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Assessment of farmers' vulnerability to climate change at river basin scale: an integrated modeling approach.

Roberto D. Ponce[1], Francisco Fernández[2], Alejandra Stehr[3], Felipe Vásquez[1,4], Alex Godoy[5]

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. Using a spatially distributed hydro-economic model, the study assesses the economic impact of climate change, considering the geographical location of each farmer's community and the spatial distribution of water resources at basin scale. A hydrological model, the SWAT model, describes the basin hydrology, while farmers' economic responses are represented using a non-linear agricultural supply model. We simulated a reduction in water endowment by perturbing the hydrologic model with a regionalized climate change scenario in order to assess the behavior of farmers' communities. We assess this behavior by 1) allowing water transfer from upstream communities and, 2) ignoring water relationship across communities. At the aggregated level we found small impacts, consistent with existent literature; however, we found large distributive impacts among farmer's communities, especially when the spatial distribution of water resources are ignored.

Keywords: Hydro-economic model, climate change, agriculture, irrigation, hydrology

[1] School of Economics and Business. Universidad del Desarrollo, Concepción-Chile (robertoponce@udd.cl)
[2] Technical University of Madrid, ETSI Agronomos. Spain.
3. Environmental Centre EULA – Universidad de Concepción, Chile.
4. Research Nucleus on Environmental and Resource Economics-MSI. Departamento de Economía, Universidad de Concepción. Chile.
5. School of Engineering, Universidad del Desarrollo, Chile.

1. Introduction

The conclusions of the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), suggests that climate change impacts on water resources will have uneven consequences across sectors and regions (Field, Barros et al. 2014). The expected impacts include changes in precipitation, temperature, and increase of extreme weather events (floods and droughts). Those impacts could seriously threaten water supply for various users, among which is the agricultural sector (Stocker, Qin et al. 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, Kundzewicz et al. 2008, Field, Barros et al. 2014). Thus, the expected changes described above gain economic meaning because those changes 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 farmers' economic responses to climate change and identifies autonomous adaptation options available for different farming communities within the Vergara river basin in Chile. This methodology links the physical impacts of climate change, restricted to changes in water availability, with farmers' economic responses. The physical impacts of climate change come from a regionalized climate change scenario that perturbs the hydrologic model for the basin (SWAT model), while farmers' economic responses are modeled using a non-linear agricultural supply model. We ran the model under two institutional schemes: 1) free water transfer across communities and, 2) autarkic scheme in which water transfer is not possible. Our results suggest that the institutional scheme affects coping with climate change impacts.

The literature suggests the use of the river basin scale as the proper spatial scale to analyze water resource management because externalities are associated with water consumption (McKinney, Cai et al. 1999, Cai, McKinney et al. 2003, Brouwer and Hofkes 2008, Harou, Pulido-Velazquez 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 water demand is satisfied in a cascading scheme. In this case, the amount of water used for one user will have impacts on the amount of water available for others downstream (Maneta, Torres et al. 2009).

During the last ten years, hydro-economic models have been widely used for the analysis of water related issues, such as water conservation (Cai, Ringler et al. 2008, Ward and Pulido-Velazquez 2008, Varela-Ortega, Blanco-Gutiérrez et al. 2011, Blanco-Gutiérrez, Varela-Ortega et al. 2013), economic impacts of water variability (Maneta, Torres et al. 2009, Maneta, Torres et al. 2009, Torres, Maneta et al. 2012, Graveline, Majone et al. 2014), water quality (Volk, Hirschfeld et al. 2008, Peña-Haro, Llopis-Albert et al. 2010, Peña-Haro, Pulido-Velazquez et al. 2011, Riegels, Jensen et al. 2011), and the economic impacts of climate change (You and Ringler 2010, Hurd and Coonrod 2012, Jiang and Grafton 2012, Varela-Ortega, Blanco-Gutiérrez et al. 2013, Yang, Brown et al. 2013, Esteve, Varela-Ortega et al. 2015), among others.

The contribution of our paper lies in developing a policy-oriented methodological framework that can be adapted to each situation depending on the amount and quality of information available, making it suitable to conduct water policy analysis in developing countries. Furthermore, the model is underpinned by a highly disaggregated hydrologic model, increasing the few number of studies using the SWAT model (Arnold, Srinivasan et al. 1998) in an integrated framework for economic analysis in the face of climate change.

2.   The Vergara River Basin

The Vergara river basin is located 600 km south Chile's capital city, Santiago. 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 4,260 km^2, including ten municipalities with a total population of almost 200,000 inhabitants, including a large share of the basins's rural population (Stehr, Debels et al. 2008).

The hydrologic cycle within the Vergara river basin is completely dependent on rainfall patterns and exhibits large seasonal variability. Runoff peaks during July. Thus, any decrease in the rainfall patterns will drive a decrease in the water availability within the basin (Stehr, Debels 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 smaller share

of agricultural activities (crops and fruits). 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 (INDAP 2014).

3   Integrated Modeling Approach

Hydro-economic models combine hydrologic and socioeconomic information at river basin scale. In general, 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 (Heinz, Pulido-Velazquez et al. 2007, Brouwer and Hofkes 2008, Harou, Pulido-Velazquez 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 for the other (Braat and Van Lierop 1986), and the holistic approach in which all variables are solved endogenously in a system of equations (Cai, McKinney 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 aggregated at the municipality level, and it is solved using a modular approach.

The basin hydrologic features are modeled using the Soil and Water Assessment Tool (SWAT; Arnold, Srinivasan et al. (1998)) developed by the United States Department of Agriculture in the 1990s. It is a conceptual, physically based, hydrological and water quality model, designed to route water, sediments and contaminants from individual watersheds through the whole of the river basin systems. The model can be classified as semi-spatially 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 (HRUs), ponds/wetlands, groundwater, and the main drainage area of each subwatershed. 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.

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. It includes the major agricultural activities within the area, and differentiates between water provision systems (rainfed and irrigated), among other features (Ponce, Blanco et al. 2014).

3.1   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. As this is a derived water demand for the baseline scenario, it is assumed that supply matches the demand. In a second stage, 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 lack of updated information for the basin, we used a regionalized climate change scenario according to the SRES A2-2040 (Nakicenovic, Alcamo 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 each municipality (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 to maximize farmers' income at the basin level subject to resources, geographical, hydrological, and institutional restrictions.

The conceptual model is presented in Figure 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 municipality. Further, each community could use all the water available or leave some water (*WNU*) for the downstream community (dash line), in this case the unused water in an upstream

community will increase the water endowment downstream, thus increasing the downstream water available for irrigation.

(Figure 1 around here)

The core model is represented by the following equations.

$$Z = \sum_{c} \sum_{a} \sum_{s} (y_{c,a,s} * p_a - AC_{c,a,s}) * X_{c,a,s} \qquad [1]$$

$$AC_{c,a,s} = \alpha_{c,a,s} * (X_{c,a,s})^{\beta_{c,a,s}} \qquad [2]$$

In Equation [1], Z is the objective function value, $AC_{c,a,s}$ is the vector of average costs per unit of activity a in community c using system s (rainfed or irrigated), p_a is the price of crop a, $y_{c,a,s}$ is the yield per hectare of crop a in community c, using system s, while 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 (Howitt 1995, Blanco, Cortignani et al. 2008, Howitt, MacEwan et al. 2010).

$$FW_c = \sum_{a} fir_{c,a,irr} * X_{c,a,irr} \qquad [3]$$

$$FW_c \leq (DW_c + WNU_{-c}) * hd_c \qquad [4]$$

In equation [3] FW_c represents the water available for irrigation 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, while [4] shows that the water available for irrigation 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. Equation [5] shows that the water not used in community c is the difference between the water endowment and the water used in community c.

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$$WNU_c = DW_c - \frac{FW_c}{hd_c} \qquad [5]$$

Finally, equations [6] and [7] show resource restrictions associated to both land and irrigated land, respectively.

$$tland_c \leq \sum_a \sum_s X_{c,a,s} \qquad [6]$$

$$iland_c \leq \sum_a \sum_{irr} X_{c,a,irr} \qquad [7]$$

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 (Nakicenovic, Alcamo et al. 2000).

4.   Case Study

The Vergara river basin includes 10 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: 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: cherries, plums, peaches, apples, walnuts, pears, and vine grapes, all of them irrigated activities.

The core information used in the model (area, production, yield) is from the year 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 2010). Prices were taken from the ODEPA website (ODEPA 2010),

while the elasticities used to calibrate the model were collected from previous studies (Quiroz, Labán et al. 1995, Britz and Witzke 2008, Foster, López de Lérida et al. 2011).

Regarding the simulated climate change impacts on water availability, due to data restrictions we rely 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 hydrologic system and the associated changes in water availability.

(Figure 2 around here)

4.1   Results

For the whole river basin, the expected changes in water availability for irrigation will have minor impacts on both total agricultural land and total income, with a decrease of 2.9% and 2.1%, respectively. However, the small aggregated impacts hide large differences across both activities and communities.

At the basin level, the decrease in total agricultural land (1,372 ha) implies a decrease of 21% for irrigated land (- 2,068 ha) and 2% increase on rainfed land (696 ha). At the community level, Negrete increases its rainfed land by 40% (72 ha), while Curacautin shows the smallest decrease in irrigated land in relative terms (-6%). (Table 1).

(Table 1 around here)

As it is shown in Table 1, the substitution of irrigated land for rainfed land is uneven across farmers' communities. Mulchen substitutes 6.3 ha of irrigated land for 6.3 ha of rainfed land, the same pattern stands for Los Sauces, Ercilla, and Collipulli. For other communities, the decrease for irrigated land (-2,002 ha) is not compensated by an increase of rainfed land (630 ha), driving the decrease for total agricultural land.

Following the income optimization rule governing the model, farmers' communities will adapt their agricultural practices, aiming to minimize 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. For instance, at the basin level, most of the farmer's communities increase the land allocated to oat and wheat (both rainfed activities), decreasing the land allocated to irrigated

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activities such as alfalfa, wheat, and sugar beet. In addition, the irrigated land decreases in Mulchen (-794,4 ha) is dominated by wheat (79%), alfalfa (11%), and maize (6%). Thus, in order to cope with climate change, farmers substitute irrigated land for rainfed land. In this case, the increase in rainfed land is equally distributed between both oat and wheat. As a result, Mulchén loses 268 ha, equivalent to -2.3%. Details for the entire basin are presented in Figure 3.

(Figure 3 around here)

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%), implying a decrease of total water demand in each community by the same rate, equivalent to 15.7 million m^3.

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 imply 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 5.5 million m^3 with Mulchen and Renaico accounting for the 80% of this figure. Due to the water transfer scheme, the water available for irrigation increases in some communities. As shown in Table 2, 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).

For some communes, the water transferred is a relevant share of the water available for irrigation. For instance, for Los Sauces the water transferred from Traiguén (293 K m^3) is 9 times the original water available for irrigation (32 K m^3), while for Renaico the water transferred from Mulchén (2.7 million m^3) is 20% of its original water available for irrigation (15 million m^3).

(Table 2 around here)

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% (274 ha), leaving 293 K m^3 of water available for Los Sauces. With this water transfer, Los Sauces increases its water available for irrigation almost 6 times, from 32 K m^3 to 208 K m^3. However, Los Sauces reduces its irrigated land in order to leave water (292 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 Figure 4 (dash-line indicates zero water transfer).

(Figure 4 around here)

The changes in both water availability and irrigated land will drive changes in production and income across communities and activities. Regarding production, most of the activities will decrease their production, with a total decrease of 41,076 ton (-11%) at the basin level. At activity level, only oat will increase its production by 1,200 ton (3%), while alfalfa shows the largest decrease (-39%). Details in Figure 5.

(Figure 5 around here)

Climate change will have uneven consequences across farmers' communities. In this regard, climate change winners are concentrated within rainfed producers, such as oat producers in Mulchen and wheat producers in Negrete, which account for 83% of the total production increase (1,494 ton). On the other hand, producers negatively affected by climate change include sugar beet producers in Mulchen, Angol and Renaico (44.5% of total production decrease), alfalfa producers in Negrete, Angol, and Renaico (20% of production decrease), apple producers in Renaico (5.6% of production decrease), and wheat producers in Mulchen (4.5% of production decrease).

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. Despite the small aggregated impact on income, $462 million (-2.1%), the expected

changes at the community level range from -4.7% (Angol) to -0.1% (Los Sauces). Details in Table 3.

(Table 3 around here)

As shown in Table 3, the most vulnerable communities in economic terms are those with the largest share of irrigated land: Angol, Nacimiento, Negrete, Renaico. Those four communities accounts for 52% of all basin income loss due to climate change. Results by activity and community show that oat producers in Mulchen and Collipulli, and wheat producers in Mulchen will be better-off due to climate change. These communes account for 83% of the income increases at basin level. On the other hand, alfalfa producers in Renaico, Collipulli, Angol, and Mulchen account for 41% of income loss at the basin level. Despite the income increase in some communes, the benefits of climate change ($19 MM) are outweighed by the losses (-$482 MM), driving a negative net income result of -$470 million (-2.1%).

We perform a sensitivity analysis regarding those parameters that could affect farmers' adaptation capacity. The selected parameters are: crop irrigation requirement and irrigation efficiency. Simulations show that our results are robust regarding both parameters. For instance, 10% increase in irrigation requirements will drive a 2% decrease in total income, while 10% decrease in it will drive a 1.2% increase in total income. The same magnitude remains for changes on irrigation efficiency, but with the opposite direction (increase in efficiency will drive an increase on total income). We also simulate changes on agricultural prices, in this case the results are more sensitive to increase in prices: 10% increase in prices implies a 17% increase on total income, while 10% decrease implies a 9% decrease in total income.

The integrated model presented here, accounts for the hydrologic relationships among communities by allowing water transfer across them. In order to evaluate the relevance of this integrated approach we ran the model restricting the water transfers across communes. Thus, each community only has water at the farm gate for agricultural production. According to our results, there is a small increase in the total income loss due to climate change, from -2.1% to -2.2%. Figure 6 shows the income differences between the original setting with water transfers and the counterfactual scenario without water transfer.

(Figure 6 around here)

Despite the negligible difference in income, some major changes occur at the community level. For instance, for Collipulli, Curacautin, and Ercilla, the income remains unchanged mainly because those communities did not transfer water to others communities downstream in the base simulation. Mulchen is an interesting case because, under the new setting, its income decrease is half of the decrease computed when water transfer was possible. Under that scheme, and due to the optimization rule, Mulchen transferred 2.7 million m^3 to Renaico, and because of that its irrigated land decreases 27%, moving its crop pattern toward rainfed activities. Now, when water is no longer transferable across communities, the decrease in irrigated land is lower, and its total income is higher. The same happens with Traiguen, which previously transferred 293 K m^3 to Los Sauces, driving a 23% decrease of its irrigated land. Under the counterfactual scenario, more water is available for irrigated activities driving an increase on its income. On the other hand, in Nacimiento and Negrete, the income loss when water transfer is not possible is 80% higher than in the base simulations. This could be explained because with less water available it is impossible to increase their irrigated land. As this exercise showed, the distributive impacts of climate change are higher under the autarkic scheme when the relationships across communities are ignored.

5.   Conclusions

Considering the results reported here, this study concludes that the Vergara River basin economy is vulnerable to changes in water availability as a consequence of climate change. At the community level, our model shows substantial reallocations of land across activities. However, this land reallocation does not seriously impact the total agricultural production at the basin level. Therefore, according to the results, even if climate change may not have large absolute consequences, it may produce large distributional consequences across producers. These distributional consequences of climate change are highly relevant for policy makers, meaning that we need differentiated policies if we want to reduce the communities' and farmers' vulnerability to changes in water availability due to climate change.

Another interesting result relates to the institutional setting and the economic impacts of climate change. As it was shown when the water flowed across communities the economic impacts for the whole basin were smaller, in both absolute and relative terms, than under the autarkic scheme. Thus, from an economic perspective, the institutional setting or the way in which water is allocated is as important as the amount of water available for irrigation. In this regard those settings allowing the allocation of water to its most valuable use could help to cope with the economic impacts of climate change.

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. Among them, one of the most relevant is associated to the productive impacts of climate change on rainfed activities. Thus, the model uses these activities as adaptation alternatives to climate change. Due to lack of data, we made this assumption that could constrain our results, but not our final findings.
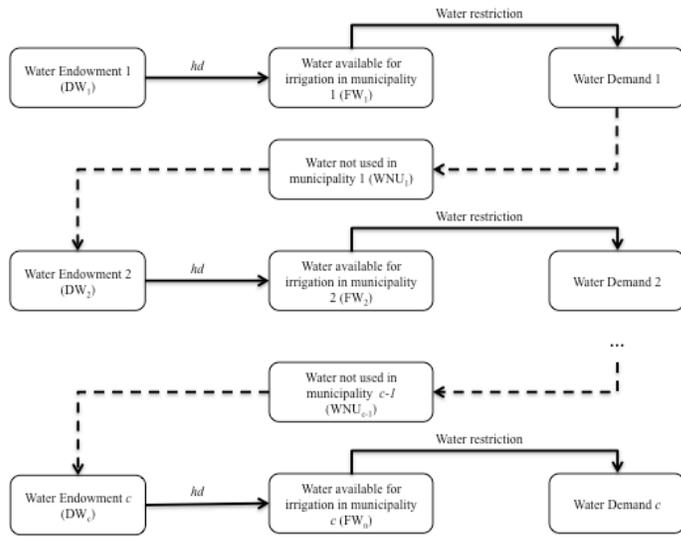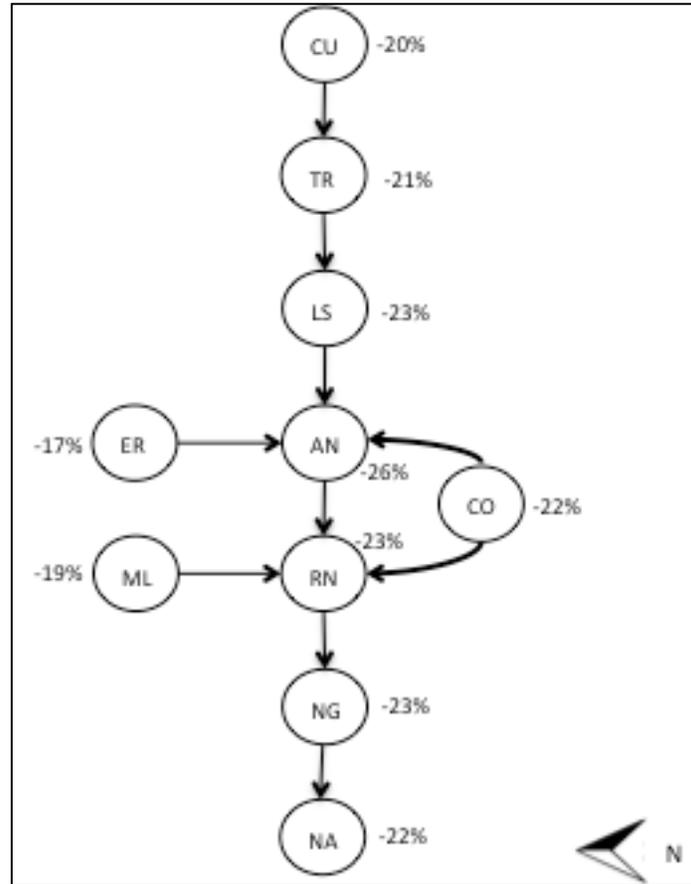
Figure 1. Conceptual Model.

Figure 2.   Vergara River Basin: Hydrological System and Changes in Water Availability.

CU: Cuaracutín, TR: Traiguén, LS: Los Sauces, AN: Angol, ER: Ercilla, CO: Collipulli, ML: Mulchén, NG: Negrete, NA: Nacimiento.

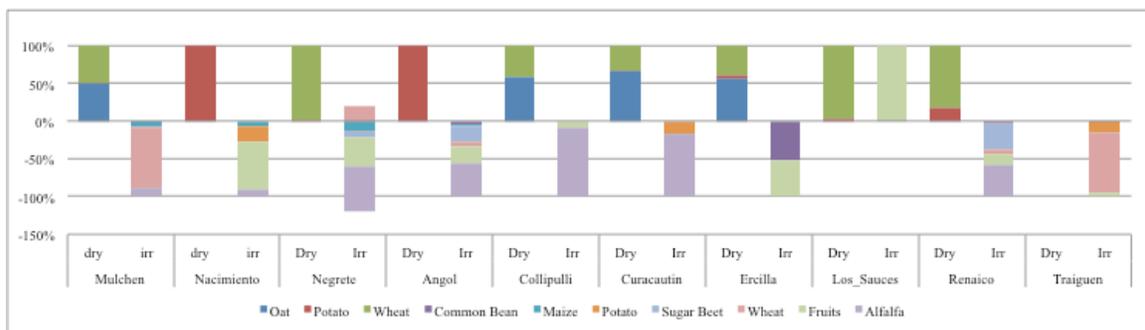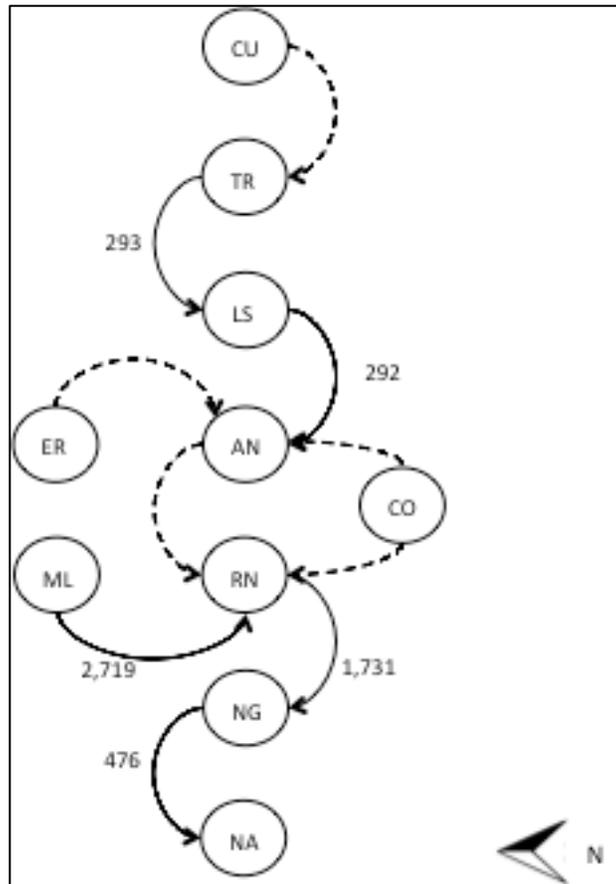Figure 3.   Land Use Change by Activity and Community (%)

Figure 4.   Water Transfer Across Communes (thousand m^3)

CU: Cuaracutín, TR: Traiguén, LS: Los Sauces, AN: Angol, ER: Ercilla, CO: Collipulli, ML: Mulchén, NG: Negrete, NA: Nacimiento.

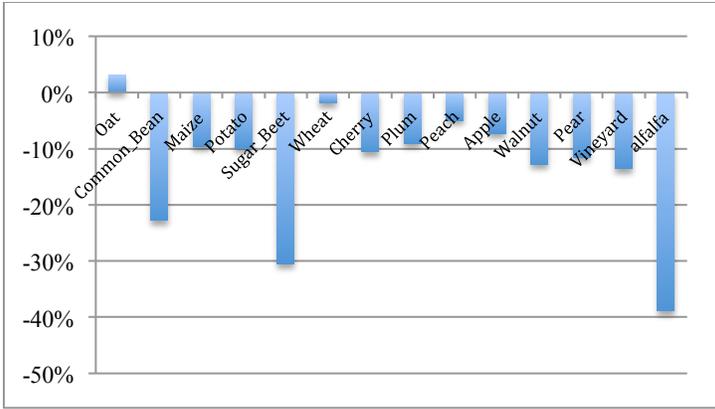Figure 5. Agricultural Production Change (%)
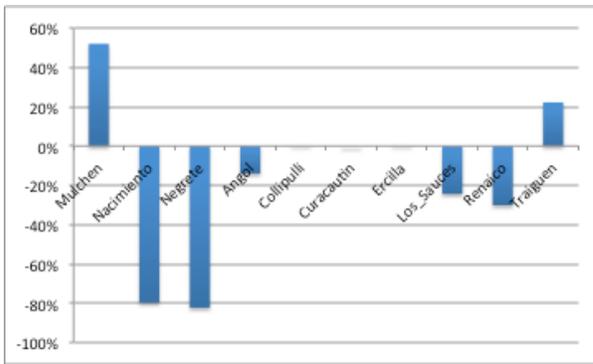
Figure 6. Income Differences

Table 1.   Agricultural Land Changes (ha)

| Community | Baseline | | Climate Change | | | |
| | Rainfed | Irrigated | Total change (ha) | | Relative change (%) | |
			Rainfed	Irrigated	Rainfed	Irrigated
Curacautin	4,678.8	104.8	6.3	-6.3	0.1	-6
Traiguen	13,352.1	1,051.9	0	-274	0	-26
Los Sauces	1,432.6	4.0	0.8	-0.8	0.06	-20.
Ercilla	3,240.6	41.1	9	-9	0.2	-21.9
Collipulli	5,689.9	265.2	49.2	-49.2	0.8	-18.5
Mulchen	8,729.0	2,908.4	525.8	-794.4	6	-27.3
Angol	333.4	1,272.3	14.5	-274.7	4.3	-21.5
Renaico	216.4	2,282.3	4.3	-435.6	1.9	-19.1
Negrete	181.8	1,420.3	72.1	-140.5	39.6	-9.9
Nacimiento	85.3	511.9	13,5	-83.7	15.8	-16.3
Total	37,939.9	9,862.3	695.7	-2,068.3	1.8	-20.9

Table 2.   Water Transfer (K m^3)

Commune	Water Endowment	Water at Farm Gate	Water Available	Water Use	WNU
Curacautin	427	256	256	256	0
Traiguen	7,626	4,576	4,576	4,400	293
Los_Sauces	54	32	208	33	292
Ercilla	415	249	249	249	0
Collipulli	3,493	2,096	2,096	2,096	0
Mulchen	23,449	14,069	14,069	12,438	2,719
Angol	12,312	7,387	7,562	7,562	0
Renaico	25,035	15,021	16,652	15,614	1,731
Negrete	14,062	8,437	9,476	9,190	476

Nacimiento	5,768	3,461	3,747	3,747	0

Table 3. Income (MM$) and Income Change (%)

Commune	BL (MM$)	CC (MM$)	Change
Mulchen	4,411	4,285	-2.8%
Nacimiento	550	530	-3.5%
Negrete	1,388	1,341	-3.4%
Angol	1,683	1,605	-4.7%
Collipulli	2,422	2,385	-1.5%
Curacautin	2,052	2,044	-0.4%
Ercilla	818	813	-0.5%
Los_Sauces	325	325	-0.1%
Renaico	3,042	2,945	-3.2%
Traiguen	4,964	4,918	-0.9%
Total	21,654	21,192	-2.1%

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