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ORIGINAL ARTICLE

Distributional impacts of climate change on basin communities: an integrated modeling approach

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Abstract Agriculture is one of the most vulnerable economic sectors to the impacts of climate change, specifically those related with expected changes in water availability. By using a hydro-economic model, this study assesses the distributional impacts of climate change, considering the geographical location of each farmer's community and the spatial allocation of water resources at basin scale. A hydrological model, the Soil and Water Assessment Tool model, describes the basin hydrology, while farmers' economic responses are represented using a non-linear agricultural supply model. We simulated a reduction in both water endowment—by perturbing the hydrologic model with a regionalized climate change scenario—and agricultural yields, in order to assess the behavior of farmers' communities. We also assessed the effectiveness of a water policy aimed at decreasing the vulnerability of farmers' communities to climate change. At the aggregated level we found relatively small impacts, consistent with the existent literature. However, we found large distributive impacts among both farmer's communities and agricultural activities. The water policy showed to be effective to reduce those impacts, but our results suggest the existence of unwanted effects on rainfed agriculture, as in some communities the level of income decreases when the policy is implemented.

Keywords Hydro-economic model · Climate change · Agriculture · Irrigation · Hydrology

Introduction

The conclusions of the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) suggest that climate change impacts on water resources will have uneven consequences across sectors and regions (IPCC 2014). The expected impacts include changes in precipitation and temperature and the increase of extreme weather events

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(floods and droughts). Those impacts could seriously threaten water supply for various users, among which is the agricultural sector (IPCC 2013).

Regarding the agricultural sector, the new climatic conditions are expected to drive changes in farmers' income, with consequences to both social and economic dimensions (Bates et al. 2008, IPCC 2014). Thus, the changes described above gain economic meaning because are expected to modify systems and processes that have impacts on human welfare.

Using a spatially explicit integrated hydro-economic model at river basin scale, this study assesses the distributional impacts of climate change across different farming communities within the Vergara river basin in Chile. This methodology links the physical impacts of climate change, with farmers' economic responses. The physical impacts of climate change come from two sources: a regionalized climate change scenario that perturbs the hydrologic model for the basin (Soil and Water Assessment Tool (SWAT) model) and changes in both rainfed and irrigated yields based on previous studies. On the other hand, farmers' economic responses are modeled through a non-linear agricultural supply model. Finally, we use this model to assess the effectiveness of a water policy aimed at decreasing the vulnerability of farmers' communities to climate change.

The literature suggests the use of the river basin scale as the proper spatial scale to analyze water resource management (McKinney et al. 1999, Cai et al. 2003, Brouwer and Hofkes 2008, Harou et al. 2009). The spatial location of each water user within the river basin is relevant for water allocation, especially in those settings in which the water demand is satisfied in a cascading scheme. In this case, the amount of water used by one user will have impacts on the amount of water available for others downstream (Maneta et al. 2009a, b).

During the past 10 years, hydro-economic models have been widely used for the analysis of water-related issues, such as water conservation (Cai et al. 2008, Ward and Pulido-Velazquez 2008, Varela-Ortega et al. 2011, Blanco-Gutiérrez et al. 2013), economic impacts of water variability (Maneta et al. 2009a, b, Torres et al. 2012, Graveline et al. 2014), water quality (Volk et al. 2008, Peña-Haro et al. 2010, 2011, Riegels et al. 2011), and the economic impacts of climate change (You and Ringler 2010, Hurd and Coonrod 2012, Jiang and Grafton 2012, Varela-Ortega et al. 2016, Yang et al. 2013, Esteve et al. 2015), among others. There is a gap on the mainstream literature, as most of the studies describe the basin hydrology using decision support systems (as the WEAP model), constraining the model to the analysis of water requirements instead of water demand.

The contribution of our paper lies in developing a policy-oriented methodological framework that is underpinned by a highly disaggregated hydrologic model. This framework allows us to analyze the economic impacts of climate change at the basin scale, with focus on the agricultural water demand, improving the economic understanding of the role played by water within different agricultural systems. On the other hand, as most of the experience on hydro-economic modeling and climate change have been concentrated in Europe, Africa, and the USA, our case study sheds light on the distributional impacts of climate change on Latin America in general and Chile in particular, both highly vulnerable regions to climate change (ECLAC 2015).

The Vergara river basin

The Vergara river basin is in a highly vulnerable zone to climate change, due to the expected changes in both temperatures and precipitations. Moreover, the region is already facing serious challenges regarding water resources within the basin (MMA 2016). Those challenges are associated with a long-term drought that has diminished water availability and management issues related to the institutional framework.

The Vergara river basin is located 600 km south of Santiago, the capital of Chile. In administrative terms, the Vergara basin lies within two regions: Biobío and Araucanía. It is the largest sub-basin of the Biobío basin, one of the most important river basins in the country. The Vergara river basin has an extension of 4260 km^2, including ten municipalities, a total population of almost 200,000 inhabitants with a large share of the basin's rural population (Stehr et al. 2008). Agricultural smallholders, forestry companies, and fruit exporters characterize the basin economy. However, current land use is dominated by forestry (64%), with a small share of agricultural activities (crops and fruits). On the other hand, the hydrologic cycle within the Vergara river basin is completely dependent on rainfall patterns and exhibits large seasonal variability, i.e., runoff peaks during July and low flows during the summer. Thus, any decrease in the rainfall patterns will lead to a decrease in water availability within the basin (Stehr et al. 2008).

Although agriculture is not the representative land use, it is the most relevant activity in socioeconomic terms with more than 14,000 smallholders distributed across the basin, with an average farm size of 20 ha (INDAP 2014). Regarding activities, 52% of farmers allocate some of their lands to main cereals (oats, maize, and wheat), legumes, and potatoes (Fernández et al. 2016).

Regarding the hydrologic system within the basin, the water flows in cascading scheme from east to west. Thus, as the amount water available for one user is affected by the amount of water used for others upstream, it is reasonable to expect distributional consequences in the face of changes in water availability. On the other hand, within the basin, as in the rest of the country, water resources are managed under the Water Code Law dated on 1981. According to this code, water is considered a public good over which the State creates, for individuals, a right of use with the same legal guarantees than those associated with private property. To do this, the law entitles individuals over water. Therefore, as long as they have the rights, acquired at the water market, individuals can freely determine the final use of water (Donoso 2006).

Finally, as part of the National Water Resources Strategy (NWRS) 2012–2025, the regional government is developing a series of actions aimed at decreasing the farmers' vulnerability to climate change, among of which are as follows: increasing water infrastructure, improving water conveyance, improving irrigation efficiency, and reservoirs construction (MOP 2012).

Integrated modeling approach

Hydro-economic models combine hydrologic and socioeconomic information at river basin scale providing a systemic view aimed to assist policy makers in integrated water resources management. The objective is to maximize the value for the whole basin, for instance, regarding income, production, or surplus subject to the hydrological, agronomic, and institutional restrictions, in order to assess the aggregated welfare effects of external shocks (Heinz et al. 2007, Brouwer and Hofkes 2008, Harou et al. 2009, Hurd 2015). Hydro-economic models typically propose two modeling approaches. The modular approach uses a connection between modeling modules (biophysical and socioeconomic) in which output data from one module provides the necessary input to the other (Braat and Van Lierop 1986) and the holistic approach in which all variables are endogenously solved in a system of equations (Cai et al. 2003).

The hydro-economic model developed for the Vergara river basin, the Vergara Hydro-economic Model (VHM) is a mathematical programming model designed to analyze agricultural water-related issues, linking farmers' economic behavior with the basin hydrologic characteristics within a flexible and comprehensive framework. The model is specified at the municipality level, and it is solved using a modular approach.

The basin hydrologic features are modeled using the SWAT (Arnold et al. 1998) developed by the US Department of Agriculture in the 1990s. The model can be classified as semi-distributed, as it uses a mixed vector- and raster-based approach (this in contrast to the fully-distributed, raster-based models). The basin is divided into sub-basins, and the input information is organized for each sub-basin into the following categories: climate, hydrologic response units, ponds/wetlands, groundwater, and the main drainage area of each subwatershed sub-basin. The hydrology of the watershed is conceptually divided into two major phases: (a) the land phase of the hydrologic cycle and (b) the routing phase.

The SWAT model was calibrated and validated for the Vergara river basin at a monthly level in the context of previous projects (Stehr et al. 2008, 2010a, b). Computed and measured monthly discharges were compared at Tijeral, Rehue, Renaico, Mininco, and Malleco gaging stations, while the model performance was assessed through RMS error, absolute error, and the Nash-Sutcliffe's efficiency and determination coefficient. The results indicate a good agreement between simulated and observed discharges, with an efficiency of 0.93 and a determination coefficient of 0.96 at Tijeral gaging station (for details see Stehr et al. 2010a).

In contrast, farmers' economic behavior is modeled using a non-linear agricultural supply model (ASM), which is a mathematical programming model designed to analyze the agricultural sector with high geographical disaggregation (municipality level). It includes the major agricultural activities within the rural area of those municipalities (hereafter: farmers communities) and differentiates between water provision systems (rainfed and irrigated), among other features (Ponce et al. 2014).

Model specification

The VHM uses a modular approach, in which for, each municipality within the basin, the ASM accounts for the derived water demand based on land allocation across crops. Since this is a derived water demand, for the baseline scenario, it is assumed that supply matches the demand, meaning that farmers have enough water rights to meet their demand. For the climate change simulations, the SWAT model is perturbed with a regionalized climate change scenario in order to compute the adjusted water supply. In this case and due to the lack of updated information for the basin, we used a regionalized climate change scenario according to the SRES A2-2040 (Nakicenovic et al. 2000). Finally, the economic impacts of climate change are computed as the income difference between the baseline and the climate change scenario.

The proposed hydro-economic model is spatially explicit by considering the geographical location of farmers' community along with the water availability in each section of the basin. This feature is modeled using an optimization model for the entire basin aimed at maximizing the agricultural income at the basin level subject to resources, geographical, hydrological, and institutional restrictions.

The conceptual model is presented in Fig. 1. The figure shows that water available for irrigation in each community (*FW*) depends on the water endowment, computed by the SWAT model (*DW*), and a water conveyance efficiency parameter (*hd*). In this setting, *FW* restricts the total amount of water that could be used in each community. As shown in Fig. 1, each community could use all the water available or leave some water (*WNU*) for others downstream (dash line), and in this case, the unused water in an upstream community will increase the water endowment downstream, and thus increasing the downstream water available for irrigation. Due to the lack of information about water trading within the basin,

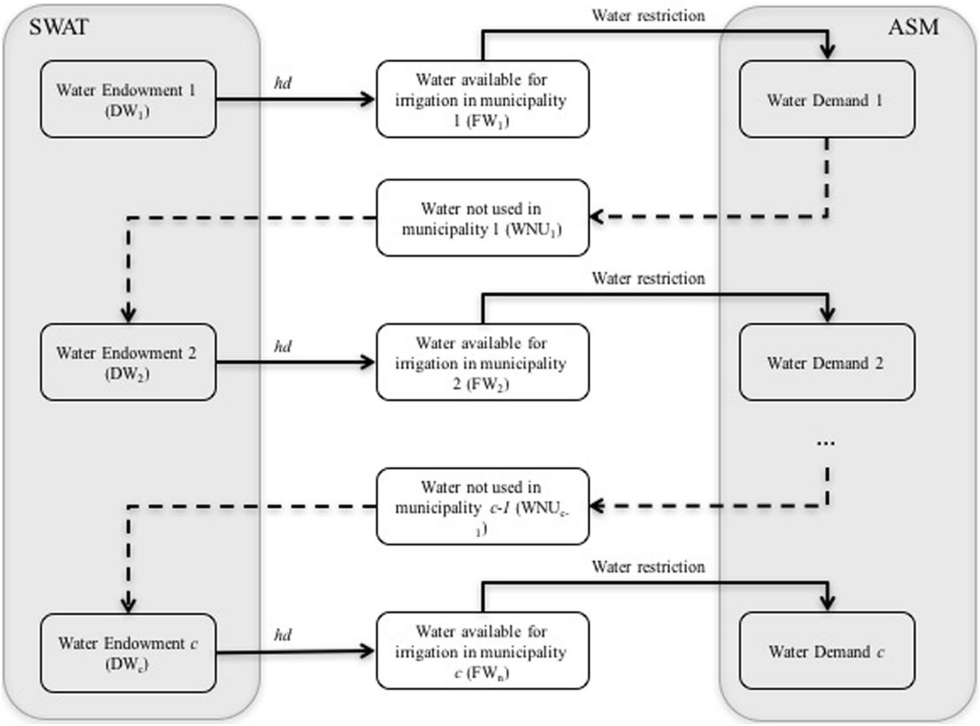


Fig. 1 Conceptual model

this modeling framework assumes that water transfer is free of charge across communities.

The integrated model is represented by the following equations.

$$Z = \sum_{c} \sum_{a} \sum_{s} \left(y_{c,a,s}{}^{*} p_a - AC_{c,a,s}\right)^{*} X_{c,a,s} \tag{1}$$

$$AC_{c,a,s} = \alpha_{c,a,s}{}^{*} \left(X_{c,a,s}\right)^{\beta_{c,a,s}} \tag{2}$$

In Eq. (1), Z is the objective function value (total agricultural income) and $X_{c,a,s}$ represents the area devoted to activity a in community c, using system s (rainfed or irrigated). In this framework, agricultural activities refer to those crops that are being cultivated within the basin. On the other hand, $y_{c,a,s}$ is the yield per hectare of activity a in community c, using system s, p_a is the price of crop a, $AC_{c,a,s}$ is the vector of average costs per unit of activity a in community c using system s. Equation (2) represents the calibrated cost function in which the cost function parameters $\alpha_{c,a,s}$ and $\beta_{c,a,s}$ are derived from a profit-maximizing equilibrium using Positive Mathematical Programming (PMP) (Howitt 1995, Blanco et al. 2008, Howitt et al. 2010).

PMP was formalized by Howitt (1995), but has been used in agricultural economics for almost three decades. PMP is a 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 to maximize the basin's farm net income by allocating land and irrigation water to agricultural activities. The model includes two resources (land and water) and a calibration constraint. 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. In the third step, once the cost function parameters have been derived, the calibrated non-linear model is specified (Howitt 1995; Heckelei 2002). 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; Blanco et al. 2008; Howitt et al. 2010; Medellín-Azuara et al. 2011).

$$WR_c = \sum_{a} fir_{c,a,irr}{}^{*} X_{c,a,irr} \tag{3}$$

$$FW_c \leq \left(DW_c + WNU_{-c}\right)^{*} hd_c \tag{4}$$

$$WR_c \leq FW_c \tag{5}$$

In Eq. (3), WR_c represents the water requirements in community c, which is equal to the crop irrigation requirements of irrigated activity a ($fir_{c,a,irr}$) multiplied by the land allocated to that activity. Equation (4) shows that the water available for irrigation (FW_c) in community c should be lower or equal than the water endowment computed by the SWAT model plus the water not used in the upstream community (WNU_{-c}) multiplied by the conveyance efficiency parameter (hd_c), while Eq. (5)

shows that water requirements should be lower (or equal) than the water available for irrigation. Equation (6) shows that the water not used in community c is the difference between the water endowment and the water used in community c.

$$WNU_c = DW_c + WNU_{-c} - \frac{FW_c}{hd_c} \tag{6}$$

Finally, Eqs. (7) and (8) show resource restrictions associated with both land ($tland_c$) and irrigated land ($iland_c$), respectively.

$$\sum_a \sum_s X_{c,a,s} \leq \mathrm{tland}_c \tag{7}$$

$$\sum_a \sum_{irr} X_{c,a,irr} \leq \mathrm{iland}_c \tag{8}$$

Climate change impacts on water resources are simulated shocking the DW_c parameter (computed by the SWAT model) using temperature and precipitation data from the PRECIS Regional Climate Modeling system that operates at a 25-km resolution, using the A2-2040 climate change scenario according to the results reported by Stehr et al. (2010a). On the other hand, climate change impacts on agricultural yields are modeled shocking the $y_{c,a,s}$ parameter. As the expected impacts on agricultural yields are not available for the basin, we modeled the shock based on the *Climate Change Action Plan for the Agricultural Sector* (MINAGRI-MMA 2013). According to this report, rainfed productivity will be the most affected by the expected changes in precipitation and temperatures in the zone in which the basin is located (south central Chile).

Data

The Vergara river basin includes ten municipalities, and its agricultural sector is represented by 14 activities, aggregated according to the following categories: crops (7) and fruits (7).

The crops considered were as follows: oats (rainfed), common beans (irrigated), maize (irrigated), potatoes (irrigated and rainfed), alfalfa (irrigated), sugar beet (irrigated), and wheat (irrigated and rainfed). On the other hand, the fruits considered were as follows: cherries, plums, peaches, apples, walnuts, pears, and wine grapes, being all of them irrigated activities.

The core information used in the model (area, production, yield) dates from 2007 and came from the National Agricultural Census (INE 2007), considering a disaggregation at the 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 a previous study developed by the Agrarian Policies and Studies Bureau (ODEPA 2010a, b). Prices were taken from the ODEPA website (ODEPA 2010a, b), while the elasticities used for the calibration of the PMP model were collected from previous studies (Quiroz et al. 1995, Britz and Witzke 2008, Foster et al. 2011).

Regarding the simulated climate change impacts on water availability, due to data restrictions on the Representative Concentration Pathways (RCP) (Van Vuuren et al. 2011), we relied on the regionalized A2-2040 SRES, which implies a 22% reduction (average) of river flows, with a maximum −26% reduction in Angol and minimum −17% in Ercilla. Figure 2 shows how the different communities are linked through the

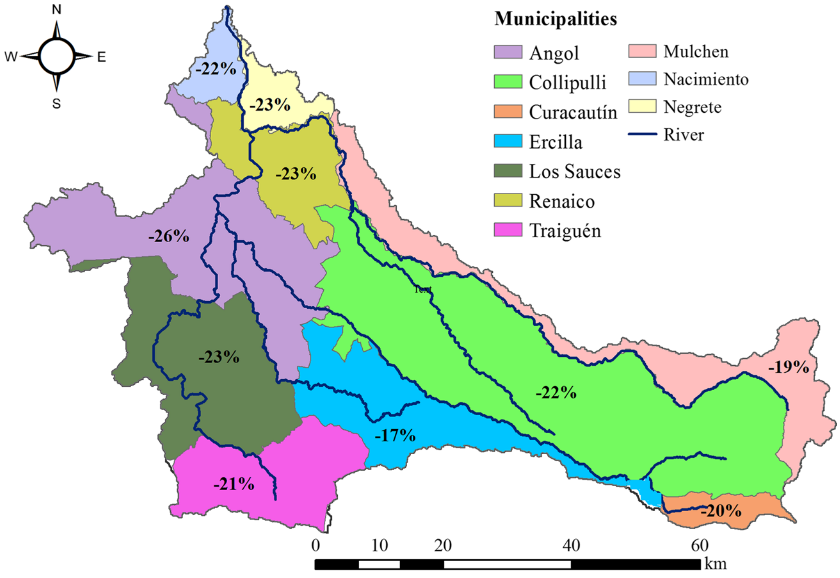


Fig. 2 Vergara river basin: hydrological system and changes in water availability

hydrologic system and the associated changes in water availability.

On the other hand, we assumed that rainfed productivity would decrease by 10%, while irrigated productivity would decrease by 5% based on the previous studies (Santibáñez et al. 2008, MINAGRI-MMA 2013). Finally, we assessed the effectiveness of 20% improvement on the water conveyance for the policy scenario according to the NWRS guidelines (MOP 2012).

Results

We conducted two simulations. In the first one, we address the distributional impacts of climate change without the policy intervention, while the second one analyzes how those impacts are modified by the water policy.

Regarding the *non-policy* simulation, at the basin level the expected impacts of climate change—changes in both water availability and agricultural productivity—will have impacts on both total agricultural land and total income, with a decrease of 8.4 and 15.2%, respectively. Our results show that these aggregated impacts hide large distributional consequences across both agricultural activities and farmers' communities.

At the basin level, the decrease in total agricultural land (4027 ha) implies a decrease of 21% for irrigated land (2111 ha) and a decrease of 5% on rainfed land (1916 ha). At the community level, Negrete increases its rainfed land by 28% (50 ha), reducing its irrigated land by 11% (153 ha) with a net decrease in agricultural land equivalent to 103 ha. On the other hand, Traiguen shows the largest decrease in irrigated land in relative terms (−26%) equivalent to 270 ha (Table 1).

As shown in Table 1, changes in rainfed land are not proportional to the productivity shock. Eight communities show the smallest changes than the productivity shock, with two of them (Collipulli and Negrete) increasing their rainfed land, despite the 10% decrease on agricultural productivity. On the other hand, irrigated land decreased for all the communities with the smallest decrease in Curacautin (−10%) and the largest decrease in Traiguen (−26%). Changes on rainfed land are concentrated in two communities, with Traiguen and Mulchen accounting for 87% of the total rainfed land decrease (1675 ha). On the other hand, the changes on irrigated land are distributed among several communities, in which only one of them (Mulchen) accounts for more than 30% of the total decrease on irrigated land (757 ha).

Following the income optimization rule governing the model, farmers' communities will adapt their agricultural practices (agricultural systems), aiming at minimizing the economic impacts of climate change, considering also their location in the basin. Within the model, the autonomous adaptation options are restricted to changes in land allocation across activities. It is noteworthy that due to the model specification—at the community level—it is not possible to identify the land substitution at the farm level.

At the basin level, rainfed activities as oat, wheat, and potato increase their land allocation in Negrete, Collipulli, Curacautin, and Los Sauces. The total increase in rainfed land is 240 ha, with oat accounting for 78%. On the other hand, irrigated wheat in Negrete increases its land allocated by 22 ha (11%). Despite this increase, all the other irrigated activities decrease their land allocation by 174.8 ha, among of which alfalfa, sugar beet, and vineyard account for 71%. For the other communities, all the activities decrease their land allocation.

Table 1 Agricultural land changes (ha)

Community	Baseline		Climate change			
	Rainfed	Irrigated	Total change (ha)		Relative change (%)	
			Rainfed	Irrigated	Rainfed (%)	Irrigated (%)
Traiguen	13,352.1	1051.9	12,072.0	781.5	−10	−26
Los Sauces	1432.6	4.0	1433.3	3.3	0	−17
Curacautin	4678.8	104.8	4689.3	94.3	0	−10
Mulchen	8729.0	2908.4	8334.9	2151.1	−5	−26
Ercilla	3240.6	41.1	2918.9	32.3	−10	−21
Collipulli	5689.9	265.2	5740.1	215.0	1	−19
Angol	333.4	1272.3	318.1	983.8	−5	−23
Renaico	216.4	2282.3	200.9	1795.2	−7	−21
Negrete	181.8	1420.3	232.0	1267.4	28	−11
Nacimiento	85.3	511.9	84.4	427.1	−1	−17
Total	37,939.9	9862.3	36,024.0	7751.0	−5	−21

Regarding rainfed activities, the largest decreases on land allocation are related to wheat and oat, in Traiguen, Mulchen, and Ercilla. For instance, wheat in Traiguen accounts for 49% of the total land decrease (935 ha). For irrigated activities, the largest decreases on land allocation are related to wheat, alfalfa, and sugar beet, in Mulchen, Angol, and Renaico. For instance, wheat in Mulchen accounts for 28% of the total land decrease (588 ha). Details for community and activity are presented in supplementary material Fig. S1.

The new land pattern is associated with a new water allocation across farmers' communities. At the basin level, the total water endowment decreases 26.3 million m^3 (−22%). For both water demand and water supply, the changes across communities are different, with some of them showing a larger decrease in supply than in demand. This result could mean a demand gap for those communities. However, as the water flows across the basin, the integrated modeling approach fills this gap by allowing water transfer from an upstream community.

At the basin level, half of the communes transfer to others downstream 5 million m^3. This water transfer is driven by differences in water productivity across both communes and activities. The largest share of this figure is related to those communities that reduce the most their irrigated land. Mulchen and Renaico account for 59% of the irrigated land decrease (1244 ha), and they account for 80% of the water transfer (4 million m^3).

Due to the water transfer scheme, the water available for irrigation increases in some communities. Table 2 shows that water endowment is the water computed by the SWAT model, water at the farm gate includes the conveyance efficiency adjustment (60%), water available is the water endowment plus the water transferred from an upstream commune (adjusted by the conveyance efficiency parameter), water use is the water used for irrigation, and water not used (WNU) is the difference between water available and water use (adjusted by the conveyance efficiency parameter).

As shown in Table 2, for some communes, the water transferred (*WNU*) is a relevant share of the water available for irrigation. For instance, for Los Sauces, the water transferred from Traiguen (271 K m^3) is eight times the original water available for irrigation (32 K m^3), while for Renaico the water transferred from Mulchen (2.2 million m^3) is 15% of its original water available for irrigation (15 million m^3).

According to Table 2, under the climate change scenario, Traiguen water endowment is 7.6 million m^3, the latter is equivalent to 4.5 million m^3 available for irrigation. As part of the optimization process, and based on the water restriction, with this amount of water, Traiguen reduces its irrigated area by 26% (270 ha), leaving 271 K m^3 of water available for Los Sauces. With this water transfer, Los Sauces increases its water available for irrigation almost six times, from 32 to 195 K m^3. However, Los Sauces reduces its irrigated land (−17%) in order to leave water (268 K m^3) to be used in Angol, which requires more water that the original water endowment (7.3 million m^3). Water transfer for all the communities are shown in supplementary material (Fig. S2, dash line indicates zero water transfer).

The physical changes, on land and water, described above will drive changes in production and income across communities and activities. Regarding production, all the activities will decrease their production, with a total decrease of 83,931 tons (−28%) at the basin level. At activity level, peach production shows the smallest decrease (−13%), while alfalfa shows the largest decrease (−63%) (see details in supplementary material, Fig. S3).

Climate change will have uneven consequences across farmers' communities. For instance, wheat production in Negrete will increase 9% (154 tons), while the largest decrease is related to alfalfa in Mulchen (−45%), sugar beet in Renaico (−44%), and common bean in Ercilla (−57%). Half of the production decrease is explained by both sugar beet in Angol and Renaico (−23,300 tons) and wheat in Mulchen and Traiguen (−19,700 tons).

Table 2 Water transfer (K m^3)

Commune	Water endowment	Water at farm gate	Water available	Water use	WNU
Traiguen	7626	4576	4576	4413	271
Los Sauces	54	32	195	34	268
Curacautin	427	256	256	256	0
Mulchen	23,449	14,069	14,069	12,701	2281
Ercilla	415	249	249	249	0
Collipulli	3493	2096	2096	2096	0
Angol	12,312	7387	7548	7548	0
Renaico	25,035	15,021	16,389	15,332	1763
Negrete	14,062	8437	9495	9214	469
Nacimiento	5768	3461	3742	3742	0

Table 3 Income (MM$) and income change (%)

Commune	BL (MM$)	CC (MM$)	Change (%)
Traiguen	4964	4110	−17.2
Los Sauces	325	272	−16.5
Curacautin	2052	1735	−15.5
Mulchen	4411	3660	−17.0
Ercilla	818	669	−18.2
Collipulli	2422	2038	−15.9
Angol	1683	1472	−12.6
Renaico	3042	2687	−11.7
Negrete	1388	1231	−11.3
Nacimiento	550	489	−11.0
Total	21,654	18,361	−15.2

The different changes described above will have economic consequences for the basin economy. Considering the uneven changes in land, water, and production across farmers' communities some will be worst-off than others under the climate change scenario. At the basin level, the basin is expected to lose $3293 million (−15.2%), while the expected income changes at the community level range from −11% (Nacimiento) to −18.2% (Ercilla) (see details in Table 3).

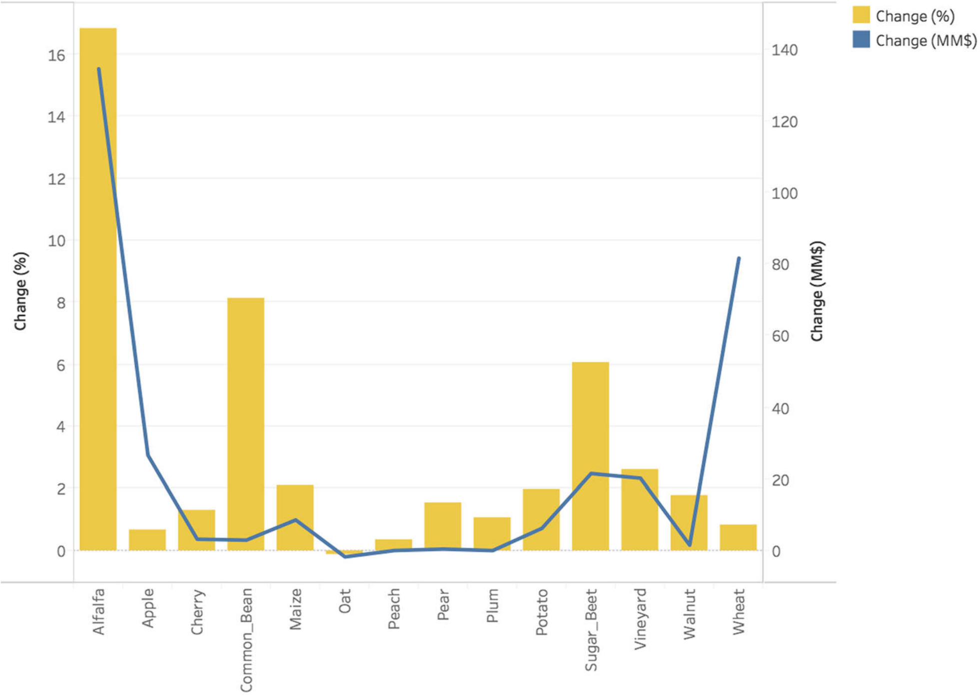
As shown in Table 3, the most vulnerable communities in economic terms are those with the largest share of rainfed land: Ercilla, Traiguen, Mulchen, and Los Sauces. Those four communities account for 55% of all basin income loss due to climate change ($1807 million). Results by activity and community show that common bean producers in Ercilla decrease their income 42%, followed by alfalfa producers in Collipulli (−35%), alfalfa producers in Curacautin (−32%), and sugar beet producers in Renaico (27%). Wheat producers, with 60% of the total income loss, face the largest burden of climate change. The largest income losses are associated to Traiguen ($728 million), Mulchen ($591 million), Curacautin ($227 million), and Collipulli ($221 million).

The regional government is analyzing a series of water policies aimed at decreasing the vulnerability of farmers' communities to climate change. We simulate the economic consequences of improvements on the water conveyance within the basin, specifically sealing or lining of open channels aimed at reducing losses through seepage. Following the NWRS guidelines (MOP 2012), we assume that these actions will increase the conveyance efficiency parameter by 20%.

In aggregated terms, this policy will reduce the economic losses of climate change by 9% with respect to the *non-policy* scenario, equivalent to $306 million. On the other hand, as the basin is more efficient in the use of water, water transfer across communities will move from 5.5 million m^3 to 2.2 million m^3 (−54%) with the associated impacts on agricultural land. Under this policy, rainfed land decreases 0.2%, while irrigated land increases 19% with respect to the *non-policy* scenario, in which 60% of the newly irrigated land is in Mulchen and Renaico. The new land allocation has impacts on agricultural production, with total production increasing 27,400 tons (9%), with irrigated activities as sugar beet and alfalfa representing 69% of the production increase (18,912 tons).

Regarding the economic impacts of the water policy, compared with the *non-policy* scenario, the income losses decrease in all the communes. However, the income gains are concentrated in those communes that increased the most their

Fig. 3 Policy scenario



irrigated land: Mulchen and Renaico. Those communes concentrate 48% of the income differences ($145 million).

Results by community and activity show that the water policy will have a small negative impact on producers from Negrete, Collipulli, and Curacautin with respect to the *non-policy* scenario. In Collipulli and Curacautin, the negative impact is restricted to rainfed producers (oat and wheat) with an income decrease of 2.8 million (equivalent to −0.7%). In Negrete, the negative impact is related to wheat producers, both rainfed wheat and irrigated wheat, with a total income decrease of 1.5 million (−1.1%). For all the other communities, the agricultural activities will decrease their losses associated with climate change due to the water policy. In this scenario, wheat producers represent 27% of the reduction in income losses due to this policy (82 million). The aggregated economic results for the basin are presented in Fig. 3 (details by community and scenario are provided in supplementary material (Table S1).

As a novel study addressing the distributional impacts of climate change at river basin scale in Chile, our results are consistent with those reported in previous studies where overall results tend to hide significant disparities on smaller scales (ODEPA 2010a, b; Samaniego et al. 2009; Ponce et al. 2014, Ponce et al. 2015; Fernández et al. 2016). The *non-policy* scenario shows large distributional impacts across both communities and activities. Those communities with a large share of rainfed land, as Ercilla, will be the most affected by climate change. In contrast, those communities with large shares of irrigated land will be affected in a smaller scale. For instance, the income losses of the communities with large irrigated shares (Renaico, Negrete, and Nacimiento), only represent 17% of the basin losses. Regarding the policy scenario, our results are in line with other studies using hydro-economic models where improvements on irrigation efficiency reduce the economic losses of climate change (Graveline et al. 2014; Varela-Ortega et al. 2016; Esteve et al. 2015; Bekchanov et al. 2016).

Conclusions

The hydro-economic model presented in this paper was used to assess the economic impacts of climate change, specifically a decrease in water for both irrigation and agricultural productivity, at basin scale in southern Chile.

Considering the results reported here, this study concludes that the Vergara river basin economy is vulnerable to climate change. At the community level, our model shows substantial reallocations of land across activities, with moderated impacts on both total agricultural production and agricultural income at the basin level. Our results are consistent with the existing literature, in which rainfed producers face the largest burden of climate change.

Therefore, according to the results, even if climate change may not have large absolute consequences, it may produce large distributional consequences across producers and communities. These distributional consequences of climate change are highly relevant for policy makers, meaning that we would need differentiated policies if we want to reduce the communities' vulnerability to climate change.

Regarding the policy assessment developed, our results show that the water policy is a key measure to reduce the economic consequences of climate change on different farming communities. According to our simulations, the increasing in the water conveyance efficiency could harm some rainfed producers (oat and wheat), located in three specific communities. This negative impact seems negligible, but it highlights the unwanted effects of public policies. On this regard, more than implementing one policy to reduce farmers' vulnerabilities, it required a policy mix in order to capture the heterogeneity across both communities and farming systems.

Our research could be extended in order to improve the results reported here. For instance, due to the lack of information regarding regionalized climate change scenarios using the RCP, we used the previous IPCC scenarios (SRES). This limitation will be easily overcome when regionalized climate models become available. On the other hand, by including a production function, instead of the yield parameter used, our model could represent farmers' responses to climate change in a better way, assessing the economic impacts of extreme weather events, changes in crop water requirements, and intra-season shocks, among other topics. Finally, in order to overcome the assumption of zero water prices, we could extend the model to explicitly consider water markets within the basin, identifying buyers, sellers, and equilibrium prices.

Compliance with ethical standards

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