The economic impacts of climate change on the Chilean agricultural sector. A non-linear agricultural supply model

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Agriculture could be one of the most vulnerable economic sectors to the impacts of climate change in the coming decades, with impacts threatening agricultural production in general and food security in particular. Within this context, climate change will impose a challenge to policy makers, especially in those countries that based their development on primary sectors. In this paper we present a non-linear agricultural supply model for the analysis of the economic impacts of changes in crop yields due to climate change. The model accounts for uncertainty through the use of Monte Carlo simulations about crop yields. According to our results, climate change impacts on the Chilean agricultural sector are widespread, with considerable distributional consequences across regions, and with fruits producers being worst-off than crops producers. In general, the results reported here are consistent with those reported by previous studies showing large economic impacts on the northern zone. However, our model does not simulate remarkable economic consequences at the country level as previous studies did.

Key words: Climate change, farming model, irrigation, uncertainty.

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 on crop production are related to changes in temperature and precipitation patterns, the frequency and magnitude of extreme weather events, and changes in seasonality and growing period, among others. All of these impacts may have consequences on agricultural production (Bates et al., 2008) and as a result, agricultural systems are forced to adapt to changing conditions. Climate Change Adaptation (CCA) thus emerges as a new field for scholars and practitioners at all levels, from local and autonomous adaptation strategies implemented by farmers, up to regional, national or global policies to orient planned adaptation.

Despite the relevance of public policies in coping with the climate change impacts, the inclusion of climate change adaptation as a new policy field is questioned (Massey and Huitema, 2013). Nevertheless, it can at least be considered as an application context for agricultural policy. A cost benefit analysis of technical and policy actions should be the basis to assist stakeholders to develop measures to reduce the vulnerability to climate change. But policies crafted to operate within a certain range of conditions may produce unexpected outcomes if applied outside of that range (Swanson et al., 2010; Iglesias et al., 2012).

The assessment of the economic impacts of climate change on the agricultural sector requires an approach aimed to provide a detailed picture of the sector and the relationships within it. In this regard, bottom-up approaches (i.e., in particular models applied at local level, but driven by global forces) could be an effective tool to evaluate the economic impacts of climate change on the agricultural sector.

Bottom-up approaches, such as bio-economic agricultural models, simulate the agents’ – e.g., farmers’ – behavior, allowing for an ex-ante evaluation of policy interventions. Agricultural models range from studies at farm level, to studies including the whole agricultural sector. The main difference is in the distinction between endogenous and exogenous variables and in particular price assumptions.

Agricultural supply models represent the agricultural sector through a series of behavioral equations, which are solved in order to maximize the farm income or the regional income, subject to technological, environmental, and institutional constraints (Howitt, 2005). The wide use of agricultural models is underpinned in the limited
The economic assessment of climate change impacts on the Chilean agricultural sector has been analyzed from different perspectives in recent years. From an economic perspective, González and Velasco (2008) developed one of the first studies on this subject. In their article authors analyzed the impact of climate change on the economic value of land, using the Ricardian approach (Mendelsohn et al., 1994). They reported a statistical relationship between climatic variables and the land value, with moderate explanatory power (R-square reported is around 30%). Nevertheless, an interesting finding is that the scenarios modeled showed less impact on the value of land than previous studies developed in Latin America.

On the other hand, from a productive perspective, the first study was developed by the University of Chile’s AGRIMED center (Center on Agricultural and Environment) in 2008 (Santibáñez et al., 2008). In this study, authors analyzed the impacts that climate change could have on the Chilean agricultural sector. The analysis is conducted using the Modelo Simulador de Productividad de Cultivos (SIMPROC model) specifically developed for the Chilean agricultural sector (Santibáñez, 2001). The results are computed at the commune level (340 communes), while the scenarios modeled are the IPCC A2 and B2 for two periods of time, around 2040 and 2070 (IPCC, 2000). According to the results, the large productive impacts are located in the northern region of Chile.

Other economic studies include Bárcena et al. (2009) and ODEPA (2010). In 2009, the Economic Commission for Latin America and the Caribbean (CEPAL) conducted a study analyzing the economic impacts of climate change in Chile (Bárcena et al., 2009). Although this study did not focus on the agricultural sector, this sector was analyzed as a part of the Chilean economy. Using an econometric model, the authors simulated the expected changes in land allocation due to climate change. The analyzed crop yield changes and activities are those computed 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. In the worst-case scenario, the agricultural sector will lose 15% of its income (A2 scenario); while in the best-case scenario the incomes will increase by 1% (B2 scenario).

The main objective of this paper was to analyze the economic impacts of changes in yields, due to climate change, on the Chilean agricultural sector. The analysis is conducted using a non-linear agricultural supply model. The model is designed specifically for the analysis of the Chilean agricultural sector, and it accounts for uncertainty about agricultural yields through the use of Monte Carlo simulations.

**MATERIALS AND METHODS**

**Model description**

The Agricultural Supply model (ASM) 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 ASM includes the behavior of the agricultural producers, which 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, yields, 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 core model is optimized considering a series of endowment restrictions, such as: total land, irrigated land, and water availability.

The model is calibrated to a single reference period using Positive Mathematical Programming (PMP). This approach was formalized by Howitt (1995), but has been used in agricultural economics for almost three decades. The PMP considers the farmer’s optimization process, allowing for a perfect calibration of area planted, for the full range of agricultural activities, avoiding the dependency between parameters and constraints. The approach followed in this paper is extensively used in agricultural economics due to its accuracy when the model calibration is based on a single base year (complemented with exogenous price elasticities) (Heckelei and Britz, 2005; Howitt et al., 2010; Medellín-Azuara et al., 2011).

Model structure

Positive Mathematical Programming is three-step procedure for model calibration assuming that farmers optimize input use in order to maximize their profits. In the first step, a linear programming model is defined 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) a set of explicit constraints related to resource availability (land, irrigated land, and water), and institutional conditions (policy and environmental).

Along with the resource and non-negativity constraints, the model includes a calibration constraint. 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):

$$Z = \sum_{i} \sum_{a} \left( P_a \cdot Y_{r,a,s} - AC_{r,a,s} \right) \cdot X_{r,a,s}$$  \hspace{1cm} [1]

$$AC_{r,a,s} = vcost_{r,a,s}$$  \hspace{1cm} [2]

$$\sum_{i} r_{i,r,a,s} \cdot X_{r,a,s} \leq b_{i,r}$$  \hspace{1cm} [3]

$$X_{r,a,s} = X_{r,a,s}^0 + e_{r,a,s}$$  \hspace{1cm} [4]

$$X_{r,a,s} \geq 0$$  \hspace{1cm} [5]

In Equation [1], $Z$ is the objective function value, $AC_{r,a,s}$ is the vector of average costs per unit of activity, $P_a$ 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 [2] $vcost_{r,a,s}$ represents the observed variable costs per unit of activity, while in Equation [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. Equation [4] represents the calibration constraint that bounds the model (in its linear specification) to the observed activity levels in the base year, in which $X_{r,a,s}^0$ denotes the land allocation in the base year, and $e_{r,a,s}$ represents a small deviation from the base year land allocation. Finally, Equation [5] represents the non-negativity constraints on land allocation.

In the second step, the dual values associated with the calibration constraint are used to specify a non-linear cost function, in which the marginal costs are equal to the market prices at the base year (Howitt, 1995; Heckelei, 2002). The model assumes constant average revenues (regardless of the level of activity) and increasing average costs, as well as a non-linear cost function, which captures all production conditions not explicitly modeled. Following Blanco et al. (2008) and Howitt et al. (2010; 2012), the average cost function of activity $a$ can be written:

$$AC_{r,a,s} = \alpha_{r,a,s} \cdot (X_{r,a,s})^{\beta_{r,a,s}}$$  \hspace{1cm} [6]

The cost function parameters $\alpha_{r,a,s}$ and $\beta_{r,a,s}$ are derived from a profit-maximizing equilibrium that maximizes Equation [1] subject to [2], [3], [4], and [5].

Additional conditions are: 1) In the base year, 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.

In the third step, once the cost function parameters have been derived, the calibrated non-linear model is specified. The ASM maximizes the net income Equation [1] subject to [3], [5], and [6].

The model as presented above reproduces the activity levels observed for the base year and allows us to simulate hypothetical climate change scenarios. The ASM anticipates farmer’s responses, in particular changes in cropland allocation and water provision systems, motivated by the differentiated effect of climate change on crop productivity, across crops and across regions. Further, the model incorporates all the available information, and it uses calibrated parameters to model all the conditions that –due to lack of data– could not be considered in an explicit way. The model is consistent with economic theory, and its structure is flexible enough to incorporate all relevant environmental constraints and policy instruments (Howitt, 1995; Heckelei, 2002; Howitt, 2005; de Frahan et al., 2007; Heckelei et al., 2012).

Uncertainty is included in the modeling framework using the Monte Carlo method. In this specific case, the model assumes that the agricultural yields are random variables following a Gamma distribution. Thus, several sets of agricultural yields are simulated using both uniform pseudo-random numbers and the inverse probability distribution function (Hardaker et al., 1997).

**RESULTS AND DISCUSSION**

Due to its geographical characteristics, Chile has various 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 semi-arid climate, includes Arica y Parinacota, Tarapacá, Antofagasta and Atacama Regions. Central Chile, characterized by a Mediterranean climate, includes Coquimbo, Valparaíso, Metropolitana, Libertador General Bernardo O’Higgins, and Maule Regions. Southern Chile, characterized by an oceanic climate, includes Biobío, La Araucanía, Los Lagos, and Los Ríos Regions, while the austral area, characterized by a sub-polar climate, includes Aysén del General Carlos Ibáñez del Campo and Magallanes y la Antártica Chilena Regions.

Within the climatic context presented above, the total agricultural land (18.4 million ha) is divided as follows: 1.7 million ha cultivated land, 14.03 million ha grassland, and 2.7 million ha 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).

Model specification
The application of the ASM included a smaller area than those considered in previous studies. The area being analyzed here included Atacama Region in the north to Los Lagos Region in the south. This area included 265 communes, grouped into 36 provinces, and 10 regions. The agricultural sector was represented by 22 activities, aggregated according to the following categories: Crops (10), fruits (10), and forestry (2); the model considers irrigated and rainfed activities, accounting for 3.3 million ha.

The crops considered were: rice (irrigated), oats (rainfed), common beans (irrigated), maize (irrigated), potatoes (irrigated and rainfed), alfalfa (irrigated), sugar beet (irrigated), and wheat (irrigated and rainfed). The fruits considered were: cherries, plums, peaches, apples, oranges, walnuts, olives, avocados, pears, grapes, and vine grapes, all of them irrigated activities. Finally, the model also included the area devoted to forestry, including: pine and eucalyptus, both rainfed activities. The agricultural sector depicted above represents 82.4% of the agricultural activities developed within the study area. The model accounts only for those activities that have a market price, excluding grassland from the analysis.

The core information used in the model (area, production, yield) was 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 used in the study of Chilean Agrarian Policies and Studies Bureau (ODEPA, 2010); prices were taken from the ODEPA website, while the elasticities used to calibrate the model were collected from previous studies (Quiroz et al., 1995; CAPRI Model, 2008; Foster et al., 2011).

Two scenarios were modeled in order to assess the economic impacts of changes in agricultural yields. In the first one, the net farm agricultural income was computed for the base year (2007) using the agricultural yields corresponding to this year, while in the second scenario the net farm agricultural income in 2007 was computed using the yields computed by Santibáñez et al. (2008) assuming the A2 scenario for 2040. Thus, the economic impacts of changes in agricultural yields were computed as the difference in the net farm agricultural income for both scenarios.

The potential agricultural yields by zone are presented in Table 1, in which northern zone includes the Regions: Atacama, Coquimbo, and Valparaíso; central zone includes Metropolitana, Libertador General Bernardo O’Higgins, and Maule Regions; while southern zone includes Biobío, La Araucanía, Los Ríos, and Los Lagos Regions. The ASM was developed using the General Algebraic Modeling System (GAMS) software (GAMS Development Corporation, Washington, D.C., USA).

Results of modeling
At the national level, the expected changes in agricultural yields have a minor impact on the total land allocation, with total agricultural land decreasing by 46 600 ha. However, as expected, the estimated impacts across regions are uneven, with the largest impacts in the northern region. For instance, both the Atacama and Coquimbo Regions decrease their agricultural land by 40%, while for the central zone the decrease is only 7.4% (on average), with a decrease of 14 825 ha. On the other hand, from the

| Activity                  | Northern Zone Baseline | Northern Zone Climate change | Central Zone Baseline | Central Zone Climate change | Southern Zone Baseline | Southern Zone Climate change |
|---------------------------|------------------------|------------------------------|-----------------------|-----------------------------|------------------------|-----------------------------|
| Crops average             | 4                      | 3.812                        | 12.860                | 8.787                       | 15.165                 | 11.130                      |
| Alfalfa                   | 13.459                 | 13.809                       | 18.442                | 19.790                      | 21.376                 | 24.488                      |
| Common bean               | 1.320                  | 0.532                        | 1.710                 | 1.469                       | 1.275                  | 1.170                       |
| Maize                     | 6.380                  | 3.886                        | 9.473                 | 7.947                       | 6.925                  | 6.204                       |
| Oat                       | 3.026                  | 2.790                        | 2.465                 | 1.437                       | 3.717                  | 4.055                       |
| Rainfed potato            | 1.200                  | 10.841                       | 3.991                 | 11.995                      | 10.647                 | 16.494                      |
| Irrigated potato          | 10.146                 | 4.177                        | 12.699                | 8.785                       | 14.898                 | 18.031                      |
| Rice                      | 0                      | 0                            | 5.046                 | 2.920                       | 4.252                  | 2.283                       |
| Sugar beet                | 0                      | 67.333                       | 27.600                | 31.957                      | 81.461                 | 30.957                      |
| Irrigated wheat           | 1.928                  | 1.689                        | 2.782                 | 1.852                       | 3.683                  | 4.278                       |
| Irrigated wheat           | 2.543                  | 0.399                        | 4.664                 | 4.073                       | 3.958                  | 3.338                       |
| Fruits Average            | 14.805                 | 5.524                        | 16.035                | 13.142                      | 12.746                 | 10.044                      |
| Apple                     | 28.571                 | 4.605                        | 34.376                | 19.114                      | 30.328                 | 27.159                      |
| Avocado                   | 8.003                  | 7.490                        | 8.704                 | 10.212                      | 9.437                  | 4.226                       |
| Cherry                    | 6.560                  | 1.913                        | 5.313                 | 5.023                       | 3.206                  | 3.335                       |
| Grapes                    | 19.140                 | 5.132                        | 20.951                | 16.292                      | 15.319                 | 12.248                      |
| Olive                     | 10.979                 | 4.310                        | 12.760                | 11.316                      | 13.026                 | 7.476                       |
| Orange                    | 18.798                 | 16.761                       | 20.350                | 23.585                      | 19.479                 | 9.759                       |
| Peach                     | 22.796                 | 7.693                        | 22.980                | 20.197                      | 13.836                 | 13.344                      |
| Pear                      | 12.171                 | 2.057                        | 15.274                | 8.625                       | 16.108                 | 12.133                      |
| Plum                      | 23.085                 | 6.985                        | 21.836                | 18.339                      | 8.525                  | 12.116                      |
| Vineyard                  | 9.864                  | 2.941                        | 11.151                | 9.337                       | 8.787                  | 7.020                       |
| Walnut                    | 2.992                  | 0.969                        | 2.693                 | 2.525                       | 2.154                  | 1.668                       |
| Forest Average            | 0.113                  | 0.088                        | 0.194                 | 0.169                       | 0.235                  | 0.265                       |
| Pine                      | 0.177                  | 0.107                        | 0.240                 | 0.200                       | 0.291                  | 0.317                       |
| Eucalyptus                | 0.049                  | 0.068                        | 0.148                 | 0.138                       | 0.179                  | 0.212                       |

Table 1. Climate change scenario: Average expected yields.
Biobío Region to the south, the decrease in agricultural land is negligible (Table 2).

Results by zone and activity show that there is not a direct relationship between the expected change in agricultural yields and the final change in land allocation. The reason for this apparent contradiction is that the final land allocated to each activity is function of its relative profit respect to other activities. In this regard, agricultural yields are one component of the profit level, along with prices and costs. For instance, within the northern zone, on the average, agricultural yields decrease by 51% with respect to the baseline, while the expected average change in land allocation is -16%. The same stands for the central and southern zones, in which a large change in agricultural yields (-24%) is foreseen, but the change in total agricultural land is quite small, -2.5% and -0.1%, respectively.

At the activity level, in the northern zone a decrease in irrigated potatoes yields of 58% drives a 98% decrease in its land allocation. This final land allocation shows that despite the high potential productivity of rainfed potatoes under the climate change scenario, this activity is less profitable than forest production, which actually increases its land allocation.

Within the central zone, the increase in rainfed potatoes yield (from 3.9 to 11.9 t ha⁻¹) would drive an increase of nine times in the land allocated to it. On the other hand, a decrease in sugar beet yields (60%) drives a smaller decrease in the land allocated to this crop (4%). The same would happen with the land allocated to rice that increases for 1.5% regardless of the large decrease in yields (-42%).

The southern zone shows an increase in the land allocated to crops (26%) despite the expected decrease in crop yield (-26.6%). Within crops, only alfalfa, rice, and sugar beet show a decrease in their land allocation. Regarding fruits, the land allocated to avocado will increase by 13%, independently of the expected change in yields (-26.6%). Within crops, only alfalfa, rice, and sugar beet show a decrease in their land allocation. Regarding fruits, the land allocated to avocado will increase by 13%, independently of the expected change in yields (-26.6%).

Agricultural production suffers from large changes due to the new land allocation across the country, with the largest negative changes faced by grape (-86%), pear (-54%), and walnut (-38%). On the other hand, most of the increase in production is associated to rainfed activities, such as: oat (125%), potato (84%), and wheat (38%).

In general, the total agricultural production changes from 10.6 million to 10.5 million tons. Results by zone and activity show that the impact on crop production is unevenly distributed across the country, with crop production decreasing by 37% in the northern zone, while in the southern zone it increases by 38%. Fruit production decreases in all regions, ranging from 53% in the northern zone to 11% in the southern zone. Forest increases its production in the northern zone (8%), while the central and southern zones show a small decrease, 4% and 2%, respectively.

In average, the northern zone will decrease its agricultural production by 492 000 t (-48%). Among crops within the northern zone, maize, potato, and wheat show the main decrease, 83%, 99%, and 52% respectively, equivalent to 92 800 t. On the other hand, this zone will lose 401 000 t fruits (-53%), with grapes, pears, and olives as the most affected activities.

The largest impact of climate change on the central zone is represented by the 19% decrease in fruits production (627 000 t). Most of this decrease is related to apple (262 000 t) and vineyard (267 000 t), which represents -84% of apple production and -69% of vineyard production. Regarding crop production, a decrease of 127 000 t (6%) is expected, with maize and potato accounting for the large share.

The southern zone shows the largest decrease in production with 1 142 000 t, representing 28% of its production. Detailed results show that crop production increases for 1 198 000 t (38%), fruits production decreases by 11% (45 000 t), and forest production decreases by 2% (10 400 t). Among crops, oat and potato increase their production more than 100%, followed by wheat (46%). Pear and apple production show the largest decrease in production, 61% and 25% respectively, while the other fruit activities increase their production within the range of 6%-39% (Table 3).

All the changes described above drive a 2.7% decrease in the agricultural net income, from USD 2235 million to USD 2176 million (equivalent to USD 59 million). At the regional level, 6 out of 10 regions show a decrease in net incomes, from Atacama to Maule Regions. Only the regions within the southern zone could have benefits due to climate change.

In relative terms, the regions within the northern zone decrease their net income by 50%, in the central zone the reduction was -17%, while the southern zone increased its income by 40%. At regional level, the most affected appeared to be Atacama Region, while Los Lagos Region gained the most. In Atacama Region impacts are associated to the decrease in production of olive, potato, vineyard, and avocado, this activities account for the 97% of the change in the agricultural production within the central zone. In relative terms, the regions within the northern zone decrease their net income by 50%, in the central zone the reduction was -17%, while the southern zone increased its income by 40%. At regional level, the most affected appeared to be Atacama Region, while Los Lagos Region gained the most. In Atacama Region impacts are associated to the decrease in production of olive, potato, vineyard, and avocado, this activities account for the 97% of the change in the agricultural production within the central zone.
Table 3. Agricultural production by activity and zone.

| Activity       | Northern Zone | Central Zone | Southern Zone |
|----------------|---------------|-------------|---------------|
|                | Climate change| Baseline    | Climate change| Baseline    | Climate change|
| Total crops    | 248 880       | 156 995     | 2 171 518     | 2 043 777   | 3 129 134     | 4 328 057     |
| Alfalfa        | 145 376       | 147 217     | 449 196       | 552 139     | 190 931       | 156 308       |
| Common bean    | 533           | 25          | 10 216        | 10 155      | 3 430         | 3 684         |
| Maize          | 15 797        | 2 609       | 966 374       | 783 335     | 93 439        | 98 260        |
| Oat            | 1 592         | 1 184       | 897           | 399         | 278 586       | 632 891       |
| Potato         | 74 361        | 618         | 141 961       | 89 778      | 557 263       | 1 337 459     |
| Rice           | 89 382        | 92 745      | 18 941        | 13 337      |
| Sugar beet     | 378 285       | 384 164     | 1 072 667     | 755 415     |
| Wheat          | 11 222        | 5 341       | 135 206       | 131 044     | 913 857       | 1 330 704     |
| Total fruits   | 761 592       | 360 480     | 3 261 668     | 2 634 250   | 397 058       | 351 577       |
| Apple          | 9 532         | 1 495       | 1 048 318     | 785 853     | 190 009       | 142 883       |
| Avocado        | 227 211       | 226 237     | 81 206        | 102 729     | 205           | 294           |
| Cherry         | 1 061         | 263         | 35 701        | 45 051      | 8 987         | 10 529        |
| Grapes         | 135 325       | 4 258       | 83 801        | 25 233      |
| Olive          | 48 338        | 9 098       | 102 576       | 81 693      | 11 339        | 15 483        |
| Orange         | 42 122        | 38 778      | 94 107        | 139 749     | 127           | 171           |
| Peach          | 122 403       | 28 239      | 242 055       | 254 762     | 786           | 961           |
| Pear           | 4 030         | 288         | 86 198        | 41 278      | 613           | 237           |
| Plum           | 6 821         | 1 898       | 350 583       | 293 297     | 256           | 250           |
| Vineyard       | 150 768       | 45 635      | 1 114 380     | 846 625     | 184 065       | 179 689       |
| Walnut         | 13 982        | 4 291       | 22 742        | 17 981      | 891           | 1 089         |
| Total forest   | 5 561         | 6 012       | 154 761       | 147 859     | 497 214       | 486 748       |
| Pine           | 1 474         | 1 346       | 136 485       | 126 084     | 353 423       | 320 735       |
| Eucalyptus     | 4 087         | 4 666       | 18 277        | 21 775      | 143 791       | 166 013       |

Table 4. Economic impacts of climate change: Net agricultural income.

| Region          | Baseline (million USD) | Climate change (million USD) |
|-----------------|------------------------|------------------------------|
| Atacama         | 13                     | 4                            |
| Coquimbo        | 112                    | 46                           |
| Valparaíso      | 202                    | 156                          |
| Metropolitana   | 186                    | 111                          |
| Libertador General Bernardo O’Higgins | 388 | 373 |
| Maule           | 430                    | 398                          |
| Biobío          | 453                    | 494                          |
| La Araucanía    | 297                    | 363                          |
| Los Ríos        | 105                    |                              |
| Los Lagos       | 50                     | 101                          |
| Total           | 2235                   | 2176                         |
CONCLUSIONS

Considering the results, the major conclusion of this study is that the Chilean agricultural sector is vulnerable to the change in agricultural yields as a consequence of climate change. At the regional level, our model shows substantial re-allocations of land, with the northern zone showing larger changes. However, this land reallocation does not seriously impact the total agricultural production at the national level. Therefore, according to the results, even if climate change may not have large absolute consequences, it may produce large distributional consequences, with fruits producers being worst-off than crops producers. In this regard, climate change could threaten a key economic sector, since fruits account for 31% of total food export. On the other hand, the statistical analysis confirmed the robustness of our results.

However, besides the high level of detail in which the agricultural sector is modeled, some drawbacks remain and they should be considered in terms of future research needs. First of all, even if our model considers a fine administrative disaggregation at commune level, results could be substantially improved by the inclusion of an agro-ecological zone disaggregation, thus providing a better representation of agro-climatic characteristics and their relationships with land suitability and productivity. Secondly, the magnitude of the projected impacts of climate change on the whole agricultural sector suggests that it is reasonable to expect that changes in production will be large enough to drive a change in agricultural prices. The Agricultural Supply model is currently not able to analyze this scenario, due to the assumptions about prices. One solution could be to move from supply modeling to sector modeling, or to general equilibrium modeling. The final choice will depend on the data availability. Another important consideration is that, although the model accounts for adaptation by allowing for changes in land allocation to cope with climate change, it does not consider other adaptation options, such as the incorporation of different techniques or technologies for farm management.

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LITERATURE CITED

Bárcena, A., A. Prado, J.L. Samaniego, y S. Malchik. 2009. La economía del cambio climático en Chile. Síntesis. Colección Documentos de Proyectos. Comisión Económica para América Latina y el Caribe (CEPAL), Naciones Unidas, Santiago, Chile. Available at http://www.eclac.cl/publicaciones/xml/8/37858/W288.pdf (accessed August 2013).
Bates, B., Z. Kundzewicz, S. Wu, and J. Palutikof (eds.) 2008. Climate change and water. 210 p. Technical Paper of the Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland.

Blanco, M., R. Cortignani, and S. Severini. 2008. Evaluating changes in cropping patterns due to the 2003 CAP Reform. An ex-post analysis of different PMP approaches considering new activities. 107th EAAE Seminar Modelling of Agricultural and Rural Development Policies, Sevilla. 29 January-1 February, European Association of Agricultural Economists (EAAE), Sevilla, Spain. CAPRI Model. 2008. CAPRI Model Documentation. In Britz, W., and P. Witzke (eds.) Available at http://www.capri-model.org/ (accessed September 2013).

de Frahan, B.H., J. Buysse, P. Polomé, B. Fermagut, O. Harmignie, L. Lauwers, et al. 2007. Positive mathematical programming for agricultural and environmental policy analysis: Review and practice. p. 129-154. In Weintraub, A., C. Romero, T. Bjurnda, R. Epstein, and J. Miranda (eds.) Handbook of Operations Research in Natural Resources. Springer, New York, USA.

Di Falco, S., and M. Veronesi. 2013. How can African agriculture adapt to climate change? A counterfactual analysis from Ethiopia. Land Economics 89(3):473-766.

Dono, G., R. Cortignani, L. Doro, L. Giraldo, L. Ledda, M. Pasqui, et al. 2013. Adapting to uncertainty associated with short-term climate variability changes in irrigated Mediterranean farming systems. Agricultural Systems 117:1-12.

Fischer, G., M. Shah, F.N. Tubiello, and H. van Velthuizen. 2005. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080. Philosophical Transactions of the Royal Society B: Biological Sciences 360:2067-2083.

Foster, W., J. López de Lérida, y A. Valdés. 2011. Impacto del nivel de distorsiones en el sector agrícola nacional. Ministerio de Agricultura, Pontificia Universidad Católica de Chile, Facultad de Agronomía e Ingeniería Forestal, Departamento de Economía Agraria, Santiago, Chile.

González, J., and R. Velasco. 2008. Evaluation of the impacts of climatic change on the economic value of land in agricultural systems in Chile. Chilean Journal of Agricultural Research 68:56-68.

Hardaker, J., R. Huime, and J. Anderson. 1997. Coping with risk in agriculture. CAB International, Oxon, UK.

Hassan, R.M. 2010. Implications of climate change for agricultural sector performance in Africa: Policy challenges and research agenda. Journal of African Economics 19 (Suppl. 2):ii77-ii105.

Hazzell, P.B.R., and R. Norton. 1986. Mathematical programming for economic analysis in agriculture. Collier Macmillan, New York, USA.

Heckelei, T. 2002. Calibration and estimation of programming models for agricultural supply analysis. 169 p. University of Bonn, Bonn, Germany. Available at http://www.ifr.uni-bonn.de/ agpo/staff/heckelei/heckelei_hab.pdf (accessed 22 July 2014).

Heckelei, T., and W. Britz. 2005. Models based on positive mathematical programming: State of the art and further extensions. p. 48-73. Modelling Agricultural Policies: State of the Art and New Challenges. Proceedings of the 89th European Seminar of the EAAE, Parma. 3-5 February. University of Parma, Department of Economic and Quantitative Studies, Parma, Italy.

Heckelei, T., W. Britz, and Y. Zhang. 2012. Positive mathematical programming approaches – Recent developments in literature and applied modelling. Bio-based and Applied Economics 1:109-124.

Henseler, M., A. Wirsig, S. Herrmann, T. Krimly, and S. Dabbert. 2008. CAPRI Model Documentation. In Britz, W., and P. Witzke (eds.) Available at http://www.capri-model.org/ (accessed September 2013).

Howitt, R.E., D. MacEwan, J. Medellín-Azuara, and J.R. Lund. 2010. Economic modeling of agriculture and water in California using the statewide agricultural production model. 25 p. University of California, Davis, California, USA. Available at http://swap.ucdavis.edu (accessed September 2013).

Howitt, R., J. Medellín-Azuara, and D. MacEwan. 2012. Economic impacts of climate-related yield changes in California. Climatic Change 109:S387-S405.

Howitt, R., K. Ward, and S. Msangi. 2001. Statewide water and agricultural production model (SWAP) (Appendix A). Department of Agricultural and Resource Economics, University of California, Davis, California, USA. Available at http://calvin.ucdavis.edu (accessed September 2013).

Iglesias, E., and M. Blanco. 2008. New directions in water resources management: The role of water pricing policies. Water Resources Research doi:10.1029/2006WR005708.

Iglesias, A., S. Quiroga, M. Moneo, and L. Garrote. 2012. From climate change impacts to the development of adaptation strategies: Challenges for agriculture in Europe. Climatic Change 112:143-168.

INE. 2007. Censo Agropecuario y Forestal. Instituto Nacional de Estadísticas (INE), Santiago, Chile.

IPCC. 2000. Emissions scenarios. In Nakicenovic, N., and R. Swart (eds.) Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland.

Kan, I., D. Haim, M. Rapaport-Rom, and M. Shechter. 2009. Environmental amenities and optimal agricultural land use: The case of Israel. Ecological Economics 68:1893-1898.

Massey, E., and D. Huitema. 2013. The emergence of climate change adaptation as a policy field: The case of England. Regional Environmental Change 13:341-352.

Mondino, B., K. F. Arfini, P. Midmore, M. Schmitz, and Y. Surry. 2011. CAP’s impacts on regional employment: A multi-modelling cross country approach. p. 10-11. In C. Moredu (ed.) Proceedings of the OECD Workshop. March 2010. Organisation for Economic Co-operation and Development (OECD), Paris, France.

Medellín-Azuara, J., J. Harou, and R. Howitt. 2009. Estimating economic value of agricultural water under changing conditions and the effects of spatial aggregation. Science of the Total Environment 408:5639-5648.

MMA. 2013. Plan de adaptación al cambio climático del sector agropecuario. Ministerio del Medio Ambiente (MMA), Santiago, Chile. Available at http://www.mma.gob.cl/1304/articles-55879_InstrumentoFinalCC_Silvoagropecuario.pdf (accessed 9 July 2014).

Nelson, G.C., M.V. Rosegrant, M.W. Palazzo, A. Gray, I. Ingersoll, C. Robertson, et al. 2010. Food security, farming, and climate change to 2050: Scenarios, results, policy options. International Food Policy Research Institute (IFPRI), Washington, D.C., USA.

Nelson, G.C., H. Valin, R.D. Sands, P. Havlik, H. Ahnamad, M. Mendelsohn, R. Nordhaus, and D. Shaw. 1994. The impact of global warming on agriculture: A Ricardian analysis. American Economic Review 84:753-771.

Odepa. 2010. Estimación del impacto socioeconómico del cambio climático en el Sector Silvoagropecuario de Chile. Oficina de Estudios y Políticas Agrarias (Odepa), Santiago, Chile. Available at http://www.odepa.cl/wp-content/files__ef/1369774422impacto_socioeconomico_cambio_climatico_sector_silvoagropecuario.pdf (accessed 9 July 2012).

Quiroz, J., R. Labán, y F. Larrain. 1995. El sector agrícola y agroindustrial frente a Nafta y Mercosur. 149 p. Sociedad Nacional de Agricultura, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura e Ingeniería Forestal, Departamento de Economía Agraria, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura, Santiago, Chile.

Santibañez, F. 2001. El modelado del crecimiento, desarrollo y cambio en el sector silvoagropecuario. Ministerio de Agricultura, Santiago, Chile.
Santibañez, F., P. Santibañez, R. Cabrera, L. Solís, M. Quiroz, y J. Hernández. 2008. Capítulo I. Resumen Ejecutivo. Impactos productivos en el sector silvoagropecuario de Chile frente a escenarios de cambio climático. In Análisis de vulnerabilidad del sector silvoagropecuario, recursos hídricos, edáficos de Chile frente a escenarios de cambio climático. Centro de Agricultura y Medioambiente (AGRIMED), Facultad de Ciencias Agronómicas, Universidad de Chile, Santiago, Chile.

Swanson, D., S. Barg, S. Tyler, H. Venema, S. Tomar, S. Bhadwal, et al. 2010. Seven tools for creating adaptive policies. Technological Forecasting and Social Change 77:924-939.

von Lampe, M., D. Willenbockel, H. Ahammad, E. Blanc, Y. Cai, K. Calvin, et al. 2014. Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agricultural Economics 45:3-20.