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Top down and Bottom up approaches.

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“Gli ostacoli non mi fermano. Ogni ostacolo si sottomette alla rigida determinazione. Chi guarda fisso verso le stelle non cambia idea”

Leonardo Da Vinci

(1452-1519)

Para Alejandra y Matilde.

Gracias por su amor incondicional

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Preface

This thesis contains three related papers addressing the economic aspects of water resources in the agricultural sector, within a climate change context.

1. The Economic Impacts of Water Availability in the Agricultural Sector: Top-Down Approach – A Literature Survey

   Fondazione Eni Enrico Mattei published part of this paper as the Working Paper. “*Integrating Water Resources into Computable General Equilibrium Models- A Survey*” (With Francesco Bosello and Carlo Giupponi)

2. Climate Change, Water Scarcity in Agriculture and Their Economy-Wide Impacts. A CGE Model Analysis.

   Part of this paper was presented at:

   - The 15th Annual Conference on Global Economic Analysis: “*Economy-Wide Impacts of Climate Change on Water Resources in Africa: A CGE Approach*”. Geneve, Switzerland. 2012.
   - Academic Seminar at the Programa de Posgrado en Economia ILADES-Georgetown University: “*Climate change, water scarcity in agriculture and the economy-wide impacts in the LAC Region*”. Santiago de Chile. 2012.
   - Academic Seminar at the University of Concepcion. “*Economic Impacts of Climate Change on Water Resources*” Concepcion, Chile 2011.

3. Climate Change, Water Scarcity in Agriculture and Their Country-Level Economic Impacts. A Multimarket Analysis.

The papers presented in this thesis are the results of research activities carried out in different institutions. Most of the first paper was written during an internship at the DEC-PG in the World Bank, Washington DC in 2009. Throughout this period at the World Bank the potential link of top/down and bottom/up approaches was analyzed with a special focus on Ethiopia.

The second paper was developed with the modeling team of Fondazione Eni Enrico Mattei in Venice, Italy. During this research period (2011-2012) a new version of the ICES model was developed which included the water endowment of each region within the modeling framework. This new version is called the ICES-W model.

Finally, the third paper was developed in the Research Centre for the Management of Agricultural and Environmental Risks (CEIGRAM), a joint research centre of the Technical University of Madrid (UPM), in 2010-2011. During this period a farm model for the Ethiopian agricultural sector was developed. This model structure was used to develop the Agricultural Multimarket model presented in the third paper.

Contents

Tables

I. General Introduction

I.1. Agricultural Water Demand and Climate Change

Currently water resources are facing several stresses in terms of quantity and quality. These pressures are closely related to the human interventions carried out in fields like: agriculture, land-use/land use change, construction/management of reservoirs, pollutant emissions, and water /wastewater treatment, among others (Bates, *et al*. 2008).

Among all the potential water uses, agriculture's water demand is the most important. The agricultural sector plays a critical role in food security, and in some developing countries it also makes up a high labor-intensive economic sector. The agricultural sector accounts for more than 70% of the global water demand, and according to the Food and Agriculture Organization (FAO) more than 75% of total agricultural land is rainfed, while the irrigated land produces one half of the world's cereal supply (Siebert, *et al.* 2010, United Nations 2012).

Within this context, the expected changes in both demographic trends and climate patterns will exacerbate the challenges faced by water resources. The conclusions of the Intergovernmental Panel on Climate Change's (IPCC) fourth assessment report suggest that climate change could threaten the agricultural sector due to changes in precipitation, temperature patterns, and an increase of extreme weather events (floods and droughts). The rainfed land will be affected by the precipitation changes, while the irrigation facilities critically depend not only on precipitation, but also on reservoirs' performance, which is linked to the glacier-melting rate (Barker, *et al.* 2007, Parry, *et al.* 2007)

It is expected that climate change impacts will be unevenly distributed across the world. Climate simulations suggest changes in precipitation patterns, with increase the water availability in high latitude areas, and decrease the water availability in mid-latitude areas. Regarding extreme weather events, climate models predict an increase of droughts in the sub-tropics by the end of the 21st century (Parry, *et al.* 2007). Furthermore, it is expected that the irrigation water demand will increase within the range of 5% - 8% globally by 2070. In relation to the local and spatial distribution of water, at low latitudes, in southeast Asia for instance, early snowmelt could cause spring flooding that may imply a summer water shortage (Bates, *et al.* 2008).

The human response within this context of changing climate, with the agricultural sector facing increasing threats, will play a key role. Adaptation strategies can reshape the human system in order to cope with the expected impacts of climate change, and if possible, take advantage of favorable opportunities. In this regard, the way in which the human system adapts (autonomously or planned) is extremely important, avoiding maladaptations, which could have unwanted results.

Adaptation should go hand in hand with mitigation policies that can reduce the determinants of climate change (greenhouse gasses emission), reducing the social costs associated with it. (Barker, *et al.* 2007).

The expected changes described above acquire economic meaning as they are expected to modify systems and processes that have impacts on human welfare.

I.2. Assessing the Economic Impacts of Water Availability in the Agricultural Sector

Assessing climate change's impact can be conducted using economic theory through two main approaches: top-down and bottom-up. The top-down approach includes among others: integrated assessment models (IAM) and general equilibrium models (CGE). IAMs are characterized by their large scope of analysis, with a broad description of their components. These kinds of models are solved for equilibrium conditions on greenhouse gas (GHG) concentrations, emissions, prices, and quantities, in all of the sectors under analysis, while the CGE models consider only the economic system, assuming endogenous prices, and solving the system for equilibrium in prices and quantities (Weyant 1985). Top-down models can range from the regional to the global level. On the other hand, a bottom-up model is characterized by a detailed description of its components, in this case the model solution is optimized/simulated, and the scope of analysis is restricted, ranging from a local level (farm level) to a national one. Examples of bottom-up approaches are: hydro-economic modeling and agricultural models, among others. (For a comprehensive revision of economic models within a climate change framework see Palatnik and Roson (2012))

Integrated assessment models include any model that merges socioeconomic and scientific aspects of climate change in order to assess policy options (Kelly and Kolstad 1999). Examples of IAMs are the IGSM model developed at the Massachusetts Institute of Technology (MIT) (Sokolov, *et al.* 2005), the WITCH model developed at the Fondazione Eni Enrico Mattei (Bosetti, *et al.* 2006), the MERGE model developed at Stanford University (Manne and Richels 2004), and the DICE-RICE models developed at Yale University (Nordhaus and Boyer 2000), among others. On the other hand, CGE models have been widely used in order to analyze climate change mitigation policies. Some examples in this regard are the Global Trade Analysis Project (GTAP-E) model (Burniaux and Truong 2002), the ICES model developed at FEEM (Eboli, *et al.* 2010), the DART model developed at the Kiel University (Klepper, *et al.* 1998), and the EPPA model developed at the Massachusetts Institute of Technology (Paltsev, *et al.* 2005), among others.

Regarding bottom-up approaches, hydro-economic models combine hydrologic information at the basin scale with socioeconomic information. The objective is to maximize the economic value for the whole basin, for instance regarding income, production, or surplus, subject to the hydrological restrictions (Brower and Hofkes 2008, McKinney, *et al.* 1999). Studies include those conducted at the Colorado River basin in the United States(Lee and Howitt 1996), the Maipo River Basin in Chile (Cai, *et al.* 2008), and the Adra river system in Spain (Pulido-Velazquez, *et al.* 2008).

Agricultural models can be classified according to assumptions about prices: exogenous or endogenous. When exogenous prices are assumed, the model is restricted to the analysis of the agricultural supply. This type of model can be solved using optimization or econometric techniques. Those models using optimization techniques are known as farm models, in this case the behavior of the agricultural producer is simulated through the maximization of the farm income, subject to technological, environmental and institutional constraints(Sadoulet and De Janvry 1995). On the other hand, those models using econometric techniques are known as Ricardian models. Under this approach, the value of land is related to environmental conditions, including climatic variables, in order to account for climate change impacts (Mendelsohn, *et al.* 1994). This method has been used in the United States (Mendelsohn, *et al.* 1998), Ethiopia (Deressa 2007), Brazil (Féres, *et al* 2008), and Israel (Fleischer, *et al.* 2008).

Agricultural multimarket models (AMM), also known as agricultural sector models, assume endogenous prices. In this case, the agricultural sector is represented through a series of behavioral equations for demand and supply, which are optimized in order to maximize the regional income, or regional surplus, subject to technological, environmental, and institutional constraints (Sadoulet and De Janvry 1995, Howitt 2005). Most of these models consider an explicit agricultural demand represented by a set of demand elasticities, while the agricultural supply is implicitly represented. These kinds of models have been widely used for policy analysis; some examples are the models applied in Madagascar (Stifel and Randrianarisoa 2004), Egypt (Siam and Croppenstedt 2007), Ethiopia (You and Ringler 2010), and Europe (Mattas, *et al.* 2011, de Frahan, *et al.* 2007, Blanco, *et al.* 2008).

The approaches described above are complements for the analysis of climate change issues. Alcamo and Henrichs (2002) suggest that top-down models could be used as a kind of screening tool, indicating where a more detailed bottom-up analysis should be conducted.

I.3. Objectives and Contribution of the Thesis

The objective of this thesis is to explore and compare the top/down and the bottom/up approaches in order to account for the economic impacts of water availability in the agricultural sector in light of climate change. In order to do that, two models were developed: computable general equilibrium and agricultural multimarket model. The models are conducted at global and national scales, respectively.

There is a large body of literature analyzing climate change impacts in the agricultural sector using global CGE models. However, none of the existing models consider water resources as it truly is: a scarce resource with no competitive market price. The CGE model proposed in this research fills this gap by considering both an explicit irrigation sector and the role played by the water endowment in lessening the impact of climate change on the agricultural sector.

On the other hand, agricultural multimarket models have been used for policy analysis with a focus on food policy, agricultural policy, and, in recent years, with a focus on climate change policy. Nevertheless, there is little evidence about agricultural multimarket models analyzing climate change impacts in developing countries. Moreover, most of the models are deterministic ignoring the uncertainty inherent to any climate change impact assessment. In this research an agricultural multimarket model is presented. The contribution of the agricultural multimarket model is twofold: first, it analyzes the economic impacts of climate change within a developing country context. Secondly, it considers the uncertainty associated with climate projections using Monte Carlo simulations for water availability.

The thesis consists of three related papers. In the first one, a literature review is carried out, focused on the analysis of water issues through the use of computable general equilibrium models. The second paper is devoted to the description of a new CGE model, called the ICES-W model, which accounts explicitly for the role played by water endowment across regions, and how this endowment could increase the resilience of the agricultural sector when faced with the impacts of climate change. Finally, the third paper depicts an agricultural multimarket model designed to analyze the economic impact of changes in water availability due to climate change, at the country level.

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II. The Economic Impacts of Water Availability in the Agricultural Sector: Top-Down Approach – A Literature Survey.

Abstract

Water resources are facing several stresses in terms of quantity and quality. These pressures are closely related to the human interventions carried out in fields like: agriculture, land-use/land use change, construction/management of reservoirs, pollutant emissions, and water /wastewater treatment, among others. Considering the critical role that water plays for agricultural production, any shock in water availability will have great implications for agricultural production, and through agricultural markets these impacts will reach the economy as a whole, with economy-wide consequences. The aim of this paper is to present a literature review about the state of the art methodology regarding the study of water issues using the CGE approach at global and national scales. The analysis of the different studies confirms the economy wide consequences of changes in water allocation, irrigation policies, and climate change, among other water related issues.

Keywords: Computable General Equilibrium Models, Water, Irrigation, Agricultural Policy, Water Allocation.

II.1. Introduction

In economics two main approaches are used to address agricultural water related issues: partial equilibrium and general equilibrium approaches. Under the partial equilibrium approach, the main interests are the equilibrium conditions of a market for one good/sector that is part of the overall economy. This approach implies both prices fixed in other markets and the minimal price interaction across markets. Within this category it is possible to identify: hydro-economic modeling, and agricultural models, among others. Some authors consider that these modeling approaches complement one another, with the former approach addressing feedback conditions that are otherwise ignored, and the latter depicting a detailed picture within a set of specific markets (Alcamo and Henrichs 2002, Weyant 1985).

This paper presents a literature review about the state of the art methodology regarding the economic modeling of water resources, focusing on those studies, which analyze water issues using CGE models. In this report several studies are reviewed, some of them addressing water issues, and others dealing with climate change issues. The objective of this report is twofold: first, it identifies those methodologies that could be useful, within the context of this thesis, to include water in CGE models, and secondly it identifies potential options to improve the water representation within economic models.

The paper is organized as follows: section two presents CGE studies at a global scale, highlighting their main research issues and contributions. Section three is devoted to studies dealing with water issues at a national scale. Finally, section four presents the key issues and future research directions for the economic modeling of water issues.

II.2. CGE Models at Global Scale

Considering the data requirements that a CGE model at global scale has, the database provided by the Global Trade Analysis Project (GTAP) is the most frequently used for the modeling of water related issues[1].

The GTAP database is distributed with a CGE model, the GTAP model (Hertel 1997). The GTAP model makes use of the Walrasian perfect competition conditions to simulate adjustment processes. Within GTAP, the industrial sector is modeled using a representative firm that maximizes profits in perfectly competitive markets. The production functions are specified using

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[1] For a full description of the GTAP database, see https://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp. For the sector disaggregation see: Narayanan, *et al* 2012. For details regardig CGE formulation see: Wing (2004).

nested Constant Elasticity of Substitution (CES) functions. According to the ‘‘Armington assumption’’, there is no perfect substitution across domestic and foreign inputs, this feature accounts for product heterogeneity.

The consumer side of the economy is represented through a representative consumer in each region who receives income defined as the service value of the national primary factors. For capital and labor, the model assumes that they are perfectly mobile domestically, but immobile internationally. National income is allocated between aggregated household consumption, public consumption, and savings.

There are two main global CGE models that analyze water related issues at the global scale using the GTAP database. Berrittella, *et al*. (2005) proposed the first, while the second was proposed by Calzadilla, *et al*. (2008). Other authors working on water issues at global scale include Roson & Sartori (2010), and Roson & Van der Mensbrugghe (2010), among others.

The first effort to analyze water issues using the GTAP model was carried out by Berrittella *et al.* (2005). Based on the GTAP-E model (Burniaux & Truong, 2002), using the aggregation of the GTAP 5 database (based on 1997), authors proposed a new modeling approach called GTAP-EWF that explicitly considers water as a production factor. The GTAP 5 aggregation presents a detailed representation of the world economy with 16 regions and 17 sectors, 6 of which are in agriculture.

The main difference of this model with the GTAP-E model is the way in which water is included within the production function. Using the Leontief formulation, water is combined with the value-added-energy nest and the intermediate inputs at the top of the production tree. This formulation implies no substitution among these three components, thus water cannot be substituted with any other input.

According to this modeling approach, water is supplied to the agricultural industry (4 primary crop activities and livestock) and water distribution services. Water is mobile within the agricultural sectors, but immobile between the agricultural sector and the water and distribution sector. The benchmark scenario assumes an unconstraint water supply, which is equivalent to assuming that the water demand is lower than the water supply (water price equal to zero).

Using information provided by AQUASTAT and FAOSTAT authors were able to define the Water Intensity Coefficient (WIC). The WIC is defined as the amount of water used by sector j in order to produce one unit of commodity *i*. The WIC includes the total water requirement per sector, both green and blue water[2].

In order to include water, the CGE modeling framework requires a price signal from the water sector. Authors simulated price signals through the emergence of economic rents due to water scarcity. If the water supply does not meet the water demand, consumers would be willing to pay a price in order to get access to the resource. The model assumes that water resources are privately or collectively owned, in which case, water scarcity will drive the emergence of economic rents. The GTAP-EWF model includes the water price as a tax that could affect the output price, so the water price is included in the equation that determines the producers' supply price (as the change in the power of the water price).

Using the water price elasticites estimated by Rosegrant *et al.* (2002), authors estimated the impact of water variability on the WIC. According to the model, when water supply decreases, assuming negative water price elasticity, it implies an increase in water prices, which at the same time, drives a decrease in water use (decrease in WIC).

The GTAP-EWF model has been applied to the analysis of virtual water, water pricing, water supply, the China South-North Water Transfer (SNWT) project, and the impact of trade liberalization.

Berrittella *et al.* (2005) analyzed virtual water flows as a consequence of a decrease in water availability. In this study, the authors simulated four different scenarios:

- Sustainable Water Supply. This scenario excludes the use of groundwater. This scenario has two versions: optimistic and pessimistic. In the former, water availability is restricted only for North Africa (NAF 44%), while in the latter water supply is restricted for NAF (44%), the United States of America (USA 1.58%), South Asia (SAS 1.58%), and China (3.92%).
- China Water Transfer. This scenario implies a 7% increase in water availability for China due to the SNWT project.
- Water Pricing. This scenario considers water charge per cubic meter (m^3) of water used. The charges are: ¢1, ¢5, and ¢10.
- Trade Liberalization. This scenario considers a full removal of all trade barriers for agricultural products.

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[2] Green water is defined as the amount of rainfall that is stored in the root zone, while blue water is defined as the amount of water diverted from the water system and applied to the crops.

Results show that water restrictions imposed by the sustainable water supply scenario imply an increase in the imports of water intensive products by water scarce countries. The welfare impacts depend on the specific country and scenario.

In the case of the China Water Transfer project, the increase in water availability positively affects its virtual water trade balance, but negatively impacts the trade balance. This is because the increase in the production of water intensive products drives a decrease in the production of all other products. As a consequence, China's gross domestic product (GDP) decreases by 0.11%.

Simulations related to water pricing confirm the expected impacts: a decrease in water demand, an increase in water intensive products' prices, and the regions with lower water productivity are worse off after the water charge. Finally, the simulated trade liberalization positively affects the world's welfare; this positive impact is attained without increasing the total demand for water.

The restricted water supply topic was analyzed by Berrittella, *et al.* (2007a). In this study the original model GTAP-EWF was renamed as GTAP-W, both models have the same structure and use the same product disaggregation. Authors simulated the economic impacts of restricted water supply in water scarce regions. They simulated 5 scenarios:

- Water shortages: NAF (10%), USA 1.58%, SAS 1.58%, and China (3.92%).
- Severe Shortage in NAF. In this case, NAF faces a decrease in water availability of 44%. All the other regions remain the same.
- Water Specific. In this case, water is sector specific for each agricultural sector.
- Water price elasticities equal to zero for all industries.

In all four scenarios, the model assumes a market solution for water scarcity. The market solution implies that property rights for water resources can be implemented and enforced. In the fifth scenario, the market assumption is relaxed. Scenario five assumes that when water becomes scarce, and there is no option to buy more water, this water scarcity is equivalent to a decrease in productivity in water demanding sectors.

As expected, the regions that face water shortage decrease their production, and regions that are not constrained increase their production. As a consequence, the world is worse off because of the restricted water supply. The intensity of the welfare changes are associated to the level of the water restriction, thus, for higher water constraints, the welfare gains (losses) are higher. Nevertheless, welfare gains respond less than proportionally, and welfare losses more than proportionally, to the water constraint.

In the analysis of the China SNWT project (Berrittella, *et al*. 2007b), authors analyzed the economy-wide impacts of the SNWT project that is intended to transfer water (44 billion m^3) to the north region of China by 2050. They simulated three scenarios:

- Water availability, which considers an increase of 7% of Chinese water availability.
- Investment, which considers only the investment needed to implement the project. This investment is about USD 7 billion per year.
- Investment and Water, which considers both scenarios at the same time.

For the benchmark, results show that due to the project the Chinese economy will be stimulated and the country's welfare will increase. When water is included in the model, the gains of the project are marginal. This is because more water reduces water's price, affecting water "owners". At a global scale, the project has minimal negative impacts on GDP.

Berrittella, *et al.* (2008a) analyzed the impacts of trade liberalization, as Doha, on water resources. The authors did not focus their analysis on water reallocation; instead they looked into the reallocation of water intensive products. They analyzed four scenarios:

- A 25% reduction in agricultural tariffs, zero agricultural subsidies and a 50% reduction in domestic farm support.
- A 50% reduction in agricultural tariffs, zero agricultural subsidies and a 50% reduction in domestic farm support.
- A 75% reduction in agricultural tariffs, zero agricultural subsidies and a 50% reduction in domestic farm support.
- For developed countries the tariff's reduction is 75%, while in developing countries it is 50%.

As a general conclusion, the authors found that the impact of trade liberalization on water demand is small, less than 10% of water use for the most aggressive reduction in tariffs. Even though the effect is small, trade liberalization puts the incentives in the right place, decreasing water use in those regions in which this resource is scarce and increasing water use in water abundant regions.

Berritella *et al* (2008b) also analyzed water taxes. In this study, they simulated the economic impacts of a tax policy applied to water resources. They simulated four different scenarios, in all of them tax is redistributed, *lump sum*, to households[3]. The four scenarios are:

- Water tax equal to ¢1/ m^3 for all industries.

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[3] A similar study, considering six scenarios, was published in 2006 (Berrittella *et al*. 2006).

- Water tax equal to ¢0.5/ m^3 for all industries.
- Water price elasticities equal to zero for all industries.
- Water taxes only for the agricultural sector (¢1/ m^3).

Simulation results show that as a consequence of the water tax, water demand decreases in many regions around the world. Nevertheless, some regions increase their production of water intensive products in order to export them. The final impact of the water tax is closely related to water efficiency, the lower the efficiency, the stronger the impact.

Calzadilla, *et al.* (2008) presented another CGE model addressing water related issues. This model presents a major improvement in contrast to the previous version presented by Berrittella *et al.* (2005). This new version considers the difference between water provision systems, such us: rainfall and irrigation. This difference is considered using an indirect approach, differentiating between rainfed and irrigated crops. The model is based on the GTAP 6 (dated in 2001)[4].

The new approach consists of splitting the original land endowment, in the value-added nest, into 3 components: pastureland, rainfed land, and irrigated land. Under this specification pasture land is the land devoted to animal production and animal products, its value is computed according to the land's value in the livestock industry. The remaining types of land differ in relation to the value of irrigation: irrigated land is more valuable as yield per hectare is higher. The authors split land into rainfed land and irrigated land using its proportional contribution to the total production.

Finally, the authors split irrigated land into the value of land and the value of irrigation through a CES irrigated land-water composite. In order to do this, they used the ratio of irrigated yield to rainfed yield provided by the IMPACT model (Rosegrant *et al*. 1998).

Considering that the authors only split the original database, the social accounting matrix remains balanced, avoiding calibration problems. This new formulation allows for substitution between irrigation and land within the irrigated agricultural production, in this case the key parameter is the elasticity of the substitution in the irrigated land-water composite.

The new production structure, as well as the data used (provided by IMPACT model), allows the model to account for differences related to the type of water used for the agricultural sector (blue/green). This is because the IMAPCT model accounts for the amount of green water used by rainfed production, and the amount of green and blue water used in irrigated production.

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[4] The aggregation of the GTAP 6 database presents a detailed representation of the world economy with 16 regions and 22 sectors, 7 of which are in agriculture.

In the benchmark, it is assumed that the water used by the irrigation sector is the same volume of water used by irrigated agriculture reported by the IMPACT model. By using information related to the volume of water used by each sector and region, as well as information about payments to the factors of production, it is possible to compute the specific shadow price of water for each sector and region. Within this framework the expected changes in water availability are modeled as exogenous changes in both productivity of rainfed and irrigated land. This model has been applied to the analysis of irrigation improvement, climate change, and sustainable water use.

Calzadilla, *et al.* (2008) analyzed the economy-wide consequences of an improvement in irrigation management. The authors defined irrigation efficiency as the "ratio between the volume of irrigation water beneficially used by the crop to the volume of irrigation water applied to the crop". They simulated three different scenarios:

- Improvement in irrigation efficiency only in water stressed regions, considering only developing regions.
- Improvement in irrigation efficiency independent of the development level.
- Improvement in irrigation efficiency in all the GTAP regions.

For all simulations, the simulated improvement in irrigation efficiency is 73% for all the crops. The results show that higher levels of irrigation efficiency have significant effects on: water use, crop production, and welfare. In some regions water use for a specific crops increases, while in others it decreases. Due to the increase in water use efficiency the rainfed sector is worse off, but its welfare losses are offset by the aggregated benefits of the whole economy.

The study of climate change impact in regional agriculture (Calzadilla, *et al*., 2009) has devoted its efforts to analyzing the economy-wide impacts of climate change on the agricultural sector in Sub Saharan Africa (SSA). Using output information from the IMPACT model, such as: demand and supply of water/food, rainfed and irrigated area/production, food prices, and trade; this study simulated two different adaptation strategies, under the IPCC scenarios SRES B2 (Intergovernmental Panel on Climate Change, 2000), for the SSA agricultural sector for 2050:

- Increase in irrigated land, assuming an increase of 100% of irrigated land.
- Increase in agricultural productivity, assuming a 25% increase in both rainfed and irrigation yields.

Results show that both adaptation strategies allow farmers to reach higher yields and revenues of agricultural production. For the first scenario, the increase in regional welfare is small (USD 119 million), while in the second scenario the welfare gains are multiplied more than a hundred times (USD 15,434 million).

In one study of sustainable water use in agriculture (Calzadilla, *et al.* 2010a), the authors defined sustainable water use as the eradication of groundwater over-exploitation by the year 2025. In this study they simulated the scenarios proposed by Rosegrant, *et al.* (2002):

- Business as usual, which assumes water withdrawal according to current trends.
- Water Crisis Scenario, which entails a deterioration of water conditions worldwide. This scenario is characterized by an increase in water use (surface and groundwater).
- Sustainable water use, implying that the overexploitation of groundwater is gradually eliminated by 2025.

The analysis assumes that by diverting more water for agricultural production, less water will be available for environmental uses; as a consequence, the results show a trade-off between agricultural production and human welfare. In the water crisis scenario, there is more water available for agriculture than in the business as usual scenario, and welfare is higher. In contrast, the sustainable water use scenario has less water for agriculture, and lower welfare. Nevertheless, the water available to the natural environment goes in the other way around, more water for agriculture means less water for the environment. In this sense, the authors argue that the costs of diverting water from environmental uses to agriculture (water crisis scenario) are quite small: USD 1.3 per person.

Calzadilla, *et al.* (2010b) analyzed climate change impacts in global agriculture using expected changes in average river flows, according to the IPCC SRES A1B and A2 (Intergovernmental Panel on Climate Change, 2000). They included the expected changes in river flows as changes in the irrigation endowments and rainfed land productivity.

These simulations suggest that climate change impacts will modify agricultural production worldwide. At a global level, total crop production will decrease for the 2020 period and increase for the 2050 period. The same pattern follows the GDP evolution.

Using the standard GTAP-E, Roson & Sartori (2010) analyzed water related issues associated with water scarcity and virtual water trade in the Mediterranean region. The database used was dated in 2004, GTAP 7.1. GTAP 7.1 presents a detailed representation of the world economy with 113 countries and 57 sectors, 13 of which are in agriculture. In order to deal with water scarcity, they translated trade flows into virtual water equivalents, using the same approach proposed by Berrittella *et al.* (2005).

The authors computed, using the mean annual runoff (MAR), an index of water constraint (IWC) that indicates to what extent a specific country is constrained by its water resources. The index was computed as the ratio of agricultural water use to MAR net of agricultural use. Using this index, the authors classified countries as: water constraint (IWC>1), partially water constraint (1<IWC<0.25), and no constraint (WIC=0).

The authors assumed that water scarcity is driven by climate change; in this sense, they link climate change with expected changes in MAR according to climate models. Furthermore, the authors assumed that the expected changes in MAR by 2050 are equal to the changes in the multifactor productivity for the agricultural sector (multiplied by WIC). Using this model, the authors simulated five scenarios: a wetter scenario, a drier scenario, an intermediate average of extreme scenarios, a virtual water trade constraint for Spain, and a reduction of 50% for all the elasticities of substitution for agricultural products.

Results show that virtual water trade may reduce the negative impacts of water scarcity. Nevertheless, the expected impacts on income and welfare are relevant. For instance, for Morocco a 14.4% decrease in its GDP is expected due to the water constraint.

Roson & Van der Mensbrugghe (2010) used the previous approach to account for climate change impacts on water resources. Using the ENVISAGE model (van der Mensbrugghe, 2009), the authors simulated six different climate change impacts: agricultural productivity, sea level rise, water availability, energy demand, human health and labor productivity. The model assumes that water cannot be substituted by any other input in the production process. On the other hand, water affects agricultural yields depending on the expected changes of the mean annual runoff.

In their simulations, the authors included no change in water availability; instead, they simulated changes in agricultural productivity as a function of changes in temperature, assuming that the change in temperature implies a change in water availability. The simulations included a decrease in agricultural productivity of 8% for some regions (Middle East and North Africa) for a one-degree increase in temperature. According to the results, the main impact is related to a decrease in labor productivity. At the regional level, the Middle East and North Africa face the highest impacts.

II.3. CGE Models at National Scale

Due to data requirements, the use of CGE models to address water related issues at the national/regional scale precedes the analyses at the global scale. One of the first efforts in this direction was carried out by Lofting & McCaughey (1968). In this study, they included water in an input-output model in order to analyze the requirements of water in California. Since then, CGE models have been used to analyze a broad array of issues, such as: water pricing policy

(Decaluwé, *et al*. 1999; Letsoalo, *et al*. 2007), water allocation (Seung, *et al.* 2000; Diao *et al.* 2005; Lennox & Diukanova, 2011; Juana, *et al.* 2011; Diao & Roe, 2003), water markets (Gomez, *et al*. 2004), irrigation policies (Roe, *et al.* 2005; Cakmak, *et al*. 2008; Strzepek, *et al*. 2008; Hassan & Thurlow, 2011), and climate change impacts (Smajgl, 2006; You & Ringler, 2010; Cakmak *et al*. 2009), among others[5].

Decaluwé *et al.* (1999), presented a CGE model applied to Morocco, analyzing the impacts on water allocation of different pricing policies. The pricing scenarios analyzed are: Boiteux-Ramsey pricing (BRP), BRP and production tax decrease, BRP and income tax decrease, marginal cost pricing (MCP), and MCP with tax decrease[6].

The model presents a detailed representation for the agricultural sector through a series of nested CES functions. In this representation agricultural production uses: capital (K_{ag}), land ($Land_{ag}$), fertilizer (Fer_{ag}), water ($water_{ag}$), and Labor (Ld_{ag}), as primary inputs. The intermediate consumption is represented through a composite (Ci_{ag}).

The model considers two different technologies to produce water: water produced by dams already in use (*Eb*), and water "produced" by both more efficiency in the retrieving of surface water and water from pumping stations (*Wat*). *Eb* is produced using only capital (*K*), while *Wat* is produced using capital (K_{eua}) and labor (Ld_{eau}).

Regarding *Eb*, capital is linked to the amount of rain needed to provide irrigation services through a linear function, while in *Wat* the specific technology used depends on the availability of surface water. If surface water becomes scarce, the potential improvement in efficiency decreases and the pumping option arises as a competitive one. The production of *Wat* is modeled using a Weibull function.

The model considers four types of agents: household, firm, government and the rest of the world (ROW). Considering the uneven distribution of water resources across Morocco, authors consider two regions: North and South. The north faces no water scarcity, while the south is an arid region. This geographical disaggregation accounts for water production, agriculture and industry.

Results show that the BRP, along with a reduction in production taxes, is the most efficient pricing policy in reducing water consumption. This policy also has a positive impact on welfare.

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[5] Among of wich the TERM model for the Australian economy has been used to study water issues. It is a regional model (*bottom up*) with a high level of dissagregation (up to 1,379 statistical local areas). For details see (Dixon, *et al*. 2012)

[6] Ramsey-Boiteux pricing consists of maximizing the total welfare under the condition of non-negative profit for the monopolist, that is, zero profit.

The MCP policy induces a more positive impact on welfare, but is not as efficient in reducing water use.

Letsoalo, *et al.* (2007) analyzed whether the setup of water charges generates triple dividends for the South African economy. In this case, the potential reduction in water use is considered the first dividend, the use of these revenues in order to stimulate economic growth is the second dividend, while the improvement of income distribution due to faster economic growth is the third dividend.

Using the South African Social Accounting Matrix (SAM), the authors divided households into 12 income and 4 ethnic groups, and distinguished 27 economic sectors. After splitting up the energy and water intensive sectors they used 39 sectors. Originally the SAM considered only one agricultural sector, but Letsoalo, *et al.* (2007) split this sector into seven subsectors in order to determine exactly which water policies would achieve the best results.

At the policy level they simulated 3 different water charges: (1) a surcharge of 10¢ per cubic meter of water used by forestry, (2) a surcharge of 10¢ per cubic meter of water used by irrigated agriculture (field crops and horticulture), and (3) a surcharge of 10¢ per cubic meter of water used by all mining industries (gold, coal, and other mining). Besides these policies, the authors also simulated 3 different tax recycling policies: (1) a decrease in the overall level of direct taxation on capital and labor, (2) a decrease in the overall level of sales tax on household consumption, and (3) a decrease in the sales tax rate on household food. Since the water price is higher, the results show that the first dividend is always reached. Reaching the double dividend is also possible in almost all of the scenarios, except for: the forestry water surcharge (for every tax scheme), the gold mining water surcharge (for every tax scheme) and the coal mining water surcharge (for the capital and labor tax schemes). The third dividend is reached for other mining water surcharges (for every tax scheme), as is it for other water surcharges, depending on the tax scheme selected.

Seung, *et al.* (2000) combined a dynamic CGE model with a recreational model to analyze the economic impacts of water reallocation from agricultural to recreational use. The model considers 8 sectors, 3 of which are in agriculture. For all sectors the technology is represented through a Cob-Douglas function. The agricultural sector uses land, capital and labor as production factors, while the remaining sectors use only capital and labor. In this model, water is entitled as water rights and these rights are associated to the amount of land. So, if water is extracted from the agricultural sector it implies a reduction of land for the agricultural sector.

The recreational sector is represented through two econometric equations: the hunting rate and the general recreation rate. Using in-site surveys the authors determined the total expenditure for both activities.

The authors evaluated a withdrawal of 30,000 acre-feet from the agricultural to the recreational sector. To do this, they computed the number of visitors and their expenditures before the policy's implementation. Then, they computed the same variable after the policy's implementation. In the CGE model, they computed the change in water availability, as a decrease in land availability for the agricultural sector, and the change in recreational expenditures as a consequence of this policy.

Their results show that as a consequence of the reallocation of water, agricultural production drops, while the number of visitors increases. Still, the increase in the number of visitors is not enough to compensate for the decrease in agricultural production. As a consequence, the impact on the total output decreases by 0.9%, while the total employment drops by 0.2%.

Diao and Roe (2003), presented a CGE model that analyzes the impact of a trade liberalization policy on water resource allocation. The authors proposed a theoretical model which links trade reform with water market creation. According to this model, the combination of a trade reform with the creation of a water user-rights market generates the most efficient allocation of water.

The CGE model proposed by the authors has twenty production sectors: 12 agricultural sectors (6 irrigated and 6 rainfed), 4 agricultural related sectors and 4 non-agricultural related sectors. The model uses labor, water, land, capital, and intermediate inputs as factors of production. Furthermore, the model is dynamic so that capital accumulates overtime. The model does not allow for factor substitution across sectors.

Their results show a close linkage between changes in the sectoral shadow price of water and the rates of trade protection. When tariff, non-tariff trade barriers, and producer subsidies are removed, a country's comparative advantage in the production of non-protected crops increases. Additionally, due to trade liberalization both income and welfare increase for the whole economy. Nevertheless, there are differences across sectors: farmers producing protected crops are worse off, in the short and medium-term, while the returns from irrigated land (associated to protected crops) decrease. Finally, when the water market is permitted, the model reallocates the water towards more productive uses, increasing the system's efficiency.

Diao, *et al.* (2005) presented a CGE model analyzing the economy-wide effects of water reallocation to its most productive use in Morocco. The model accounts for spatial heterogeneity within the country among seven major irrigation zones, the model also differentiates between irrigated and rainfed crops.

The agricultural sector is modeled using a series of nested CES functions for the primary inputs, while the intermediate consumption is assumed to be Leontief. Agricultural production uses labor, capital, land and water. Labor could be rural or urban. Rural labor is mobile only among agricultural sectors (including primary and processing agriculture). Capital and land are mobile within irrigation zones. Land could be irrigated or rainfed, and the supply of irrigated land is fixed. Finally, water is mobile within each region, but not across regions.

Their results suggest that trade liberalization in the water market increases agricultural output in each region (8%). According to their results, irrigated agriculture will be better off, while rainfed crops will be worse off.

Diao, *et al.* (2008) presented an extension of the model presented by Diao, *et al.* (2005). The new version of the model explicitly includes a difference between surface (SW) and groundwater (GW). The authors simulated three scenarios: an increase in groundwater pumping costs (20%), a decrease in surface water (one standard deviation) and a re-allocation between rural and urban water (one third).

Simulations confirm the direction of the expected changes associated with each scenario simulation, but more interesting is the fact that the three scenarios have similar impacts on economy-wide variables. “Especially the drought impact on the SW supply and the increase in the cost of extracting GW. Drought affects most of the economy’s sectors in a similar way, with regions that have better access to GW facing a less dramatic effect”.

Lennox and Diukanova (2011) presented a regional CGE model suitable for the analysis of water policies. They analyzed agricultural water issues in Canterbury, New Zaeland.

The modeling approach represents the agricultural sector through a series of nested CES functions for the primary inputs, in which agricultural production uses labor and a composite land and capital. The composite land and capital is further disaggregated into the demand of land and the demand of capital. At the bottom of the productive structure, water is linked in fixed proportions to the land endowment.

The authors simulated three different scenarios: a decrease in irrigated land (10%), an increase in availability of labor and capital (10%), and an increase in world agricultural prices (5%). For the first scenario, the results show negative impacts on the water-intensive agricultural sectors, with a decrease in production and an increase in prices. In general terms, those impacts do not affect the performance of other economic sectors. Scenarios two and three show the expected results for production, prices and total welfare.

Juana, *et al.* (2011) analyzed the economic impacts of the reallocation of water from the agricultural sector to other sectors in the South African economy. Using information from 19 water management areas, the authors defined the amount of water used by each sector. The municipal water tariff schedule was used to assign a monetary value to the water used by each sector.

The model considers water as a new primary factor, along with capital and labor. The production structure is modeled using CES functions with the exception of capital, which is modeled through fixed proportions. Water and labor are freely mobile across sectors, while capital is sector specific.

The authors simulated four water reallocation scenarios of 30%, 20%, 10, and 5%. Their results show that the reallocation of water increases the sectoral output, but reduces the output of agriculture, beverages, and the services sector.

Gomez, *et al.* (2004) presented a CGE model for the Balearic Islands in which they analyzed the welfare gains associated with trade liberalization in water markets. They divided the economy into 10 sectors, two of them in the agricultural sector: irrigated agriculture and rainfed agriculture. They also considered two sectors producing drinking water: the traditional and the desalination sector. Both sectors produce the same product (water) but under different cost structures.

This model considers five production factors: labor, capital, land, water and seawater. Water is distributed among farmers and water supply firms, and they cannot trade water between each other (in the benchmark).

Both agricultural sectors were modeled using a series of nested CES functions. For the irrigated sector, water enters in the production structure at the bottom level through a Leontief function of groundwater and energy. The production structure also considers a Capital-Land CES composite. The rainfed sector follows the same approach, but in this case the groundwater-energy Leontief composite does not apply.

The water production and distribution sector produces water using two technologies: groundwater extraction and desalination. In the first case, water is produced using capital, labor and intermediate inputs in fixed proportions. In the second case, water is produced using the same inputs under a Leontief formulation. The total drinking water produced is the sum of both sectors. Desalination water operates only when the amount of groundwater is below a threshold that is defined exogenously. In the benchmark scenario, the model assumes that the desalination sector is not active.

Their results show that trade liberalization in the water market has benefits for the whole economy. Through water markets it is possible to reduce the negative impact of droughts on urban water consumption. Even though, under this water market scheme, the output of irrigated agriculture decreases, this profit loss is compensated for with the income generated in the water market.

Roe, *et al.* (2005) analyzed the macro-micro feedback links between economy wide and irrigation policies in Morocco[7]. They examined the impact of trade reforms on a farm level economy, and the impact of new irrigation policies on the whole economy. In order to do this, the authors built a soft link between a CGE model and a farm model. The farm model developed by the authors considers only irrigated crops.

The authors identified three macro-micro links (1) prices of inputs and outputs that are determined at the macro level, prices that are exogenous for the farmers, (2) trade policies which can affect the prices of inputs and outputs faced by the farmers, and (3) water projects which impact the water supply faced at the micro level. Regarding micro-macro links, the authors identified any policy that could affect the allocation of inputs at the farm level, examples of these policies are: the water pricing method, water institution, and water allocation rules. The implementation of these policies will affect the demand of inputs at the micro level, and when all the farmers change their demands, the impacts will affect the entire economy.

Assuming optimal behavior at both the macro and micro scale, authors link both models through prices. Output and input prices are established at the macro scale, those prices are taken as given by farmers. When a shock is applied to the macro model, the prices faced by the farmers change, modifying their optimal behavior.

The empirical model is applied to the Moroccan economy, which is regionalized according to irrigation districts. The model includes 88 activities, 49 commodities and 9 irrigation zones. The model differentiates between agricultural (rainfed and irrigated) and non-agricultural activities/commodities.

The authors linked both models using prices for both output and input, and as a consequence of this interaction, they identified two effects: direct and indirect. The former is the effect of a trade

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[7] A previous version of this study was published as a Policy Research Paper of the World Bank (Roe *et al.* 2005).

policy on the output prices faced by the farmers, while the latter is the effect this change in output price has on rental rates (input prices) and domestic prices.

The authors show that the indirect effects, represented by the economy-wide impacts, modify and, in some cases, reverse direct effects. They also found that micro and macro policies have different impacts: trade reforms have a higher impact than the micro reform.

Cakmak, *et al.* (2008) analyzed the macro-micro feedback of irrigation management in Turkey. The authors analyzed the economy-wide impacts of an increase in agricultural prices and climate change, through a soft link between a CGE model and a farm model.

The CGE model includes 20 agricultural and 9 non-agricultural activities and it divides Turkey into 5 zones. The model specifically accounts for water, which is used in agricultural activities. The farm model is formulated as a programming problem, which assumes that water is supplied free of charge but the supply is limited to a certain amount. This approach tries to estimate the shadow water price by asking the farmers how much they are willing to pay for relaxing the water constraint. The derived demand of water estimated is then used to compute the water rent, which is added to the farmers' irrigation payments.

Their results show that these climate change simulations have a serious effect on a macroeconomic level. In this case the nominal GDP declines drastically, nevertheless the real impact is limited. The increase in agricultural prices reduces all the macroeconomic indicators, except for the agricultural exports.

Strzepek, *et al.* (2008) presented a CGE model for the Egyptian economy, which analyzed the economic impact of Aswan Dam's construction. Considering that the Aswan Dam was built in 1952, the authors compared the Egyptian economy in 1997 to the 1997 economy as it would have been without the Dam, which implies high flow variability in the Nile River.

The model assumes that farmers use land and water in fixed proportions. The choice of land-water combination by a crop is a maximization problem in which a farmer chooses the combination of land-water based on the price of both inputs. The model distinguishes two types of land and water: summer land/water and winter land/water. On the contrary, the scenario with the dam considers an even distribution of water within a year, while the scenario without the dam considers floods in the winter and droughts in the summer. This last scenario implies different water prices for each season.

The maximization problem's solution generates a land-water aggregate for each agricultural sector. Then, this land-water aggregate goes into the production function along with capital and labor.

The agricultural sector is modeled using a Leontief demand for intermediate inputs, a CES function for the value added, and a linear programming model for land and water use.

According to the results, the construction of the dam has had negative impacts on agricultural production, specifically on summer crops. Simulations show that by removing the dam, the summer agricultural output would be higher than recorded outputs. However, just the opposite is true for transportation, tourism, and the electrical sector. Thus, the dam presents a positive net impact on the Egyptian economy.

Hassan and Thurlow (2011) developed a CGE model following the approach proposed by Roe, *et al.* (2005), with South Africa as a case study. In this new study, the authors included water within the CGE model, while the previous report considered water through a farm model[8]. The objective of this study is to account for the economy-wide effects of: (1) water market within districts, (2) water markets within and across districts, (3) water competition between agricultural and non-agricultural uses (without water markets), (4) the same as (3) but including water markets.

The SAM used in this study specifically accounts for water and includes 40 sectors (17 of which are in the agricultural sector). The agricultural sector includes: field crops, horticultural crops, livestock, fishing and forestry. Only field crops are further disaggregated into rainfed and irrigated. Production and consumption activities are modeled at the water district scale, in this sense the SAM is disaggregated into 19 districts.

Using experimental data, the authors estimated the shadow price of water through econometric quadratic functions that relate crop yield to water use. The estimated coefficients are applied to the crop yield reported in the agricultural census in order to estimate the current water use by crop. The marginal value of water is computed using the crop prices,. Finally, subtracting non-water irrigation costs from the marginal value of water leads to the water shadow price. The water shadow price is then multiplied by the crop yield in order to account for the total shadow value of every crop, which is then subtracted from the capital value-added account of the SAM. Using information recorded in the SAM, the model also accounts for non-agricultural water (heavy industry, and light industry and household). The results show water markets' usual benefits, in which the economy is better off when market liberalization policies are implemented.

Smajgl (2006) analyzed climate change impacts on the Great Barrier Reef (GBR) region in Australia. The author presented an integrated analysis at a catchment level using a CGE, which includes non-market values for water use. Within this framework the CGE model is coupled with

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[8] A previus version of this study was published as a Policy Research Paper of The World Bank (Hassan *et al.*, 2008).

two different models: hydrologic and ecological. The non-market values are quantified using a multi criteria analysis (MCA) and a food-web model. The model considers 8 regions and 34 economic sectors. The model analyzes the economic impacts of a decrease in water quality and quantity. The former is due to an increase in fertilizer use, while the latter is due to climate change.

The production sector is specified using a series of nested CES functions. The production inputs are: capital (K), labor (L), fertilizer (N), irrigation water (W), and tourist attractions (TA). The model differentiates among five geographical zones.

According to the model, irrigation could be offered using surface or groundwater. The use of groundwater reduces the water table, while the use of surface water increases the water table. If farmers have access to both types of water, they can alternate between them, and the amount of unused water goes to the non-market side of the model.

Tourist attractions are sector specific for the tourism sector. This sector uses 7 different species as inputs and it assumes that a decrease in the number of species will have a negative impact on the tourism sector. Finally, a representative consumer demands market goods, as well as non-market goods.

This model focuses on water quality and water quantity. In the first case, the model assumes that the use of fertilizers consumes water quality, modeled as a virtual good. This virtual good is used by both sea-grass and environmental quality. An increase in the use of fertilizers decreases the habitat suitability for sea-grass, which at the same time is consumed by certain species (*i.e* dolphins). As dolphins are inputs for the tourism sector, this sector is affected. In the second case, the model assumes a decrease in rainfall, due to climate change. This decrease of water availability influences the entire economy, affecting both market and non-market goods.

Simulations show that a decrease in rainfall drives an increase in groundwater use, affecting both agriculture and tourism. The impact on the agricultural sector depends on the geographical area, but as a general result the total agricultural output increases. Regarding tourism, simulations show the existence of autonomous adaptation in this sector.

Cackmak, *et al.* (2009) presented a CGE model for Turkey, analyzing climate change impacts. The model differentiates among agricultural and non-agricultural sectors, regions, and irrigated and rainfed agriculture. At an institutional level, the authors differentiate among government, households and Water User Associations (WUA). Households are further desegregated into 5 regions.

The production structure is defined as a series of nested CES functions for each activity. The model considers 5 production factors: labor, capital, irrigated land, rainfed land, and water. The derived water demand is computed as a linear programming model at the farm level. The shadow water price computed under this approach is then added to the current payment made for irrigation.

The authors analyzed three different scenarios: an increase in agricultural prices, water re-allocation from rural to urban (irrigation water), and the impact of climate change on agriculture (reduction in agricultural yields). Results show a negative impact on the GDP for almost all the simulated scenarios, and climate change is reported to have serious impacts. The exception is the urbanization scenario, which implies a reduction in water for the irrigated agricultural sector. Under this scenario, the irrigated agricultural output decreases, while the rainfed output increases. As a consequence, there is an increase in the total GDP.

Smajgl, *et al.* (2009) presented a methodological approach that integrates a CGE model at the catchment level with an agent-based model (ABM) for the GBR in Australia. Through the integration of both models, the CGE results show spatially differentiated results. The aim of the study is to improve the water policy assessment in the area.

The CGE model used in this study is the PIA model proposed by Smajgl (2006). This model includes market and non-market values for the GBR region, and is intended to analyze scenarios related to water trading systems, fertilizer use, and precipitation changes. The agent-based model used is the SEPIA model, which simulates both land use and water use decisions at a micro scale. The SEPIA model is not an optimization model; instead, the model assumes agents' behavior as a consequence of global dynamics. This type of model assumes that agents' decisions are driven by market and non-market conditions, within an uncertain framework. The rules governing this model should be defined through a deep involvement with the catchment's stakeholders. The result of the SEPIA model is the land allocation of the catchment users, and this allocation is spatially explicit through a geographical information system (GIS). This land allocation is included within the PIA CGE model.

You and Ringler (2010) investigated the impacts of climate change on the Ethiopian economy. The impacts under analysis are: water availability, floods, and the impact of CO_2 on agriculture. The authors expanded the existing multimarket model used by Diao and Nin-Pratt (2005) and its further modifications.

This model considers only benefits and includes a huge desegregation of the Ethiopian agricultural sector (34 activities); the remaining economic activities are analyzed through two aggregated non-agricultural sectors. The last version of the model also includes a module that accounts for water stress, as well as a module that accounts for extreme events (floods and droughts). The authors extended the model to include the impact of the CO_2 concentration on agricultural production.

The impact of water stress is included through the Climate Yield Factor (CYF). This factor considers several climate variables and determines the suitability of growing of a certain crop. Depending on the value of CYF, yields are constrained by water availability; this yield information is then included as an input for the multimarket model. Regarding extreme events, the model uses the Flood Factor (FF) to determine the probability of the occurrence of monthly precipitation. Based on the flood losses estimated by the FF, as reduction in both agricultural and non-agricultural commodities, the multimarket model estimates the economic impact of the extreme event.

The impact of the CO_2 concentration on agricultural production is analyzed using the concept of potential yield, which results from the interaction of climate, CO_2, and crop type. In this case, the authors use a logarithmical relationship among these variables. The impact of CO_2 on agricultural production is then included as an input into the multimarket model. The simulation shows that climate change's severe impacts on the Ethiopian economy are due to the more frequent occurrence of extreme weather events that could cause losses in both the agricultural and non-agricultural sectors.

II.4. Key Issues and Future Research Directions

At the global level, although some improvements have been made since the first model proposed by Berritella, *et al.* (2005), several drawbacks remain. These limitations are related to a lack of reliable data, as well as model specification.

Regarding data, there are two major issues. The first is related to the industrial water demand; all of the economic models presented above consider only one industrial sector, and thus there is no option to reallocate water across subsectors according to differences in water productivity. The second is related to the water price elasticities used, the parameters used in the GTAP-W models were collected by Rosegrant, *et al.* (2002) and they lack empirical basis in their computation.

In terms of model specification, the way in which some models analyze water issues does not allow for accounting for water itself. Most importantly, all the simulated changes found in these approaches are consequence of exogenous shocks in productivity, instead of changes in water availability. Considering that water productivity is not included, these approaches exclude substitution options between water and other inputs.

Although the model proposed by Calzadilla, *et al.* (2008) presented an improvement regarding previous work, the approach used by the authors still does not allow for the analysis of substitution options between water and other inputs, such as capital in the irrigation composite. Moreover, the model differentiates between productivity differences between rainfed and irrigated land, but it does not model explicitly the irrigation sector.

Studies at the national scale look for a detailed representation of the market under analysis. In this regard, the studies presented above lack comprehensive representations of other economic sectors, with the exception of the agricultural sector. With the data available at the country level, it is possible to build a model that accounts for water competition among sectors: urban, industrial, environmental, and agricultural. The assumption of *ceteris paribus* for other markets does not seem realistic.

Future research directions should be oriented towards improving the data used for global models, as well as their specifications. In this regard, the main issues of interest are the potential substitutions of inputs across sectors, with special focus on the agricultural sector.

Considering the expected impacts of climate change on water resources, substitution among inputs arises as an adaptation strategy. On the other hand, considering that the irrigation sector is a large consumer of capital, models should further disaggregate the agricultural sector in order to account for the impact of capital movements across regions and sectors.

Finally, considering the key role that water plays for agriculture, it could be reasonable to consider the initial water endowment in each region, and analyze the way in which the water endowment could moderate the expected impacts of climate change on the agricultural sector.

Within the context of this review, the main contribution of this thesis is methodological, improving the representation of water in global CGE models. In the next section, two drawbacks identified in this research are addressed: explicit representation of the irrigation sector, and the inclusion of the water endowment within the modeling framework.

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III. Climate Change, Water Scarcity in Agriculture and Their Economy-Wide Impacts. A CGE Model Analysis.

Abstract

Water resources are facing several stresses in terms of quantity and quality. These pressures are closely related to the human interventions carried out in fields like: agriculture, land-use/land use change, and pollutant emissions, among others. Within this context, the expected changes in climate patterns will exacerbate the challenges faced by water resources. Considering the critical role that water plays for agricultural production, any shock in water availability will have great implications for agricultural production, and through agricultural markets these impacts will affect the economy as a whole with economy-wide consequences. In this paper, a new modeling approach is developed aiming to explicitly include water within the global ICES CGE model. In order to reach this objective, a new database has been built to explicitly consider water endowments, precipitation changes, and unitary irrigation costs. The results suggest different economic consequences of climate change depending on the specific region. The impacts are related to change in crop production, endowment demands, and international trade.

Keywords: CGE Models, Climate Change, Agriculture, Water Resources, Irrigation

III.1. Introduction

Among all the natural resources available, water resources are one of the most important for human activities. Besides the relevance of water as a key element to sustain life, water is one of the most important inputs for many economic activities, and it is present in many of the products traded.

Even though more than 75% of the earth is covered by water, it is a scarce resource. In fact, less than 1% is available for human consumption (UNESCO 2003). Thus, any policy addressing water resources should consider its scarce nature.

Among all the potential water uses, agriculture is by far the most intensive water user, accounting for more than 70% of global water withdrawals. Therefore, we must consider the wide scientific consensus about how climate change will affect water resources, including its uneven consequences across the world, especially within the agricultural sector. Some of climate change's expected impacts on the agricultural sector are: changes in precipitation and temperature patterns, along with an increase of extreme weather events (floods and droughts), among others. (Parry, *et al.* 2007, Bates, *et al.* 2008).

In economic terms, the agricultural sector is a principal player within international trade. In developing countries, this sector has been increasing in relevance, while for developed countries it has shown a slight decreasing pattern throughout the last decade (Aksoy and Ng 2010). The deep connection created through international markets implies that shocks in agricultural production have important consequences across the globe. Climate Change is not the only threat to the agricultural sector. Considering only expected population increases, a large investment in the agricultural sector, specifically in irrigation schemes, will be needed in order to assure the food supply, which implies re-allocating resources from other economic sectors.

Considering the global consequences of climate change, as well as the strong dependency of the agricultural sector on international trade, an approach that represents the deep connections among different sectors of the economy in order to account for the economic consequences of changes in water availability is necessary. In this regard, the general equilibrium approach seems to be an appropriate tool to analyze water related issues along with the impacts of climate change, specifically for the agricultural sector (Weyant 1985).

The general equilibrium approach uses computable general equilibrium models as analytical tools. CGE models simulate the equilibrium theory formalized by Arrow and Debreu (1954) with real economic data, aiming to numerically solve for different economic variables (supply, demand, and prices) that support equilibrium across specified market sets.

Water resources have been widely analyzed using CGE models. In a recent review of CGE studies, the authors presented a detailed description of several exercises carried out at two scales, global and national (Ponce, *et al*. 2012). At the global scale, the most relevant studies are those conducted using the GTAP framework (Berrittella, *et al.* 2005, Calzadilla *et al*. 2008). These studies are focused on the global welfare consequences of changes in agricultural trade patterns, due to changes in water availability. On the other hand, the studies conducted at national scale are focused on the evaluation of different policy instruments, such as: water pricing, irrigation policies, and water allocation, among others (Decaluwé, *et al* 1999, Lennox and Diukanova 2011, Strzepek, *et al.* 2008, Hassan and Thurlow 2011). In addition to the difference in scale, another important difference between these two modeling approaches is the level of detail/assumptions in which the economy is depicted.

In this paper a new modeling approach is developed, aiming to explicitly include water as a production factor within a global CGE framework. The model's structure is based on the ICES model (Eboli, *et al.* 2010). It represents the key features of the world economy, in 2007, with a detailed representation of the agricultural sector.

The paper is structured as follows: section two presents a full description of the new modeling approach, highlighting the new production structure, as well as the methodology used. In section three, the model is used to quantify the economic impacts of climate change on the agricultural sector in Latin America. Finally, in section four the main conclusions are presented.

III.2. The ICES-W Model

III.2.1 Model Description

The Intertemporal Computable Equilibrium System (ICES) is a multi-region and multi-sector dynamic CGE model developed by Fondazione Eni Enrico Mattei (Eboli, *et al.* 2010). The model is based on the GTAP model (Hertel 1997), and its further modification GTAP-E (Burniaux and Truong 2002). The ICES model is a recursive dynamic model that solves a series of equilibrium points across time assuming a dynamic myopic behavior by the agents.

The multi-sector, multi-region ICES-W model is based on the static version of the ICES model. The ICES-W model was developed to account explicitly for the role played by both the irrigation sector and the water endowment in each region, in order to cope with the climate change impacts on the agricultural sector. Thus, the climate change impacts considered in the model are only those which affect water availability; the modeling approach does not account for the further climate change impacts described by the literature: temperature changes, CO2 fertilization, changes in growth periods, and extreme weather events. (Bates, *et al.* 2008, Parry, *et al.* 2007).

At this stage, the analysis is limited to the agricultural sector since it is the largest water consumer worldwide. In this regard, the modeling approach follows the one used by the GTAP-W model (Calzadilla, *et al.* 2008), which considers two different agricultural sectors depending on the way in which water is provided: rainfed agriculture and irrigated agriculture. Regardless of this similarity, the current approach includes the irrigation sector, as well as the role played by the water endowment.

The model considers two different ways in which water is provided to the agricultural sector: irrigation and precipitation. There is a large body of literature that justifies the inclusion of irrigation schemes as one of the major adaptation options to cope with climate change impacts, specifically for developing countries (Smit and Skinner 2002, Hallegatte 2009, Bryan, *et al.* 2009, Dinar, *et al.* 2008).

Considering the development of irrigation schemes as an adaptation strategy to climate change, it would be reasonable to expect diverse impacts for both rainfed crops and irrigated crops (FAO 2011). The model considers these diverse impacts, accounting for productivity differences between rainfed and irrigated land.

Despite the relevance of water as a key input for the agricultural sector, one major challenge remains in order to account for water within a CGE framework: water does not have a price that reflects its marginal productivity. Furthermore, in most cases water simply has no price at all. Empirical evidence shows that the lack of a competitive market price is one of the drivers of water's inefficient use (Johansson, *et al.* 2002).

In order to overcome this shortcoming, water is modeled as a physical endowment that affects the productivity of the agricultural sector. Thus, it is not necessary to set an explicit price for the water endowment in the benchmark model calibration. Nevertheless, it is assumed that, due to changes in precipitation, this endowment and its variations would influence the agricultural sector's productivity.

Water affects agricultural productivity depending on the type of agriculture: *i*) in rainfed agriculture, productivity depends directly on precipitation, *ii*) in irrigated agriculture, productivity depends on the specific investments made to provide irrigation services, and on the water endowment in the water reservoirs (FAO 2011). In addition to water, three new endowments are considered: *Irrigation Capital, Irrigated Land, and Rainfed Land.*

The irrigation capital includes the investments made in a specific type of capital aimed to deliver water from the reservoir to the field. Within this framework, changes in water availability will have different impacts depending on the agricultural sector. For irrigated agriculture, changes in water availability are modeled as the change in the water endowment available for irrigation. On the other hand, for rainfed agriculture changes in water availability are modeled as changes in precipitation.

III.2.2 Model Structure

The ICES-W model is based on the structure of the ICES model (Eboli, *et al.* 2010). It is a multiregion model using the GTAP 7 database as benchmark for the economic equilibrium. (Narayanan and Walmsley 2008).

The ICES-W model makes use of the Walrasian perfect competition conditions to simulate adjustment processes. Within the ICES-W, the industrial sector is modeled using a representative firm that maximizes profits in perfectly competitive markets. The production functions are specified using nested Constant Elasticity of Substitution (CES) functions. The model uses the ‘‘Armington assumption’’, implying that there is no perfect substitution across domestic and foreign inputs/commodities, this feature allows for differences among products.

The consumer side of the economy is represented through a representative consumer in each region who receives income defined as the service value of the national primary factors. In the case of capital and labor, the model assumes that they are perfectly mobile domestically, but immobile internationally. National income is allocated between aggregate household consumption, public consumption, and savings.

In the original ICES formulation, the production structure is represented through a series of CES nested production functions that combine primary endowments with a capital-energy composite on the third level generating a value-added energy composite. The endowments in their original formulation are: Natural Resources Fishery, Natural Resources Forestry, Natural Resources Fossil Fuel, Land, and Labor. On the second level, the value-added energy composite is combined with other inputs in order to generate the final output[9].

The ICES-W model maintains some of the features of the original ICES model; the main changes are included on the base level of the production function. The model's production structure is depicted in Figure 3.1. As shown in this figure, on the third level the model considers six inputs: natural resources (3), land, labor, and the capital-energy composite. On the fourth level, the

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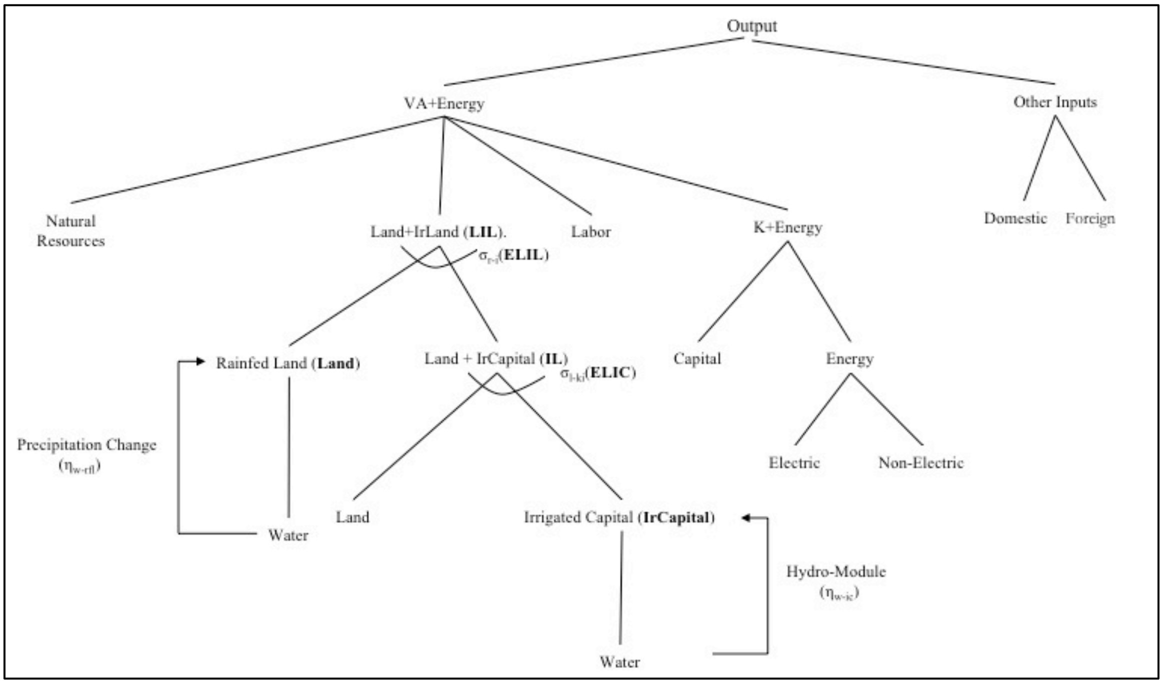
[9] A production tree is presented in Annex III.1.

model differentiates between rainfed land and irrigated land, in order to account for productivity differences, as well as for climate change impacts.

On the next level, irrigation land is a composite of land itself, and the capital devoted to irrigation. The capital devoted to irrigation is a sector specific input associated with the irrigated land. Finally, the model assumes that the productivity of the capital devoted to irrigation, as well as the productivity of rainfed land, depends on the endowment of water and the precipitation level, respectively.

Figure 3.1. ICES-W Production Tree



The production structure presented above applies to the agricultural sector only, which includes the following commodities: rice, wheat, cereals, vegetables and fruits, oilseeds, sugar cane, sugar beets, and plant fibers. For the other sectors, the ICES's production structure is used.

Including water within this new framework implies gathering additional information to incorporate it in the existing database. In this regard, we must:

a. Splitting the land endowment into:

- Rainfed land (*Land*)
- Irrigated Land (*IrLand*)

b. Splitting the capital endowment for agricultural sectors into:

- Irrigation capital (*IrCapital*)
- Rest of physical capital (*Capital*)

c. Build an external module linking the behavior of the irrigation sector with the water endowment in each region.

Each of these steps is explained below.

a. Splitting the land endowment

Irrigated land $(ILND_{i,r})$ was computed using the share of area actually irrigated over the total cultivated area, by region and commodity, according to the information contained in the global groundwater irrigation inventory (Siebert, *et al.* 2010). The inventory includes information about the area equipped for irrigation (AEI), the area actually irrigated (AAI), and consumptive water use for irrigation (ICWU). The information is available for 204 countries worldwide.

b. Splitting the capital endowment for the agricultural sector

The capital devoted to irrigation represents the investments made in building irrigation schemes. Within the GTAP framework, the Capital endowment represents the capital rents associated with each sector. Thus, in order to identify the share of capital devoted to irrigation (*IrCapital*) it is necessary to quantify this type of capital's economic returns. This information was computed using a database containing more than 1,200 irrigation projects worldwide. Four main sources of information were used: FAO (FAO 2003), IWMI (Inocencio, *et al.* 2007), You *et al* (2009), and the World Bank Implementation, Completion and Results Report (2007a).

FAO (2003) published information for 248 irrigation projects. The geographical disaggregation includes 5 regions: Eastern Asia (EA); Southern Asia (SA); sub-Saharan Africa (SSA); Near East & North Africa (NENA); Latin America and the Caribbean (LAC). The database is focused on developing countries (33 countries). The information includes: type of investment (rehabilitation/ new development) and investment cost (expressed in 2000 USD), among other information. The represented projects include investments for USD 8 billion, and an irrigated area of 7.3 million hectares during the 1980-2000 period.

Inocencio, *et al.* (2007) presented a comparative study of investment costs for different regions. The sample includes 314 irrigation projects in 6 regions: Sub-Saharan Africa (45), the Middle East and North Africa (51), Latin America and the Caribbean (41), South Asia (91), Southeast

Asia (68), and East Asia (18). The total sample includes 51 countries. The report includes information about: year when the project started, area under new construction, area under rehabilitation, and total irrigation costs (expressed in 2000 USD), among others. The study reports projects for USD 43.9 billion and 53.6 million hectares from 1965 to 1998.

You, *et al.* (2009) presented a study regarding irrigation spending needs in Africa in order to reach the irrigation potential within the region. The study includes large and small-scale irrigation facilities as operational alternatives. Regarding large-scale irrigation, the study considers 620 dams, in 41 countries. Information about dams includes: number of dams (operational, rehabilitated, planned), hydroelectric capacity (operational, rehabilitated, planned), reservoir capacity (operational, rehabilitated, planned), and investment expenditure, among others.

The internal rates of return for the irrigation projects were extracted from the World Bank Implementation, Completion and Results Report (The Word Bank 2007a). When this information was not available for a specific country, the interest rate from the GTAP database was used.

Information about water storage capacity was collected from the International Commission on Large Dams (ICOLD 2012). The ICOLD database has information for more than 33,000 dams worldwide. Considering that dams could have multiple uses, the model considers only those that have irrigation as one of their possible uses: 18,353 dams in 104 countries.

Using the merged information presented above, it is possible to compute both the total investment in irrigation in each region, per commodity $(II_{i,r})$, and the capital rents associated with the *IrCapital* $(KRNT_{i,r})$. The equations are presented below.

$$II_{i,r} = UIC_r * AAI_{i,r} \qquad [3.1]$$

where UIC_r is the unitary investment cost in irrigation in region *r*, while $AAI_{i,r}$ is the area actually irrigated by commodity *i*, and IRR_r is the irrigation projects' internal rate of return in region *r*. The model assumes that the unitary investment cost is the same for all the agricultural commodities within the same region, and that irrigation projects' internal rate of return is the same for all the agricultural commodities within the same region.

$$KRNT_{i,r} = II_{i,r} * IRR_r \qquad [3.2]$$

In order to split the original ICES database it is necessary to modify three headers in the database: $VFM_{i,j,r}$ represents the producer's expenditure on commodity *i* in sector *j* in region *r* valued at market prices; $EVOA_{i,r}$ represents the value of endowment commodity *i* output in region *r,;* and $EVFA_{i,j,r}$ represents value of purchases of endowment commodity *i* by firms in sector *j* of region *r* evaluated at agents' prices. These headers are modified using the computed shares $KRNT_{i,r}$ and $ILND_{i,r}$, as is shown below.

$$VFMI_{IrCapital,j,r} = VFM_{Capital,j,r} * KRNT_{j,r} \qquad [3.3]$$

$$VFMI_{IrLand,j,r} = VFM_{Land,j,r} * ILND_{j,r} \qquad [3.4]$$

$$EVFAI_{IrCapital,j,r} = EVFA_{Capital,j,r} * KRNT_{j,r} \qquad [3.5]$$

$$EVFAI_{IrLand,j,r} = EVFA_{Land,j,r} * ILND_{j,r} \qquad [3.6]$$

$$EVOAI_{IrCapital,r} = EVOA_{Capital,r} * \overline{KRNT} \qquad [3.7]$$

$$EVOAI_{IrLand,r} = EVOA_{Land,r} * \overline{ILND} \qquad [3.8]$$

where $VFMI_{i,j,r}, EVFAI_{i,j,r}, EVOAI_{i,r}$ are the modified headers associated with the agricultural commodities. Since $EVOA_{i,r}$ represents the aggregated value paid for the use of capital and land from agricultural commodities, a weighted average share was computed to split these flows: $\overline{KRNT}$, for irrigated capital, and $\overline{ILND}$, for irrigated land. The procedure is described below:

$$\overline{KRNT} = \frac{\sum_r KRNT_r * VFM_r(IrCapital)}{\sum_r VFM_r(Capital)} \qquad [3.9]$$

$$\overline{ILND} = \frac{\sum_r ILND_r * VFM_r(ILAND)}{\sum_r VFM_r(LAND)} \qquad [3.10]$$

For simplicity it is assumed that the new endowments (*IrCapital*, *IrLand*) face the same tax level as the original ones (Capital, Land).

c. *External module linking the behavior of the irrigation sector with the water endowment in each region*

The model differentiates between the expected impacts of changes in water availability for both rainfed and irrigated land. For rainfed land, the model assumes that a decrease in precipitation will have impacts on the rainfed land productivity on the same amount, assuming a direct link between precipitation and the agricultural land productivity (η_{w-rfl}).

For irrigated land, this direct relationship does not hold, considering that the capital devoted to irrigation moderates the impact of precipitation changes. A decrease in precipitation affects the productivity of irrigated land by changing the productivity of the capital devoted to irrigation. The hydrologic module links this decreases in precipitation with the changes in water availability that affect the productivity of the capital devoted to irrigation. Finally, the impact of climate change on the productivity of the capital for irrigation was computed as the change in the irrigated areas due to the changes in water availability.

The hydrologic module represents the output flow used for irrigation as a function of changes in precipitation, river flow, temperatures, evapotranspiration, and the evolution of the reservoir's capacity. The module assumes that each region has a unique water storage device (reservoir), with a capacity that is equal to the sum of the reservoirs' capacities of the different countries within the region. It also assumes that the water storage capacity is equivalent to the current water endowment.

The current water balance, relating input and output flows, is depicted in equation [3.11].

$$Q_{EA} + P_A = Q_{SA} + E_A \qquad [3.11]$$

where Q_{EA} represents the current input flow, P_A the current precipitation levels, Q_{SA} the current output flow, and E_A the current evapotranspiration of the reservoir. On the other hand the current output flow is a function of the irrigation demand plus other water uses, as is shown in equation [3.12].

$$Q_{SA} = ID_A + OU \qquad [3.12]$$

The irrigation demand uses share α of the total output flow

$$ID_A = \alpha * Q_{SA} \tag{3.13}$$

The future climate change scenario implies changes in both river flows and precipitation:

$$Q_{EF} = (1 + x) * Q_{EA} \tag{3.14}$$

$$P_F = (1 + \gamma) * P_A \tag{3.15}$$

where Q_{EF} represents the future input flow, P_F is the future precipitation level, and x, γ represent the expected changes in these variables. The changes in the current values of both input and output flows will drive a change in the reservoir's water volume. The change in the reservoir's water volume, ΔV, is the difference between future input flows and current output flows, and it is related to the maximum water volume in the reservoir:

$$\Delta V = R * V_{MAX} = Q_{EF} + P_F - Q_{SA} - EA \tag{3.16}$$

where *R* is the proportion to which the volume of water in the reservoir will change. *R* could be written as:

$$R = \frac{-x * Q_{EA} - \gamma * P_A}{V_{MAX}} \tag{3.17}$$

The greater the *R* value, the greater the impacts of climate change on the water volume in the reservoir. Regions with small water endowments, V_{MAX}, will face large changes in their reservoir's water volume.

The future irrigation demand, ID_F, is:

$$ID_F = \sum_{i=1}^{N} C_i * A_{iF} = \sum_{i=1}^{N} C_i * (1 - z) * A_{iA} \tag{3.18}$$

were C_i represents the irrigation requirements for crop *i*, A_{iA} represents the current area of crop *I* under irrigation, while A_{iF} represents the future irrigated area of crop *i*, and z represents the change in the irrigated area. Using equations [3.11] to [3.17], the change in the irrigated area can be written as:

$$z = 1 - \frac{\alpha * \left[\frac{DR_A}{\alpha} - \frac{DR_A}{\alpha} * x + P_A * x - E * x - P_A * \gamma \right]}{\sum_{i=1}^{N} C_i * A_i} \qquad [3.19]$$

According to equation [3.19], negative changes in both precipitation and river flows have negative impacts on the irrigated area, reducing the productivity of the capital devoted to irrigation by the same amount.

Finally, the elasticities of substitution used in this model, *ELIL* and *ELIC*, were defined based on guesstimates due to lack of empirical evidence supporting specific values. In order to allow for substitution among the new inputs, the elasticity of substitution Rainfed Land-Irrigated Land (*ELIL*) is greater than the elasticity of substitution Land-Irrigated Capital (*ELIC*).

III.3. The ICES versus the ICES-W Model.

In order to demonstrate the advantages of using the ICES-W model instead of the standard ICES model, both models are affected by the same productivity shock. In the standard ICES model the climate shock implies a decrease in land productivity of 15%, while in the ICES-W model the productivity changes are -15% for rainfed land and -15% for irrigated land. The analysis of both models is restricted to input relationship (rainfed/irrigated land), crop production, crop prices, international trade, and the impact on the global GDP[10].

Regarding inputs, in the standard version of ICES the decrease in land productivity generates an increase of 74.5% in the average price paid for land. At the regional level, EU27 shows the main increase in the price paid for land in the rice sector (139%), while SEA shows the small increase in the price paid for land in the wheat sector (33.18%). Regarding land demand, on average it increases by 2.7%. However, the SEA region shows a decrease in its demand (-13.69%), while in the EU27 the demand for land increases by 21.51%. This result is consistent with each area's cost

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[10] A detailed breakdown of regions and sectors is presented in Annex III.2.

structure, in which the cost share of land for rice production in the EU27 is the smallest (6%). On the other hand, the cost share of land for wheat production in SEA is the greatest (34.6%)[11]. Table 3.1 and 3.2 present details about land demand and land prices, respectively.

In order to sustain the level of production, the standard ICES model allows for substitution among inputs at the top level of the production tree. The increase in the land prices drives a substitution between land and other inputs, such as labor and capital. The model predicts an increase in both inputs, with labor demand increasing by 3.23% and capital demand increasing by 3.48%. Rice production in the EU27 region presents the main substitution between land and labor, as well as between land and capital. Both changes are driven by the large increase in land prices faced by the EU27 (Details in Table 3.4 and 3.4).

Table 3.1. Changes in Land Demand (%): Standard ICES Model.

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	15.6	0.7	7.9	7.3	2.7	3.6	2.1
China	4.3	2.6	4	3.6	-0.2	4	5
EastAsia	2.3	-3.3	-0.2	1.1	-12.1	1.4	2.4
SEA	6.3	-13.7	-3.3	0.3	-1.7	6.6	-9.7
SouthAsia	6.4	4.2	2.6	5.8	-0.1	6.7	3.2
India	3	0.1	0.3	1	2.4	3.4	1
USA	7.8	-5	2.6	4.2	2	4.7	-0.2
RoNAmerica	-3.6	11.4	2.1	1.5	13.7	3.9	2.8
Argentina	5.6	-0.7	3.2	2.3	3.7	1.5	1.2
Bolivia	1.5	5.1	3.1	2.6	1.6	1.8	12.5
Brazil	0.6	6.5	2.4	2.2	6.1	0.6	1.3
Chile	2.8	2	4.5	1.9	5.1	2.9	2.5
Peru	5.6	-4.3	0.9	3.3	2.9	5.6	3.1
RoLAC	3.7	-2.9	3	4.4	2.3	4.1	3.4
EU27	21.5	4.6	2.7	1.4	2.4	0.6	-1.2
MENA	5.2	4	9	2.1	2.5	0.4	3.7
SSA	3.4	4.2	2.2	1.3	0.3	0.4	2.3
RoW	5	1.4	2	2.6	0.8	3.2	4.5

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[11] Details regarding baseline information are shown in Annex III.3.

Table 3.2. Changes in Land Prices (%): Standard ICES Model

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	91.6	66.9	78.9	77.9	70.3	71.7	69.3
China	73.7	70.9	73.2	72.5	66.3	73.3	75
EastAsia	100.7	89.8	95.8	98.4	72.6	99	100.9
SEA	64	33.2	49.3	54.8	51.8	64.6	39.4
SouthAsia	49.4	46.3	44.1	48.6	40.4	49.9	44.9
India	76.6	71.7	72	73.1	75.6	77.3	73.3
USA	85.6	63.6	76.7	79.5	75.7	80.4	71.9
RoNAmerica	65.2	91	75	74.1	95	78.1	76.1
Argentina	70.9	60.8	67.1	65.6	67.9	64.3	63.8
Bolivia	57.7	63.3	60.1	59.3	57.8	58.2	74.7
Brazil	83.7	94.5	87.1	86.7	93.7	83.6	85
Chile	82	80.7	85.1	80.5	86.1	82.3	81.6
Peru	69	53.1	61.5	65.4	64.7	69	65
RoLAC	66	55.4	64.9	67.1	63.7	66.7	65.6
EU27	139.5	106.1	102.4	99.9	101.8	98.2	94.7
MENA	88.5	86.3	95.2	82.9	83.6	79.9	85.8
SSA	91.2	92.6	89	87.3	85.5	85.7	89.1
RoW	70	64.2	65.1	66.2	63.3	67.1	69.2

Table 3.3. Changes in Labor Demand (%): Standard ICES Model

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	18.3	-0.1	8.8	8	2.4	3.4	1.7
China	4.8	2.7	4.4	3.9	-0.7	4.5	5.7
EastAsia	5.8	-1.1	2.7	4.3	-12.1	4.8	6
SEA	5.7	-18.1	-5.8	-1.5	-3.9	6.2	-13.4
SouthAsia	4	1.3	-0.5	3.2	-3.7	4.4	0.1
India	5	1.4	1.6	2.4	4.2	5.5	2.5
USA	9.5	-6.2	3.1	5.1	2.4	5.7	-0.4
RoNAmerica	-4.5	14.1	2.5	1.8	17	4.7	3.3
Argentina	5.8	-1.8	2.9	1.8	3.5	0.8	0.4
Bolivia	0.1	4.5	2	1.4	0.1	0.5	13.5
Brazil	2.1	9.5	4.4	4.1	9	2.1	3
Chile	4.1	3.2	6.3	3	7	4.3	3.8
Peru	5.5	-6.5	-0.2	2.7	2.2	5.5	2.4
RoLAC	3	-5	2.2	3.9	1.3	3.6	2.7
EU27	30.8	8.8	6.4	4.8	6	3.7	1.5
MENA	7.5	5.9	12.1	3.5	4.1	1.5	5.6
SSA	5.8	6.7	4.3	3.1	1.9	2	4.3
RoW	4.9	0.5	1.2	2	-0.2	2.7	4.3

Table 3.4. Changes in Capital Demand (%): Standard ICES Model

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	18.3	-0.1	8.8	8	2.4	3.4	1.6
China	5	3.1	4.7	4.2	-0.4	4.8	6.1
EastAsia	5.8	-1.1	2.7	4.3	-12.1	4.8	5.9
SEA	5.8	-18	-5.6	-1.4	-3.7	6.5	-13.2
SouthAsia	4.4	1.8	-0.2	3.5	-3.4	4.8	0.5
India	5.2	2.1	2.1	2.9	4.7	5.9	3
USA	9.5	-6.3	3	5.1	2.3	5.7	-0.4
RoNAmerica	-4.5	14.1	2.5	1.8	17	4.7	3.3
Argentina	6.1	-1.6	3.1	1.9	3.7	1	0.7
Bolivia	0.2	4.6	2.1	1.4	0.2	0.6	13.6
Brazil	2.1	9.5	4.4	4.1	9	2.1	3
Chile	4.1	3.2	6.3	3	7	4.3	3.8
Peru	5.5	-6.5	-0.1	2.8	2.3	5.6	2.5
RoLAC	3.1	-4.9	2.3	4	1.4	3.7	2.8
EU27	30.8	8.7	6.3	4.7	6	3.6	1.4
MENA	7.5	6	12.2	3.6	4.1	1.5	5.6
SSA	6	6.9	4.5	3.3	2.1	2.2	4.5
RoW	5	0.7	1.4	2.1	0	2.8	4.5

As a consequence of the decrease in productivity, the price paid for both types of land (rainfed and irrigated) increases in the ICES-W. On average, the rainfed land increases its prices by 70.4%, while the irrigated land increases its prices by 86.2%. The EU27 presents the greatest increase in rainfed land price (140%) and South Asia presents the smallest increase in rainfed land price (27.6%). In general, under the ICES-W model's structure most of the products and regions pay lower prices for rainfed land, the exception is rice production in the EU (details can be found in Table 3.5).

At the country level, the main differences in land prices are reported for Chile's cereal production and for the EU27's rice production. In the first case, the land's price is higher under the standard ICES specification, while in the latter the land's price is larger under the ICES-W specification. In general, the lower prices showed by the ICES-W specification are due to the new substitution options presented in this model.

Rainfed land and irrigated land are substitutes if an increase in the price of rainfed land drives an increase of the demand for irrigated land. According to the ICES-W model, the demand for irrigated land presents a small increase of 0.06%. A closer look at the country level shows that in those countries with large irrigated land endowment, the substitution is more likely. An example in this regard is Chile with 63% of its agricultural land under irrigation, in this case the substitution between rainfed and irrigated land holds for 6 out of seven agricultural products. For those countries with small areas under irrigation, such as Bolivia (3.4%), Argentina (4%), and Brazil (4.6%), the substitution, from rainfed land to irrigated land, does not hold due to the relative scarcity of irrigated land (details can be found in Table 3.6 and Table 3.7).

In general terms both models, the static ICES model and the ICES-W model, present similar results in terms of change in production, international trade, and the impact on global GDP. Regarding production, in the ICES model the agricultural production decreases by 1.8%, while in the ICES-W model the decrease is 1.82%. At the regional scale, the differences in production are negligible. As a result of this decrease in production, the increase in the market price is around 15% for both models. At the GDP level, the simulations show a decrease of 0.4% in both cases (details can be found in Annex III.4).

The main conclusion of this section is the quite clear substitution between irrigated and rainfed land for agricultural production. Due to this feature of the ICES-W model, the increase in the price paid by land is smaller than the increase showed by the standard ICES model. It is worth noticing that the analysis presented here constrains the substitution options within the ICES-W model because the productivity shock faced by irrigated land is the same as that faced by rainfed land, taking no notice of the role played by the water endowment, which reduces the shock for the irrigated land through changes in irrigation capital productivity.

Table 3.5. Changes in Rainfed Land Prices (%): ICES-W Model.

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	91.4	66.7	78.5	77.4	70.1	71.1	68.7
China	65.4	62.4	63.7	63.9	57.5	64.9	66
EastAsia	94.7	84.1	89.9	92.4	67.3	92.9	94.9
SEA	62.8	32.3	48.3	53.8	50.6	63.4	38.4
SouthAsia	37.8	34.1	31.6	36.6	27.6	38.6	32.7
India	71.3	66.5	66.9	67.9	70.4	71.9	67.9
USA	84	61.9	74.8	77.6	73.9	78.5	70.1
RoNAmerica	64.2	90	73.9	73	93.8	76.9	75
Argentina	70.7	60.7	66.8	65.3	67.6	63.9	63.4
Bolivia	57	62.7	59.5	58.7	57.1	57.4	74.4
Brazil	80.3	90.9	83.6	83.2	90.3	80.3	81.7
Chile	66.5	65.3	68.3	64	70	66.8	65.8
Peru	64.9	49.3	57.5	61.3	60.6	64.9	60.9
RoLAC	64.2	53.6	63.1	65.3	61.9	64.9	63.9
EU27	140	105.5	101.6	99.1	101.1	97.3	93.9
MENA	81.3	78.8	87.6	75.8	76.4	73	78.6
SSA	90.7	92.1	88.5	86.6	84.9	84.9	89
RoW	67.7	61.7	62.8	63.6	60.8	64.4	66.5

Table 3.6. Changes in Rainfed Land Demand (%): ICES-W Model.

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	16.2	1.1	8.3	7.6	3.2	3.8	2.4
China	10.4	8.5	9.3	9.4	5.2	10.1	10.8
EastAsia	5	-0.7	2.4	3.7	-9.8	4	5.1
SEA	7.1	-13	-2.5	1.2	-0.9	7.5	-9
SouthAsia	15	11.9	9.8	14	6.5	15.6	10.7
India	5	2.1	2.3	3	4.4	5.4	3
USA	9.1	-4	3.6	5.3	3.1	5.8	0.8
RoNAmerica	-2.8	12.4	2.9	2.3	14.7	4.7	3.5
Argentina	6	-0.3	3.5	2.6	4	1.7	1.4
Bolivia	1.7	5.4	3.3	2.8	1.8	2	13
Brazil	0.9	6.8	2.7	2.5	6.5	0.9	1.7
Chile	11.1	10.3	12.3	9.4	13.4	11.3	10.7
Peru	8	-2.3	3.1	5.6	5.1	8	5.4
RoLAC	4.9	-1.9	4.1	5.5	3.4	5.3	4.6
EU27	23	5.3	3.3	2	3.1	1.1	-0.6
MENA	8.2	6.8	12	4.9	5.3	3.3	6.6
SSA	3.6	4.4	2.4	1.4	0.5	0.4	2.7
RoW	6	2.2	2.9	3.4	1.6	3.9	5.2

Table 3.7. Changes in Irrigated Land Demand (%): ICES-W Model.

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	10	-4.3	2.4	1.9	-2.4	-1.7	-3.1
China	1	-0.8	0	0.1	-3.8	0.7	1.3
EastAsia	1.2	-4.2	-1.2	0	-13	0.4	1.3
SEA	4.9	-14.8	-4.5	-0.9	-3	5.3	-10.8
SouthAsia	2.3	-0.5	-2.3	1.4	-5.3	2.9	-1.5
India	1.5	-1.3	-1.1	-0.4	1	1.9	-0.4
USA	5.3	-7.3	0.1	1.7	-0.4	2.2	-2.6
RoNAmerica	-6.7	8.5	-1.1	-1.7	10.8	0.5	-0.5
Argentina	2.8	-3.3	0.4	-0.5	0.9	-1.3	-1.6
Bolivia	-0.9	2.7	0.7	0.2	-0.8	-0.6	10.1
Brazil	-2.4	3.3	-0.7	-0.9	3	-2.5	-1.7
Chile	1.1	0.3	2.1	-0.5	3.2	1.2	0.6
Peru	4	-5.9	-0.7	1.7	1.2	4	1.4
RoLAC	0.2	-6.3	-0.5	0.8	-1.2	0.6	0
EU27	19.7	2.4	0.5	-0.7	0.3	-1.7	-3.3
MENA	2	0.6	5.6	-1.1	-0.7	-2.7	0.5
SSA	1.4	2.6	0.4	-0.4	-1.5	-1.2	0.5
RoW	2.2	-1.1	-0.7	0.2	-1.7	0.7	2.1

III.4. The Economy-Wide Impacts of Climate Change on the Latin American Agricultural Sector.

Climate change is already happening in the Latin American Region. According to the Economic Commission for Latin America and the Caribbean (CEPAL 2010), the region has shown an increase in the median temperature within the 1906-2005 period. Regarding precipitations, within the same period, some countries in the region (Paraguay, Uruguay, and Bolivia) faced increases in precipitation, while in the north, northeast, and northwest regions precipitation has decreased. Furthermore, there is evidence showing a decrease in glaciers' surface areas, threatening the long-term water supply.

The expected impacts of climate change during the current century imply an increase in temperatures, ranging from 1 to 6 degrees depending on the scenario analyzed, while a change in precipitations within the range -40% to 10% is also predicted. According to the projections, the most vulnerable sectors are: agriculture, health, coastal zones, and biodiversity (Parry, *et al.* 2007).

The Latin American Region, like many developing regions, has based its development on rural natural resource activities (agriculture, forestry and fishing). Agriculture is a key economic sector within the Latin American region, accounting for 6% of the GDP in 2010, and 15% of the total employment in 2009 (The World Bank 2007b). The agricultural sector also plays an important role in international markets: Argentina and Brazil are major producers of sugar cane, wheat, maize, and fruits, among other products (FAO 2010). Within this context, any shock in agricultural production in the Latin American region will have regional and global consequences.

This section presents the application of the ICES-W model that was described in section III.2; it aims at accounting for the economy-wide impacts of climate change on the Latin American agricultural sector. The modeling framework differentiates between rainfed and irrigated agricultural, accounting for different climate change impacts, the former through changes in precipitations, and the latter through changes in irrigated areas.

III.4.1 Model Specification

The ICES-W model includes 18 regions, among 6 of which are in Latin America (Argentina, Brazil, Bolivia, Chile, Peru, Rest of LAC), and 19 sectors among 7 of which are in agriculture (rice, wheat, cereals, vegetables and fruits, oilseeds, sugar cane and sugar beet, and plant fibers).

In the baseline scenario, the average irrigated land (*ILND*) is 22%, while the capital devoted to irrigation (*KRNT*) represents 2.1% of the total capital rents. Details per region are presented in Table 3.8.

Table 3.8. Baseline Irrigated Land and Capital for Irrigation

Region	ILND	KRNT
Oceania	2%	1.8%
China	43%	1.5%
EastAsia	49%	0.5%
SEA	19%	1.4%
SouthAsia	49%	9.6%
India	34%	6.6%
USA	14%	1.1%
RoNAmerica	8%	0.8%
Argentina	4%	1.3%
Bolivia	3%	1.5%
Brazil	5%	1.7%
Chile	63%	0.5%
Peru	34%	1.9%
RoLAC	11%	1.0%
EU27	9%	0.5%
MENA	27%	1.6%
SSA	3%	1.3%
RoW	11%	3.9%

Regarding the climate shock, Calzadilla, *et al.* (2010) reported how both precipitation and river flows would change according to the A2 IPCC scenario in 2040 (Intergovernmental Panel on Climate Change 2000). According to this information, it is expected that global precipitation will increase by 1.2%, while global river flow is likely to decrease by 0.2%, driving a decrease of irrigated land (-0.21%). In Latin America a decrease of 6.1% in precipitation is expected, while the river flows are predicted to decrease by 11.3%, driving a decrease of 11.3% in the irrigated area. Table 3.9 presents details associated with the shock imposed to the model: precipitation changes, water endowment, river flow changes, and the expected change in irrigated land according to the reduced form hydro-module.

The model assumes that the current level of precipitation is the optimum for the current level of agricultural production. In this regard, the model simulates the impacts of a decrease in precipitation, while an increase in precipitation has no impact on agricultural production. On the other hand, the data collected from the ICOLD database (ICOLD 2012) contains dams that have irrigation as only one of their purposes. Thus, it is possible to have dams that provide water for both irrigation and power generation uses. Considering this feature, the model assumes that 60% of the water endowment in each region is used for irrigation.

Table 3.9. Precipitation Changes and Water Endowment

Region	Precipitation Change (%)	Water Endowment (1,000 m3)	River Flow Changes (%)	Change on Irrigated Area (*z*)
Oceania	-6.1%	43,952,190	6.1%	6.10%
China	1.9%	353,014,985	-0.7%	-0.67%
EastAsia	5.4%	32,091,159	10.7%	10.67%
SEA	3.0%	110,067,892	2.3%	2.30%
SouthAsia	2.6%	29,686,787	9.0%	8.99%
India	12.0%	250,733,288	35.0%	35.00%
USA	3.0%	358,361,628	2.3%	2.30%
RoNAmerica	9.7%	90,670,783	4.2%	4.22%
Argentina	-1.5%	186,000,000	-6.0%	-6.00%
Bolivia	-6.0%	161,500	-12.0%	-12.00%
Brazil	-6.0%	68,239,288	-12.0%	-12.0%
Chile	-1.5%	7,741,090	-6.0%	-6.00%
Peru	-6.0%	3,104,600	-12.0%	-12.00%
RoLAC	-15.4%	65,000,720	-19.9%	-19.85%
EU27	1.5%	80,355,319	-0.5%	-0.47%
MENA	25.3%	218,429,701	20.7%	20.70%
SSA	-1.5%	322,517,661	-25.3%	-25.26%
RestofWorld	0.5%	411,038,083	0.3%	0.27%

III.4.2 Results

Climate change impacts are not the same across regions, generating diverse impacts on water availability. The expected change in precipitation at the global level (1.2%) will drive an increase in the price paid for rainfed land in all regions (5.1% on average). For the Latin American region, the expected change is 10.9%, consistent with the large climate shock faced by this region. At the regional level, the main increase in rainfed land prices is reported in RoLAC, which is also the region facing the largest decrease in precipitation. On the other hand, Argentina and SSA report almost the same increase in rainfed land prices, 5% and 6.1% respectively, which is consistent with their decreases in precipitation (Table 3.10).

Irrigated land prices increase by an average of 2.8% worldwide, while the Latin American region presents a larger increase in this price (6.3%). At the regional level, the RoLAC region presents the largest regional increase in prices (12.63%). This is explained, in part, by the small proportion of capital available for irrigation (1%), which drives a large decrease in irrigated areas (-19.8%).

On the other hand, China shows the smallest average increase in the irrigated land's price (0.68%), this is expected due to the small decrease in irrigated land (-0.67%). For details see Table 3.11.

The main improvement gained by using the ICES-W model is related to the new substitution options between land types within the agricultural sector. Results show that the substitution feature is a function of the share of irrigated land, water endowment (through the change in irrigated areas), and the productivity shock.

Nevertheless, the substitution feature does not hold for Chile since it is the country with the largest irrigated land share (63%). A closer look into the Chilean agricultural structure shows that the small share of irrigation capital drives a large decrease in irrigated land productivity, which is four times the decrease in rainfed land productivity. For this reason, the substitution options are constrained by the large decrease in the productivity of the substitute input.

For Brazil, a major player in the agricultural sector, the substitution between irrigated and rainfed land holds for rice, cereals, and sugar cane/beets. On average, the irrigated land demand decreases by 0.3% in Brazil. This could be explained by the small share of irrigated land (5%), and by the large decrease in irrigated land agriculture (12%).

Oceania is affected differently by the impacts of climate change, depending on the land type: there is a null impact for irrigated land, and a negative impact for rainfed land. In this case, the demand for irrigated land decreases when the rainfed land price increases. Nevertheless, there are signs to move from rainfed land to irrigated land (due to the relatively large water endowment); however, the region has little space to do this due to the small share of irrigated land (Table 3.12).

Table 3.10. Changes in Rainfed Land Price. (%).

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	8.7	4.8	8.2	9.6	6.5	10.4	8.1
China	0.4	0.7	0.9	0.4	0.8	0.4	0.6
EastAsia	0.7	1.5	1	0.7	1.1	0.6	0.9
SEA	0.8	1.6	1.2	0.9	0.9	0.8	1.3
SouthAsia	0.4	0.7	0.7	0.4	0.9	0.3	0.5
India	0.4	0.5	0.5	0.4	0.4	0.4	0.4
USA	4.5	2.8	2.9	2.5	2.8	2.2	2.3
RoNAmerica	2.4	3.4	2.5	2.7	3.3	2.1	2.1
Argentina	8.9	3.9	4.4	4.5	4.5	4.4	4.6
Bolivia	14.7	13.9	14.3	13.9	14.1	14.7	13.9
Brazil	16.7	11.5	15.1	15.7	15.2	16.6	13.7
Chile	3.2	3.2	4.1	3.9	3.5	3.2	3.2
Peru	8.1	6.1	7.2	7.5	8	8.1	7.6
RoLAC	21.6	11.9	18.2	20.9	19.7	26.2	21.3
EU27	3	2.5	2.8	2.8	3.2	2.2	2.3
MENA	1.1	1.5	1.7	1.2	1.7	1	1.3
SSA	6.1	6.1	6.2	6.3	6.2	6.5	5.7
RoW	0.8	1	1	0.9	1.3	0.8	1

Table 3.11. Changes in Irrigated Land Price (%).

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	7.4	3.6	7	8.3	5.3	9.2	6.8
China	0.5	0.7	1	0.5	0.9	0.5	0.7
EastAsia	0.7	1.6	1	0.7	1.2	0.7	0.9
SEA	0.9	1.7	1.2	0.9	1	0.8	1.3
SouthAsia	0.6	1	0.9	0.7	1.1	0.6	0.8
India	0.4	0.5	0.5	0.4	0.4	0.4	0.4
USA	4.8	3	3.2	2.8	3.1	2.5	2.6
RoNAmerica	2.7	3.7	2.8	3	3.5	2.4	2.4
Argentina	7.3	2.4	2.9	3	3	2.8	3.1
Bolivia	9.1	8.4	8.7	8.4	8.6	9.1	8.4
Brazil	5.2	0.5	3.7	4.3	3.9	5.1	2.5
Chile	3.6	3.6	4.5	4.3	3.9	3.6	3.6
Peru	6	4.1	5.2	5.4	6	6	5.6
RoLAC	14.1	5.1	11	13.5	12.4	18.5	13.9
EU27	3.1	2.7	2.9	2.9	3.3	2.4	2.4
MENA	1.3	1.7	1.9	1.4	1.9	1.2	1.4
SSA	-8.2	-9	-8.4	-8.6	-8.4	-8.8	-8.6
RoW	0.9	1.1	1.1	1	1.4	0.9	1.1

Table 3.12. Changes in Irrigated Land Demand. (%).

Commodities	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	0.4	-3.2	0	1.3	-1.6	2	-0.2
China	-0.1	0.2	0.4	-0.1	0.3	-0.1	0.1
EastAsia	-0.1	0.8	0.2	-0.1	0.4	-0.1	0.1
SEA	-0.1	0.7	0.2	-0.1	0	-0.1	0.3
SouthAsia	-0.1	0.2	0.1	-0.1	0.4	-0.2	0
India	0	0	0	0	0	-0.1	0
USA	1.8	0.1	0.2	-0.2	0.1	-0.5	-0.4
RoNAmerica	-0.2	0.7	-0.1	0.1	0.6	-0.5	-0.5
Argentina	4.3	-0.5	0	0	0.1	-0.1	0.2
Bolivia	0.5	-0.2	0.1	-0.2	0	0.5	-0.2
Brazil	1.2	-3.3	-0.2	0.4	0	1.2	-1.4
Chile	-0.6	-0.6	0.4	0.1	-0.2	-0.6	-0.6
Peru	0.7	-1.1	-0.1	0.2	0.7	0.7	0.3
RoLAC	1.3	-6.7	-1.5	0.7	-0.2	5.2	1.1
EU27	0.2	-0.2	0	0	0.4	-0.5	-0.4
MENA	-0.2	0.2	0.4	-0.1	0.4	-0.3	0
SSA	0.3	-0.5	0.1	-0.1	0.1	-0.4	-0.1
RoW	-0.2	0	0.1	0	0.3	-0.2	0

Climate change will drive a decrease of 0.5% in the agricultural output at the global level. For the Latin American region, this change will be -1.6%. At the regional level, in the RoLAC region, a decrease of 6.3% in agricultural output is expected, which is explained by the large productivity shock in both types of land, both rainfed (-15.4%) and irrigated (-19.9%). On the other hand, regions that do not face productivity shocks (East Asia, SEA, South Asia, India, USA, RoNAmerica, and MENA) show an output increase.

Brazil and Bolivia show the main reductions within the Latin American region (-1.6% and -1.7%). For Chile, nevertheless, a decrease in the irrigated land demand is expected, causing quite large productivity impacts. Chile also shows an increase of 0.23% in its agricultural output, which also occurred in Argentina. This increase in production is reached through an increase of land (0.47%), labor (0.47%), and capital demand (0.48%). These demand increases compensate for the productivity shock faced by both rainfed and irrigated land. At the activity level, Argentina shows the main increase in rice production (5%), while the RoLAC region shows the largest decrease in wheat production (-13.3%). In general, wheat it the most affected activity with a decrease in production of -1.3% (Table 3.13).

At the international level, it is expected there be an inverse relationship between change in the agricultural output and the direction of the international commerce. For those countries facing a decrease in their agricultural output, there is an increase of imports and a decrease of exports. At the global level, a decrease of -1.2% is expected in agricultural exports. For the Latin American region, the decrease in exports is 6%, while the increase in imports is 1.8%.

At the regional level, RoLAC shows the largest decrease in exports (17.7%), and the largest increase in imports (7.33%). At the activity level, Argentina's large increase in rice production drives a change in rice exports (17.3%), in fact only rice production increases in Argentina. The sugar and wheat trade is the most affected by the climate change impacts, with an increase in the dependency on the national production for Bolivia, India, RoNAmerica, East Asia and SSA. On the other hand, only for Brazil, Chile and the United States are the changes in exports larger than the changes in imports (Table 3.14 and Table 3.15).

Table 3.13 Changes in Agricultural Production

	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	-1.9	-6.0	-2.4	-0.9	-4.2	0.0	-2.6
China	0.0	0.3	0.6	0.0	0.5	0.0	0.3
EastAsia	0.0	1.1	0.4	0.1	0.6	0.0	0.3
SEA	0.0	0.9	0.4	0.1	0.1	0.0	0.5
SouthAsia	0.0	0.4	0.3	0.0	0.6	-0.1	0.1
India	0.0	0.1	0.1	0.1	0.0	0.0	0.1
USA	2.7	0.7	0.8	0.4	0.7	0.0	0.2
RoNAmerica	0.4	1.6	0.4	0.7	1.4	0.0	0.1
Argentina	5.0	-0.7	-0.1	-0.1	-0.1	-0.3	0.2
Bolivia	-1.2	-2.0	-1.7	-2.0	-1.8	-1.2	-2.0
Brazil	0.1	-5.1	-1.5	-0.8	-1.3	0.1	-2.9
Chile	-0.1	-0.1	1.0	0.7	0.3	-0.1	-0.1
Peru	-0.1	-2.2	-1.0	-0.8	-0.2	-0.1	-0.5
RoLAC	-4.6	-13.3	-7.6	-5.2	-6.3	-0.4	-4.8
EU27	0.9	0.4	0.7	0.7	1.2	0.0	0.1
MENA	0.1	0.6	0.8	0.2	0.8	0.0	0.3
SSA	-0.4	-0.4	-0.2	-0.2	-0.2	-0.1	-0.8
RoW	0.0	0.2	0.3	0.2	0.6	0.0	0.2

Table 3.14. Export Changes (%).

	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	-8.9	-6.9	-5.1	-3.2	-4.5	-5.6	-5.8
China	2.9	5.6	2.6	1.6	2.5	2.3	2.6
EastAsia	2.7	3.5	3.1	1.3	2.0	2.3	2.8
SEA	1.9	0.9	1.6	0.5	1.2	1.3	0.0
SouthAsia	2.5	1.1	1.6	0.9	1.4	1.7	1.6
India	2.4	3.8	2.4	1.6	2.6	2.0	1.3
USA	8.1	0.9	1.8	0.8	1.5	17.1	0.8
RoNAmerica	0.0	1.7	3.3	1.8	1.9	0.9	1.8
Argentina	17.3	-0.9	-0.1	-0.2	0.3	-1.9	2.8
Bolivia	-16.5	-10.1	-12.1	-8.9	-2.2	-9.6	-3.5
Brazil	2.3	-7.6	-6.8	-3.3	-2.9	-7.5	-5.6
Chile	-0.5	-0.6	2.3	0.8	0.6	0.2	-2.5
Peru	-18.1	-13.1	-5.9	-2.4	-5.8	-7.7	1.7
RoLAC	-24.8	-23.1	-18.0	-12.3	-10.5	-21.0	-13.9
EU27	2.0	1.1	2.1	1.5	2.7	1.0	0.9
MENA	2.1	2.1	2.8	1.7	2.7	2.2	1.5
SSA	-3.1	-1.0	-0.6	-0.4	-0.6	-0.7	-1.0
RoW	1.4	1.5	2.2	1.5	2.4	1.2	1.1

Table 3.15. Import Changes (%).

	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	3.3	1.3	1.9	1.9	0.8	3.0	2.0
China	-1.3	-1.2	-1.7	-0.5	-0.3	-3.5	-0.7
EastAsia	-1.8	-0.3	-0.6	-0.5	-0.2	-1.6	-0.5
SEA	0.6	-0.2	-0.2	0.0	-0.3	-1.3	-0.2
SouthAsia	-1.5	-1.6	-0.5	-0.2	-0.8	-1.6	-0.5
India	-1.0	-0.2	-0.7	-0.6	-0.7	-2.0	-0.8
USA	2.0	0.7	-2.7	-1.4	-0.4	-0.7	-0.4
RoNAmerica	-0.2	-0.1	-0.8	-0.2	-0.2	-1.0	-0.4
Argentina	1.6	2.1	-1.8	-2.0	-5.5	0.0	-1.0
Bolivia	7.8	0.2	5.0	3.7	3.0	3.2	-1.4
Brazil	-3.9	-0.1	2.3	2.2	-4.7	3.2	-0.2
Chile	-0.7	-0.4	-0.3	-2.7	-0.1	-1.0	-0.2
Peru	3.6	3.8	2.7	2.5	0.3	3.6	0.9
RoLAC	19.9	2.9	9.2	6.1	1.5	4.4	5.8
EU27	-0.2	-0.2	-0.9	0.0	-0.9	-0.9	-0.5
MENA	0.3	-0.9	-0.9	-0.3	-0.9	-0.9	-0.6
SSA	1.7	0.1	0.1	0.5	0.2	0.1	-0.4
RoW	-0.4	-0.7	-0.8	-0.9	-0.6	-0.4	-0.3

The climate shock drives an increase in prices for all regions and products. This is determined by the -0.5% decrease in agricultural production. The raise in agricultural prices is 1%, with rice increasing the most (1.2%), and wheat and plant fibers increasing the least (0.8%). At the regional level, the biggest change is reported in RoLAC (5.2%), followed by Bolivia (2.8%) and Peru (2.1%). Regarding agricultural commodities, the main increase in prices is related to the large decrease in production. An exception in this regard is the market price in Peru, where rice production decreases -0.1% and the price increases 2.6%. This situation could be explained by the change in international trade flows, in which the large decrease in exports is not compensated for by the increase in imports, pushing the price up (Table 3.16).

Table 3.16. Price Changes (%).

	Rice	Wheat	CerCrops	VegFruits	OilSeeds	SugarC_B	PlantFiber
Oceania	-1.9	-6.0	-2.4	-0.9	-4.2	0.0	-2.6
China	0.0	0.3	0.6	0.0	0.5	0.0	0.3
EastAsia	0.0	1.1	0.4	0.1	0.6	0.0	0.3
SEA	0.0	0.9	0.4	0.1	0.1	0.0	0.5
SouthAsia	0.0	0.4	0.3	0.0	0.6	-0.1	0.1
India	0.0	0.1	0.1	0.1	0.0	0.0	0.1
USA	2.7	0.7	0.8	0.4	0.7	0.0	0.2
RoNAmerica	0.4	1.6	0.4	0.7	1.4	0.0	0.1
Argentina	5.0	-0.7	-0.1	-0.1	-0.1	-0.3	0.2
Bolivia	-1.2	-2.0	-1.7	-2.0	-1.8	-1.2	-2.0
Brazil	0.1	-5.1	-1.5	-0.8	-1.3	0.1	-2.9
Chile	-0.1	-0.1	1.0	0.7	0.3	-0.1	-0.1
Peru	-0.1	-2.2	-1.0	-0.8	-0.2	-0.1	-0.5
RoLAC	-4.6	-13.3	-7.6	-5.2	-6.3	-0.4	-4.8
EU27	0.9	0.4	0.7	0.7	1.2	0.0	0.1
MENA	0.1	0.6	0.8	0.2	0.8	0.0	0.3
SSA	-0.4	-0.4	-0.2	-0.2	-0.2	-0.1	-0.8
RoW	0.0	0.2	0.3	0.2	0.6	0.0	0.2

Finally, the changes in both production and prices driven by climate change will have a negative impact on the global GDP. At the global level, the GDP will decrease 0.03%, with Bolivia and RoLAC facing the largest decreases, -0.2% and -0.17% respectively (Table 3.17). The final impact on these regions is explained by the international trade flow changes, with a large decrease in agricultural exports.

Table 3.17. GDP Changes (%)

Region	GDP Change
Oceania	-0.0205
China	-0.0021
EastAsia	-0.0001
SEA	-0.0012
SouthAsia	-0.0021
India	-0.0008
USA	-0.0007
RoNAmerica	-0.0051
Argentina	-0.0297
Bolivia	-0.204
Brazil	-0.0559
Chile	-0.0009
Peru	-0.0665
RoLAC	-0.1773
EU27	-0.003
MENA	-0.0017
SSA	-0.0323
RoW	-0.0022

Comparing the results computed here with the ones reported in previous studies (i. e Calzadilla, *et al*. 2010) show that the impacts on agricultural production are the same (-0.5%). However, the total impact on welfare, measured as changes on GDP, are lower under the ICES-W model, -0.03% versus -0.28%. This could be explained by the way in which the irrigation sector is included within the ICES-W model. Unfortunately, this statement cannot be proved due to lack of information on land prices reported by Calzadilla, *et al*. (2010).

III.5. Conclusions

Climate change poses a huge challenge to the agricultural sector, with economic impacts that could be significant, depending on the specific region. Since water is a key input for the agricultural sector, a serious drawback for economic modeling is the lack of information about its market price.

In this regard, the relevance of the model presented in this paper is twofold. First, it considers water as a physical endowment that modifies agricultural productivity, differentiating between irrigated and rainfed agriculture. Secondly, it explicitly considers the investment in irrigation schemes. The way in which the model considers the physical endowment of water, linking the CGE model and the hydro-module, is innovative and it allows us to overcome the "*non-market*" price feature of water resources.

The use of the ICES-W model provides a wider economic impact assessment of climate change than previous global CGE models addressing water issues. For instance, the model accounts for distributional effects, not only across sectors, but also within sectors differentiating between rainfed and irrigated agriculture. Furthermore, the model quantifies the strong link between the agricultural sector and water endowment (through the capital needed for irrigation), highlighting the economic consequences of relatively small water storage facilities.

The study of the economic impacts of climate change on the Latin American agricultural sector shows the expected results in accordance with the shock imposed. There is an increase in the demand of endowments (land and capital for irrigation), a decrease in agricultural production, and only a small change in GDP. Specifically for Bolivia, the results confirm the relevance of the water endowment, with larger economic impacts in those regions with small reservoir capacity.

The ICES-W model could be used to assess the economic impacts of increasing investments in irrigation within the agricultural sector as an adaptation strategy. This is not a minor issue, considering the large amount of economic resources that should be extracted from other economic sectors; an example of the latter is the construction of the South North Water Transfer Project in China.

Climate change impacts are essentially dynamic over long time periods. In this regard, the static feature of the ICES-W model do not account for optimal path solutions, which is a limitation of the model. Nevertheless, it is possible to extend this model into a dynamic version, including the time variable in the hydro-module once the data becomes available.

Despite the high level of aggregation presented by both the CGE model and the hydro-module, the modeling approach represents the role played by the water endowment in order to cope with climate change impacts. To the best of our knowledge, this is the first global CGE model that considers both the water endowment and the irrigation sector as this model does. Nevertheless, some limitations remain, such as: the analysis is restricted to the agricultural sector and does not account for water competition across sectors (industrial, municipal, environmental).

The model does not consider specific geographic conditions that could refine the results. The optimal solution is working with data at river basin scale, but this information is very difficult to collect. One option in this regard is to extend the model toward agro-ecological zone disaggregation. On the other hand, the model assumes a raw relationship between water and agricultural productivity (for both rainfed and irrigated land), by including region specific water response functions for agricultural productivity, following the same model structure it would be possible get finer results.

Finally, an inherent feature of the CGE models is the level of aggregation used, in which the modeling approach does not consider the specific features of every sector under analysis. This approach is often criticized due to its inability to clearly reflect reality, nevertheless its real usefulness is to provide a general picture of the situation under study, highlighting feedback effects that are otherwise impossible to identify.

III.6. References

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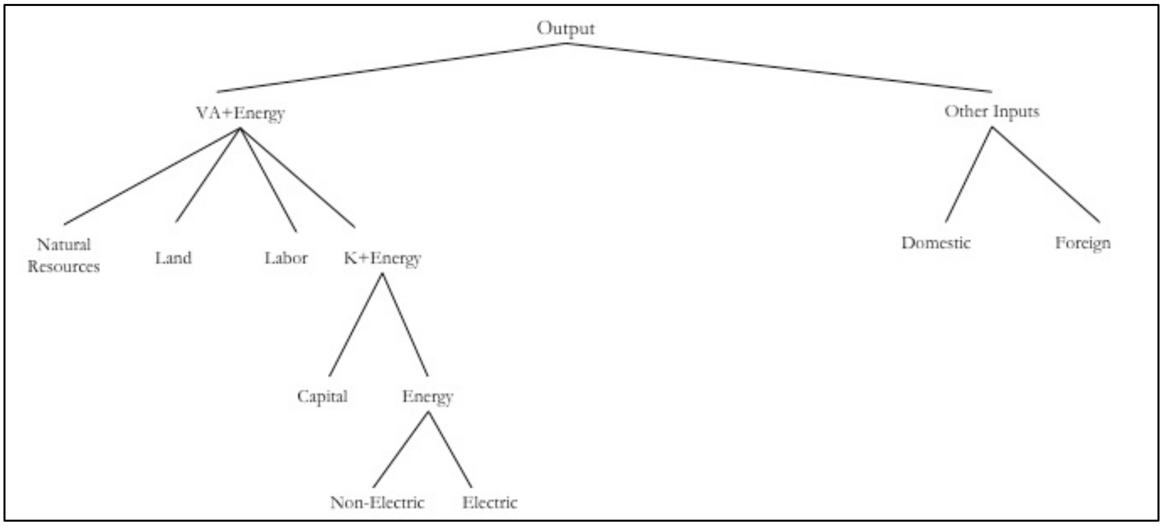
Annex III.1. ICES Model: Production Tree



Annex III.2. ICES-W: Regional and Commodity Disaggregation

Table A.III.2.1 Regional Disaggregation: ICES-W Model.

Region	GTAP Region	Region	GTAP Region	Region	GTAP Region
Oceania	Australia	EU_27	Austria	SSA	Nigeria
	New Zealand		Belgium		Senegal
	Rest of Oceania		Cyprus		Rest of Western Africa
China	China		Czech Republic		Central Africa
EastAsia	Hong Kong		Denmark		South Central Africa
	Japan		Estonia		Ethiopia
	Korea		Finland		Madagascar
	Taiwan		France		Malawi
	Rest of East Asia		Germany		Mauritius
SEA	Cambodia		Greece		Mozambique
	Indonesia		Hungary		Tanzania
	Lao People's Democratic Rep.		Ireland		Uganda
	Myanmar		Italy		Zambia
	Malaysia		Latvia		Zimbabwe
	Philippines		Lithuania		Rest of Eastern Africa
	Singapore		Luxembourg		Botswana
	Thailand		Malta		South Africa
	Viet Nam		Netherlands		Rest of South African Customs
	Rest of Southeast Asia		Poland	ROW	Bangladesh
SouthAsia	Pakistan		Portugal		Rest of EFTA
	Sri Lanka		Slovakia		Albania
	Rest of South Asia		Slovenia		Belarus
India	India		Spain		Croatia
USA	USA		Sweden		Russian Federation
RoNAmerica	Canada		United Kingdom		Ukraine
	Mexico		Switzerland		Rest of Eastern Europe
	Rest of North America		Norway		Rest of Europe
Argentina	Argentina		Bulgaria		Kazakhstan
Bolivia	Bolivia		Romania		Kyrgyztan
Brazil	Brazil	MENA	Rest of Western Asia		Rest of Former Soviet Union
Chile	Chile				
Peru	Peru				Armenia
RoLAC	Uruguay		Egypt		Azerbaijan
	Venezuela				
	Rest of South America		Morocco		Georgia
	Costa Rica				
	Guatemala				
	Nicaragua		Tunisia		Iran Islamic Republic of
	Panama				
	Rest of Central America		Rest of North Africa		Turkey
	Caribbean				

Table A.III.2.2 Commodity Disaggregation: ICES-W Model.

N	New Code	Sector Description
1	Rice	Paddy rice
2	Wheat	Wheat
3	CerCrops	Cereal grains nec
4	VegFruits	Vegetables, fruit, nuts
5	OilSeeds	Oil seeds
6	SugarC_B	Sugar cane, sugar beet
7	PlantFiber	Plant-based fibers
8	Animals	Cattle,sheep,goats,horses
9	Coal	Coal
10	Oil	Oil
11	Gas	Gas
12	Oil_Pcts	Petroleum, coal products
13	Electricity	Electricity
14	En_Int_ind	Minerals nec
15	Oth_ind	Meat: cattle,sheep,goats,horse
16	Water	Water
17	MServ	Construction
18	NMServ	PubAdmin/Defence/Health/Educat

Annex III.3. Baseline Information for ICES and ICES-W Models

Table A.III.3.1 Cost Share: ICES Model (%)

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
	Cost Share Land																	
Rice	11.5%	19%	19%	39%	25%	39%	15%	21%	13%	21%	10%	14%	28%	17%	6%	9%	10%	21%
Wheat	13.5%	12%	11%	35%	22%	23%	15%	9%	16%	9%	7%	12%	25%	16%	5%	5%	8%	13%
CerCrops	12.3%	15%	15%	37%	32%	33%	17%	18%	16%	19%	10%	13%	23%	19%	7%	6%	10%	16%
VegFruits	12.0%	19%	17%	41%	29%	33%	15%	18%	18%	20%	9%	19%	24%	17%	7%	8%	10%	15%
OilSeeds	13.0%	19%	21%	39%	31%	33%	15%	8%	15%	18%	8%	3%	26%	16%	6%	7%	10%	14%
SugarC_B	12.3%	17%	13%	35%	26%	35%	20%	21%	17%	9%	8%	11%	21%	17%	6%	8%	7%	11%
PlantFiber	10.8%	11%	6%	32%	27%	33%	13%	5%	9%	11%	10%	2%	15%	12%	6%	6%	9%	8%
	Cost Share Labor																	
Rice	28%	38%	31%	34%	26%	34%	21%	36%	22%	35%	14%	23%	48%	29%	36%	47%	54%	24%
Wheat	33%	25%	28%	44%	19%	20%	21%	21%	27%	14%	11%	20%	43%	26%	20%	24%	39%	31%
CerCrops	29%	31%	31%	32%	29%	28%	23%	32%	27%	33%	15%	22%	40%	32%	33%	30%	51%	32%
VegFruits	32%	39%	32%	36%	25%	29%	21%	32%	30%	34%	13%	31%	40%	29%	35%	40%	54%	38%
OilSeeds	31%	39%	37%	34%	28%	28%	21%	19%	26%	30%	12%	5%	45%	27%	31%	37%	54%	32%
SugarC_B	30%	35%	33%	31%	23%	31%	27%	37%	28%	15%	13%	19%	37%	28%	26%	43%	31%	26%
PlantFiber	26%	23%	6%	28%	24%	29%	18%	10%	15%	18%	15%	4%	25%	20%	31%	30%	45%	18%
	Cost Share Capital																	
Rice	15%	8%	15%	5%	11%	16%	18%	20%	11%	19%	36%	12%	4%	15%	11%	26%	13%	12%
Wheat	18%	5%	17%	4%	9%	10%	19%	20%	14%	8%	28%	11%	4%	14%	6%	14%	13%	11%
CerCrops	16%	6%	17%	5%	13%	13%	20%	21%	14%	17%	37%	12%	3%	17%	10%	17%	15%	10%
VegFruits	16%	8%	16%	5%	12%	14%	19%	20%	16%	18%	32%	17%	3%	16%	11%	23%	16%	14%
OilSeeds	17%	8%	19%	5%	13%	13%	19%	20%	14%	16%	30%	3%	4%	14%	9%	21%	15%	11%
SugarC_B	16%	7%	18%	5%	11%	15%	24%	21%	15%	8%	31%	10%	3%	15%	8%	24%	12%	11%
PlantFiber	14%	5%	1%	4%	11%	14%	16%	7%	8%	10%	37%	2%	2%	11%	10%	17%	12%	8%

Annex III.4. ICES and ICES-W Results

Table A.III.4.1 Changes in Total Output (%): ICES Model

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
Rice	12.8	-0.9	-1.2	-3.2	-2.3	-4.4	3.7	-9.0	2.2	-4.7	-1.3	-1.9	-1.3	-2.1	26.5	4.7	2.6	-1.9
Wheat	-3.8	-2.3	-5.4	-22.2	-4.4	-5.3	-10.3	9.8	-6.1	-0.9	5.7	-2.6	-11.5	-9.1	4.8	3.3	3.6	-3.3
CerCrops	4.1	-1.2	-2.8	-12.5	-6.6	-6.7	-2.3	-2.5	-2.0	-3.1	0.8	0.1	-6.0	-2.8	2.8	9.3	1.2	-3.4
VegFruits	3.7	-1.7	-1.9	-9.0	-3.3	-6.0	-0.6	-3.2	-3.0	-3.6	0.7	-2.9	-3.6	-1.4	1.5	1.0	0.2	-2.0
OilSeeds	-1.7	-5.7	-16.7	-11.0	-9.1	-4.6	-3.1	12.8	-1.2	-4.7	5.1	0.7	-4.1	-3.6	2.7	1.6	-1.0	-4.1
SugarC_B	-0.5	-1.1	-0.2	-2.4	-2.2	-3.5	-0.2	-0.9	-4.0	-4.4	-1.2	-1.7	-1.1	-1.6	0.2	-0.9	-1.0	-1.2
PlantFiber	-2.2	0.5	-4.0	-18.8	-5.8	-5.8	-5.4	-0.8	-2.3	7.0	-0.4	-1.8	-3.6	-2.4	-1.5	3.1	1.2	1.4

Table A.III.4.2 Changes in Total Output (%): ICES-W Model

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
Rice	13.2	-0.9	-1.2	-3.3	-2.6	-4.4	3.9	-8.9	2.3	-4.8	-1.3	-1.6	-1.3	-2.1	27.5	4.7	2.7	-1.9
Wheat	-3.6	-2.4	-5.3	-22.2	-5.3	-5.4	-10.2	10.1	-6.0	-0.8	5.7	-2.4	-11.6	-9.2	5.0	3.1	3.8	-3.3
CerCrops	4.3	-1.9	-2.7	-12.5	-8.0	-6.7	-2.3	-2.5	-1.9	-3.0	0.8	-0.4	-6.1	-2.9	2.9	9.3	1.3	-3.4
VegFruits	3.9	-1.9	-1.9	-8.9	-4.0	-6.1	-0.6	-3.2	-3.0	-3.6	0.7	-3.4	-3.6	-1.4	1.6	0.9	0.3	-2.0
OilSeeds	-1.4	-6.2	-16.7	-11.1	-10.8	-4.6	-3.0	13.1	-1.1	-4.6	5.2	0.7	-4.1	-3.6	2.9	1.5	-0.9	-4.1
SugarC_B	-0.5	-1.1	-0.2	-2.5	-2.3	-3.6	-0.2	-0.9	-4.0	-4.4	-1.3	-1.4	-1.1	-1.6	0.2	-0.9	-1.0	-1.2
PlantFiber	-2.2	0.1	-4.0	-18.8	-6.8	-5.9	-5.4	-0.7	-2.3	7.3	-0.4	-1.8	-3.6	-2.3	-1.4	3.1	1.6	1.5

Table A.III.4.3 Changes in Market Prices (%): ICES Model

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
Rice	13.3	18.6	24.9	36.0	17.3	38.1	16.7	19.7	10.9	14.7	10.9	14.3	25.5	15.5	9.6	9.6	12.5	21.2
Wheat	12.5	11.5	13.4	18.2	14.6	21.2	13.3	9.7	12.7	7.7	9.3	11.9	20.0	13.1	6.5	7.3	9.1	12.1
CerCrops	13.2	16.8	18.7	27.1	20.0	30.8	17.0	17.7	14.1	14.7	11.5	13.8	21.2	16.3	9.0	6.7	11.2	15.1
VegFruits	12.3	18.4	21.8	31.4	19.0	31.5	16.0	17.5	15.4	15.3	10.2	18.9	22.2	15.1	9.0	8.4	11.0	13.2
OilSeeds	12.9	16.7	20.8	30.3	17.6	32.2	16.0	8.9	13.2	13.3	9.6	10.6	23.9	14.3	7.3	7.9	11.5	12.9
SugarC_B	12.1	16.3	15.7	30.5	20.5	34.7	21.0	22.3	13.3	9.4	9.1	13.3	21.1	14.9	7.5	7.8	7.5	11.0
PlantFiber	12.5	10.2	8.4	19.8	17.0	30.8	13.1	6.7	6.6	9.0	10.5	8.3	14.6	11.2	7.2	5.7	10.3	6.4

Table AIII.4.4 Changes in Market Prices (%): ICES-W Model

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
Rice	13.6	20.2	25.3	36.4	19.5	38.8	17.1	20.0	11.1	14.8	11.2	15.0	26.0	15.8	9.8	10.0	12.7	21.5
Wheat	12.7	12.4	13.7	18.5	16.3	21.7	13.5	10.0	13.0	7.8	9.6	12.6	20.4	13.4	6.6	7.5	9.2	12.3
CerCrops	13.5	18.0	19.0	27.5	22.4	31.4	17.3	18.0	14.4	14.8	11.8	14.3	21.6	16.6	9.1	7.0	11.3	15.3
VegFruits	12.6	19.9	22.2	31.9	21.5	32.1	16.3	17.8	15.7	15.5	10.5	19.6	22.7	15.5	9.1	8.8	11.2	13.4
OilSeeds	13.2	18.0	21.2	30.7	19.4	32.8	16.3	9.2	13.4	13.5	9.8	10.9	24.3	14.7	7.4	8.2	11.7	13.1
SugarC_B	12.4	17.7	16.0	30.9	23.2	35.4	21.4	22.7	13.5	9.4	9.3	14.0	21.5	15.2	7.6	8.1	7.6	11.2
PlantFiber	12.8	11.0	8.5	20.1	19.0	31.4	13.3	6.8	6.7	9.1	10.8	8.5	14.8	11.4	7.3	6.0	10.5	6.5

Table A.III.4.5 Changes in Exports (%): ICES Model

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
Rice	66.2	37.3	-3.5	-72.7	-4.2	-79.0	10.8	-1.1	16.7	58.9	67.4	33.5	-48.0	-3.9	63.9	87.7	63.7	-20.7
Wheat	-4.3	7.7	-16.8	-39.3	-29.2	-50.1	-13.1	10.5	-6.5	14.4	5.9	-17.3	-55.5	-15.0	15.8	20.0	12.9	-10.3
CerCrops	9.5	-0.1	-9.0	-35.4	-19.8	-47.6	-5.3	-10.5	0.0	-5.9	8.9	2.8	-29.5	-3.6	11.5	33.1	8.6	-8.0
VegFruits	18.5	2.3	-2.2	-22.1	-1.4	-34.5	0.7	-4.9	-3.3	-7.4	10.7	-3.0	-6.6	0.1	5.2	15.0	10.2	-0.5
OilSeeds	-1.9	-10.7	-16.0	-38.0	-15.3	-49.7	-5.7	17.1	6.9	9.1	13.2	7.8	-36.2	-3.0	9.0	12.6	0.2	-6.5
SugarC_B	17.6	-14.8	-11.9	-54.4	-26.8	-61.6	-22.4	-23.6	-2.0	18.5	20.0	-1.8	-16.7	-5.7	18.1	25.1	30.1	3.4
PlantFiber	-4.0	5.3	12.1	-28.5	-19.8	-53.4	-8.0	15.9	13.1	15.5	1.6	-1.0	-14.7	-2.2	7.5	21.4	2.5	12.3

Table A.III.4.6 Changes in Exports (%): ICES-W Model

Product	Oceania	China	EastAsia	SEA	SouthAsia	India	USA	RoNAmerica	Argentina	Bolivia	Brazil	Chile	Peru	RoLAC	EU27	MENA	SSA	RoW
Rice	68.4	26.9	-1.8	-72.6	-16.4	-79.2	11.2	1.4	17.4	62.9	68.8	30.7	-47.8	-3.9	66.6	88.0	67.0	-19.7
Wheat	-4.0	2.7	-16.7	-39.3	-36.4	-50.7	-13.0	10.9	-6.4	15.4	5.9	-19.7	-55.9	-15.2	16.3	19.4	13.4	-10.2
CerCrops	10.0	-3.4	-8.7	-35.3	-25.7	-48.0	-5.2	-10.4	0.3	-5.5	8.9	1.7	-29.8	-3.8	11.9	33.0	9.1	-7.9
VegFruits	19.1	-0.4	-1.8	-21.7	-5.9	-34.7	0.9	-4.8	-3.2	-7.1	10.8	-3.7	-6.6	0.1	5.4	14.9	10.6	-0.4
OilSeeds	-1.5	-13.6	-16.0	-38.0	-19.4	-50.2	-5.6	17.5	7.5	9.7	13.4	7.6	-36.4	-3.1	9.5	12.1	0.7	-6.4
SugarC_B	19.3	-19.1	-11.9	-54.5	-34.4	-62.3	-22.7	-23.7	-1.8	19.5	20.2	-3.8	-16.9	-5.8	18.5	24.3	31.0	3.5
PlantFiber	-3.8	3.0	12.9	-28.1	-24.7	-53.5	-7.8	16.6	13.7	16.0	1.8	-1.2	-14.7	-1.9	8.2	21.5	3.0	12.8

Table A.III.4.7 Changes in Global GDP (%): ICES Model

Region	Change (%)
Oceania	-0.06
China	-0.48
EastAsia	-0.06
SEA	-0.68
SouthAsia	-1.06
India	-1.72
USA	-0.04
RoNAmerica	-0.13
Argentina	-0.40
Bolivia	-0.70
Brazil	-0.20
Chile	-0.18
Peru	-0.57
RoLAC	-0.33
EU27	-0.02
MENA	-0.13
SSA	-0.31
RoW	-0.25

Table A.III.4.8 Changes in Global GDP (%): ICES-W Model

Region	Change (%)
Oceania	-0.06
China	-0.49
EastAsia	-0.06
SEA	-0.68
SouthAsia	-1.08
India	-1.72
USA	-0.04
RoNAmerica	-0.13
Argentina	-0.40
Bolivia	-0.70
Brazil	-0.20
Chile	-0.18
Peru	-0.57
RoLAC	-0.33
EU27	-0.02
MENA	-0.13
SSA	-0.31
RoW	-0.25

IV. Climate Change, Water Scarcity in Agriculture and Their Country-Level Economic Impacts. A Multimarket Analysis.

Abstract

Agriculture could be one of the most vulnerable economic sectors to the impacts of climate change in the coming decades. Considering the critical role that water plays for agricultural production, any shock in water availability will have great implications for agricultural production, land allocation, and agricultural prices. In this paper, an Agricultural Multimarket model is developed to analyze climate change impacts in developing countries, accounting for the uncertainty associated with the impacts of climate change. The model has a structure flexible enough to represent local conditions, resource availability, and market conditions. The results suggest different economic consequences of climate change depending on the specific activity, with many distributional effects across regions.

Keywords: Agricultural Multimarket Model, Climate Change, Agriculture, Water Resources, Uncertainty.

IV.1. Introduction

The agricultural sector could be one of the most vulnerable economic sectors to the impacts of climate change in the coming decades. Climate change impacts are related to changes in the growth period, extreme weather events, and changes in temperature and precipitation patterns, among others. All of these impacts will have consequences on agricultural production (Bates, *et al.* 2008).

Regarding crop production, the impacts will be a function of the geographical location with an increase in yields in high-latitude areas with rising temperatures, and a decrease in yields in low-latitude areas. Simulation results show that the positive impacts of climate change outweigh the negative ones (Parry, *et al.* 2007).

Taking into account the key role that water plays for agricultural production, changes in water availability will have a direct impact on the agricultural sector. Simulation results show an increase in the irrigation demand at the global level throughout the 21st century, in order to cope with both climate change and population growth (Doll 2002, Fisher, *et al*. 2006, Alcamo, *et al*. 2003, Arnell, *et al*. 2011).

The magnitude of climate change impacts will demand an urgent policy response in order to cope with the consequences. Considering the high level of policy intervention that the agricultural sector already experiences (quotas, taxes, band prices), the required climate change adaptation policies could lead to undesirable outcomes if all the potential linkages within the agricultural sector are not considered as part of a single system. The welfare consequences of poor policies could be large, especially for developing countries where the agricultural sector not only has economic relevance, but is also a keystone for food security (FAO 2010).

A main issue regarding climate change impacts is related to the uncertainty associated with their occurrence. Climate change impacts, as described above, are the outcome of models based on several assumptions, among which the future emissions of greenhouse gasses are the most relevant. These emission scenarios are storylines associated with different assumptions about climate and socioeconomic conditions (Intergovernmental Panel on Climate Change 2000). Within this context, climate change impact assessment should consider this uncertainty in order to produce valuable information for policymakers.

The effectiveness of public policies will depend on local characteristics, such as: climate and socioeconomic conditions. In order to address the challenges imposed by climate change from an economic perspective, an approach that provides a detailed picture of the agricultural sector and the relationships within it is essential. In this regard, bottom-up approaches could be an effective tool to evaluate the economic impacts of climate change on the agricultural sector.

Bottom-up approaches, such as: agricultural models and hydro-economic models are characterized by the detailed description of their components. For most of them, their advantages are also their main drawbacks, principally because of the large amount of data needed to conduct this kind of research. This is relevant for the analysis of agricultural issues in developing countries.

Agricultural models simulate the agents' optimal behavior, allowing for an *ex-ante* evaluation of policy intervention. Agricultural models range from studies at farm level, to studies including the whole agricultural sector. The main difference is related to price assumptions. Considering that all the agricultural agents will be affected by climate change impacts, the most suitable agricultural model structure is that which analyzes the whole agricultural sector assuming endogenous prices, namely agricultural multimarket models. (Hazzel and Norton 1986, Sadoulet and De Janvry 1995, Howitt 2005).

Nevertheless, agricultural multimarket models fall short in relation to the complexities of computable general equilibrium (CGE) models. Their results account for direct and indirect effects restricted to the agricultural markets under analysis, in this sense the use of agricultural multimarket models is an improvement over single market models (Croppenstedt, *et al.* 2007).

Agricultural multimarket models represent the agricultural sector through a series of behavioral equations, which are optimized in order to maximize the farm income, regional income, or regional surplus, subject to technological, environmental, and institutional constraints (Howitt 2005). The core equations of a multimarket model include prices, supply, consumption, income, stock variables, and market clearance conditions. The analyses are carried out on markets that have strong links, through the demand or supply side, on issues that have sectoral relevance with differentiated impacts among model components (Croppenstedt, *et al.* 2007).

This paper presents an agricultural multimarket (AMM) model, which analyzes the economic impacts of changes in water variability due to climate change. The model's structure is designed to be used within a context of information restriction, this feature is especially valuable for use in developing countries. The multimarket model is designed specifically for the analysis of the Chilean agricultural sector, and it accounts for uncertainty through the use of Monte Carlo simulations about water availability.

The paper is structured as follows: section two presents a brief literature review about previous studies, while section three presents a full description of the new modeling approach, highlighting the new production structure, as well as the methodology used. In section four, the model is used to quantify the economic impacts of climate change on the Chilean agricultural sector. Finally in section five the main conclusions are presented.

IV.2. Previous Studies

IV.2.1 Agricultural Models

The study of water resources using agricultural multimarket models dates back to when the first studies of agricultural issues were carried out from an economic perspective. Since water is a key input for the agricultural sector, its analysis could not be neglected in these kinds of models. Taking into account that the agricultural sector is subject to high governmental intervention, such as: subsidies, taxes, price bands, and quotas, it is advantageous to have some idea of what the expected results of such policies could be in advance. In this regard, modeling the agricultural sector sheds some light on the consequences that specific policies may have on a defined set of markets (Croppenstedt, *et al.* 2007).

Multimarket models have been widely used for the analysis of agriculture related policies. The World Bank developed the first models, whose main purpose was to analyze the impact of price policies on production, demand, income, trade, and government revenues (Lundberg and Rich 2002a).

For developing countries, the work done by Lundberg and Rich (2002a) can be considered as a cornerstone model. Originally, the study was developed for Madagascar as a generic model that could be used as an analytical tool for other African countries. Regarding its structure, the models consider four sectors: food crops, livestock, non-agricultural products, and fertilizers. The agricultural sector is represented through a block of six equations: prices, supply quantities, consumption quantities, household income, stock (input, output), and market clearance conditions.

The simulation scenarios include an improvement in rice productivity (20% increase), subsidies for fertilizers (20% for all farmers, and 20% for poor farmers), trade liberalization (a decrease in rice tariffs), and infrastructure improvement (a 20% reduction in marketing margins).

Results show that the increase in rice productivity has wide impacts on the agricultural sector, with an increase in rice production, a reduction in coarse grain production, and an increase in the consumption of agricultural products. International trade is affected by a 60% reduction in rice imports. Regarding the fertilizer policy, results show a small increase in general agricultural production (2%), while the tariff reductions lead to a small reduction in rice production (1%).

Finally, the decreasing of the marketing margin drives an increase of between 8% and 33% in the producer's price for rice and livestock, respectively.

Lundberg and Rich (2002b) applied the same model to Malawi. Using the same structure, authors simulated an increase in maize productivity (20%), fertilizer subsidy (20%), and infrastructure improvements (a decrease of 20% in the marketing margin). The Results are similar to those reported for Madagascar.

Using the same model, Stifel and Randrianarisoa (2004), analyzed the impact of agricultural reforms in Madagascar. The authors looked into the impacts of tariff changes, infrastructure improvements, and yield increases.

FAO used these models in order to develop multi-market models for Egypt, Indonesia and Paraguay. These models aim to analyze the impact of agricultural policies on poverty and food security.

Siam and Croppenstedt (2007) analyzed the impact of wheat market liberalization in Egypt; their model is based on Stifel and Randrianarisoa's model (2004). The production side includes nine agricultural products and two inputs. It does not include seasonality, an aggregate for all other food, or non-food commodities. Authors simulated 4 scenarios: complete liberalization, an import price increase, increases in stock, and increases in yield. Results show that wheat market liberalization implies a large cost for both consumers and producers, with producers facing the most serious impact.

Multi-market models use mathematical programming (MP) to compute their solutions. The wide use of this method is underpinned in the limited amount of data required for their development. This feature is well appreciated, especially by researchers conducting studies in developing countries. (Howitt 1995, Hazzel and Norton 1986).

Despite the wide use of MP, the method has a series of caveats, among which the calibration process is the most important (Howitt 1995). To solve this critical issue, Howitt (1995) presented the Positive Mathematical Programming approach (PMP). Using the PMP approach it is possible to achieve a perfect calibration on: area planted, products, and prices, avoiding the dependency between parameters and constraints.

Since the first study using PMP was published, the PMP approach has been widely used for the analysis of agricultural issues. The application of this method includes exercises at farm, basin, and regional scales (for reviews of PMP applications see (Heckelei and Britz 2005).

Despite PMP's widespread use, it has several drawbacks. According to de Frahan, *et al.* (2007) the main limitations of PMP are related to the unequal treatment of marginal and preferred activities, the lack of representation of economic activities with zero level of supply during the reference period, and the integration of risk, among others. Efforts to overcome these flaws are presented in studies by Rohm and Dabbert (2003), and Paris and Arfini, (2000).

Models using PMP in their multiple versions have been applied to several agricultural models, like models analyzing the expected impacts of the Common Agricultural Policy (CAP) in regions like Belgium, UK, Greece, Germany, and Sweden. (Mattas, *et al.* 2011, de Frahan, *et al.* 2007, Blanco, *et al.* 2008). Other applications include the estimation of the economic value of water and land (Medellín-Azuara, *et al*. 2009, Howitt, *et al.* 2001, Cortigiani and Severini 2009, Kan, *et al.* 2009), climate change impacts (Howitt, *et al.* 2009, Henseler, *et al.* 2009) and water allocation in a holistic model at the basin scale (Cai and Wang 2006).

Blanco, *et al.* (2008) used an agricultural model to evaluate the predictive capacity of three PMP approaches: standard PMP, Rohm and Dabbert, and Maximum Entropy. None of these methods is able to simulate farmers' behavior for activities that are not represented in the base year. To overcome this problem, the authors proposed a wide-scope PMP approach. The new approach is based on farmers' preferences and local conditions that are represented through a new cost parameter on the average cost function. The capacity of these methods was tested in an irrigated region in central Italy.

Results show that when the wide-scope approach is included, two out of the three methods show a better match between the predicted and the real crop area when no pre-existent activities are included. The efficiency gains are around 5%. The opposite is the case with the Rhom and Debbert method, which shows a better performance when pre-existent activities are not included.

Medellin, *et al.* (2009) analyzed the economic value of water for irrigated agriculture. To do so, the authors used a CES production function and a quadratic cost function, both of which are calibrated using the standard PMP approach. The authors analyzed the impact of four scenarios on the value of irrigation water: technological change, warm-dry climate, irrigation costs, and crop prices. The model was tested in the Rio Bravo basin, with both a farm and regional analysis.

Results show that the impact on the value of water is different depending not only on the scenario, but also on the regional scale. For example, for a warm-dry climate around 44% of farms have no change in the value of water, while at the regional level, this proportion is 15%. The authors show the impact on farmers' revenues; in this case the higher impacts are related to technological change, while climate change has a higher variability.

Regarding climate change impacts, Howitt, *et al.* (2009), analyzed the economic impacts for California using the SWAP model. The SWAP model includes 21 regions and 12 crops and considers the expected impacts in 2050. The model uses a CES production function and an exponential cost function, both of which are calibrated using PMP. The authors simulated a reduction in agricultural land (5%), an increase in crop yield (0.9% to 1.57% per year), an increase in the demand for Californian crops (3% to 45% in 2050), a change in crop yields because of climate change (-11% to 5%), and a reduction in water availability (15% to 25%).

Results show that the main impact expected is an increase in the economic value of water due to the water shortage. This shortage drives a reduction in the area of irrigated crops that is greater than the area needed for urban expansion.

IV.2.1 Climate Change Impacts on the Chilean Agricultural Sector

Climate change impacts on the Chilean agricultural sector have been widely analyzed from different perspectives in recent years. The first study on this subject was conducted by the University of Chile’s AGRIMED center in 2008 (Santibáñez, *et al.* 2008). In this study, authors analyzed the productive impacts that climate change could produce within the Chilean agricultural sector. In order to analyze the expected impacts new climate conditions would have on different agricultural activities, they used the SIMPROC model. The SIMPROC model simulates both the growth and the productivity of a crop by integrating the crop’s ecophysiological processes and its climatic regulation. Crop growth is simulated from emergence to harvest. The input data used includes climatic data and ecophysiological data. On the other hand, the output information includes: dry matter production, grain/fruit yield, optimal sowing and harvesting dates, and water consumption, among other information. The model considers the following activities: wheat, maize, potatoes, sugar beets, common beans, peaches, apples, oranges, grapes, and forestry. The results are computed at the commune level (340 communes), while the scenarios modeled are the IPCC A2 and B2 for two periods: 2040 and 2070 (Intergovernmental Panel on Climate Change 2000). According to the results, the most affected activities due to the impacts of climate change are located in the northern region.

In 2009, the Economic Commission for Latin America and the Caribbean (CEPAL) conducted a study analyzing the economic impacts of climate change in Chile (CEPAL 2009). Although the study does not focus on the agricultural sector, this sector is analyzed as part of the Chilean economy. Using an econometric model (assuming exogenous prices), the authors simulated the expected changes in land allocation due to climate change. The analyzed crop yield changes and activities are those used by Santibáñez, *et al.* (2008).

Their results suggest that net incomes will increase from the Biobío region to the south, while in the northern region the net incomes will decrease. This is because climate scenarios predict a large decrease in precipitation in the northern region. In the worst-case scenario, the agricultural sector will loose 15% of its income (A2 scenario), while in the best scenario the incomes will increase by 1% (B2 scenario).

Using the yield changes computed by Santibáñez, *et al.* (2008), the Agricultural National Research Center (INIA) conducted a study in 2009 analyzing both vulnerability and adaptation options to climate change in two agro-ecological zones in central Chile (Gonzalez 2009). Using yield changes, the author computed the net income at a farm level (current and simulated). With this information, and using primary information collected through surveys, the author defined the vulnerability level using indexes such as: ratio of irrigated to rainfed land, a farm's use of capital, and the link with foreign trade.

Results show that under the A2-2020 scenario, the economic impacts due to yield changes are within the range -USD11 million to -US20 million. The negative impacts are associated with decreases in the central valley's fruit productivity, while the positive impacts are related to increases in the sub-Andean region's crop productivity.

Finally, in 2010 the Agricultural Agency conducted a study at the national level in order to account for the magnitude of the economic impacts climate change could have on the Chilean agricultural sector (ODEPA 2010). The study updates the information generated by Santibáñez, *et al*. (2008), increasing the number of activities analyzed, from 17 to 25. In this study, the authors used an econometric model (assuming exogenous prices) in order to account for the land allocation change due to expected yield changes, and expected changes in the labor demand.

The main conclusions of the study show that climate change will have uneven impacts across the country, with the northern region being the most affected. Results also show a southward movement of the land allocated to annual crops and cereals. In general terms, a 7% decrease in the land devoted to cereal and fruit production is expected under the A2-2040 and B2-2040 scenarios. While the forestry sector shows an increase of 3% in all scenarios. The net income decreases by 5% under the A2-2040 and B2-2040 scenarios.

In general, the use of agricultural multimarket models has been restricted to policy analysis, with few studies addressing climate change impacts in general, and water issues in particular. On the other hand, climate change impacts on the Chilean agricultural sector have mainly been analyzed through the use of econometric techniques, or using simple accounting methods. In each case, the exogenous price assumption is used. The model presented in the next section assumes endogenous prices, which is a major improvement in relation to the previous studies in Chile and Latin America. Furthermore, the use of mathematical programming methods is more suitable to analyze agricultural issues than the econometric techniques. This is mainly because these techniques make it possible to analyze *ex-ante* policy consequences, and answer “*what if*...” questions, which are especially relevant in order to analyze the consequences of policies addressing climate change issues.

IV.3. The Agricultural Multimarket Model

IV.3.1 Model Description

The Agricultural Multimarket model (AMM) is a mathematical programming model designed to analyze the agricultural sector with high geographical disaggregation. It includes the major agricultural activities within the area, and differentiates between water provision systems (rainfed and irrigated), among other features.

The core of the AMM includes two sets of equations. The first set describes the behavior of the agricultural producers (supply), while the second set describes the behavior of the consumers (demand). Within this framework, the model maximizes the total surplus of the agricultural sector: producer surplus plus consumer surplus (*CPS*).

The supply side is characterized by detailed information at the producer level in order to represent a system of outputs supply and inputs demand, which is the result of the assumed profit maximization behavior. The information is differentiated by activity and geographical area, including: area planted, yield, variable costs, and labor demand, which is used to compute total costs, gross margin, and net revenues. The information presented above is complemented with supply elasticities for each activity.

The demand side of the agricultural multimarket model is composed of a matrix of own-price elasticities for agricultural products, which are used to calibrate a linear demand system. These parameters indicate which changes are expected in the demand when supply prices change as a result of a certain policy, or in this specific case, as a consequence of climate change.

The last section of the model includes a set of equations representing the market clearing conditions. The clearing conditions are imposed on each activity and its associated product, implying that production should be equal to consumption.

The core model is optimized considering a series of endowment restrictions, such as: total land, irrigated land, and water. These restrictions imply that the use of a certain resource cannot be larger than its initial endowment.

Using Positive Mathematical Programming (PMP), the model is calibrated to the base year. Using the PMP method it is possible to achieve a perfect calibration for: area planted, products and prices, avoiding the dependency between parameters and constraints (Howitt 1995).

IV.3.2 Model Structure

The model's development involves a three-step procedure. In the first step, a mathematical programming model is built in order to maximize the region's farm net income by allocating land and irrigation water to crops. This model takes all relevant data and farming conditions into account, and includes: 1) the objective function describing the farmers' behavior as rational agents; 2) the set of explicit constraints related to resource availability (land, irrigated land, water) and institutional conditions (policy and environmental).

The main decision variables are cropland allocation and irrigation technology choice. $X_{r,a,s}$ denotes the area (ha) allocated to crop *a* with farming system *s* in region *r*. The model can be compactly written as (subscript *i* denotes the resource type):

$$Z = \sum_r \sum_a \sum_s \left(p_a * y_{r,a,s} - AC_{r,a,s}\right) * X_{r,a,s} \qquad [4.1]$$

$$AC_{r,a,s} = v\cos t_{r,a,s} \qquad [4.2]$$

$$\sum_a \sum_s r_{i,r,a,s} * X_{r,a,s} \le b_{i,r} \qquad [4.3]$$

$$X_{r,a,s} \ge 0 \qquad [4.4]$$

In equation [1], *Z* denotes the objective function value (profit function), $AC_{r,a,s}$ is the vector of average costs per unit of activity, $v\cos t_{r,a,s}$ represents the observed variable costs per unit of activity. In equation [4.1] p_a is the price of crop *a*, $y_{r,a,s}$ is the yield per hectare of crop *a*, in region *r*, using system *s*. In equation [4.3] $r_{i,r,a,s}$ represents the matrix of coefficients in resource/policy constraints, and $b_{i,r}$ is the vector of available resource quantities. Finally, equation [4.4] represents the non-negativity constraints on land allocation.

The resource constraints depicted in equation [4.3] include: total land, irrigated land, and water availability. The model considers that climate change will modify the water availability in each region.

In the second step, a non-linear objective function is calibrated using PMP based on observed activity levels for the base situation. The model assumes constant average revenues (regardless of the level of activity) and increasing average costs, as well as non-linear cost function, which captures all production conditions not explicitly modeled. The average cost function of activity *a* can be written:

$$AC_{r,a,s} = \alpha_{r,a,s} * \left(X_{r,a,s}\right)^{\beta_{r,a,s}} \qquad [4.6]$$

The cost function parameters $\alpha_{r,a,s}$ and $\beta_{r,a,s}$ are derived from a profit-maximizing equilibrium that maximizes equation [4.1] subject to [4.3], [4.4], and [4.6].

Additional conditions are: 1) In the base-run, the estimated average cost equals the observed average cost for each activity; 2) supply elasticities are exogenous; 3) The assumption of optimal farmers' behavior can be extended to new activities, and cost function parameters can then be approximated by means of optimality conditions.

On the other hand, the model demand core includes a set of lineal demand equations as presented below:

$$P_p^d = \varphi_p + \lambda_p * q_p^d \qquad [4.7]$$

Where P_p^d is the demand price of product *p*, φ_p is the constant term of the demand function, λ_p is the slope term of the demand function, and q_p^d is the quantity demanded of product *p.*

In the third step, once the cost function parameters have been derived, the calibrated non-linear model is specified. The AMM maximizes the *CPS* [4.8] subject to [4.3], [4.4], [4.6], and [4.7]. Following McCarl and Spreen (2011), the final model is presented below.

$$Max : cps = \sum_p \left(\varphi * q_p^d + \frac{1}{2} * \lambda_p * \left(q_p^d\right)^2 \right) - TTC \qquad [4.8]$$

$$\sum_a \sum_s r_{i,r,a,s} * X_{r,a,s} \le b_{i,r}$$

$$X_{r,a,s} \ge 0$$

$$AC_{r,a,s} = \alpha_{r,a,s} * \left(X_{r,a,s}\right)^{\beta_{r,a,s}}$$

$$P_p^d = \varphi_p + \lambda_p * q_p^d$$

Where *TTC* represents the total costs:

$$TTC = \sum\sum\sum\left(AC_{r,a,s} * X_{r,a,s}\right) \qquad [4.9]$$

The model as presented above reproduces the activity levels observed for the base-run and allows us to simulate hypothetical climate change scenarios. The model structure is flexible enough to incorporate all relevant environmental constraints and policy instruments.

Uncertainty is included in the modeling framework using the Monte Carlo method. The Monte Carlo method allows us to simulate the behavior of a random variable according to its distribution. In this specific case, the model assumes that the water availability is random variables. Considering that it is uncertain how climate change impacts will affect water availability, it is necessary to assume a probability distribution to represent its behavior. Based on expert opinions, it is assumed that water availability follows a Gamma distribution. Thus, several sets of water availability scenarios are simulated using both uniform pseudo-random numbers and the inverse probability distribution function (Hardaker, Huirne and Anderson 1997). The Gamma probability distribution function (PDF) and its key parameters are shown in equations [4.10] to [4.12].

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\exp\left(-\frac{x}{\beta}\right)x^{\alpha-1} \qquad [4.10]$$

$$\alpha = \frac{\left[E(x)\right]^2}{\sigma^2} \qquad [4.11]$$

$$\beta = \frac{\sigma^2}{E(x)} \qquad [4.12]$$

Where, α is the shape parameter, and β the inverse scale parameter. With $\alpha,\beta > 0$. *E(x)* is the mean of the distribution, and σ^2 the variance.

IV.4. The Economic Impacts of Climate Change on the Chilean Agricultural Sector.

Chile is a long, narrow country located in the southeast corner of South America. It covers 756,000 km^2, with a coastline of 4,300 km, and a population of 17.4 million inhabitants.

Due to its geographical characteristics, Chile has diverse climatic conditions throughout its diverse regions. The climate ranges from desert in the north, to alpine tundra and glaciers in the eastern and southeastern areas. At the administrative scale, northern Chile, characterized by an arid and semiarid climate, includes regions [XV-III]. Central Chile, characterized by a Mediterranean climate, includes regions [IV-VIII]. Southern Chile, characterized by an oceanic climate, includes regions [IX-IX], while the austral area, characterized by a sub-polar climate, includes the XII region (see Annex IV.1).

Chile has a large endowment of water resources in both surface and groundwater. However, the water resources are characterized by a high variability in water supply, as well as an uneven distribution of water across the country. Water availability throughout the year is characterized by seasonal behavior, with high precipitation in the winter, and water shortages in the summer.

Across regions, the mean annual rainfall varies between 0-10 millimeters in the northern desert, to more than 3,000 millimeters in the southern region. This uneven distribution has serious impacts on the water available for human consumption, as well as for the agricultural sector.

Within the climatic context presented above, the total agricultural land (18.4 million ha) is divided as follows: 1.7 million ha of cultivated land, 14.03 million ha of grassland, and 2.7 million ha of forested land. Considering only the cultivated land (1.7 million ha), 76% is devoted to annual and permanent crops, while 23.5% is devoted to fodder (INE 2007).

The main annual and permanent crops are: fodder (29.9%), cereals (28%), fruits (18%), industrial crops (8.3%), vineyards (7.6%), and vegetables (5.5%), among other agricultural activities. Regarding farm size, more than 90% of farms have an area within the range of 1 ha to 20 ha (INE 2007).

Irrigation is a widely spread practice across the country. Chile has 1.1 million ha under some irrigation scheme, representing 64.7% of the total cultivated land. The main activities under irrigation are: industrial crops, fruits, and vineyards (INE 2007). At the macroeconomic level, the agricultural sector represents 4% of the Chilean GDP, and it employs 13.6% of the total labor force (The World Bank 2007).

IV.4.1 Model Specification

The application of the multimarket model includes a smaller area than those considered in previous studies. The area being analyzed here includes regions from Atacama in the north to Los Lagos in the south. This area includes 265 communes, grouped into 36 provinces, and 10 regions. The agricultural sector is represented by 21 activities, aggregated according to the following categories: Crops (9), Fruits (10), and Forestry (2); the model considers irrigated and rainfed activities, accounting for 3.3 million ha.

The crops considered are: rice (irrigated), oats (rainfed), common beans (irrigated), maize (irrigated), potatoes (irrigated and rainfed), alfalfa (irrigated), and wheat (irrigated and rainfed). The fruits considered are: cherries, plums, peaches, apples, oranges, walnuts, olives, avocadoes, pears, grapes, and vine grapes. Finally, the model also includes the area devoted to forestry, including: pine and eucalyptus, both rainfed activities. The agricultural sector depicted above represents 95.5% of the agricultural activities developed within the study area.

The core information used in the model (area, production, yield) is from the year 2007, and comes from the National Agricultural Census (INE 2007), considering a disaggregation at communal level. The information about costs per commune, activities and watering systems (irrigated, rainfed), as well as labor intensity is the same information that was used in the ODEPA study (ODEPA 2010). Prices were taken from the Agricultural Agency's website (ODEPA 2010), while the elasticities used to calibrate the model were collected from previous studies (Quiroz, *et al*. 1995, Foster, *et al.* 2011, CAPRI Model 2008).

The current water availability per commune was computed using the crop irrigation requirements simulated by Santibáñez *et al.* (2008). In order to include climate change impacts, a 25% decrease in water availability was assumed for the Atacama region (Zone 1), -35% for the Coquimbo and Valparaiso regions (Zone 2), and -25% for the Metropolitana region to the south (Zone 3), according to the expected changes in precipitation for the A2-2040 climate change scenario. (CEPAL 2009)

IV.4.2. Results

At the national level, the expected changes in water availability have a minor impact on the total land allocation, with total agricultural land decreasing by 8,300 ha. However, the expected impact across regions is uneven, with the largest impacts in the northern region. For instance, the Atacama region decreases its agricultural land by 13%, equivalent to 412 ha, while for both the Coquimbo and the Valparaiso regions the decrease is only 7.6% (on average), with a decrease of

2,800 ha and 4,800 ha, respectively. On the other hand, from the Metropolitana region to the south, the decrease in agricultural land is negligible (0.04%). Due to the decrease in water availability, the total rainfed land decreases by 40,200 ha, while the irrigated land increases by 31,900 h. (Table 4.1).

Table 4.1. Land Allocation (ha)

Region	Rainfed Land		Irrigated Land	
	Baseline	Climate Change	Baseline	Climate Change
Atacama	0	0	3,151.8	2,738.8
Coquimbo	342.3	423.7	28,770	25,811
Valparaiso	46,094.8	47,698.7	45,222	38,744.4
Metropolitana	7,847.2	5,992.8	68,945.4	70,743.1
Ohiggins	133,900	124,229.6	140,042.5	149,705
Maule	489,754.8	467,521.3	145,586.9	167,820.4
Biobio	1,019,463.9	1,010,598.7	66,250.6	75,115.9
Araucania	702,407.2	703,015.1	9,865.3	9,201.2
Los Rios	253,127	253,266.2	939.6	800.4
Los Lagos	110,027.4	110,017.7	413.9	423.6

Although the change in total land allocation is minor, the impact this has on agricultural production is quite relevant, with fruit production increasing by 15% (700,000 ton) and forest production decreasing by 2% (12,000 ton). On the other hand, crop production decreases by 3% (133,000 ton). These figures imply that the expected impact of climate change will have serious distributional effects with significant differences across sectors and regions. At the regional level, the O'Higgins region represents 29% of the total crop production reduction; and the Maule region represents 63% of the increase in fruit production, as well as 42% of the increase in forest production. Detailed results are presented in Table 4.2.

Detailed results show that land allocated to plums decreases by 76%, followed by walnuts (-53%), pears (-41%), and olives (-29%). On the other hand, vineyards increase by 43%, followed by oranges (34%), and apples (30%). Details are shown in Table 4.3.

Table 4.2. Agricultural Production (ton)

Region	Crops		Fruits		Forest	
	Baseline	Climate Change	Baseline	Climate Change	Baseline	Climate Change
Atacama	3,226	3,976	31,546	27,153	0	0
Coquimbo	69,799	61,088	330,008	328,453	0	0
Valparaiso	175,855	178,131	400,038	363,314	5,561	5,769
Metropolitana	425,425	445,401	545,950	532,821	684	497
Ohiggins	766,499	727,789	1,402,048	1,608,156	30,190	28,392
Maule	601,308	582,089	1,313,670	1,753,406	123,887	118,657
Biobio	696,142	751,222	268,899	358,119	269,530	266,041
Araucania	887,860	925,987	98,943	120,962	150,553	148,977
Los Rios	175,261	194,844	20,040	17,905	64,830	64,694
Los Lagos	297,205	361,754	9,176	10,230	12,301	11,924

Table 4.3. Land Allocation by Activity (ha)

Activity	Baseline	Climate Change
Alfalfa	42,520	43,292
Apple	35,642	46,478
Avocado	35,857	34,737
Cherry	8,483	5,792
Common Bean	7,617	9,025
Eucalyptus	878,268	860,535
Grapes	8,544	9,288
Maize	95,275	91,375
Oat	61,520	61,760
Olive	12,365	8,694
Orange	6,186	8,290
Peach	15,366	15,759
Pear	5,887	3,456
Pine	1,631,131	1,593,414
Plum	16,207	3,919
Potato Rainfed	28,653	37,250
Potato Irrigated	19,309	20,006
Rice	21,193	25,507
Vineyard	118,880	169,636
Walnut	12,702	5,929
Wheat Rainfed	163,393	169,805
Wheat Irrigated	47,157	39,921

Results by area and activity show that there is a direct relationship between the expected change in water availability and the final change in land allocation. As was established above, the total agricultural land decreases by 8,300 ha, out of which the area most affected by climate change, Zone 2, accounts for 95% (7,751 ha).

Detailed results by zone show that in relative terms, Zone 1 is the most affected by climate change, with a 13% (413 ha) decrease in agricultural land. Within Zone 1, the land allocated to pears, plums, and walnuts is zero under the climate change scenario. On the other hand, common beans, vineyards, and oranges show the largest increase in land allocation, 83%, 49% and 41%, respectively.

The largest decrease in land allocation within Zone 2 is related to avocadoes (5,824 ha), walnuts (3,756 ha), and olives (2,300 ha). On the other hand, the activities that increase their land are vineyards (2,787 ha), eucalyptus (930 ha), and oranges (642 ha).

In general, land allocation in Zone 3 remains almost unchanged under the climate change scenario, with a decrease of 121 ha. However, this zone shows great differences across activities, with a large reallocation of land from forest to crops and fruits. Among crops, the largest increase is reported for rainfed potatoes (8,597 ha), followed by rainfed wheat (6,239 ha), and rice (4,314 ha). Regarding fruits, the most extreme values are those representing the increase in land devoted to vineyards (47,700 ha), and the decrease in land devoted to plums (12,000 ha), these figures represent a change of 46% and -75%, respectively. Details are shown in Table 4.4[12].

The total agricultural production increases by 9%, despite the decrease of 8,300 ha due to climate change. The largest decreases are reported for plums (-76%), walnuts (-55%) and pears (38%), these fruits reduce their production by 330,000 ton. On the other hand, vineyards, oranges and apples increase their production by more than 1,000,000 tons. In general, the total agricultural production changes from 9.1 million tons to 9.9 million tons (Table 4.5).

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[12] Detailed results in Annex IV.2

Table 4.4 Land Allocation by Activity and Zone.

Activity	Zone 1		Zone 2		Zone 3	
	Baseline	A240	Baseline	A240	Baseline	A240
Crops	235	292	17,585	17,151	468,817	480,498
Alfalfa	0	0	7,887	7,347	34,633	35,945
Common Bean	5	9	314	334	7,298	8,683
Maize	0	0	1,502	1,558	93,773	89,816
Oat	0	0	402	411	61,118	61,349
Rainfed Potato	0	0	0	0	28,653	37,250
Irrigated Potato	230	283	4,538	4,408	14,541	15,314
Rice	0	0	0	0	21,193	25,507
Sugar Beet	0	0	2,001	2,174	161,393	167,632
Rainfed Wheat	0	0	942	918	46,215	39,003
Irrigated Wheat	2,917	2,447	58,809	49,989	214,391	259,542
Fruits	0	1	259	303	35,382	46,175
Apple	380	410	25,482	19,657	9,995	14,669
Avocado	0	0	172	20	8,311	5,772
Cherry	0	0	5,268	5,422	3,276	3,865
Grapes	1,977	1,257	2,787	485	7,601	6,953
Olive	100	141	1,731	2,374	4,354	5,775
Orange	15	15	4,610	4,796	10,741	10,948
Peach	4	0	309	1	5,574	3,455
Pear	0	0	292	0	15,915	3,919
Plum	417	624	13,616	16,404	104,846	152,609
Vineyard	23	0	4,283	528	8,396	5,402
Walnut	0	0	44,035	45,538	2,465,364	2,408,411
Forest	0	0	7,279	7,853	1,623,852	1,585,561
Pine	0	0	36,756	37,685	841,512	822,850
Eucalyptus	235	292	17,585	17,151	468,817	480,498

Table 4.5. Agricultural Production (ton).

Activity	Baseline	Climate Change
Alfalfa	785,503	802,623
Apple	1,247,859	1,628,683
Avocado	308,622	310,624
Cherry	45,749	31,723
Common Bean	14,179	16,882
Eucalyptus	166,155	163,568
Grapes	219,126	238,168
Maize	1,075,610	1,030,975
Oat	281,075	282,663
Olive	162,053	122,838
Orange	136,355	183,357
Peach	365,244	375,072
Pear	90,841	56,019
Pine	491,382	481,383
Plum	357,640	83,653
Potato	773,605	911,366
Rice	108,323	129,438
Vineyard	1,449,213	2,073,711
Walnut	37,615	16,673
Wheat	1,060,285	1,058,336

Results by zone and activity show that the impact on crop production is unevenly distributed across the country, with crop production increasing by 23% in Zone 1 and by 4% in Zone 3, while in Zone 2 it decreases by 3%. Fruit production decreases by 10% on average in Zone 1 and 2. Forestry production remains unchanged in Zone 1, increases by 4% in Zone 2, and decreases by 2% in Zone 3.

Potato production is the only crop that increases its production within Zone 1, by approximately 750 tons (23%). Regarding fruits, the largest decrease is reported in olive production (7,800 tons - 43%). On the other hand, vineyards increase their production by approximately 2,000 tons, representing an increase of 48%.

Zone 2 reports a decrease of 44,500 tons (-5%) in agricultural production, out of which avocadoes, olives, and walnuts account for the largest share. On the other hand, vineyards, oranges, and grapes increase their production by 48,000 tons.

The largest increase in production in Zone 3 is reported for vineyards (590,000 tons), representing an increase in production of 46%. In relative terms, avocadoes show an increase in production of 58%, equivalent to 47,000 tons. Wheat and maize decrease their production by 47,000 tons, making maize the most affected crop (-45,000 tons). This decrease in production is compensated by the increase reported for potatoes (140,00 tons). Due to this figure, the final crop production increases by 139,000 tons (4%). Details are presented in Table 4.6.

Table 4.6. Agricultural Production by Activity and Zone

	Zone 1		Zone 2		Zone 3	
Activity	Baseline	Climate Change	Baseline	Climate Change	Baseline	Climate Change
Crops	3,226	3,976	245,654	239,220	3,849,699	3,989,087
Alfalfa	0	0	145,376	140,337	640,127	662,286
Common Bean	7	14	526	568	13,646	16,300
Maize	0	0	15,797	16,516	1,059,813	1,014,459
Oat	0	0	1,592	1,626	279,483	281,037
Potato	3,219	3,962	71,142	68,600	699,244	838,804
Rice	0	0	0	0	108,323	129,438
Wheat	0	0	11,222	11,573	1,049,063	1,046,763
Fruits	31,546	27,153	730,046	691,767	3,658,726	4,401,600
Apple	9	12	9,523	11,104	1,238,327	1,617,566
Avocado	5,519	5,802	221,692	176,340	81,411	128,482
Cherry	0	0	1,061	110	44,688	31,613
Grapes	0	0	135,325	139,291	83,801	98,876
Olive	18,366	10,533	29,972	6,596	113,716	105,708
Orange	3,150	4,443	38,972	53,217	94,234	125,698
Peach	266	266	122,137	127,140	242,841	247,665
Pear	47	0	3,983	14	86,811	56,004
Plum	9	0	6,811	0	350,819	83,653
Vineyard	4,132	6,096	146,637	176,591	1,298,445	1,891,023
Walnut	48	0	13,934	1,363	23,633	15,310
Forest	0	0	5,561	5,769	651,975	639,183
Pine	0	0	1,474	1,576	489,908	479,807
Eucalyptus	0	0	4,087	4,193	162,068	159,375

Along with the agricultural supply impacts described above, the AMM model also accounts for impacts on agricultural demand. As is shown in Table 4.5, the impacts of climate change affect the agricultural supply differently, with some products increasing their supply (for instance: alfalfa, apples, and avocadoes), while others decrease their supply (for instance: cherries, maize, and olives). Table 4.7 shows the associated demand prices for each activity. As is shown in this table, the inverse relationship between demand and supply holds for the agricultural sector.

Table 4.7. Demand Prices (USD/ton)

Product	Baseline	Climate Change	% Change
Alfalfa	174.3	164.8	-5.4%
Apple	692.3	340.2	-50.9%
Avocado	8,487.7	8,418.8	-0.8%
Cherry	1,444.8	2,183.0	51.1%
Common Bean	2,279.6	1,410.6	-38.1%
Eucalyptus	2,193.4	2,278.8	3.9%
Grapes	534.0	476.0	-10.9%
Maize	217.3	239.8	10.4%
Oat	195.8	194.7	-0.6%
Olive	1,128.1	1,469.3	30.2%
Orange	1,331.3	413.5	-68.9%
Peach	446.5	429.3	-3.8%
Pear	428.4	633.7	47.9%
Pine	1,265.2	1,329.5	5.1%
Plum	202.0	395.5	95.8%
Potato	636.3	258.6	-59.4%
Rice	1,272.6	652.4	-48.7%
Wine	1,568.7	817.6	-47.9%
Walnut	2,604.0	4,416.2	69.6%
Wheat	286.5	288.2	0.6%

According to Table 4.7, crop prices decrease by 20%; this change is driven by the large decrease in the price of potatoes and rice, 59% and 49%, respectively. On the other hand, fruit prices increase by 16%, with plums (96%), walnuts (69%), and oranges (69%) being the most affected products.

All the changes described above drive a 16% decrease in the agricultural net income, equivalent to USD344 million (171,8 billion Chilean Pesos). At the regional level, the Metropolitana, O'Higgins and Maule regions account for 67% of the total decrease in income (USD 248 million).

The Metropolitana region loses the largest proportion of its net income: -54%, followed by the Valparaiso region (-27%), and the Atacama region (15%). On the other hand, the Los Rios, Araucania, and Los Lagos regions experience the smallest losses due to climate change (1%-3%). Results by Zone show that losses in Zone 3 are the smallest across the country (-14%), followed by Zone 1(-23%), and Zone 2 (-21%). Details are presented in Table 4.8.

Table 4.8. Net Income by Region (Million USD)

Region	Baseline	Climate Change	Change (%)
Atacama	13	10	-23%
Coquimbo	112	95	-15%
Valparaiso	202	147	-27%
Metropolitana	186	89	-52%
Ohiggins	388	308	-21%
Maule	425	359	-16%
Biobio	437	418	-4%
Araucania	296	291	-2%
Los Rios	104	103	-1%
Los Lagos	50	48	-3%
Total	2,212	1,868	-16%

As is shown in Table 4.8, the zone most affected by climate change (Zone 2) is not the most affected in economic terms. This is because land distribution across zones is uneven, with Zone 1 accounting for 0.1% of the total agricultural land, Zone 2 (3.7%), and Zone 3 (96.2%). Thus, to have a better picture of the economic impacts by Zone, it is necessary to adjust the net income according to the agricultural land that exists in each zone.

By adjusting the net income by zone, the results are consistent with the simulated climate change scenarios, with Zone 2 showing the largest decrease in its income per hectare (-18%), followed by Zone 3 (-14%), and Zone 1 (-12%). Table 4.9 shows details at the regional level.

Table 4.9. Net Income by Hectare (USD)

Region	Baseline	Climate Change
Atacama	4,120	3,642
Coquimbo	3,836	3,612
Valparaiso	2,215	1,704
Metropolitana	2,420	1,165
Ohiggins	1,415	1,124
Maule	668	565
Biobio	403	385
Araucania	415	409
Los Rios	410	407
Los Lagos	450	434

This figure should be considered carefully, mainly because the land allocation computed by the AMM model is not the result of a profit maximization problem, instead the model maximized the total welfare associated with the Chilean agricultural sector, using the Consumer plus Producer Surplus (CPS) as the measurement unit. By using the *CPS*, the impact of climate change on the agricultural welfare is USD 757 million, changing from USD15.6 billion to USD14.8 billion (-4.8%), approximately 378 billion Chilean Pesos.

Considering that the agricultural model presented here accounts for climate change impacts on water availability, the welfare implications should be considered as a lower bound because the model does not account for climate change impacts on rainfed agriculture. In order to have an approximation about the consequences of this approach, a new version of the model was running. The new version includes the expected changes on rainfed yields (reported by Santibáñez, *et al*. 2008), along with changes in water availability.

Results suggest that the differences on welfare are quite small, with loses in the *CPS* equivalent to 3.9%, versus the 4.8% computed in the original version. However, the net income increases 3.7% (USD 71 million), versus the decrease showed in the original version (-3.9%). This income difference is explained by the increase reported for oat, potatoes, and wheat producers. (Details in Annex IV.3).

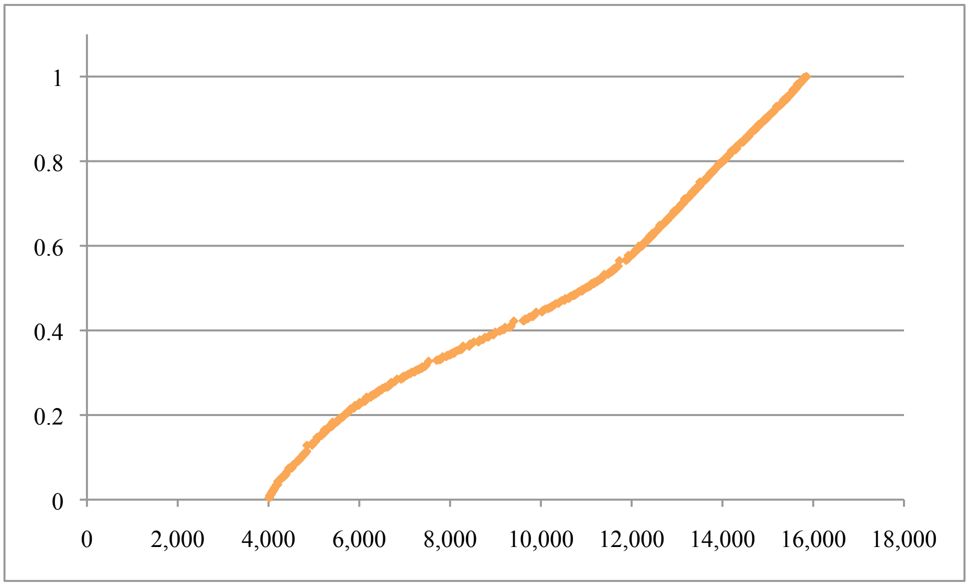
In order to account for the uncertainty associated with the change in water availability, a series of Monte Carlo simulations were developed. The objective is to determine the probability of a certain *CPS* level's occurrence, depending on the water scenario analyzed. As was established before, the model assumes that the water availability follows a Gamma distribution.

For simplicity, the Gamma distribution parameters are computed per activity and Zone, using the mean and the variance of the water availability sample. Using these parameters, a series of 400 water scenarios were computed. The cumulative distribution function for the Consumer plus Producer Surplus at the country level is presented in Figure 4.1.

Figure 1 shows that the cumulative distribution function does not start in zero, this is because the impacts of climate change are associated to the irrigated agriculture. Thus, even with zero water availability for irrigation the *CPS* is positive due to the demand and supply interaction within the rainfed sector.

The analysis of the distribution shows that the 25th percentile is USD6.347 billion, the 50th percentile is USD11 billion, and the 75th percentile is USD13.5 billion. Considering these figures, the welfare impact reported for the climate change scenario (USD14.8 billion) is above the 75th percentile implying a likely result.

Figure 4.1. Cumulative Distribution Function: Consumer plus Producer Surplus (USD).



In general, the results reported here are consistent with those reported by previous studies with large impacts on the northern zone. However, the AMM does not predict negative impacts on fruits production, or cereals, as previous studies did (Gonzalez, 2009; ODEPA, 2010). This is because in the model structure the demand prices play a key role on the final land allocation, by changing the relative profits.

IV.5. Conclusions

Climate change will have vast and diverse impacts on the agricultural sector across the world, with developing countries presenting the most vulnerable regions. Considering the high level of policy intervention that the agricultural sector already has, a modeling approach that considers all the connections within it is essential; and the model presented in this study fulfills this requirement. In addition, the model presents a very detailed picture of the agricultural sector, with a high level of geographical detail aiming to identify local conditions that could influence the final economic consequences of climate change.

The model depicted here is a tool flexible enough to be applied in several situations in which information access is a constraint. As was shown, the main source of information is the Agricultural Census, which is complemented with secondary data that should be easy to collect if the objective is to use this model in other countries.

Climate change impacts on the Chilean Agricultural sector are vast, with considerable economic consequences across regions. At the regional level, there is a complete re-allocation of land, with the northern zone showing large changes. However, this land reallocation does not seriously impact the total agricultural production. On the other hand, the results do not show a clear southward movement, as previous studies have. This is because the AMM considers feedback effects that moderate the impacts of the expected water availability changes, mainly through prices.

According to the results, climate change will not have significant absolute consequences. However, climate change will have large distributional consequences, with plum, walnut, and avocado producers being worse-off compared to vineyard, orange, and apple producers. This could worsen the inequity that already exists in Chile, presenting additional challenges for coping with climate change.

Regarding demand prices, the average decrease of 1% within agricultural products hides large differences across sectors. For instance, the 16% increase in fruits could have serious impacts on the family budget, since fruits are a typical component of the basic diet in Chile.

However, despite the high level of detail in which the agricultural sector is modeled, some drawbacks remain. These limitations are related to the demand system, input substitution, and irrigation facilities.

The way in which the demand system is modeled, does not allow for the analysis of poverty issues, that could be a consequence of changes in the agricultural sector’s production structure.

Nevertheless the model includes uncertainty the predicted prices do not consider critical issues for agricultural prices, such as the impact of the storage capacity, or international markets.

Due to a lack of information, the model does not account for substitution options between water and other inputs, nor does it consider the use of irrigation deficits as an adaptation option to climate change. On the other hand, the model assumes that the expansion of the irrigated area is costless, underestimating the costs associated to the change in the crop pattern. Finally, climate change impacts on the rainfed sector are modeled as a productivity shock, without an explicit functional form relating water and agricultural yields. Nevertheless, the structure of the model allows us to include these topics once the data becomes available.

The re-allocation of land across the country implies several impacts that are not modeled here, such as: environmental impacts due to land use changes, as well as social impacts. Regarding the latter, the use of these types of models should be part of a more complete analysis of climate change in the agricultural sector, these analyses should explicitly include the social component. This is very important considering the social consequences of changes in farming practices that are deeply rooted within the farmers' communities.

IV.6. References

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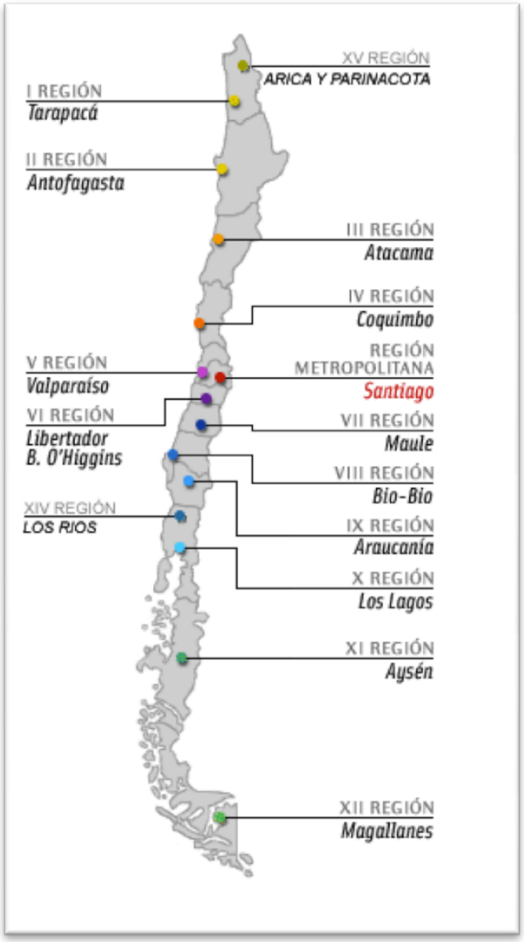
Annex IV.1. Map of Chile

Figure A.IV.1.1 Map of Chile



Annex IV.2. Detailed Results

Table A.IV.2.1 Land Allocation by Activity and Region.

Zone	Region	Activity	System	Baseline	Climate Change
1	Atacama	Common Bean	Irrigated	4.7	8.6
1	Atacama	Potato	Irrigated	230.2	283.4
1	Atacama	Plum	Irrigated	0.4	
1	Atacama	Peach	Irrigated	14.9	14.8
1	Atacama	Apple	Irrigated	0.4	0.5
1	Atacama	Orange	Irrigated	100.3	141.4
1	Atacama	Walnut	Irrigated	22.6	
1	Atacama	Olive	Irrigated	1,976.6	1,256.6
1	Atacama	Avocado	Irrigated	380.1	409.9
1	Atacama	Pear	Irrigated	4.4	
1	Atacama	Vineyard	Irrigated	417.3	623.7
2	Coquimbo	Common Bean	Irrigated	154.3	160.6
2	Coquimbo	Maize	Irrigated	530.2	532.9
2	Coquimbo	Potato	Irrigated	3,064.6	2,647.2
2	Coquimbo	Wheat	Rainfed	341.1	421.8
2	Coquimbo	Wheat	Irrigated	879.1	852.4
2	Coquimbo	Cherry	Irrigated	26.5	
2	Coquimbo	Peach	Irrigated	616.3	604.7
2	Coquimbo	Apple	Irrigated	3.6	4.7
2	Coquimbo	Orange	Irrigated	724.2	969.4
2	Coquimbo	Walnut	Irrigated	1,619.3	213.0
2	Coquimbo	Olive	Irrigated	1,771.6	162.5
2	Coquimbo	Avocado	Irrigated	6,660.4	5,750.4
2	Coquimbo	Pear	Irrigated	220.2	0.8
2	Coquimbo	Grapes	Irrigated	5,267.9	5,422.1
2	Coquimbo	Vineyard	Irrigated	6,443.6	8,178.6
2	Coquimbo	Alfalfa	Irrigated	788.4	311.8
2	Coquimbo	Pine	Rainfed	1.2	1.8
2	Valparaiso	Oat	Rainfed	402.0	410.7
2	Valparaiso	Common Bean	Irrigated	159.6	173.2
2	Valparaiso	Maize	Irrigated	971.6	1,025.3
2	Valparaiso	Potato	Irrigated	1,473.1	1,761.2
2	Valparaiso	Wheat	Rainfed	1,659.5	1,751.9
2	Valparaiso	Wheat	Irrigated	63.3	65.9
2	Valparaiso	Cherry	Irrigated	145.6	20.2
2	Valparaiso	Plum	Irrigated	291.5	
2	Valparaiso	Peach	Irrigated	3,993.4	4,191.5
2	Valparaiso	Apple	Irrigated	255.8	298.4
2	Valparaiso	Orange	Irrigated	1,007.1	1,404.4
2	Valparaiso	Walnut	Irrigated	2,663.9	314.6

2	Valparaiso	Olive	Irrigated	1,015.6	322.2
2	Valparaiso	Avocado	Irrigated	18,821.3	13,907.1
2	Valparaiso	Pear	Irrigated	89.1	
2	Valparaiso	Vineyard	Irrigated	7,172.5	8,225.0
2	Valparaiso	Alfalfa	Irrigated	7,098.6	7,035.5
2	Valparaiso	Pine	Rainfed	7,277.7	7,850.7
2	Valparaiso	Eucalyptus	Rainfed	36,755.6	37,685.3
3	Metropolitana	Oat	Rainfed	109.8	117.6
3	Metropolitana	Common Bean	Irrigated	194.4	214.0
3	Metropolitana	Maize	Irrigated	11,561.8	11,846.4
3	Metropolitana	Potato	Irrigated	4,412.6	4,955.1
3	Metropolitana	Wheat	Rainfed	587.5	599.5
3	Metropolitana	Wheat	Irrigated	2,236.2	1,896.8
3	Metropolitana	Cherry	Irrigated	811.0	458.6
3	Metropolitana	Plum	Irrigated	5,231.7	368.3
3	Metropolitana	Peach	Irrigated	2,812.3	2,896.1
3	Metropolitana	Apple	Irrigated	259.2	341.6
3	Metropolitana	Orange	Irrigated	887.4	1,218.0
3	Metropolitana	Walnut	Irrigated	4,905.8	3,012.2
3	Metropolitana	Olive	Irrigated	1,198.6	883.7
3	Metropolitana	Avocado	Irrigated	7,163.9	9,710.5
3	Metropolitana	Pear	Irrigated	707.7	100.9
3	Metropolitana	Grapes	Irrigated	3,276.4	3,865.5
3	Metropolitana	Vineyard	Irrigated	11,360.6	16,640.6
3	Metropolitana	Alfalfa	Irrigated	11,925.8	12,334.9
3	Metropolitana	Pine	Rainfed	31.4	32.0
3	Metropolitana	Eucalyptus	Rainfed	7,118.5	5,243.7
3	Ohiggins	Rice	Irrigated	100.5	141.6
3	Ohiggins	Common Bean	Irrigated	633.5	635.4
3	Ohiggins	Maize	Irrigated	46,486.5	43,178.6
3	Ohiggins	Potato	Rainfed	13.7	17.2
3	Ohiggins	Potato	Irrigated	1,533.3	1,564.6
3	Ohiggins	Wheat	Rainfed	1,968.8	1,466.2
3	Ohiggins	Wheat	Irrigated	3,023.9	2,020.5
3	Ohiggins	Cherry	Irrigated	3,669.0	2,944.6
3	Ohiggins	Plum	Irrigated	9,766.2	3,473.4
3	Ohiggins	Peach	Irrigated	7,452.1	7,557.7
3	Ohiggins	Apple	Irrigated	10,251.8	13,451.3
3	Ohiggins	Orange	Irrigated	3,433.9	4,511.4
3	Ohiggins	Walnut	Irrigated	2,523.8	1,919.8
3	Ohiggins	Olive	Irrigated	2,268.4	2,514.8
3	Ohiggins	Avocado	Irrigated	2,756.5	4,722.6
3	Ohiggins	Pear	Irrigated	3,510.1	2,499.2
3	Ohiggins	Vineyard	Irrigated	35,248.3	50,777.2

3	Ohiggins	Alfalfa	Irrigated	7,384.7	7,792.2
3	Ohiggins	Pine	Rainfed	83,264.3	77,891.5
3	Ohiggins	Eucalyptus	Rainfed	48,653.3	44,854.7
3	Maule	Rice	Irrigated	17,212.2	19,657.9
3	Maule	Oat	Rainfed	70.8	62.9
3	Maule	Common Bean	Irrigated	4,495.4	5,335.7
3	Maule	Maize	Irrigated	26,637.6	24,956.0
3	Maule	Potato	Rainfed	185.6	238.7
3	Maule	Potato	Irrigated	2,812.5	3,107.6
3	Maule	Wheat	Rainfed	3,672.7	3,708.9
3	Maule	Wheat	Irrigated	17,147.8	12,910.0
3	Maule	Cherry	Irrigated	2,229.6	1,514.7
3	Maule	Plum	Irrigated	905.0	77.5
3	Maule	Peach	Irrigated	440.3	455.5
3	Maule	Apple	Irrigated	19,595.6	26,012.7
3	Maule	Orange	Irrigated	27.7	39.0
3	Maule	Walnut	Irrigated	607.0	252.0
3	Maule	Olive	Irrigated	3,389.3	2,919.6
3	Maule	Avocado	Irrigated	55.2	169.4
3	Maule	Pear	Irrigated	1,319.2	829.8
3	Maule	Vineyard	Irrigated	42,921.4	63,795.9
3	Maule	Alfalfa	Irrigated	5,791.0	5,787.0
3	Maule	Pine	Rainfed	434,641.9	414,868.6
3	Maule	Eucalyptus	Rainfed	51,183.7	48,642.1
3	Biobio	Rice	Irrigated	3,880.2	5,707.3
3	Biobio	Oat	Rainfed	12,431.0	12,377.4
3	Biobio	Common Bean	Irrigated	1,893.5	2,397.4
3	Biobio	Maize	Irrigated	8,997.5	9,756.0
3	Biobio	Potato	Rainfed	5,440.7	7,001.4
3	Biobio	Potato	Irrigated	2,293.5	2,617.6
3	Biobio	Wheat	Rainfed	40,090.1	41,619.1
3	Biobio	Wheat	Irrigated	22,319.0	21,120.5
3	Biobio	Cherry	Irrigated	1,425.9	741.7
3	Biobio	Plum	Irrigated	12.1	
3	Biobio	Peach	Irrigated	34.7	36.4
3	Biobio	Apple	Irrigated	1,834.1	2,387.3
3	Biobio	Orange	Irrigated	4.9	7.0
3	Biobio	Walnut	Irrigated	284.5	165.0
3	Biobio	Olive	Irrigated	744.7	635.0
3	Biobio	Avocado	Irrigated	19.3	66.7
3	Biobio	Pear	Irrigated	9.0	1.2
3	Biobio	Vineyard	Irrigated	15,295.6	21,371.7
3	Biobio	Alfalfa	Irrigated	7,202.2	8,105.3
3	Biobio	Pine	Rainfed	652,635.1	641,830.5

3	Biobio	Eucalyptus	Rainfed	308,867.0	307,770.2
3	Araucania	Oat	Rainfed	39,310.1	39,434.3
3	Araucania	Common Bean	Irrigated	81.4	100.4
3	Araucania	Maize	Irrigated	89.6	79.2
3	Araucania	Potato	Rainfed	10,653.0	13,826.2
3	Araucania	Potato	Irrigated	3,028.0	2,702.8
3	Araucania	Wheat	Rainfed	89,311.8	92,974.9
3	Araucania	Wheat	Irrigated	1,488.0	1,055.2
3	Araucania	Cherry	Irrigated	168.4	106.0
3	Araucania	Peach	Irrigated	1.9	2.0
3	Araucania	Apple	Irrigated	2,558.6	3,130.9
3	Araucania	Walnut	Irrigated	74.9	52.4
3	Araucania	Pear	Irrigated	24.8	23.5
3	Araucania	Vineyard	Irrigated	20.2	23.6
3	Araucania	Alfalfa	Irrigated	2,329.5	1,925.2
3	Araucania	Pine	Rainfed	320,697.3	317,342.3
3	Araucania	Eucalyptus	Rainfed	242,435.0	239,437.5
3	Los Rios	Oat	Rainfed	3,401.6	3,370.8
3	Los Rios	Potato	Rainfed	3,243.1	4,234.9
3	Los Rios	Potato	Irrigated	362.5	292.7
3	Los Rios	Wheat	Rainfed	14,417.6	15,213.9
3	Los Rios	Cherry	Irrigated	6.6	6.1
3	Los Rios	Apple	Irrigated	570.5	501.6
3	Los Rios	Pine	Rainfed	109,995.8	110,886.8
3	Los Rios	Eucalyptus	Rainfed	122,068.9	119,559.8
3	Los Lagos	Oat	Rainfed	5,795.2	5,986.2
3	Los Lagos	Potato	Rainfed	9,116.6	11,931.4
3	Los Lagos	Potato	Irrigated	98.8	74.1
3	Los Lagos	Wheat	Rainfed	11,344.3	12,049.1
3	Los Lagos	Apple	Irrigated	312.3	349.2
3	Los Lagos	Pear	Irrigated	2.8	0.3
3	Los Lagos	Pine	Rainfed	22,585.8	22,709.4
3	Los Lagos	Eucalyptus	Rainfed	61,185.5	57,341.5

Table A.IV.2.2 Agricultural Production by Activity and Region.

Zone	Region	Type	Activity	Baseline	Climate Change
1	Atacama	Crop	Common Bean	7.4	13.6
1	Atacama	Crop	Potato	3,218.7	3,962.2
1	Atacama	Fruit	Plum	9.4	
1	Atacama	Fruit	Peach	265.8	266.3
1	Atacama	Fruit	Apple	9.4	12.2
1	Atacama	Fruit	Orange	3,149.6	4,442.8
1	Atacama	Fruit	Walnut	47.7	
1	Atacama	Fruit	Olive	18,366.3	10,533.2
1	Atacama	Fruit	Avocado	5,519.3	5,801.8
1	Atacama	Fruit	Pear	46.6	
1	Atacama	Fruit	Vineyard	4,131.5	6,096.3
2	Coquimbo	Crop	Common Bean	265.3	265.2
2	Coquimbo	Crop	Maize	4,213.1	4,209.9
2	Coquimbo	Crop	Potato	55,385.3	49,743.8
2	Coquimbo	Crop	Wheat	4,533.8	4,550.8
2	Coquimbo	Fruit	Cherry	192.6	
2	Coquimbo	Fruit	Peach	18,469.5	18,133.7
2	Coquimbo	Fruit	Apple	116.1	150.7
2	Coquimbo	Fruit	Orange	17,835.8	23,692.7
2	Coquimbo	Fruit	Walnut	4,868.1	394.1
2	Coquimbo	Fruit	Olive	16,785.7	1,763.5
2	Coquimbo	Fruit	Avocado	59,084.1	51,634.6
2	Coquimbo	Fruit	Pear	2,822.7	14.5
2	Coquimbo	Fruit	Grapes	135,325.0	139,291.1
2	Coquimbo	Fruit	Vineyard	74,508.3	93,377.8
2	Coquimbo	Crop	Alfalfa	5,401.7	2,318.5
2	Coquimbo	Forest	Pine	0.0	0.1
2	Valparaiso	Crop	Oat	1,591.5	1,626.4
2	Valparaiso	Crop	Common Bean	260.4	302.7
2	Valparaiso	Crop	Maize	11,583.9	12,306.1
2	Valparaiso	Crop	Potato	15,757.1	18,856.1
2	Valparaiso	Crop	Wheat	6,687.9	7,022.1
2	Valparaiso	Fruit	Cherry	868.0	109.6
2	Valparaiso	Fruit	Plum	6,811.5	
2	Valparaiso	Fruit	Peach	103,667.6	109,006.1
2	Valparaiso	Fruit	Apple	9,406.6	10,953.7
2	Valparaiso	Fruit	Orange	21,136.1	29,524.0
2	Valparaiso	Fruit	Walnut	9,065.9	968.8
2	Valparaiso	Fruit	Olive	13,185.8	4,832.6
2	Valparaiso	Fruit	Avocado	162,607.7	124,705.7
2	Valparaiso	Fruit	Pear	1,160.7	
2	Valparaiso	Fruit	Vineyard	72,128.4	83,213.6

2	Valparaiso	Crop	Alfalfa	139,974.2	138,018.2
2	Valparaiso	Forest	Pine	1,473.9	1,575.8
2	Valparaiso	Forest	Eucalyptus	4,087.2	4,193.2
3	Metropolitana	Crop	Oat	629.6	674.9
3	Metropolitana	Crop	Common Bean	327.5	364.9
3	Metropolitana	Crop	Maize	132,107.9	136,022.3
3	Metropolitana	Crop	Potato	76,903.8	87,354.6
3	Metropolitana	Crop	Wheat	14,670.8	12,894.1
3	Metropolitana	Fruit	Cherry	4,893.3	2,760.6
3	Metropolitana	Fruit	Plum	118,158.2	7,823.3
3	Metropolitana	Fruit	Peach	69,126.2	71,246.5
3	Metropolitana	Fruit	Apple	9,482.7	12,506.0
3	Metropolitana	Fruit	Orange	18,271.3	25,089.9
3	Metropolitana	Fruit	Walnut	14,763.3	9,177.4
3	Metropolitana	Fruit	Olive	20,152.6	15,637.2
3	Metropolitana	Fruit	Avocado	54,368.8	79,979.7
3	Metropolitana	Fruit	Pear	10,960.2	1,717.7
3	Metropolitana	Fruit	Grapes	83,801.3	98,876.5
3	Metropolitana	Fruit	Vineyard	141,971.9	208,006.7
3	Metropolitana	Crop	Alfalfa	200,785.3	208,089.9
3	Metropolitana	Forest	Pine	4.9	4.6
3	Metropolitana	Forest	Eucalyptus	679.0	492.0
3	Ohiggins	Crop	Rice	535.0	771.3
3	Ohiggins	Crop	Common Bean	1,223.7	1,233.9
3	Ohiggins	Crop	Maize	569,872.6	529,265.0
3	Ohiggins	Crop	Potato	21,791.6	22,429.4
3	Ohiggins	Crop	Wheat	23,009.8	15,997.8
3	Ohiggins	Fruit	Cherry	19,249.6	15,776.2
3	Ohiggins	Fruit	Plum	209,409.6	73,884.5
3	Ohiggins	Fruit	Peach	163,031.6	165,361.8
3	Ohiggins	Fruit	Apple	371,750.4	487,978.0
3	Ohiggins	Fruit	Orange	75,037.3	99,302.7
3	Ohiggins	Fruit	Walnut	6,806.2	5,045.1
3	Ohiggins	Fruit	Olive	32,791.8	36,882.2
3	Ohiggins	Fruit	Avocado	26,211.2	45,860.4
3	Ohiggins	Fruit	Pear	55,154.3	40,553.4
3	Ohiggins	Fruit	Vineyard	442,606.2	637,511.9
3	Ohiggins	Crop	Alfalfa	150,066.7	158,091.9
3	Ohiggins	Forest	Pine	21,528.5	20,305.4
3	Ohiggins	Forest	Eucalyptus	8,661.8	8,086.9
3	Maule	Crop	Rice	88,846.8	100,844.4
3	Maule	Crop	Oat	267.6	237.6
3	Maule	Crop	Common Bean	8,664.9	10,330.1
3	Maule	Crop	Maize	264,393.5	248,077.2

3	Maule	Crop	Potato	43,265.7	48,478.4
3	Maule	Crop	Wheat	97,525.0	76,034.7
3	Maule	Fruit	Cherry	11,558.3	8,451.9
3	Maule	Fruit	Plum	23,015.6	1,945.4
3	Maule	Fruit	Peach	9,897.0	10,232.9
3	Maule	Fruit	Apple	667,084.8	886,164.0
3	Maule	Fruit	Orange	797.9	1,123.6
3	Maule	Fruit	Walnut	1,172.9	559.5
3	Maule	Fruit	Olive	49,631.8	43,575.1
3	Maule	Fruit	Avocado	626.1	1,934.5
3	Maule	Fruit	Pear	20,084.0	13,281.4
3	Maule	Fruit	Vineyard	529,801.5	786,137.8
3	Maule	Crop	Alfalfa	98,344.4	98,086.8
3	Maule	Forest	Pine	114,951.4	110,118.2
3	Maule	Forest	Eucalyptus	8,935.7	8,538.4
3	Biobio	Crop	Rice	18,941.0	27,822.3
3	Biobio	Crop	Oat	52,207.8	52,034.4
3	Biobio	Crop	Common Bean	3,324.8	4,241.9
3	Biobio	Crop	Maize	92,458.2	100,248.6
3	Biobio	Crop	Potato	87,680.9	106,916.2
3	Biobio	Crop	Wheat	305,520.2	307,131.0
3	Biobio	Fruit	Cherry	8,286.1	4,185.3
3	Biobio	Fruit	Plum	236.0	
3	Biobio	Fruit	Peach	756.4	793.1
3	Biobio	Fruit	Apple	63,394.9	83,035.8
3	Biobio	Fruit	Orange	127.4	181.6
3	Biobio	Fruit	Walnut	731.9	419.0
3	Biobio	Fruit	Olive	11,139.5	9,613.9
3	Biobio	Fruit	Avocado	204.5	707.0
3	Biobio	Fruit	Pear	131.4	19.2
3	Biobio	Fruit	Vineyard	183,891.2	259,164.4
3	Biobio	Crop	Alfalfa	136,008.9	152,827.4
3	Biobio	Forest	Pine	206,365.2	203,074.9
3	Biobio	Forest	Eucalyptus	63,164.9	62,966.4
3	Araucania	Crop	Oat	182,465.8	183,285.6
3	Araucania	Crop	Common Bean	105.0	129.3
3	Araucania	Crop	Maize	981.3	845.5
3	Araucania	Crop	Potato	208,604.0	239,330.2
3	Araucania	Crop	Wheat	440,781.8	457,206.5
3	Araucania	Fruit	Cherry	681.0	421.5
3	Araucania	Fruit	Peach	29.7	31.1
3	Araucania	Fruit	Apple	97,454.3	119,769.1
3	Araucania	Fruit	Walnut	158.9	109.5
3	Araucania	Fruit	Pear	444.9	428.6

3	Araucania	Fruit	Vineyard	173.8	202.3
3	Araucania	Crop	Alfalfa	54,922.0	45,190.1
3	Araucania	Forest	Pine	101,622.4	100,527.6
3	Araucania	Forest	Eucalyptus	48,930.7	48,449.5
3	Los Rios	Crop	Oat	15,993.4	15,934.9
3	Los Rios	Crop	Potato	65,509.1	79,924.6
3	Los Rios	Crop	Wheat	93,758.3	98,984.6
3	Los Rios	Fruit	Cherry	19.7	17.8
3	Los Rios	Fruit	Apple	20,020.3	17,886.9
3	Los Rios	Forest	Pine	39,826.8	40,141.1
3	Los Rios	Forest	Eucalyptus	25,003.3	24,553.3
3	Los Lagos	Crop	Oat	27,918.9	28,869.3
3	Los Lagos	Crop	Potato	195,489.0	254,370.5
3	Los Lagos	Crop	Wheat	73,796.9	78,514.5
3	Los Lagos	Fruit	Apple	9,139.2	10,226.4
3	Los Lagos	Fruit	Pear	36.7	3.9
3	Los Lagos	Forest	Pine	5,608.5	5,635.7
3	Los Lagos	Forest	Eucalyptus	6,692.2	6,288.8

Annex IV.3. Alternative Model: Scenarios and Results

Table A.IV.3.1 Rainfed Yield Scenarios (ton/ha)

	Eucalyptus		Oat		Pine		Potato		Wheat	
Region	Baseline	Climate Change	Baseline	Climate Change	Baseline	Climate Change	Baseline	Climate Change	Baseline	Climate Change
Atacama	0.001	0.003								
Coquimbo	0.005	0.028	1.095	1.095	0.028	0.029			1.351	1.330
Valparaiso	0.079	0.097	3.991	3.637	0.187	0.134	1.200	10.841	2.696	2.167
Metropolitana	0.084	0.077	4.618	1.893	0.148	0.141	2.000	8.151	3.600	1.579
Ohiggins	0.156	0.144	2.004	1.066	0.240	0.209	4.674	12.251	2.791	1.754
Maule	0.177	0.170	2.273	1.542	0.252	0.230	3.861	12.861	2.670	2.001
Biobio	0.210	0.217	2.552	2.424	0.311	0.296	7.028	16.141	2.666	2.482
Araucania	0.190	0.214	3.348	4.605	0.298	0.311	8.977	9.554	3.831	4.871
Los Rios	0.192	0.248	4.271	6.155	0.347	0.395	14.925	6.838	5.960	7.608
Los Lagos	0.098	0.183	3.733	5.259	0.216	0.330	17.556	26.206	4.480	5.236

Table A.IV.3.2 Income per Activity Under Different Climate Shocks (% Change)

Activity	Only Irrigated	Irrigated and Rainfed
Alfalfa	17.7%	18.1%
Apple	0.3%	73.2%
Avocado	15.3%	16.4%
Cherry	-6.3%	-5.6%
Common Bean	12.3%	97.1%
Eucalyptus	-1.6%	26.0%
Grapes	-26.4%	-26.3%
Maize	-74.7%	-74.6%
Oat	1.3%	1.3%
Olive	28.8%	29.1%
Orange	33.0%	32.8%
Peach	-58.2%	-58.1%
Pear	-30.9%	-30.8%
Pine	-39.3%	-39.2%
Plum	-37.5%	-37.3%
Potato	5.6%	5.5%
Rice	41.0%	40.1%
Vineyard	-4.7%	-3.0%
Walnut	-2.4%	-2.4%
Wheat	-2.0%	8.9%

V. General Conclusions

Several regions of the world are already suffering the consequences of a changing climate, with the developing world being the most affected mainly due to its fragile economic system based on natural resource exploitation. Within this context, the agricultural sector is, without a doubt, one of the most vulnerable to climate change.

Of all the different climate change impacts threatening the agricultural sector, this study considers the consequences of changes in water availability. The consequences of changes in water availability were analyzed using two different approaches: top/down and bottom/up; the former is represented by a Computable General Equilibrium model, while a Multimarket model represents the latter.

In the first paper "*The Economic Impacts of Water Availability in the Agricultural Sector: Top-Down Approach – A Literature Survey*" state of the art methodology was presented highlighting the main methodological issues, as well as the steps needed in order to improve water representation within computable general equilibrium models. A key element identified in this paper is the lack of representation of the irrigation sector from an economic perspective. Currently, most of the global CGE models assume that developing irrigation schemes is free. Considering the enormous economic resources used for irrigation, this assumption does not seem realistic and restricts the scope of these analyses.

The second paper "*Climate Change, Water Scarcity in Agriculture and Their Economy-Wide Impacts. A CGE Model Analysis*" addressed one of the caveats identified in the literature: including irrigation as an economic sector within the global CGE modeling framework. This topic was analyzed using a new CGE model, called ICES-W. The addition of the irrigation sector implied the incorporation of water within the CGE, including it as an endowment that could affect agricultural productivity. The main contribution of this paper is its ability to model the link between water and irrigated agriculture. This is modeled through a hydrologic module representing the behavior of the water available for irrigation.

The third paper "*Climate Change, Water Scarcity in Agriculture and Their Country-Level Economic Impacts. A Multimarket Analysis*" exploits the potential of Multimarket models for the analysis of water related issues in the agricultural sector. This paper analyzes the sectoral consequences of climate change with a highly disaggregated agricultural model. The model presented in this paper represents differences among activities within the agricultural sector with a structure that allows for microanalysis in a context of restricted access to agricultural information. Although, the agricultural multimarket model falls short in relation to the complexities of the CGE model presented in the second paper, the results account for indirect effects allowing for a detailed economic impact assessment.

One point mentioned in the literature is the potential benefit of linking top-down and bottom-up approaches. Within the context of this thesis, this implies linking the ICES-W general equilibrium model with the agricultural multimarket partial equilibrium model. The objective of this exercise is to take advantage of both modeling approaches: the highly detailed representation of the agricultural sector in the AMM and the economy-wide treatment of the ICES-W model.

Even though both models analyze the agricultural sector, their results are not the same. This is because the models represent the agricultural sector differently, with different levels of detail. Besides, CGE models account for feedback effects that are neglected by partial equilibrium models. Thus, even if the same data is used (aggregated according to each model's structure) the results are never the same.

The exercise of linking the ICES-W model and the AMM implies identifying connections between both models, differentiating between directions of the link, from the ICES-W model to the AMM, and from the AMM to the ICES-W model. Considering that the models are connected through the agricultural markets, the linking variables will be those associated with this market (prices, quantities).

The link between the ICES-W model and the AMM implies that all the exogenous variables of the AMM, but endogenous to the ICES-W (*i.e.* international prices) will remain fixed for the AMM. In the case of the AMM's endogenous variables, the results of the ICES-W model associated with these variables are ignored for the analysis (*i.e.* Chilean agricultural prices). On the other hand, the link between the AMM and the ICES-W model implies that the ICES-W model uses the endogenous variables of the AMM. Endogenous variables are input demands, agricultural supply, agricultural prices, and water demand. In order to be used by the ICES-W model, these variables should be aggregated to the proper scale: the national level, the agricultural activities should be aggregated for demand and supply, and computed in a way that is useful for the ICES-W model in terms of value (price * quantities).

The linking process implies several steps must be followed, including the representation of the agricultural labor demand in the AMM. Once the communication links between both models are identified, it will be necessary to define the algorithms that will allow for that communication. The linking of these models is useful for addressing the described gaps in the literature and improving the scope of current approach's analyses. The exercise of linking both models is considered a natural enlargement of this thesis.

Estratto per riassunto della tesi di dottorato

Studente: Roberto Daniel Ponce Oliva matricola: 955565
Dottorato: Scienza e Gestione dei Cambiamenti Climatici
Ciclo: 24º

Titolo della tesi: Economic Modeling of Water Resources in Agriculture. Top down and Bottom up approaches.

Abstract: Agricultural sector plays a critical role in food security, and in some developing countries it also makes up a high labor-intensive economic sector. The conclusions of the Intergovernmental Panel on Climate Change's (IPCC) fourth assessment report suggest that climate change could threaten the agricultural sector due to changes in precipitation, temperature patterns, and an increase of extreme weather events. The objective of this thesis is to explore and compare the top/down and the bottom/up approaches in order to account for the economic impacts of water availability in the agricultural sector. In order to do that, two models were developed: Computable General Equilibrium and Agricultural Multimarket model. The models are conducted at global and national scale, respectively. At the global scale, the study of the economic impacts of climate change, through the ICES-W model, shows the expected results in accordance with the shock imposed; there is an increase in the demand of endowments (land and capital for irrigation), a decrease in agricultural production, and only a small change in GDP. On the other hand, the study of the economic impacts of climate change at national level, through the Agricultural Multimarket Model, shows small absolute economic impacts. However, results suggest large distributional effects across regions and activities.

Estratto: L'agricoltura è uno dei principali consumatori della risorsa idrica. Il settore agricolo è fondamentale per la sicurezza alimentare e, in alcuni paesi in via di sviluppo, crea opportunità lavorative più alte degli altri settori. In questo contesto, è probabile che un aumento della domanda d'acqua dovuto alla crescita demografica e ai cambiamento climatici aumenterà il rischio di una insufficiente disponibilità per il settore agricolo. Questa tesi esplora e compara metodologie top/down e bottom/up per calcolare l'impatto economico del variare della disponibilità idrica per l'agricoltura, grazie all'utilizzo di due modelli, uno di equilibrio generale a scala globale e uno per la simulazione del multimercato agricolo a scala nazionale. A scala globale lo studio, effettuato con il modello ICEW-W, mostra come previsto che al diminuire delle precipitazioni e all'aumentare della temperatura, la domanda per la risorsa (terra e capitale per l'irrigazione) cresce e la produttività agricola diminuisce, mentre il PIL rimane pressoché invariato. L'impatto economico a scala nazionale è ancora più limitato, nonostante i risultati suggeriscano comunque un'eterogeneità significativa tra diverse regioni ed attività economiche.

Firma dello studente

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