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RESEARCH

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

Roberto Ponce[1*], Maria Blanco[2], and Carlo Giupponi[3]

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

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[1] Universidad del Desarrollo, Facultad de Economía y Negocios, Ainavillo 456, Concepción, Chile.
[*] Corresponding author (robertoponce@udd.cl).
[2] Universidad Politécnica de Madrid, Departamento de Economía y Ciencias Sociales Agrarias, Avda. Complutense 3, 28040, Madrid, España.
[3] Ca'Foscari University, Department of Economics, S. Giobbe 873, 30121 Venezia, Italy.
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amount of data required for their development (Hazzell and Norton, 1986; Howitt, 1995; Howitt et al., 2010).

Agricultural supply models in their multiple versions have been applied to several agricultural issues, including models analyzing the expected impacts of the Common Agricultural Policy (CAP) in regions such as Belgium, UK, Greece, Germany, and Sweden (de Frahan et al., 2007; Blanco et al., 2008; Mattas et al., 2011). Other applications include the estimation of the economic value of water and land (Howitt et al., 2001; Iglesias and Blanco, 2008; Medellín-Azuara et al., 2009; Kan et al., 2009), and climate change impacts (Henseler et al., 2009; Howitt et al., 2010; Medellín-Azuara et al., 2011; Howitt et al., 2012) (for reviews of other case studies see Heckelei et al., 2012).

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 Agrarian Policies and Studies Bureau (ODEPA) conducted a study at the national level in 2010 in order to account for the magnitude of the economic impacts climate change could have on the Chilean agricultural sector (ODEPA, 2010). The study updated 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 in order to account for the land allocation change due to the expected yield changes. 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 scenario, while the net income decreases by 5%.

In general, there are a growing number of studies addressing climate change impacts using economic models and, hence, taking into account farmers' adaptation strategies (Fischer et al., 2005; Howitt et al., 2010; Nelson et al., 2010; Medellín-Azuara et al., 2011; Nelson et al., 2013; von Lampe et al., 2014). However, the economic impacts of climate change on the Chilean agricultural sector have mainly been analyzed through the use of econometric techniques, or by using simple accounting methods, disregarding the adaptation options available for the farmers.

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):

$$Z = \sum_r \sum_a \sum_s (Pa * Y_{r,a,s} - AC_{r,a,s}) * X_{r,a,s} \qquad [1]$$

$$AC_{r,a,s} = v\mathrm{cost}_{r,a,s} \qquad [2]$$

$$\sum_a \sum_s r_{i,r,a,s} * X_{r,a,s} \leq b_{i,r} \qquad [3]$$

$$X_{r,a,s} = X^0_{r,a,s} + e_{r,a,s} \qquad [4]$$

$$X_{r,a,s} \geq 0 \qquad [5]$$

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] $v\mathrm{cost}_{r,a,s}$ 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 $X^0_{r,a,s}$ 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:

$$AC_{r,a,s} = \alpha_{r,a,s} * (X_{r,a,s})^{\beta r,a,s} \qquad [6]$$

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 semiarid 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, avocadoes, 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

Table 1. Climate change scenario: Average expected yields.

	Northern Zone		Central Zone		Southern Zone	
Activity	Baseline	Climate change	Baseline	Climate change	Baseline	Climate change
	t ha^{-1}					
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	3.177	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	0	67.333	27.600	81.461	30.957
Rainfed 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	6.550	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	16.671	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	2.892	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

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 small 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 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 (-55%), the same happens with land allocated to oranges.

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.

Table 2. Land allocation: Baseline and climate change.

	Rainfed land		Irrigated land	
Region	Baseline	Climate change	Baseline	Climate change
	ha			
Atacama	0.0	0.0	3 151.8	1 631.7
Coquimbo	342.3	362.6	28 770.0	15 818.1
Valparaíso	46 094.8	48 036.6	45 222.0	38 202.7
Metropolitana	7 847.2	9 946.6	68 945.5	52 020.5
Libertador General Bernardo O'Higgins	133 900.0	136 089.2	140 459.8	132 241.8
Maule	489 754.8	491 913.3	150 286.1	144 487.7
Biobío	1 019 464.0	1 020 940.5	78 712.9	74 999.4
La Araucanía	702 407.2	702 011.3	10 495.3	10 531.3
Los Ríos	253 127.0	253 094.4	1 366.0	1 398.6
Los Lagos	110 027.4	109 997.4	413.9	443.9

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

Table 3. Agricultural production by activity and zone.

	Northern Zone		Central Zone		Southern Zone	
Activity	Baseline	Climate change	Baseline	Climate change	Baseline	Climate change
	t					
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	783 353	93 439	98 260
Oat	1 592	1 184	897	399	278 586	632 891
Potato	74 361	618	141 961	89 778	557 283	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	284
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	11 139	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	236	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

region. On the other hand, our simulations show that Los Lagos Region doubles its agricultural production, with potato, wheat, and oat being the most important activities. A detailed picture at national level is presented in Table 4.

Regarding activities, the distributional effects among farmers are large. Annual crop producers are better-off under the climate change scenario than in the baseline, while fruits producers are worst-off under the climate change scenario. Farmers growing rainfed crops increase their net income by 88% (in average), with oat (132%), potato (93%), and wheat (39%) being the most profitable activities (Figure 1). In general, farmers growing crops will increase their income by USD 141 million. On the other hand, only those farmers growing cherry, orange, and avocado will increase their income (USD 24 million), while those growing grape and apple will decrease their income by USD 157 million. In general, fruits producers will decrease their income by USD 208 million.

All the results were presented so far as crisp values, without consideration of probabilities and uncertainty. In order to account for the uncertainty associated to the change in agricultural yields, a series of Monte Carlo simulations were developed. The objective was to determine the probability of a certain income level's occurrence, depending on the yield scenario analyzed. As it was established before, our model assumes that the agricultural yields follow a Gamma distribution. For simplicity, the Gamma distribution parameters are computed per activity for the whole country, using the mean and the variance of the agricultural yield sample. In order to compute the cumulative distribution function (CDF) for the net agricultural income, a series of 400 yield scenarios were computed. The CDF is presented in Figure 2.

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	130
Los Lagos	50	101
Total	2235	2176

The analysis of the net agricultural income distribution shows that the 25th percentile was USD 627 million, 50th percentile was USD 1155 million, and 75th percentile was USD 2083 million. Considering these figures, the income reported for the climate change scenario, USD 2176 million, was above the 75th percentile, thus supporting the robustness of results obtained, even when consideration of yield variability is included in the calculations.

In general, the results reported here are consistent with those reported by previous studies for Chile, showing large economic impacts on the northern zone. However, the ASM does not predict large economic consequences at the country level as previous studies did. Previous studies quantified the economic impacts of climate change, under the A2-2040 scenario, with losses between 10% (Bárcena et al., 2009) to 5% (ODEPA, 2010) of the agricultural income, while our results quantified those impacts in -3% of the agricultural income. This difference is related to the methodology used, in which the farmer could reallocate land in order to maximize the net income under different yield conditions. On the other hand, the results could be useful for the implementation of the National Plan for Climate Change Adaptation of Agriculture (MMA, 2013), in which irrigation improvement, a better access to markets, and the optimization of the use of water resources are defined as strategic actions to cope with climate change impacts at national level.

In a wider context, our results are in line with other studies across the world in which climate change could threaten the agricultural sector. For instance, Di Falco and Veronesi (2013) analyzed the impact of different adaptation strategies on crop net revenues in the Nile Basin of Ethiopia, finding significant positive effects of adaptation (e.g. changing crop varieties) on farm net revenues. At larger geographical scale (11 countries in Africa, with 10 000 farm household surveys) Hassan (2010) demonstrates that African agriculture and the related welfare are vulnerable to climate change, in particular for what concerns crop and livestock farming in dry lands, while Dono et al. (2013) observed that the most important economic impacts are derived from yield instability.

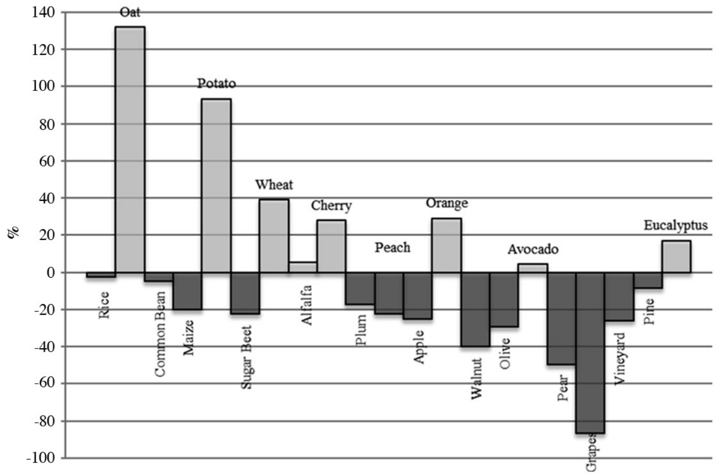

Figure 1. Agricultural net income change.

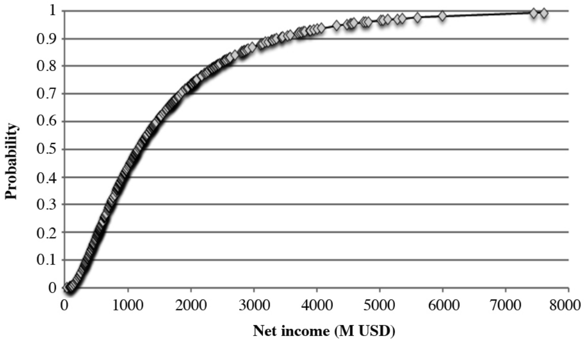

Figure 2. Cumulative distribution function: Agricultural net income.

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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