10	8	-13
Fertilization	0	0	0	**Fertilization**	4	0	5
Irrigation	1	0	2	**Irrigation**	4	0	5
Planting Date	16	-7	18	**Planting Date**	12	-4	13
Overall Technology	56	26	59	**Overall Technology**	60	34	62

The variations shown in Figure 31 are average changes with respect to the Baseline. In the short run, the most effective adaptation option to increase GDP is the Overall Technology Improvement (56 to 70% increases on average, for the A220s and B220s scenarios respectively). The second most effective adaptation option is the change of the planting date, showing increases of 12 to 16%. The increases in average per capita income are similar to those of GDP. The other adaptation options are effective as well but with much more modest increases. The most sustainable adaptation option is the change of the planting date given that with this adaptation, the deforestation is reduced from -4 to -7% with respect to the baseline. On the other hand, the overall technology improvement increases the deforestation from 26 to 34% with respect to the baseline (around 2,000,000 additional hectares of deforestation by year).

Figure 32: Adaptation Options Impacts in GDP, Deforestation and Per Capita Income for the Long Run (2070s)



A270s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)				B270s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)			
A270s Scenario	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**	**B270s Scenario**	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**
Climate Change Impacts	-2	7	-15	**Climate Change Impacts**	-8	21	-19
Fertilization	-4	28	-16	**Fertilization**	-11	17	-19
Irrigation	0	36	-10	**Irrigation**	-8	21	-15
Planting Date	-2	26	-9	**Planting Date**	-11	13	-18
Overall Technology	13	-3	10	**Overall Technology**	11	-6	11

In the long run, the only effective adaptation measure for increasing GDP and per capita income is the Overall Technology Improvement, with GDP increases from 11 to 13% and per capita income increases of around 10% on average. This adaptation option is the most sustainable option as well, given that it reduces the deforestation from -3 to -6% (around 10,000 hectares of less deforestation by year on average).

5.3 Micro and Macroeconomic Climate Policy Mainstreaming for Sustainable Development

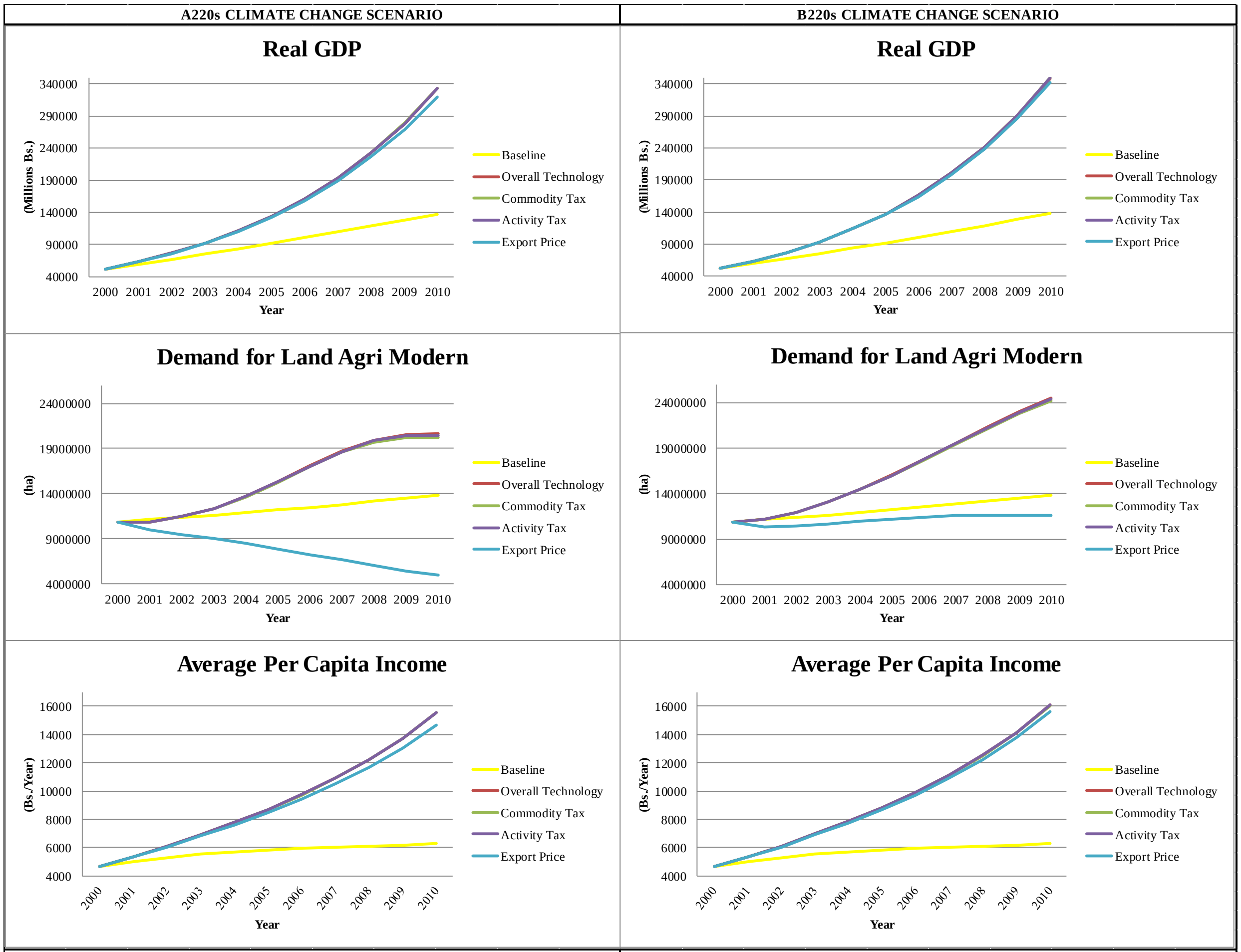
In this section, the most effective microeconomic policy is combined with 3 different macroeconomic policies for achieving sustainable development, in other words higher GDP and incomes with a lower and more stable deforestation rate. The most efficient microeconomic policy is the Overall Technology Improvement, which is combined with the 3 following different macroeconomic policies for reducing the demand for land coming from incentives of higher yields per hectare:

Table 47: Macroeconomic Policies Combined with Overall Technology Production for Sustainable Development

Number	Parameter in the CGE Model	Macroeconomic Policy	% Variation / year
1)	STAXGR(C,SIM,YR)	30% increase on Industrial Agriculture Commodity Tax	(+30%) per annum
2)	ATAXGR(A,SIM,YR)	30% increase on Modern Agriculture Activity Tax	(+30%) per annum
3)	PWEGR(C,R,SIM,YR)	30% reduction on Modern Agriculture Export Price	(-30%) per annum

The proportion 30% is chosen for all the cases, given that in the short run the higher yields of agriculture due to the overall technology improvement give adverse incentives to demand more Modern Agriculture Land (as proxy of deforestation), in the range of +26 to +34% (+30% on average). Modern Agriculture Activity Tax in the baseline is 0.03% of total activity production; while Industrial Agriculture Commodity Tax is 3% of total commodity production; and finally, Modern Agriculture Export Price is determined as the demand of commodities from the rest of the world, therefore, with this policy there is a -30% reduction of demand. The results of these experiments are summarized in the following Figures:

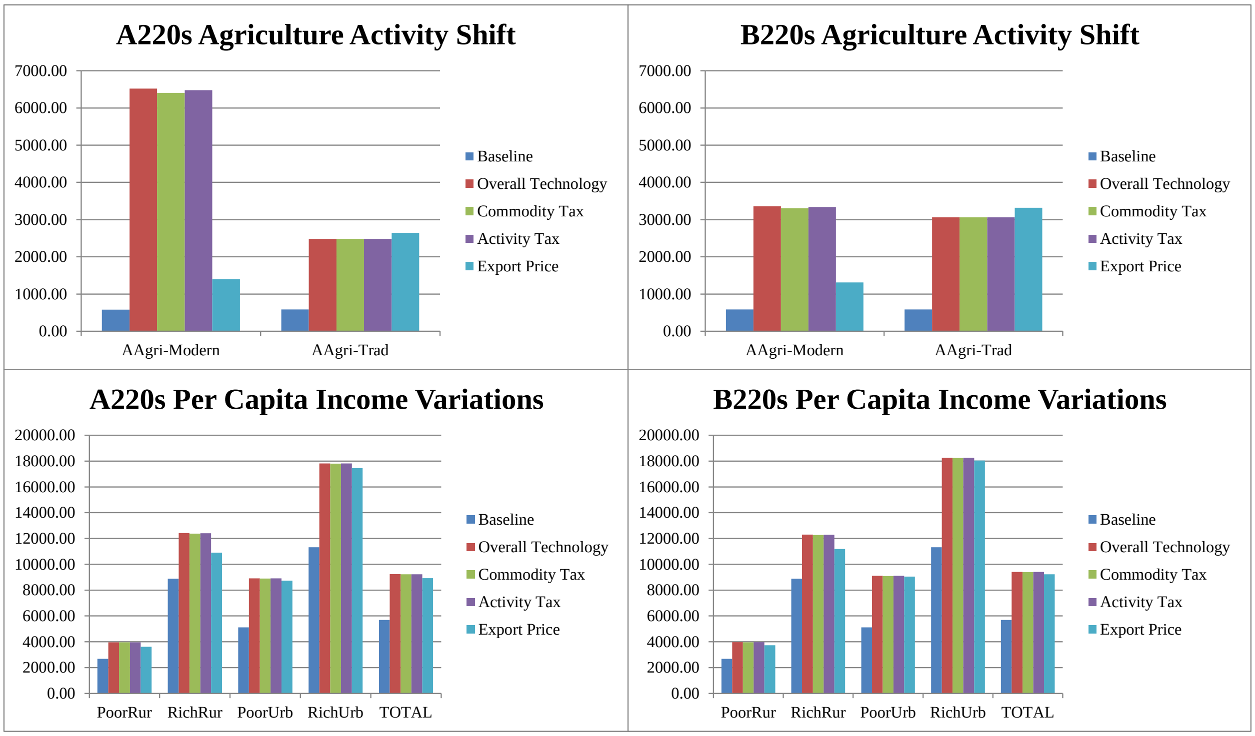
Figure 33: Microeconomic and Macroeconomic Climate Policy Mainstream Impacts on GDP, Deforestation and Income in the Short Run (2020s)



A220s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)				B220s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)			
A220s Scenario	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**	**B220s Scenario**	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**
CC Impacts (W/O Policy)	-10	7	-14	**CC Impacts (W/O Policy)**	-10	8	-13
Overall Technology (alone)	56	26	59	**Overall Technology (alone)**	60	34	62
OT Combined w Commodity Tax	56	25	59	**OT Combined w Commodity Tax**	60	33	62
OT Combined w Activity Tax	56	25	59	**OT Combined w Activity Tax**	60	34	62
OT Combined w Export Price	53	-35	54	**OT Combined w Export Price**	59	-9	59

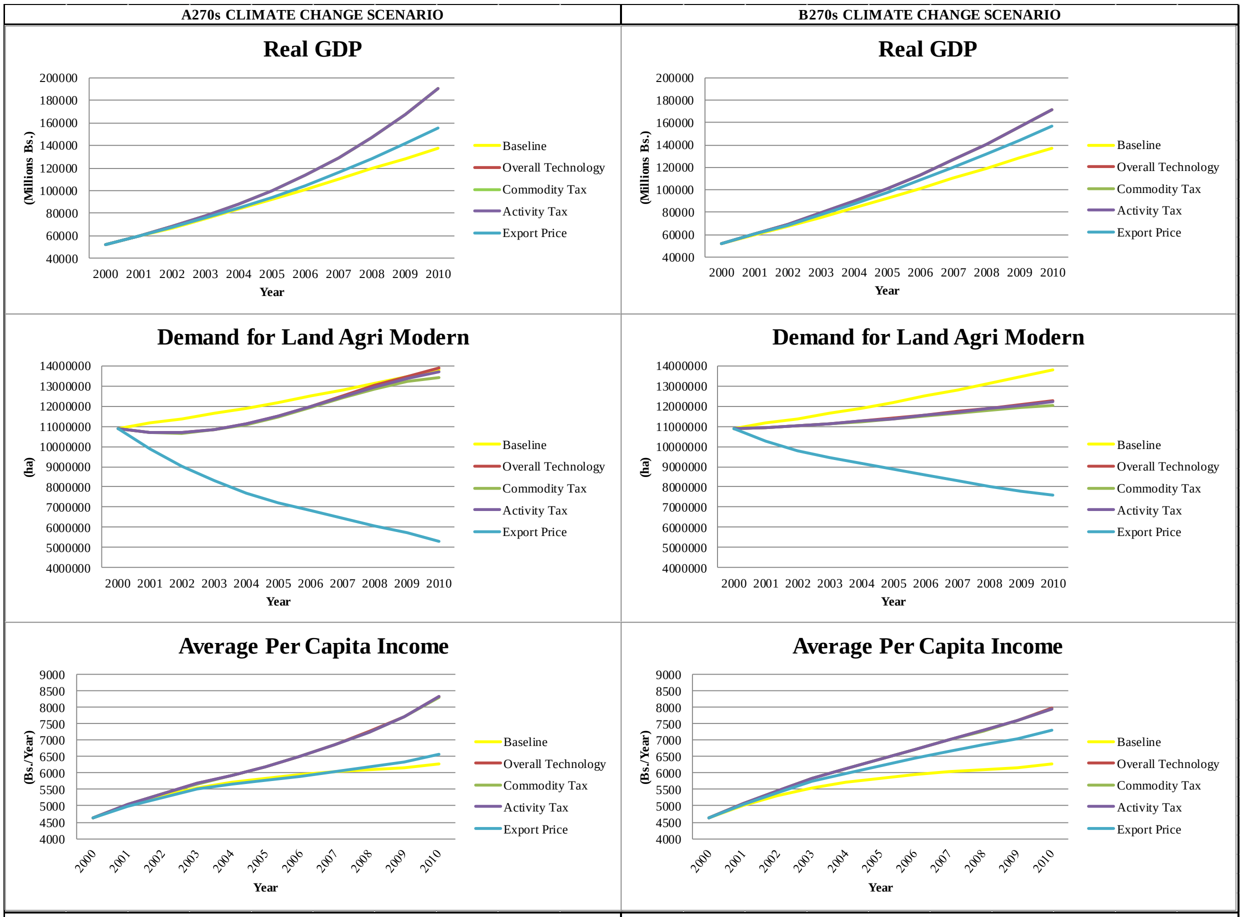
Figure 33, shows variations of GDP, deforestation and income in the short run (2020s) with respect to the baseline. Commodity Tax and Activity Tax have a minimal impact on GDP and deforestation when combined with the Overall technology Improvement; the former remains almost constant, and the latter is reduced by -1%. Average per capita income remains unchanged also. On the other hand, the Commodity Export Price Reduction, seems to be the most sustainable macroeconomic policy, showing increases on GDP of around +53%, reductions in the deforestation (-35% on average) and increases in the mean per capita income (+54% on average) when combined with the overall technology improvement microeconomic policy with respect to the Baseline. This combination of policies reduces the GDP and per capita income by -5% on average, but this reduction is more than exceeded with the reduction of forest loss of about -35% on average when compared with the Overall Technology Improvement microeconomic policy alone.

Figure 34: Climate Policy Mainstreaming Impacts on Agriculture's Activity Shift to Other Activities and Per Capita Income in the Short Run (2020s)



In the short run, Commodity Taxes seem to be more efficient than activity taxes for reducing the Modern Agriculture activity. Both of the taxes reduce rich rural households which are the most affected. When applying the Modern Agriculture Commodity Price reduction, the Modern Agriculture Activity is reduced, and there is a small shift into Traditional Agriculture, while the highest reduction on per capita income is observed in rich rural households and companies.

Figure 35: Microeconomic and Macroeconomic Climate Policy Mainstream Impacts on GDP, Deforestation and Income in the Long Run (2070s)

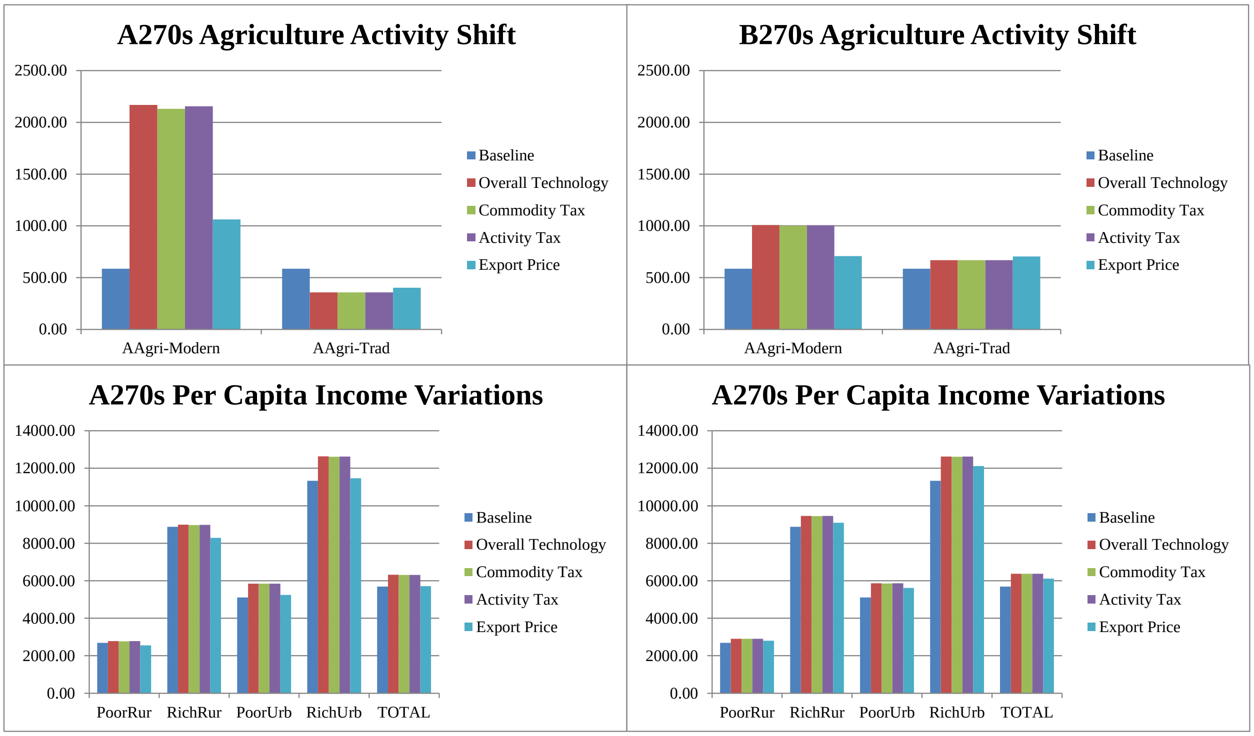


A270s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)			
A270s Scenario	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**
CC Impacts (W/O Policy)	-2	7	-15
Overall Technology (alone)	13	-3	10
OT Combined w Commodity Tax	13	-4	10
OT Combined w Activity Tax	13	-4	10
OT Combined w Export Price	4	-37	0

B270s SCENARIO AVERAGE IMPACTS OF POLICY OPTIONS FOR THE WHOLE PERIOD (2000 - 2010)			
B270s Scenario	**GDP (%)**	**Deforestation (%)**	**Per Capita Income (%)**
CC Impacts (W/O Policy)	-8	21	-19
Overall Technology (alone)	11	-6	11
OT Combined w Commodity Tax	11	-7	11
OT Combined w Activity Tax	11	-6	11
OT Combined w Export Price	6	-26	7

Figure 35, shows variations of GDP, deforestation and income in the long run (2070s) with respect to the baseline. Commodity Tax and Activity Tax have a minimal impact on GDP and deforestation when combined with the Overall technology Improvement; the former remains almost constant, and the latter is reduced by -1%. Average per capita income remains unchanged also. On the other hand, the Commodity Export Price Reduction, seems to be the most sustainable macroeconomic policy for the long run too, showing increases on GDP of around +6%, reductions in the deforestation (-26% on average) and increases in the mean per capita income (+7% on average) when combined with the overall technology improvement microeconomic policy with respect to the Baseline. This combination of policies reduces the GDP and per capita income by -7% on average, but this reduction is more than exceeded with the reduction of forest loss of about -31% on average when compare with the Overall Technology Improvement microeconomic policy alone.

Figure 36: Climate Policy Mainstreaming Impacts on Agriculture's Activity Shift to Other Activities and Per Capita Income in the Long Run (2070s)



In the long run, Commodity Taxes seem to be more efficient than activity taxes for reducing the Modern Agriculture activity too. In this case, companies' incomes are the most affected, while households' incomes remain almost unchanged. When applying the Modern Agriculture Commodity Price reduction, the Modern Agriculture Activity is reduced, and there is a small shift into Traditional Agriculture for the B270s Scenario only, while the highest reduction on per capita income is observed in rich rural and urban households and companies.

5.4 Estimated Forest Conservation Social Costs

The policies taken by Governments for reducing deforestation and forest degradation are very important for Global Climate Stability; given that forests provide environmental services to the livelihoods and also are carbon sinks which reduce the CO_2 concentration in the Atmosphere. When protecting a given forested area, households are restricted to convert forest lands in other more profitable uses like agriculture, livestock, among others. This has consequences in their incomes and also in the Aggregate National GDP. For this reason, some schemes are available to pay off these households, such as the Payment for Ecosystem Services (PES) and the Reducing Emissions from Deforestation and Degradation (REDD+) schemes, where owners of forested lands are economically compensated if they conserve forests. This "economic incentive" funds, come from different sources, on one hand PES (generally private and public local Institutions); and on the other hand, REDD+ schemes with international and global financial resources, in general. In this sense, Table 48 shows the GDP, demand for land and the estimated social cost of forest protection ($/ha) per annum for the short and long runs in Bolivia, using the Overall Technology Improvement Scenario alone, and the same scenario combined with a decrease in the Exports Commodity Price:

Table 48: Estimated Forest Conservation Social Cost in the Context of PES and REDD Schemes for the Short and Long Runs in Bolivia ($/ha/year)

SHORT RUN (2020s)							
A220s ESTIMATED FOREST CONSERVATION COST ($/ha/year)				B220s ESTIMATED FOREST CONSERVATION COST ($/ha/year)			
GDP A220 OT	22,771,263,505	Land Demand A220 OT	15,591,585	GDP B220 OT	23,503,355,072	Land Demand B220 OT	16,691,752
GDP A220 OT+EP	22,088,125,599	Land Demand A220 OT+EP	10,134,530	GDP B220 OT+EP	23,268,321,522	Land Demand B220 OT+EP	15,189,495
A220 GDP Reduction	**683,137,905**	A220 Land Demand Reduction	**5,457,055**	B220 GDP Reduction	**235,033,551**	B220 Land Demand Reduction	**1,502,258**
A220 Cost of Forest Protection (GDP Red/Land Dem Red)			**125.18**	B220 Cost of Forest Protection (GDP Red/Land Dem Red)			**156.45**
LONG RUN (2070s)							
A270s ESTIMATED FOREST CONSERVATION COST ($/ha/year)				B270s ESTIMATED FOREST CONSERVATION COST ($/ha/year)			
GDP A270 OT	15,722,965,613	Land Demand A270 OT	11,875,812	GDP B270 OT	15,253,230,698	Land Demand B270 OT	11,474,085
GDP A270 OT+EP	14,307,898,708	Land Demand A270 OT+EP	7,481,761	GDP B270 OT+EP	14,490,569,163	Land Demand B270 OT+EP	8,490,823
A270 GDP Reduction	**1,415,066,905**	A270 Land Demand Reduction	**4,394,050**	B270 GDP Reduction	**762,661,535**	B270 Land Demand Reduction	**2,983,262**
A270 Cost of Forest Protection (GDP Red/Land Dem Red)			**322.04**	B270 Cost of Forest Protection (GDP Red/Land Dem Red)			**255.65**

As it is observed in Table 48, a proxy of the forest conservation social cost for the short and long runs is estimated. For this purpose, two different set of results are compared in all the Scenarios: GDP and Land Demand of the Overall Technology Improvement (OT), on one hand; and on the other hand, GDP and Demand for Land of the Overall Technology Improvement plus the Reduction in the Export Price macroeconomic policy (OT+EP). Then, the GDP and Land Demand Reductions are quantified by subtracting the OT+EP from the OT results. The GDP reduction is then divided by the Land Demand Reduction, having as final a result, a proxy of the social cost of conserving 1 hectare of forest. The social cost ranges from 125 to 156 $/ha per year (140 $/ha on average) in the short run (A220 and B220, respectively). While, in the long run, this cost ranges from 255 to 322 $/ha per year (289 $/ha on average), for the B270 and A270 scenarios, respectively.

6. Conclusions and Recommendations

Deforestation in Bolivia has reached alarming levels in the last decade. According to the last studies for the period 2004 to 2005 the level of deforestation was 278,000 ha/year, while for the year 2006, the deforestation reached 307,000 ha (Wachholtz et al., 2006 y 2007). This increase is attributed to the agriculture frontier expansion especially in the Santa Cruz Department (75% of national total). Historically, government policies and the economic context have promoted the agriculture expansion in the country reducing the natural forested areas, only recently in the 1990s, the sustainable use of natural resources was considered in the Government agenda. Nevertheless, problems related to weak institutional capacity, land property rights insecurity and pressure of agricultural markets, have prevented sustainable policies to have the desired impact. With this situation plus the impending climate change effects and population growth, in the future more hectares of agriculture land will be required in to meet the demand for foods. For this reason, it is extremely important to have microeconomic policies for increasing crop yields per unit area (adaptation measures), accompanied by macroeconomic policies in order to achieve sustainable development (policy mainstreaming). A linked Crop-CGE model is used to quantify the impacts of climate change, adaptation measures at the micro level and macroeconomic policy mainstreaming in Bolivia for the A2 and B2 IPCC's SRES Scenarios for the short and long runs (2020s and 2070s, respectively). In this sense, after the calibration and validation, the CGE model represents the Bolivian Economy very precisely for the time horizon.

Climate Change is going to have negative effects in the agricultural sector and in the whole Bolivian Economy if no actions are taken. In the short run, the reductions on national GDP are about 10% (1,350,899,987 US$ per year), and the increases in deforestation of 7 to 8% (approximately 85,000 ha/year of additional forest loss). While in the long run the impacts are -2 to -8% of reduction on GDP and a higher deforestation (+21 to +29%), in other words, 240,000 to 320,000 hectares of additional deforestation per year. This is explained by the lower yields per unit area in Modern and Traditional Agriculture Activities, the lower yields reduce net incomes and increases the demand of land given that more hectares of land are required to achieve the demand for foods.

When applying the adaptation measures at the micro level, higher yields per unit area are observed in most of the scenarios. In this case, the increase in crop yields per unit area gives the adverse incentive of increasing land demand, given the new profitability of these activities. For controlling this demand, 4 adaptation options are tested: fertilization, irrigation, change on the planting date and overall technology improvement, which involves all the previous 3 adaptation options. Fertilization and irrigation alone do not have the expected increase in crop yields. Thus, soil fertility does not seem to be a problem in the most important production zones of Bolivia. On the other hand, irrigation alone does not have a positive impact on crop yields, given that in most of the climate change scenarios precipitation is increased in different proportions (from +10 to +74%), therefore water stress is not a problem either for the analyzed scenarios. However, in the B2 scenario for the long run (B270s) there is a reduction on precipitation, where irrigation is a good adaptation measure (+1 to +11% increases in maize and rice yields).

When analyzing, the change of the planting date, it is a very effective measure in the short run, given that crop yields increase from +23 to +35%, increasing GDP by +12 to +16%. In the long run, this adaptation is not enough given that climate change impacts are higher (warmer conditions and reduction in precipitations). In this sense the most effective adaptation measure for the short and long runs is the overall technology improvement, which increases GDP by +56 to +60% in the short run and +11 to +13% in the long run. These higher yields come with higher demand for land; therefore, deforestation is increased by +26 to +34% in the short run and -3 to -6% in the long run. Per capita mean incomes follow a similar increasing trend as GDP.

To meet the demand for foods and also preserve natural forests, micro and macro policies must be coordinated. In this regard, the most efficient adaptation measure at the micro level (overall technology improvement) is combined with 3 different macroeconomic policies: +30% increases on Industrial Agriculture Commodity Tax, +30% increases on Modern Agriculture Activity Tax and -30% reductions on Modern Agriculture Export Price. Commodity Tax and Activity Tax have a minimal impact on GDP and deforestation; deforestation in the former remains almost constant and in the latter is reduced by -1%. Average per capita income remains unchanged also. This can be explained by the low levels of taxes observed in the Baseline scenario (0.03% and 3% for Modern Agriculture Activity and Industrial Agriculture Commodity taxes, respectively). However, a more strict fiscal policy can have the desired impacts on reducing deforestation, and higher government incomes which then will be re-distributed to households, thus increasing their welfare. On the other hand, the Commodity Export Price Reduction, seems to be the most sustainable macroeconomic policy, showing increases on GDP of around +53% for the short run and +4% in the long run, reductions in the deforestation of -35% in the short run and -33% in the long run on average, and increases in the mean per capita income of +54% in the short run and +6% in the long run on average when combined with the overall technology improvement microeconomic policy with respect to the Baseline. This combination of policies reduces the GDP and per average per capita income by -5% on average, but this reduction is more than exceeded with the reduction of forest loss of about -35%.

The reduction on GDP and Per Capita Income caused by forest protection has to be compensated to households for keeping their level of welfare. In this regard, there is the option to access to PES and/or REDD+ schemes, where developing countries with natural forests can receive benefits from the public and/or private, local and/or international sectors, if they protect their forested lands. The final result of the present study estimated a proxy of the social cost of forest conservation in Bolivia, which would maintain society's welfare for foregoing the more profitable activities on forested lands. The cost for the short run is 140 $/ha per annum, and for the long run is 289 $/ha per annum on average. These costs can be used as starting points for PES and REDD+ negotiation schemes in the context of Global Climate Change Agreements, and are very useful to be compared with the same costs derived from other environmental valuation techniques, such as the contingent valuation method.

The thesis is confirmed by the simulations, where climate change impacts is counterproductive for the agriculture sector and the economy as a whole, adaptation measures at the micro level can increase crop yields per hectare having the collateral adverse demand for land given the profitability of agriculture, which can be reduced with coordinated macroeconomic policies of forest protection, having a win-win situation. The study is novel in the context of sustainability science and adaptation/mitigation schemes, but it can be further improved with a more detailed and updated SAM, where the agriculture sector should be more disaggregated by individual activities and commodities (soybeans, maize, rice, sugar cane, among others). In the same way, it is recommended to construct the treatment of land as a heterogeneous production factor for agriculture or forestry, as alternative land use activities.

The main objective of the study is fulfilled, proving that climate policy mainstreaming is a very effective, efficient and equitable manner to reach the dual objective of meeting the needs of society and to maintain life support systems of the planet, and it also confirms the importance of the science and decision making dialogue, for achieving sustainable development.

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APPENDIX A: CGE Model Specification

Symbol

Sets	Explanation
$a \in A$	Activities
$a \in ALEO(\subset A)$	Activities with a Leontief function at the top of the technology nest
$c \in C$	Commodities
$c \in CD(\subset C)$	Commodities with domestic sales of domestic output
$c \in CDN(\subset C)$	Commodities not in CD
$c \in CE(\subset C)$	Exported commodities
$c \in CEN(\subset C)$	Commodities not in CE
$c \in CM(\subset C)$	Aggregate imported commodities
$c \in CMN(\subset C)$	Commodities not in CM
$c \in CT(\subset C)$	Transaction service commodities
$c \in CX(\subset C)$	Commodities with domestic production
$f \in F$	Factors
$i \in INS$	Institutions (domestic and rest of world)
$i \in INSD(\subset INS)$	Domestic institutions
$i \in INSDNG(\subset INSD)$	Domestic nongovernment institutions
$h \in H(\subset INSDNG)$	Households

Parameters

Parameter	Explanation
Latin Symbols	
$cwts_c$	Weight of commodity c in the CPI
$dwts_c$	Weight of commodity c in the producer price index
ica_{ca}	Quantity of c as intermediate input per unit of activity a
$icd_{cc'}$	Quantity of commodity c as trade input per unit of c’ produced and sold domestically
$ice_{cc'}$	Quantity of commodity c as trade input per exported unit of c’
$icm_{cc'}$	Quantity of commodity c as trade input per imported unit of c’
$inta_a$	Intermediate input per activity unit
iva_a	Quantity of aggregate intermediate input per activity unit
$\underline{mps_i}$	Base savings rate for domestic institution i
$mps01_i$	0-1 parameter with 1 for institutions with potentially flexed direct tax rates
pwe_c	Export price (foreign currency)
pwm_c	Import price (foreign currency)
$qdst_c$	Quantity of stock change
$\underline{qg_c}$	Base-year quantity of government demand
$\underline{qinv_c}$	Base-year quantity of private investment demand

$shif_{if}$	Share for domestic institution i in income of factor f
$shii_{ii'}$	Share of net income of i’ to i (i’ ϵ INSDNG’; i ϵ INSDNG)
ta_a	Tax rate for activity a
te_c	Tax rate for export commodity *c*
tf_f	Direct Tax rate to factor *f*
$\underline{tins}_i$	Exogenous direct tax rate for domestic institution i
$tins01_i$	0-1 parameter with 1 for institutions with potentially flexed direct tax rates
tm_c	Import tariff rate
tq_c	Rate of sales tax
$trnsfr_{if}$	Transfer from factor f to institution i
tva_a	Tax rate for value added of activity *a*

Greek Symbols

α_a^a	Efficiency parameter in the CES activity function
α_a^{va}	Efficiency parameter in the CES value added function
α_a^{ac}	Shift parameter for domestic commodity aggregation function
α_c^q	Armington function shift parameter
α_c^t	CET function shift parameter
β^a	Capital sectorial mobility factor
β_{ch}^m	Marginal share of consumption spending on marketed commodity c for household h
δ_a^a	CES activity function share parameter
δ_{ac}^{ac}	Share parameter for domestic commodity aggregation function
δ_c^q	Armington function share parameter
δ_c^t	Share Parameter for CET function
δ_{fa}^{va}	Share Parameter for aggregated CES value added function of factor *f* in activity a
υ_f	Capital depreciation rate
γ_{ch}^m	Subsistence consumption of marketed commodity c for household h
θ_{ac}	Yield of output c per unit of activity a
ρ_a^a	CES production function exponent
ρ_a^{va}	CES value-added function exponent
ρ_a^{ac}	Domestic commodity aggregation function exponent
ρ_c^q	Armington function exponent
ρ_c^t	CET function exponent
η_{fat}^a	Sector share of new capital

Variables

Variable	Explanation
Exogenous Variables	
$\underline{CPI}$	Consumer price index
$\underline{DTINS}$	Change in domestic institution tax share (= 0 for base; exogenous variable)
$\underline{FSAV}$	Foreign savings (FCU)
$\underline{GADJ}$	Government consumption adjustment factor
$\underline{IADJ}$	Investment adjustment factor
$\underline{MPSADJ}$	Savings rate scaling factor (= 0 for base)
$\underline{QFS_f}$	Quantity supplied of factor
$\underline{TINSADJ}$	Direct tax scaling factor (= 0 for base; exogenous variable)
$\underline{WFDIST_{fa}}$	Wage distortion factor for factor f in activity a
Endogenous Variables	
AWF_{ft}^{a}	Average capital rental rate in time period t
$DMPS$	Change in domestic institution savings rates (= 0 for base; exogenous variable)
DPI	Producer price index for domestically marketed output
EG	Government expenditures
EH_h	Consumption spending for household
EXR	Exchange rate (LCU per unit of FCU)
$GOVSHR$	Government consumption share in nominal absorption
$GSAV$	Government savings
$INVSHR$	Investment share in nominal absorption
$MPSi$	Marginal propensity to save for domestic non-government institution (exogenous variable)
PA_a	Activity price (unit gross revenue)
PDD_c	Demand price for commodity produced and sold domestically
PDS_c	Supply price for commodity produced and sold domestically
PE_c	Export price (domestic currency)
$PINTA_a$	Aggregate intermediate input price for activity a
PK_{ft}	Unit price of capital in time period t
PM_c	Import price (domestic currency)
PQ_c	Composite commodity price
PVA_a	Value-added price (factor income per unit of activity)
PX_c	Aggregate producer price for commodity
$PXAC_{ac}$	Producer price of commodity c for activity a
QA_a	Quantity (level) of activity
QD_c	Quantity sold domestically of domestic output
QE_c	Quantity of exports
QFf_a	Quantity demanded of factor f from activity a
QG_c	Government consumption demand for commodity

QH_{ch}	Quantity consumed of commodity c by household h
$QINTA_{ca}$	Quantity of aggregate intermediate input
$QINT_{ca}$	Quantity of commodity c as intermediate input to activity a
$QINV_{c}$	Quantity of investment demand for commodity
QM_{c}	Quantity of imports of commodity c
QQ_{c}	Quantity of goods supplied to domestic market (composite supply)
QT_{c}	Quantity of commodity demanded as trade input
QVA_{a}	Quantity of (aggregate) value added
QX_{c}	Aggregated quantity of domestic output of commodity
$QXAC_{ac}$	Quantity of output of commodity c from activity a
RWF_{f}	Real average factor price
$TABS$	Total nominal absorption
$TINS_{i}$	Direct tax rate for institution I (i ϵ INSDNG)
$TRII_{ii'}$	Transfers from institution i’ to i (both in the set INSDNG)
WF_{f}	Average price of factor
YF_{f}	Income of factor f
YG	Government revenue
YI_{i}	Income of domestic nongovernment institution
YIF_{if}	Income to domestic institution i from factor f
ΔK_{fat}^{a}	Quantity of new capital by activity a for time period t

Model Equations

	Equation		Explanation
Prices			
1)	$PM_c = pwm_c \cdot (1+tm_c) \cdot EXR + \sum_{c' \in CT} PQ_{c'} \cdot icm_{c'c}$	$c \in CM$	Import Price
2)	$PE_c = pwe_c \cdot (1-te_c) \cdot EXR + \sum_{c' \in CT} PQ_{c'} \cdot ice_{c'c}$	$c \in CE$	Export Price
3)	$PDD_c = PDS_c + \sum_{c' \in CT} PQ_{c'} \cdot icd_{c'c}$	$c \in CD$	Domestic Commodity Price of non-Tradable
4)	$PQ_c \cdot (1-tq_c) \cdot QQ_c = PDD_c \cdot QD_c + PM_c \cdot QM_c$	$c \in (CD \cup CM)$	Absorption
5)	$PX_c \cdot QX_c = PDS_c \cdot QD_c + PE_c \cdot QE_c$	$c \in CX$	Sale Commodities Value
6)	$PA_a = \sum_{c \in C} PXAC_{ac} \cdot \theta_{ac}$	$a \in A$	Activity Price
7)	$PINTA_a = \sum_{c \in C} PQ_c \cdot ica_{ca}$	$a \in A$	Aggregated Intermediate Input Price
8)	$PA_a \cdot (1-ta_a) \cdot QA_a = PVA_a \cdot QVA_a + PINTA_A \cdot QINTA_a$	$a \in A$	Revenues and Costs by Activity
9)	$\overline{CPI} = \sum_{c \in C} PQ_c \cdot cwts_c$		Consumer Price Index
10)	$DPI = \sum_{c \in C} PDS_c \cdot dwts_c$		Producer Price Index

Production and Trade

11)	$QVA_a = iva_a \cdot QA_a$	$a \in ALEO$	Aggregated Value Added Demand: Leontief Technology
12)	$QINTA_a = inta_a \cdot QA_a$	$a \in ALEO$	Aggregated Intermediate Input Demand: Leontief Technology
13)	$QVA_a = \alpha_a^{va} \cdot \left(\sum_{f \in F} \delta_{f\,a}^{va} \cdot \left(\alpha_{f\,a}^{va\,f} \cdot QF_{f\,a} \right)^{-\rho_a^{va}} \right)^{-\frac{1}{\rho_a^{va}}}$	$a \in A$	Factor and Value added Demands
14)	$W_f \cdot WFDIST_{f\,a} = PVA_a \cdot (1 - tva_a) \cdot QVA \cdot \left(\sum_{f \in ''F'} \delta_{f\,a}^{va} \cdot \left(\alpha_{f\,a}^{vaf} \cdot QF_{f\,a} \right)^{-\rho_a^{va}} \right)^{-1} \cdot$ $\delta_{f\,a}^{va} \cdot \left(\alpha_{f\,a}^{va\,f} \cdot QF_{f\,a} \right)^{-\rho_a^{va} - 1}$	$a \in A$ $f \in F$	Factors Demand
15)	$QINT_{c\,a} = ica_{c\,a} \cdot QINTA_a$	$a \in A$ $c \in C$	Non aggregated Inputs Demand
16)	$QXAC_{a\,c} + \sum_{h \in H} QHA_{a\,c\,h} = \theta_{a\,c} \cdot QA_a$	$a \in A$ $a \in CX$	Commodity Production and Allocation
17)	$QX_c = \alpha_c^{ac} \cdot \left(\sum_{a \in A} \delta_{a\,c}^{ac} \cdot QAXC_{a\,c}{}^{-\rho_c^{ac}} \right)^{-\frac{1}{\rho_c^{ac} - 1}}$	$c \in CX$	Aggregated Production Function
18)	$PXAC_{a\,c} = PX_c \cdot QX_c \left(\sum_{a \in A'} \delta_{a\,c}^{ac} \cdot QXAC_{a\,c}{}^{-\rho_c^{ac}} \right)^{-1} \cdot \delta_{a\,c}^{ac} \cdot QXAC_{a\,c}{}^{-\rho_c^{ac} - 1}$	$a \in A$ $a \in CX$	CPO for Aggregated Production Function

19)	$QX_c = \alpha_c^t \cdot \left(\delta_c^t \cdot QE_c^{\rho_c^t} + (1-\delta_c^t) \cdot QD_c^{\rho_c^t}\right)^{\frac{1}{\rho_c^t}}$	$c \in (CE \cap CD)$	(CET) Production Transformation Function
20)	$\frac{QE_c}{QD_c} = \left(\frac{PE_c}{PDS_c} \cdot \frac{1-\delta_c^t}{\delta_c^t}\right)^{\frac{1}{\rho_c^t - 1}}$	$c \in (CE \cap CD)$	Supply Relation Export-Domestic
21)	$QX_c = QD_c + QE_c$	$c \in (CD \cap CEN)$ $\cup (CE \cup CDN)$	Production Transformation for non-Exported Commodities
22)	$QQ_c = \alpha_c^q \cdot \left(\delta_c^q \cdot QM_c^{-\rho_c^q} + (1-\delta_c^q) \cdot QD_c^{\rho_c^q}\right)^{-\frac{1}{\rho_c^q}}$	$c \in (CM \cap CD)$	(Armington) Supply Function
23)	$\frac{QM_c}{QD_c} = \left(\frac{PDD_c}{PM_c} \cdot \frac{\delta_c^q}{1-\delta_c^q}\right)^{\frac{1}{1+\rho_c^q}}$	$c \in (CM \cap CD)$	Demand Relation Import-Domestic
24)	$QQ_c = QD_c + QM_c$	$c \in (CD \cap CMN)$ $\cup (CM \cup CDN)$	Supply of non-Imported Commodities and non-Produced Imports
25)	$QT_c = \sum_{c' \in C'} (icm_{c\,c'} \cdot QM_{c'} + ice_{c\,c'} \cdot QE_{c'} + icd_{c\,c'} \cdot QD_{c'})$	$c \in CT$	Transaction Services Demand
26)	$\frac{QFS_f}{QFS_f^0} = \left(\frac{RWF_f}{RWF_f^0}\right)^{etals_f}$	$f \in F$	Factors Supply
27)	$RWF_f = \left(\frac{YF_f}{QFS_f}\right) \Big/ \left(\frac{CPI}{CPI^0}\right)$	$f \in F$	Factor Average Real Wage

Institutional

28)	$YF_f = \sum_{a \in A} WF_f \cdot \overline{WFDIST_{f\,a}} \cdot QF_{f\,a}$	$f \in F$	Factors Revenue
29)	$YIF_{i\,f} = shif_{i\,f} \cdot \left\lfloor (1 - tf_f) \cdot YF_f - trnsfr_{row\,f} \cdot EXR \right\rfloor$	$i \in INSD$ $f \in F$	Institutional Factors Revenues
30)	$YI_i = \sum_{f \in F} YIF_{i\,f} + \sum_{i' \in INSDNG'} TRII_{i\,i'} + trnsfr_{i\,gov} \cdot \overline{CPI} + trnsfr_{i\,row} \cdot EXR$	$i \in INSDNG$	Revenue of non-Governmental Domestic Institutions
31)	$TRII_{i\,i'} = shii_{i\,i'} \cdot (1 - MPS_{i'}) \cdot (1 - TINS_{i'}) \cdot YI_{i'}$	$i \in INSDNG$ $i' \in INSDNG'$	Intra-institutional Transfers
32)	$EH_h = \left(1 - \sum_{i \in INSDNG} shii_{i\,h} \right) \cdot (1 - MPS_h) \cdot (1 - TINS_h) \cdot YI_h$	$h \in H$	Household Consumption Expenditure
33)	$PQ_c \cdot QH_{c\,h} = PQ_c \cdot \gamma^m_{c\,h} + \beta^m_{c\,h} \cdot \left(EH_h - \sum_{c' \in C} PQ_{c'} \cdot \gamma^m_{c'h} - \sum_{a \in A} \sum_{c' \in C} PXAC_{a\,c'} \cdot \gamma^h_{a\,c'h} \right)$	$c \in C$ $h \in H$	Marketed Commodities Households Demand
34)	$PXAC_{a\,c} \cdot QHA_{a\,c\,h} = PXAC_{a\,c} \cdot \gamma^h_{a\,c\,h} + \beta^h_{c\,h} \cdot \left(EH_h - \sum_{c' \in C} PQ_{c'} \cdot \gamma^m_{c'h} - \sum_{a \in A} \sum_{c' \in C} PXAC_{a\,c'} \cdot \gamma^h_{a\,c'h} \right)$	$a \in A$ $c \in C$ $h \in H$	Auto-Consumption Commodity Households Demand
35)	$QINV_c = \overline{IADJ} \cdot \overline{qinv_c}$	$c \in CINV$	Investment Demand
36)	$QG_c = \overline{GADJ} \cdot \overline{qg_c}$	$c \in C$	Government Consumption Demand

37)	$YG = \sum_{i \in INSDNG} TINS_i \cdot YI_i + \sum_{f \in F} tf_f \cdot YF_f + \sum_{a \in A} tva_a \cdot PVA_a \cdot QVA_a + \sum_{a \in A} ta_a \cdot PA_a \cdot QA_a + \sum_{c \in CM} tm_c \cdot pwm_c \cdot QM_c \cdot EXR + \sum_{c \in CE} te_c \cdot pwe_c \cdot QE_c \cdot EXR + \sum_{c \in C} tq_c \cdot PQ_c \cdot QQ_c + \sum_{f \in F} YIF_{gov\,f} + trnsfr_{gov\,row} \cdot EXR$		Government Revenue
38)	$EG_c = \sum_{c \in C} PQ_c \cdot QG_c + \sum_{i \in INSDNG} trnsfr_{i\,gov} \cdot \overline{CPI}$		Government Expenditure

System Constraints and Macroeconomic Closures

39)	$\sum_{a \in A} QF_{f\,a} = QFS_f$	$f \in F$	Factors Market
40)	$QQ_c = \sum_{a \in A} QINT_{c\,a} + \sum_{h \in H} QH_{c\,h} + QG_c + QINV_c + qdst_c + QT_c$	$c \in C$	Commodity Market
41)	$\sum_{c \in CM} pwm_c \cdot QM_c + \sum_{f \in F} trnsfr_{row\,f} = \sum_{c \in CE} pwe_c \cdot QE_c + \sum_{i \in INSD} trnsfr_{i\,row} + \overline{FSAV}$		Current Account Balance with the Rest of the World (foreign currency)
42)	$YG = EG + GSAV$		Government Balance
43)	$TINS_i = \overline{tins}_i + \left(1 + \overline{TINSADJ} \cdot tins01_i\right) + \overline{DTINS} \cdot tins01_i$	$i \in INSDNG$	Institutional Direct Tax Rate
44)	$MPS_i = \overline{mps}_i + \left(1 + \overline{MPSADJ} \cdot mps01_i\right) + \overline{DMPS} \cdot mps01_i$	$i \in INSDNG$	Institutional Savings Rate
45)	$\sum_{i \in INSDNG} MPS_i \cdot (1 - TINS_i) \cdot YI_I + GSAV + EXR \cdot \overline{FSAV} = \sum_{c \in C} PQ_c \cdot QINV_c + \sum_{c \in C} PQ_c \cdot qdst_c$		Savings-Investment Balance

46)

$$TABS = \sum_{h\in H}\sum_{c\in C} PQ_c \cdot QH_{c\,h} + \sum_{a\in A}\sum_{c\in C}\sum_{h\in H} PXAC_{a\,c} \cdot QHA_{a\,c\,h} + \sum_{c\in C} PQ_c \cdot QG_c$$
$$+ \sum_{c\in C} PQ_c \cdot QINV_c + \sum_{c\in C} PQ_c \cdot qdst_c$$

Total Absorption

47)

$$INVSHR \cdot TABS = \sum_{c\in C} PQ_c \cdot QINV_c + \sum_{c\in C} PQ_c \cdot qdst_c$$

Investment –
Absorption Relation

48)

$$GOVSHR \cdot TABS = \sum_{c\in C} PQ_c \cdot QG_c$$

Absorption –
Government
Consumption Relation

Accumulation Equations and Capital Allocation

49)

$$AWF^{a}_{f\,t} = \sum_{a}\left[\left(\frac{QF_{f\,at}}{\sum_{a'} QF_{f\,a't}}\right) \cdot WF_{f\,t} \cdot WFDIST_{f\,at}\right]$$

f es capital

$a \in A$

$a' \in A$

$t \in T$

50)

$$\eta^{a}_{f\,at} = \left(\frac{QF_{f\,at}}{\sum_{ä'} QF_{f\,a't}}\right) = \left(\beta^{a} \cdot \left(\frac{WF_{f\,t} \cdot WFDIST_{f\,at}}{AWF^{a}_{f\,t}} - 1\right) + 1\right)$$

f es capital

$a \in A$

$a' \in A$

$t \in T$

51)

$$\Delta K^{a}_{f\,at} = \eta^{a}_{f\,at} \cdot \left(\frac{\sum_{c} PQ_{c\,t} \cdot QINV_{c\,t}}{PK_{f\,t}}\right)$$

f es capital

$a \in A$

$c \in C$

		$t \in T$
52)	$PK_{f\,t} = \sum_{c} PQ_{c\,t} \cdot \frac{QINV_{c\,t}}{\sum_{c'} QINV_{c'\,t}}$	*f es capital* $a \in A$ $c \in C$ $c' \in C$ $t \in T$
53)	$QF_{f\,a\,t+1} = QF_{f\,a\,t} \cdot \left(1 + \frac{\Delta K^{a}_{f\,a\,t}}{QF_{f\,a\,t}}\right) - \upsilon_{f}$	*f es capital* $a \in A$ $t \in T$
54)	$QFS_{f\,t+1} = QFS_{f\,t} \cdot \left(1 + \frac{\sum_{a} \Delta K_{f\,a\,t}}{QFS_{f\,t}} - \upsilon_{f}\right)$	*f es capital* $a \in A$ $t \in T$

Source: Own elaboration, based on Löfgren et al., 2002 and Thurlow, 2004.

APPENDIX B: Social Accounting Matrix for Bolivia (2000)

(Thousands of Bolivians)

	A	P	Tr	C	Ti	Rn	H	E	G	Row	S-I	CS	PRDTX	DIRTX	INDTX	IMPTX	**Total**
Actividades (A)		88.635.731															**88.635.731**
Productos (P)	43.590.912	6.547.185					39.706.364		7.651.521	9.168.860	9.248.209	213.082					**116.126.134**
Trabajo (Tr)	24.013.422									123.935							**24.137.357**
Capital (C)	18.362.768																**18.362.768**
Tierra (Ti)	1.810.308																**1.810.308**
Recursos naturales (Rn)	616.422																**616.422**
Hogares (H)			24.137.357	7.330.091	1.810.308	616.422		2.115.008	2.426.200	427.579							**38.862.965**
Empresas (E)				11.032.678			1.382.060		1.534.239								**13.948.977**
Gobierno (G)							527.541	142.311		577.513			241.898	2.337.828	6.205.650	633.395	**10.666.136**
Resto del mundo (Row)		14.104.173						1.189.198		-4.935.313							**10.358.058**
Ahorro - Inversión (S-I)							-3.226.595	8.638.226	-945.823	4.995.484							**9.461.292**
Cambio de stock (CS)											213.082						**213.082**
Imp. producción (PRDTX)	241.898																**241.898**
Imp. directo (DIRTX)							473.595	1.864.233									**2.337.828**
Imp. indirecto (INDTX)		6.205.650															**6.205.650**
Imp. importacion (IMPTX)		633.394															**633.394**
Total	**88.635.731**	**116.126.134**	**24.137.357**	**18.362.768**	**1.810.308**	**616.422**	**38.862.965**	**13.948.977**	**10.666.137**	**10.358.058**	**9.461.291**	**213.082**	**241.898**	**2.337.828**	**6.205.650**	**633.395**	

Source: Own elaboration, based on Lay et al., 2006.

APPENDIX C: Solver Solution in GAMS

```
          S O L V E      S U M M A R Y

     MODEL   STANDCGE
     TYPE    MCP
     SOLVER  PATH              FROM LINE  2733

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL

 RESOURCE USAGE, LIMIT          0.078      1000.000
 ITERATION COUNT, LIMIT         0          1000
 EVALUATION ERRORS              0             0

PATH-C       Jan 19, 2004 WIN.PT.PT 21.3 020.027.041.VIS Path 4.6.04

474 row/cols, 2364 non-zeros, 1.05% dense.

Path 4.6.04 (Wed Jan 14 13:47:36 2004)
Written by Todd Munson, Steven Dirkse, and Michael Ferris



               L O O P S           SIMCUR BASE
                                   YRCUR 2010

               S O L V E      S U M M A R Y

     MODEL   STANDCGE
     TYPE    MCP
     SOLVER  PATH              FROM LINE  4912

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL

 RESOURCE USAGE, LIMIT          0.125      1000.000
 ITERATION COUNT, LIMIT         3         10000
 EVALUATION ERRORS              0             0

PATH-C       Jan 19, 2004 WIN.PT.PT 21.3 020.027.041.VIS Path 4.6.04

474 row/cols, 2284 non-zeros, 1.02% dense.

Path 4.6.04 (Wed Jan 14 13:47:36 2004)
Written by Todd Munson, Steven Dirkse, and Michael Ferris
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APPENDIX D: Model Simulation Results for the Baseline

GDP and Main Macroeconomic Accounts in Bolivia for the Baseline (Millions of Bs.)

Indicator	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Real GDP	51883.87	59636.33	67119.17	75263.49	83507.89	92043.26	100831.10	110012.55	119220.97	128393.76	137420.70
Private Consumption	39706.36	44639.40	49208.74	53946.70	58448.16	63209.05	68060.63	73157.25	78172.63	83270.56	88332.60
Fixed Investment	9248.21	11147.16	13459.76	15673.93	18309.28	21086.48	24145.60	26900.74	29542.22	31847.00	33788.33
Government Consumption	7651.52	8572.00	9172.90	10365.09	11472.68	12469.96	13347.10	14676.79	16228.35	17998.43	20022.00
Exports	9168.86	10967.92	12910.94	15051.24	17323.93	19841.10	22585.11	25528.51	28538.36	31592.10	34609.80
Imports	-14104.17	-15903.23	-17846.26	-19986.55	-22259.24	-22259.24	-27520.42	-30463.82	-33473.67	-36527.41	-39545.11
Stock Variation	213.08	213.08	213.08	213.08	213.08	213.08	213.08	213.08	213.08	213.08	213.08
TOTAL	**51883.86**	**59636.33**	**67119.16**	**75263.49**	**83507.89**	**94560.43**	**100831.10**	**110012.55**	**119220.97**	**128393.76**	**137420.70**

Demand for Land in Bolivia for the Baseline (Hectares)

Indicator	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Demand for Land AgriModern	10874048.0	11167163.7	11384959.3	11636942.6	11903087.6	12187465.8	12499703.2	12818263.3	13141216.3	13467225.7	13795078.15
Variation AgriModern	0.0	293115.7	217795.6	251983.2	266145.0	284378.2	312237.4	318560.1	322953.0	326009.4	327852.45
Demand for Land AgriTrad	15584615.0	16653595.5	17550866.4	18386727.5	19168549.9	19895690.3	20545519.1	21135835.2	21668612.1	22135967.5	22523842.32
Variation AgriTrad	0.0	1068980.5	897270.9	835861.1	781822.4	727140.4	649828.8	590316.1	532776.9	467355.4	387874.78
TOTAL Land	**26458663.0**	**27820759.2**	**28935825.7**	**30023670.1**	**31071637.5**	**32083156.2**	**33045222.3**	**33954098.4**	**34809828.4**	**35603193.2**	**36318920.47**
Variation Total	0.0	1362096.2	1115066.5	1087844.4	1047967.5	1011518.7	962066.1	908876.1	855730.0	793364.8	715727.23

Households Per Capita Income in Bolivia for the Baseline (Bs./year)

Indicator	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
PoorRurhouhol	1799.95	2010.17	2196.22	2374.17	2550.85	2722.76	2889.42	3042.75	3185.38	3312.43	3421.24
RichRurhouhol	6961.50	7675.57	8220.39	8702.80	8957.30	9123.24	9303.76	9454.41	9558.22	9713.93	10032.69
PoorUrbhouhol	3738.65	4096.70	4399.86	4690.90	4965.25	5221.31	5461.62	5674.67	5859.44	6009.30	6123.28
RichUrbhouhol	11368.77	11903.55	12178.41	12331.78	12073.49	11669.68	11305.58	10926.02	10498.62	10186.25	10156.90
TOTAL	**4633.05**	**5006.97**	**5294.32**	**5548.67**	**5707.72**	**5824.71**	**5939.92**	**6033.21**	**6097.77**	**6164.71**	**6270.60**

Indicator	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	AVERAGE
AAgri-Trad	492.93	527.41	551.46	572.93	589.85	603.35	612.7	619.59	623.66	625.29	624.21	585.76
AAgri-Modern	347.68	390.61	433.35	477.92	552.97	569.93	618.71	668.83	718.97	768.88	817.62	578.68
AForeFish	63.38	72.44	82.11	92.05	102.51	113.1	124.03	134.28	143.92	152.65	160.4	112.81
AFoodProcess	1175.3	1302.25	1409.21	1518.4	1619.46	1718.57	1813.93	1910.76	2004.56	2097.02	2186.26	1705.07
AMiningAndOil	1091.09	1369.34	1638.81	2039.69	2419.44	2852.91	3335.61	3865.82	4412.25	4973.05	5532.79	3048.25
Industry	591.65	681.58	776.46	878.24	983.21	1090	1199.63	1306.32	1408.41	1504.54	1594.11	1092.20
Construction	431.44	519.38	625.98	728.35	849.9	977.96	1118.89	1246.15	1368.31	1475.2	1565.6	991.56
TradeAndTrans	1605.56	1828.65	2047.88	2280.54	2513.42	2754.62	3002.93	3254.69	3500.47	3739.46	3967.62	2772.35
Services	3064.55	3510.28	3902.5	4359.25	4814.43	5275.22	5737.32	6253.62	6796.61	7367.11	7962.86	5367.61
TOTAL	8863.58	10201.94	11467.76	12947.37	14445.19	15955.66	17563.75	19260.06	20977.16	22703.2	24411.47	

Estratto per riassunto della tesi di dottorato

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Dottorato: *Dottorato di ricerca in Scienza e Gestione dei Cambiamenti Climatici* __________________

Ciclo: *26* ___________

Titolo della tesi : *Climate Change Impacts and Efficient Adaptation Options in the Bolivian Agriculture: From Crop Models to Integrated Assessments.* ____

Abstract: The agricultural sector could be one of the most vulnerable economic sectors to climate change impacts during the coming decades. These impacts are related to change in the growth period, agricultural yields, extreme weather events, change in temperature and precipitation patterns, among others. All these impacts will have consequences on the agricultural production. Given the lack of substantial studies for climate change impacts on agriculture in Bolivia, the thesis dissertation develops an analysis and quantification of climatic change impacts and adaptation options using different model techniques, both, bottom-up and top-down, and in the last chapter an integrated assessment is developed. Crop model results obtained at a local scale, are inside the range of previous studies made on larger scales for Latin America and the whole World. On the other hand, the response functions developed by using regression techniques show crop yields with a very high level of accuracy with those of crop models. What is more, when using crop models for adaptation analysis, simulation results show that crop models are sensitive enough to detect optimal changes for different scenarios, and the Cost-Benefit analysis results confirm that changing the planting date is a very feasible and low-cost adaptation measure to face climate change effects. Finally, the Integrated model results show that microeconomic and macroeconomic policies applied together can lead to sustainable development, thus increasing Gross Domestic Product (GDP) and per capita income and reducing deforestation rates at the same time, and the identified forest conservation social cost is a good starting point for PES and REDD+ negotiation schemes in the context of Global Climate Change Agreements.

Estratto: Il settore agricolo potrebbe rivelarsi nelle prossime decadi uno dei settori economici più vulnerabili agli impatti dei cambiamenti climatici. Questi impatti possono riguardare il periodo di crescita, le rese colturali, gli eventi meteorologici estremi, le variazioni di temperature e la distribuzione delle piogge. Tutti questi impatti avranno conseguenze sulle produzioni agricole. Considerata la mancanza di studi rilevanti sugli impatti dei cambiamenti climatici sull'agricoltura in Bolivia, la tesi discute lo sviluppo di un'analisi ed una valutazione degli impatti dei cambiamenti climatici e delle opzioni di adattamento utilizzando differenti modelli, sia con approccio bottom-up (dal basso verso l'alto) che top-down (dall'alto verso il basso), e, nell'ultimo capitolo, viene poi sviluppata una valutazione integrata. I risultati ottenuti con i modelli colturali su scala locale, sono comparabili con quelli ottenuti in precedenti studi effettuati su più larga scala sia per L'America Latina che a livello mondiale. Inoltre le funzioni di risposta sviluppate con tecniche di regressione mostrano rese colturali con elevati livelli di accuratezza rispetto a quelle ottenute con i modelli colturali. Per di più, quando si utilizzano modelli colturali per l'analisi di adattamento, i risultati delle simulazioni mostrano che i modelli colturali sono

abbastanza sensibili nel rilevare le variazioni ottimali per i differenti scenari e i risultati dell’analisi Costi-Benefici confermano che la variazione della data di semina è una misura di adattamento facilmente attuabile e poco costosa per affrontare gli effetti del cambiamento climatico. Infine, i risultati del modello integrato mostrano che le politiche microeconomiche e macroeconomiche applicate assieme possono portare ad uno sviluppo sostenibile, aumentando così il Prodotto Interno Lordo (PIL) e il reddito pro capite, riducendo i tassi di deforestazione e, allo stesso tempo, il costo sociale di conservazione identificato si rivela un buon punto di partenza per sistemi di negoziazione PES e REDD+ nel contesto degli accordi globali sul cambiamento climatico.

Firma dello studente

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