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

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

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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 impactscould seriously threaten water supply for different users, among of which is the agricultural sector (Stocker, Qin et al. 2013).

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

Within the agricultural sector, previous studies identify smallholders among the most vulnerable groups to climate change (Bellon et al. 2011; Easterling et al. 2007; Kurukulasuriya and Rosenthal 2013; Morton 2007). As smallholders' income comes from agricultural activities that are developed within a complex and diverseenvironment, it is expected thatthe exposure to climate change will exacerbate their intrinsic vulnerability(Chambers and Thrupp 1994; Morton 2007).

Using a hydro-economic model,at river basin scale, this study assesses farmers' vulnerability 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 with farmers' economic responses. The physical impacts of climate change come from a regionalized climate change scenario that perturbsthe hydrologic model for the basin, while farmers' economic responses are modeled using a non-lineal agricultural supply model.

The literature suggests the use of river basin scale as the proper spatial scale to analyze water resources management because externalities associated with water consumption(McKinney 1999, Cai, McKinney et al. 2003, Brouwer and Hofkes 2008, Harou, Pulido-Velazquez et al. 2009, Hurd and Coonrod 2012).

During the last ten years, hydro-economic models have been widely used for the analysis of several 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 (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), among others.

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 (EULA 2004), with an area of 4,260 km2, including ten municipalities with a total population of almost 200,000 inhabitants with a large share of rural population.

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 rain will drive a decrease in the water availability within the basin. The basin land use capability shows that 45% of the basin is seriously limited for field crop activities, and in those areas most of the land is devoted to forestry activities mainly due to slope characteristics, soil degradation, and soil quality.

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). Although agriculture is not the representative land use, it is the most relevant activity in socioeconomic terms with more than 14,000 smallholders under some form of government support program (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). Hydro-economic models 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 commune level.

The basin hydrologic features are modeled using the Soil and Water Assessment Tool (SWAT; Arnold 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.

On the other hand, farmers' economic behavior is modeled usinga non-lineal agricultural supply model (ASM), 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 et al, 2014).

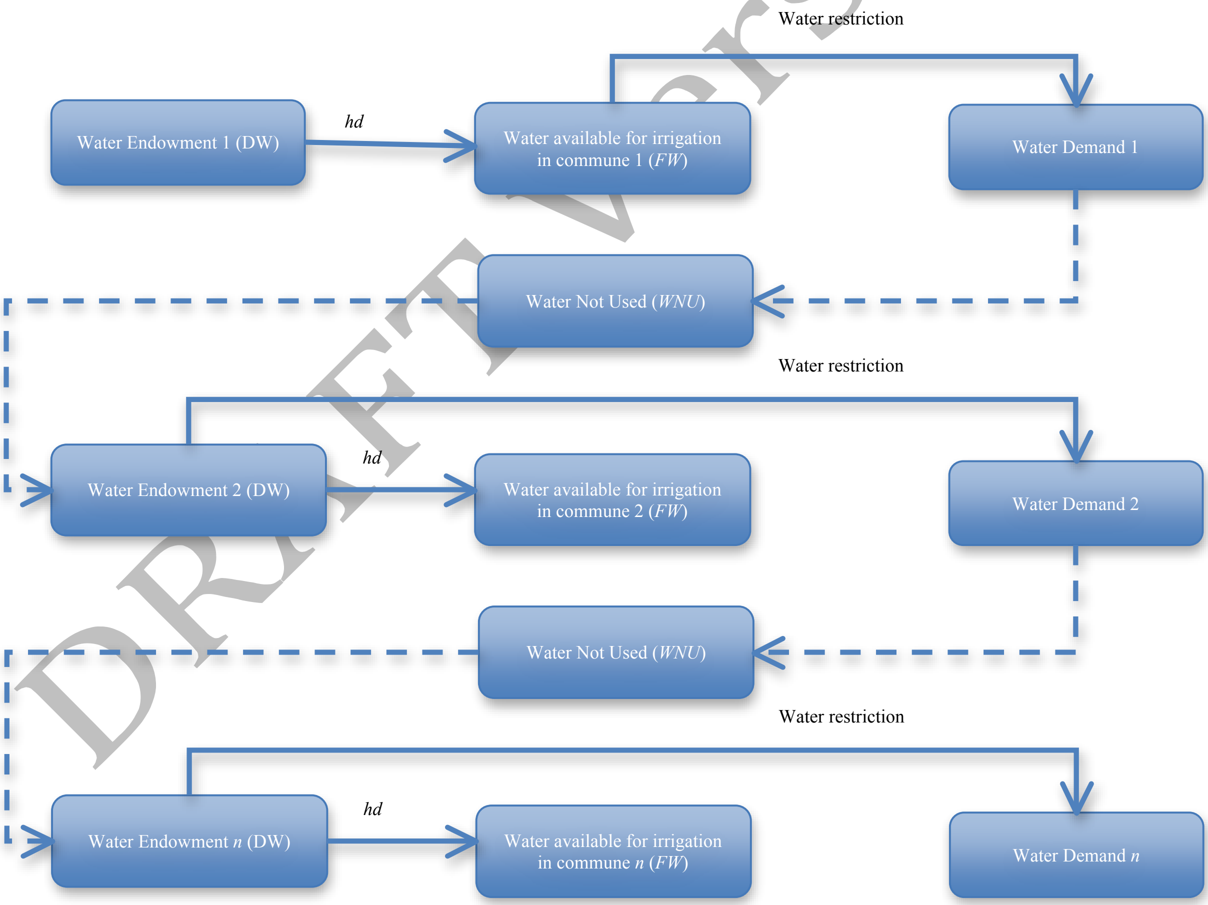
3.1 Model Specification

The VHM uses a modular approach in which, for each commune 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. Then, in a second stage the SWAT model is perturbed with a regionalized climate change scenario, in order to compute the new water supply. In this case and due to lack of updated information for the basin, we used 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 commune, along with the water availability in each section of the basin. This feature is modeled using an optimization model for the entire basin, in order to maximize total farmers' income subject to resources, and geographical restrictions.

The conceptual model is presented in Figure 1. This figure shows that water available for irrigation in each commune (*FW*) is restricted by the water endowment computed by the SWAT model (*DW*) including a water conveyance efficiency parameter (*hd*). Further, each commune could use all the water available or leave some water (*WNU*) for the downstream commune (dash line), in this case the unused water in an upstream commune will increase the water available for the downstream commune (Figure 1)

Figure 1. Conceptual Model.



The core model is represented by the following equations.

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

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

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 commune *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 commune*c*, using system *s,* whileequation [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(Blanco et al., (2008), Howitt et al., (2009), and Howitt et al., (2010)).

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

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

In equation [3] FW_c represents the water available for irrigation in commune *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 commune *c* should be lower than the water endowment computed by the SWAT model plus the water not used in the upstream commune (WNU_{-c}). Equation [5] shows that the water not used in commune *c* is the difference between the water endowment and the water used in commune *c*.

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

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

	$tland_c = \sum_a \sum_s X_{c,a,s}$	[6]
	$iland_c = \sum_a \sum_{irr} X_{c,a,irr}$	[6]

4. Case Study

The Vergara river basin includes 10 communes 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). 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 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 a 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 et al., 1995;CAPRI Model, 2008; Foster et al., 2011).

Regarding the simulated climate change impacts on water availability, according the A2-2040 SRES scenario implies an average reduction of 22% on river flows, with a maximum reduction of -26% in Angol and a minimum of -17% in Ercilla (Table 1).

Table 1. Expected changes in water availability (%)

Commune	Change
Curacautin	-20%
Traiguen	-21%
Los Sauces	-23%
Ercilla	-17%
Collipulli	-22%
Mulchen	-19%
Angol	-26%
Renaico	-23%
Negrete	-23%
Nacimiento	-22%

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. Despite these small changes at basin level, climate change will impose vast distributional effects across communes and activities. For instance, the decrease on total agricultural land (1,372 ha) implies a decrease of 21% on irrigated land, while rainfed land increases 2%. At commune level, Negrete increases its rainfed land by 40% (72 ha), while with -6% Curacautin shows the smallest decrease on irrigated land (Table 2).

Table 2. Agricultural Land Changes (ha)

	Baseline		Climate Change	
Commune	Rainfed	Irrigated	Rainfed	Irrigated
Curacautin	4,678.8	104.8	4,685.1	98.5
Traiguen	13,352.1	1,051.9	13,352.1	777.9
Los Sauces	1,432.6	4.0	1,433.4	3.2
Ercilla	3,240.6	41.1	3,249.6	32.1
Collipulli	5,689.9	265.2	5,739.1	216.0
Mulchen	8,729.0	2,908.4	9,254.8	2,114.0
Angol	333.4	1,272.3	347.9	997.6
Renaico	216.4	2,282.3	220.7	1,846.7
Negrete	181.8	1,420.3	253.9	1,279.8

Nacimiento	85.3	511.9	98.8	428.2
Total	37,939.9	9,862.3	38,635.6	7,794.0

As the different communes are linked among them through the hydrologic model, irrigated land across communes depends on the amount of water available for irrigation. At the basin level, Traiguen, Los Sauces, Mulchen, Renaico, and Negrete, leave 5.5 million m^3 of water for other communes downstream. For instance, under the climate change scenario Traiguen reduces its water endowment by 2.083 million m^3 of water, reaching a new water endowment of 7.6 million m^3, the latter is equivalent to 4.5 million m^3 available for irrigation (considering a 60% conveyance efficiency). 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 293,000 m^3 available for Los Sauces. With this water transfer, Los Sauces increases its water available for irrigation 6 times, from 32,000 m^3 to 208,000 m^3. However, Los Sauces reduces its irrigated land in order to leave water (292,000 m3) to be used in Angol that requires more water that the water endowment (Table 3).

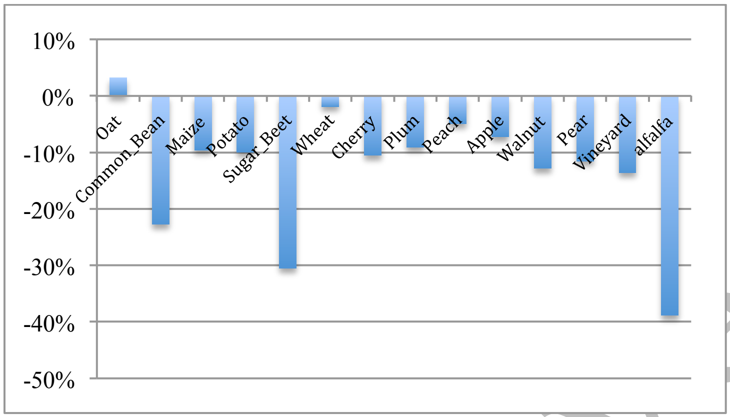
Table 3. Water Transfer (th m^3)

Commune	Water Endowment	Water Available	Water Use	WNU*
Curacautin	427	256	256	0
Traiguen	7,626	4,576	4,400	293
Los_Sauces	54	208	33	292
Ercilla	415	249	249	0
Collipulli	3,493	2,096	2,096	0
Mulchen	23,449	14,069	12,438	2,719
Angol	12,312	7,562	7,562	0
Renaico	25,035	16,652	15,614	1,731
Negrete	14,062	9,476	9,190	476
Nacimiento	5,768	3,747	3,747	0

*WNU: Not used water

The changes on both water availability and irrigated land will drive changes on production and income. Regarding production, most of the activities will decrease their production, with a total change of 41,076 ton (-11%) at the basin level. At activity level, only oat will increase their production by 1,200 ton, while sugar beet shows the largest decrease equivalent to 20,000 ton. The expected changes are presented in Figure 2.

Figure 2. Agricultural Production Change (%)



The land reallocation, along with the water transfer across communes will have distributional consequences across communes some of them will be worst-off than others under the climate change scenario. At the aggregated level, the basin will lose $462 million (-2.1%), with Los Sauces keeping its income unchanged, and Angol suffering the largest proportional decrease (-5%). Details in Table 4.

Table 4. 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%

	21,654	21,192	-2.1%

Considering the results reported here, the major conclusion is that the basin economy is vulnerable to the change in water availability as a consequence of climate change. At the commune level, our model shows substantial re-allocations 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.

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