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ORIGINAL ARTICLE

# Implications of climate change for semi-arid dualistic agriculture: a case study in Central Chile

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## Abstract

The nexus between climate change, agriculture, and poverty has become a major topic of concern, especially for dry regions, which represent a large share of the world's population and ecosystems vulnerable to climate change. In spite of this, to date, few studies have examined the impacts of climate change on agriculture and the adaptation strategies of vulnerable farmers from emerging semi-arid regions with dualist agriculture, in which subsistence farms coexist with commercial farms. This study aims to assess the micro-level impact of climate change and the farm household adaptation strategies in a semi-arid region in Central Chile. To this end, we develop a modelling framework that allows for (1) the assessment of farm-household responses to both climate change effects and adaptation policy scenarios and (2) the identification of local capacities and adaptation strategies. Aggregated results indicate that climate change has a substantial economic impact on regional agricultural income, while the micro-level analysis shows that small-scale farm households are the most vulnerable group. We observe that household characteristics determine to a large extent the adaptation capacity, while an unexpected result indicates that off-farm labour emerges as a powerful option for adapting to climate change. As such, our approach is well suited for ex ante micro-level adaptation analysis and can thereby provide useful insights to guide smart climate policy-making.

**Keywords** Adaptation · Climate change · Dualistic agriculture · Farm household heterogeneity · Semi-arid regions

## Introduction

Despite undeniable advances in the assessments of the economic impacts of climate change on agriculture, little attention has been paid to the links among climate change, agriculture, and poverty (Hertel and Rosch 2010). The latest report from Working Group II of the Intergovernmental Panel on Climate Change (IPCC WG2) states that most research on the poverty–climate nexus has focused on the poorest countries (Olsson et al. 2014), neglecting the change that has occurred in the

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distribution of poverty, both in poor countries and in countries with a higher average per capita income (Sumner 2010; Sumner 2012). Paradoxically, the shift in global poverty distribution and the economic growth in developing countries have generated emerging economies with dualistic agricultural sectors, that is, heterogeneous agricultural regions where peasant agriculture coexists alongside a large-scale farming sector (Kostov and Lingard 2002; Phororo 2001). Thus, more research is required to understand how climate change may affect these heterogeneous groups, and further distinguish their intrinsic adaptive capacities and their responses to adaptation policies.

Irrigated arid and semi-arid regions are a common example of dualistic agricultural sectors. Those regions represent approximately 30% of the world's total land area (Newton and Tejedor 2011), host more than one third of the world's population (Mortimore et al. 2009), and are a crucial source of grains, vegetables, and fruits (Koohafkan and Stewart 2008). The vulnerability of dry regions to climate change (Kurukulasuriya and Rosenthal 2003; Reed et al. 2012) increases the urgency for farm households to adapt to new climate conditions. Overall, adaptation measures have the potential to lessen the negative effects of climate change; however, adaptation responses could differ considerably across farm household groups due to their different socioeconomic and productive features.

Several authors highlight the need of household level assessments for climate change policy (Jones and Thornton 2003; Pandey et al. 2015; Skjeflo 2013, 2014). These assessments require not only the understanding of household characteristics, but also the contexts in which households interact (Skjeflo 2014). Additionally, these assessments could strengthen the link between local adaptation needs and plans, which have tended to overemphasise technological and infrastructural measures while not addressing specific farm household needs (Agrawal and Perrin 2009).

In this research, we address those gaps by developing an assessment framework based on household-level information. Through multivariate statistics, we capture households' heterogeneity, while using a mathematical programming model we simulate farm households' responses to potential effects of climate change, assessing how different households react to adaptation policies. As a case study, we applied the method in a dualistic agricultural region in Central Chile.

Many modelling approaches assess climate change impacts on agriculture and adaptation measures (Fernández and Blanco 2015). Since the 1990s, most of these economic assessments have been based on market equilibrium models that assess the future impacts of climate change on agri-food production, consumption, trade, prices (Blanco et al. 2017; Fischer et al. 2005; Nelson et al. 2014; Reilly and Hohmann 1993), and the economy-wide impact of different climate scenarios (Baldos and Hertel 2015). Although these assessments include autonomous adaptation to climate change and represent valuable contributions to understanding the impacts of crop yield changes on prices, they are inadequate for predicting farm household-level responses (Reidsma et al. 2015).

Other market approaches, based on computable general equilibrium models (Hertel et al. 2010; Skjeflo 2013), have quantified the impacts of climate change on livelihoods and food security by disaggregating household impacts. However, those studies allowed for limited household heterogeneity and assume perfect markets, failing to consider that many constraints to adaptation at the household level are related to household characteristics and market imperfections (Deressa et al. 2009; Skjeflo 2014).

At the farm level, several authors have assessed the impacts of climate change using bioeconomic farm models (BEFM) (Bobojonov and Aw-Hassan 2014; Kanellopoulos et al. 2014; Reidsma et al. 2015) that simultaneously consider the biophysical changes and farm decisions on different farms, making it possible to understand how farm-level responses influence the final economic impacts of climate change. However, its economic component is commonly based on farm supply models that assume the decision-making process of representative farmers is the same as that of commercial farms, failing to capture the heterogeneity of households' decisions in dualistic agricultural regions.

The main contribution of this paper is the development of a modelling framework capable of capturing the heterogeneous response of agricultural households to climate change in regions with dualistic agricultural sectors. Few studies have examined the impacts of climate change on vulnerable farmers from emerging semi-arid regions with dualistic agriculture, in which subsistence farms coexist with commercial farms. We go further than that, as our modelling framework allows us to identify how adaptation policies counterbalance the negative impacts of climate change on heterogeneous households and to understand the different autonomous adaptation strategies rooted in household characteristics. The inclusion of behavioural variables to capture the dynamic nature of the problem goes beyond the scope of this paper. Despite this limitation, based on our results, it is possible to extract an explicit set of measures that can be implemented in irrigated dry regions to reduce farm household vulnerability to climate change and improve the resilience of farming systems.

## Materials and methods

### Area of study

The study area embraces four central valley communes in the Maule Region in South-Central Chile (San Clemente, Pencahue, Parral, and Cauquenes). This representative semi-arid region is an agricultural zone characterised by dualistic agriculture (Berger and Troost 2014) and features irrigated and rain-fed areas, a large proportion of small-scale farms (INE 2007), and high poverty levels (CASEN 2015). Within this region, and in the entire country, water resources are managed under the Water Code Law from 1981. Under this law, water is a public good over which the State creates a right of use entitled to individuals that can freely determine its final use (Donoso 2006).

Each commune surveyed has different agrological and socioeconomic characteristics. Pencahue and Cauquenes are dryland areas, the latter characterised by its restrictive growing conditions and lack of irrigation infrastructure. San Clemente has considerable irrigated land in the Andean foothill. Parral is located within the central irrigated valley (Roco et al. 2017).

The drylands of South-Central Chile have already been affected by an upward trend in temperature (Falvey and Garreaud 2009) and a high strain on water resources (Hannah et al. 2013). Agriculture in South-Central Chile is highly sensitive to climate change and likely to experience one of the greatest freshwater impacts in the Mediterranean-climate growing regions (Berger et al. 2006; Hannah et al. 2013). Additionally, these impacts are expected to result in uneven economic consequences within the region (Fernández et al. 2016; Ponce et al. 2014).

The Maule Region (Fig. 1) is a major contributor to the agricultural output of Chile and covers a large share of total agricultural land. The Maule Region's share of national land dedicated to cereal crops, legumes and tubers, watermelon, and melon is 16.5, 14.9, 43, and 17.8%, respectively (INE 2013). Its agricultural sector generated approximately 12% of Maule's regional gross domestic product in 2013, agricultural activities generated 29% of local employment between December 2014 and February 2015 (ODEPA 2015), and family farm agriculture accounts for 16% of the national total (Jara-Rojas et al. 2012).

The Maule Region is especially vulnerable to climate change for four reasons: (1) a high rural population (35.5%) (UNDP 2008), (2) a large proportion of small-scale farms (16%) (INE 2007), (3) a large share of agricultural production that depends on annual crops (FIA 2010), and (4) its relatively high poverty levels compared to other regions (CASEN 2015).

Finally, the farm structure within the region is highly heterogeneous, ranging from large-scale, export-oriented enterprises to peasant farm households (Berger et al. 2006). In this context, better understanding of the local capacities is crucial to design adaptation policies (Roco et al. 2014; Wang et al. 2013).

## Farm household modelling framework

The modelling framework developed in this study provides detailed results at the farm household scale and captures heterogeneity across households, allowing us to better understand farm household responses within the context of climate change.

The farm household model comprises four representative farm household types from the aforementioned communes in the Maule Region (Fig. 1). The primary mathematical structure of the model is based on the farm household model presented by Louhichi et al. (2013). We adapt it to (1) the agricultural and socioeconomic features of Chilean agriculture and (2) the availability of data for this region. This is a static, non-linear optimisation model that relies on the household's general utility framework and the farm's technical production constraints. The weighted sum of the farm households' expected income represents the objective function, which is subject to resource (water, land, and labour), consumption, and cash constraints.

The overall mathematical design of the model is

$$\max U = \sum_{h=1}^{H} w_h R_h \qquad (1)$$

s.t.

- Resource constraints
- Consumption constraint using a linear expenditure system
- Price bands and complementary slackness conditions
- Commodity balances at the farm level
- Cash constraint

where $U$ is the value of the objective function, $h$ denotes a farm household, and $w$ is its weight within the Maule Region. $R$ is the farm household's expected revenue. A detailed description of the overall structure of the model can be found in Online Resource 2, where the main constraints are described in detail.

We consider the impact of climate change on 14 crops of crucial importance to the rural economies of this region. We group these crops into three categories: (1) grains for crops like wheat, oat, and rice; (2) spring crops, which include maize, common bean, green bean, chickpea, and potato; and (3) spring vegetables, which include pea, onion, tomato, melon, watermelon, and squash. For each crop, we simulate different productivity shocks. The following subsections describe each stage of the model development, from the typology construction to the simulation of alternative scenarios.

### Typology construction

From a 2011 survey of farmers in Central Chile (see Roco et al. 2014 and Roco et al. 2015 for more detail), we extracted the main information used to create the household typology. To define the typology, we performed a multivariate analysis, involving selection of variables, correlation coefficient

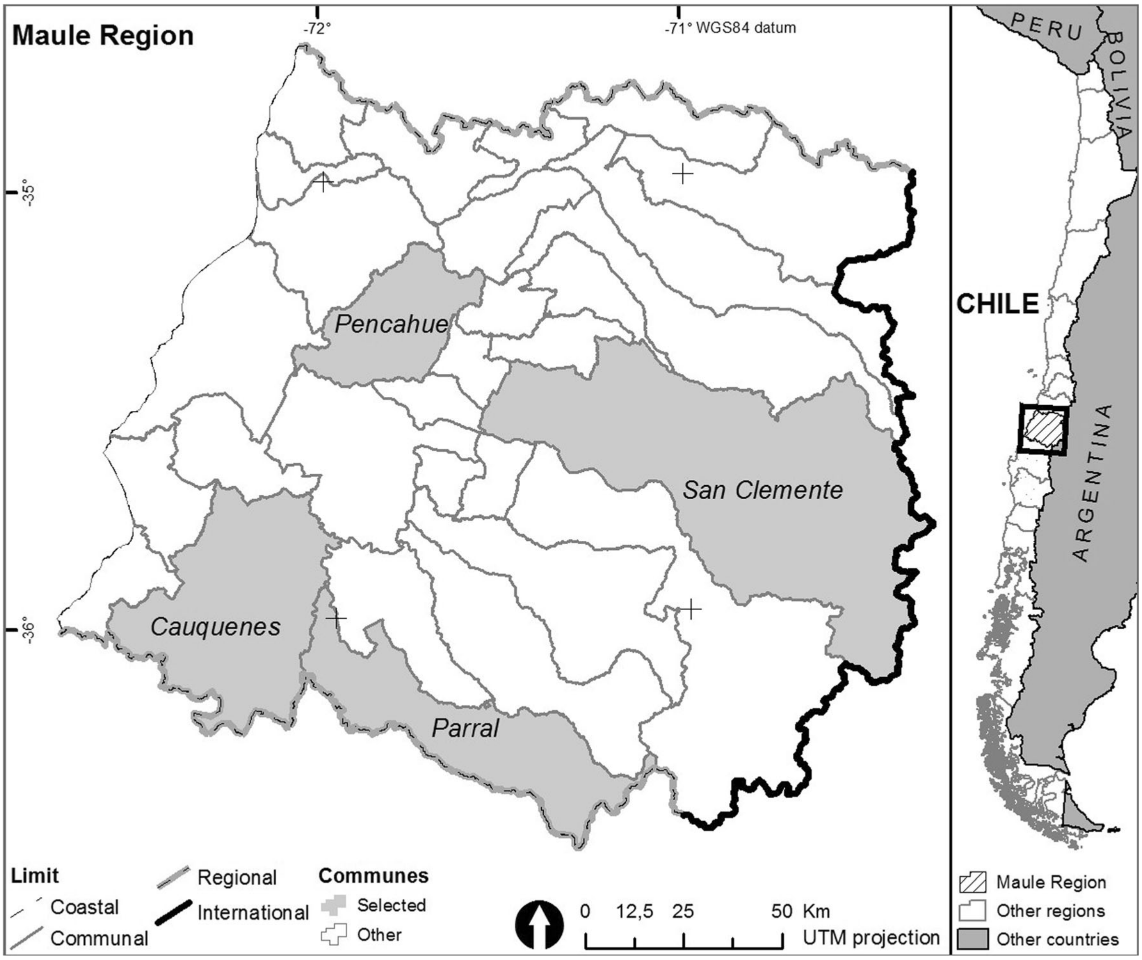

**Fig. 1** Study Area and location of the communes selected

analysis, data control, principal component analysis, and cluster analysis. After a first run of the PCA, we discarded the variables not well represented in the framework and those that did not appear to offer additional information. The following variables were retained: farm size (ha), hired labour ratio (hired/total labour), total labour (workday/years/ha), total revenue ($CLP/ha), share of grain crops on total land (%), share of spring vegetables on total land (%), share of spring crops on total land (%), and consumption (ton/year).

Through the hierarchical cluster analysis of the PCA results, four farm household types were identified. Table 1 presents the main characteristics of the clusters and their frequencies in the database. A detailed description of each one follows.

The *Medium-mixed-farm* is a medium-sized farm (average size of 8.4 ha) that mainly produces spring vegetables (65%): tomato crops represent 20% of the total area, followed by melons (13.9%), watermelons (9.6%), and onions (6.8%). Spring crops also represent an important proportion (27%) of the total area. Most crops (91.6%) are irrigated. Hired labour represents 69.5% of the total labour, which is mainly distributed among spring vegetables. This cluster accounts for 19.2% of all farm households surveyed and controls 13.7% of the agricultural land represented in this survey. Most of these farms are located in the communes of Pencahue (60%) and San Clemente (36%).

The *Large-SpringCrop-farm* is a large farm that mainly cultivates spring crops, which represent 95% of the total area and are mostly maize (87.8%), common beans (2.8%), and potatoes (0.9%). Grains and spring vegetables represent only 7.1 and 1.1% of the total area, respectively. Nearly 95% of this farm's land is irrigated. Hired labour represents 68.5% of its total labour. Its average farm size is approximately 25 ha. This cluster accounts for 13.4% of all farm households surveyed and controls 28.9% of all agricultural land represented in this study. These farms are mainly located in San Clemente (57%), Pencahue (17%), and Parral (17%).

*Medium-Grain* is a medium farm type (approximately 20 ha) that produces mainly grains, which represent 87% of the total area. These grains mostly consist of rice (46.9%) and wheat (39.4%). Spring crops, which are predominantly maize, represent 8.3% of the total area. Within this farm type, 86.6% of all land is irrigated, but there is also a crucial share of rainfed crops (mainly wheat). Hired labour represents 45.8% of

**Table 1** Main characteristics of farm households types

| Household-cluster name | Mean size (ha) | Irrigated land (%) | Mean revenue (CLP$ million/ha) | Frequency (%) |
|---|---|---|---|---|
| Medium-mixed-farm | 8.4 | 91.6 | 11.2 | 19.2 |
| Large-SpringCrop-farm | 24.9 | 94.9 | 37.8 | 13.4 |
| Medium-Grain | 19.8 | 86.6 | 16.3 | 28.4 |
| Smallholder farm | 2.5 | 17.5 | 0.8 | 38.8 |

the total labour, which is distributed mostly among maize and grains. This farm type accounts for 28.4% of all farm households surveyed, which accounts for 48.8% of all agricultural land represented in this study. This medium farm type is mainly located in San Clemente (41.9%) and Parral (41.9%).

*Smallholder Farm* is a small-scale farm type (less than 3 ha) that cultivates mainly wheat (85% of the total area) and oats (10.7% of the total area), with the remaining 4.3% of land allocated for legumes, maize, and rice. Only 17.5% of all land within this farm type is irrigated. This farm type tends to primarily use family labour, which represents 84.4% of total labour. This farm type accounts for nearly 40% of all farm households surveyed but controls only 8.5% of the agricultural land represented in this survey. Most of these farms are located in Cauquenes (73%) and Parral (17.8%).

A complete report of the typology construction process and their results are presented in Online Resource 1.

## Application to the assessment of climate impacts

The model presented here simulates the potential effects of climate change, which is represented as a series of productivity shocks on irrigated and rain-fed crops, as well as shocks to water availability because of climate change. To represent yield changes, we adjusted the yield parameters in the function of produced goods (Eq. 2) at the farm household level:

$$Q_{h,j}=\sum_a\sum_s y_{h,a,s,j}\times X_{h,a,s}=S_{h,j}+C^s_{h,j} \tag{2}$$

where $Q$ is the $(n\times 1)$ vector of the produced quantities of goods $j$ by a household $h$, $y$ is the $(n\times 1)$ vector of yields of activity $a$, and $X$ is the $(n\times 1)$ vector of the simulated levels of the agricultural activities $a$ per system $s$ in household $h$. This function also determines the self-consumed and sold quantities of goods, where $S$ represents the $(n\times 1)$ vector of sold quantities of goods and $C^s$ is the $(n\times 1)$ vector of self-consumed quantities of goods. Therefore, any change in yields directly affects the agricultural income ($Zh$), which is calculated using Eq. 3:

$$Z_h=\sum_j\left(S_{h,j}+C^s_{h,j}\right)P_{h,j}+sb_h-\sum_a\sum_s\Big(\Big(\alpha_{h,a,s}\times\left(X_{h,a,s}\right)^{\beta_{h,a,s}\times X_{h,a,s}}\Big) \tag{3}$$

$$-\sum_{ls}\mathrm{labwage}\times\mathrm{HLABOUR}_{h,ls}$$

where $P$ is the $(n\times 1)$ vector of prices of good $j$, $sb$ is the vector $(n\times 1)$ of the subsidies, $\alpha$ and $\beta$ are cost function parameters estimated using a variant of the Positive Mathematical Programming Approach (Howitt 1995), labwage is the average hired labour wage (in millions of $CLP per work day), and HLABOUR is the $(n\times 1)$ vector of hired labour by household $h$ and in labour season $ls$.

To determine water availability, we implement an adjustment by changing the gross water delivered parameter ($gwd$), which is used to determine water constraints. These water constraints indicate that the total amount of water used for irrigation at the household level cannot exceed farm water availability $FW$ (in thousand m$^3$) (Eq. 4), where $fir_{h,\ a}$ refers to the farm gate irrigation requirements of the irrigated crops (thousand m$^3$/ha) and $irr_h$ refers to the irrigated crops of each household type.

$$\sum_a fir_{h,a}X_{h,a,s}\le FW_h \qquad \forall s=irr_h \tag{4}$$

Equation 4 considers the conveyance and distribution efficiency of the water network $hd$ and the gross water delivered $gwd$ (m$^3$) at household level $h$ (Eq. 5). A change in $gwd$ directly affects farm water availability, which affects the level of irrigated agricultural activities ($X_{h,a,s}$) and changing agricultural income.

$$FW_h=gwd_h\times hd \tag{5}$$

The base year information is from 2011, whereas for the baseline, the model uses a business-as-usual scenario, which implies a simple projection of the current situation (up to 2040) and assumes no changes. For water resources within the baseline, it is assumed that supply matches demand; consequently, farmers have sufficient water rights to meet their irrigation water demand.

Three scenarios are simulated, and their results are compared with those of the baseline. These include two scenarios depicting climate change effects and one assuming an improvement in irrigation efficiency. We base these scenarios on data from the recent National Climate Change Action Plan 2017–2022 (PANCC), developed by the Chilean Ministry of the Environment (MMA 2016). This report compiles the results of several assessments of climate change impacts in Chile, in which several studies assess the impacts of climate change on agricultural productivity, precipitation, and the availability of water for irrigation.

The PANCC's report, based on Santibáñez et al. (2008), indicates that rain-fed agriculture will be the most affected by climate change because of changes in temperature and precipitation. Santibáñez et al. (2008) estimated a probably yield reduction by 2040, between 5 and 10% for irrigated wheat, between 10 and 30% for rain-fed wheat, and a decrease between 10 and 20% for irrigated maize. Because maize and wheat represent nearly two thirds of the total land considered in this study, these yield changes were the main information extracted.

These data from Santibáñez et al. (2008) have been widely used by both academic and governmental impact studies (MMA 2016; ODEPA 2010; Ponce et al. 2014). Although these data do not cover the set of crops modelled here or the specific communes of the study area, they do represent the most reliable information on climate change's effects on crop yields in Chile. These data make it possible to approximate the likely crop yield changes under climate change conditions and reflect the different impacts between rain-fed and irrigated crops within the central valley of Chile. In this context, the first scenario (*YdChg*) assumed a yield decrease of 30% for rain-fed crops and 10% for irrigated crops, based on climatic scenario A2-2040 SRES.

A second scenario (*Yd_lessW*) assumes that yields will decrease, as in the first scenario, but also an additional 30% reduction in water availability from the baseline, keeping irrigation efficiency fixed. This scenario is based on recent projections obtained using data from the ensemble mean of different global circulation models using Representative Concentration Pathway (RCP) 8.5 (Rojas 2012). This study projects a 15% decrease in precipitation by the year 2030, compared with historically simulated values for the period 1961–1990. Rojas (2012) also indicates that this process will be intensified in the period 2031–2050, significantly reducing the monthly mean flow rates of rivers in the central valley of Chile.

Although there could be an inconsistency between the climate scenarios underlying the biophysical effects on yields and water availability, the literature that has compared climate scenarios supports our decision. For $CO_2$ concentration, which is a critical factor for climate and crop productivity changes, the literature indicates that RCP8.5 is somewhat comparable to the A2 scenario until mid-century (van Vuuren and Carter 2014).

Finally, recent studies within the region have suggested that the proposed incentives for adaptation strategies should focus on promoting irrigation efficiency (Roco et al. 2014). A third scenario (*Yd_irrEff*) assumes a 20% improvement in irrigation efficiency, which is reflected in the parameter of conveyance and the distribution efficiency *hd* in Eq. 5. The Organization for Economic Co-operation and Development (OECD) and the Economic Commission for Latin America and the Caribbean (ECLAC) support this scenario, based on previous investments in irrigation infrastructure and subsidies in on-farm irrigation made by Chile (OECD/ECLAC 2016). A comparison between the 1997 and 2007 agricultural censuses reveals that the average irrigation efficiencies increased from 41 to 51% at the national level (Donoso 2015). The Maule Region also has the highest share of incentives for the adoption of water-saving technologies by farmers (CNR 2015) and is one of the areas with the most surface interventions by the National Irrigation Commission (Salinas and Mendieta 2013). In this scenario, it is difficult to determine the real cost of irrigated production by farm households; thus, we assumed no adjustment costs. A summary of the scenarios and their key assumptions is presented in Table 2.

## Results

Figure 2 demonstrates that at the regional level, the percentage share of the crop categories is subject to minor changes across all three scenarios (see Table 2 for a summary of the scenarios); however, the results show decreases in the total cultivated land, particularly for the scenario *Yd_lessW*. Figure 2 also shows that the *YdChg* scenario leads to a substitution of spring vegetable activities, largely in the group of spring crops, while also inducing an increase in irrigated land (0.1%; 2.65 ha) because of the higher impact on rain-fed crops. In the same scenario, total land will decrease by 2.4% (73.9 ha). In this case, within the group of grains, the impact of climate change on rain-fed crops is offset by the increase in irrigated oat and maize on some farm households. The decrease in spring vegetable crops is not counterbalanced by other crops of the same group, which explains their loss of share over the total land (although this is not significant (−0.4%)).

For the *Yd_lessW* scenario, Fig. 2 shows a sharp decrease in the total cultivated land (31%), with the total irrigated land decreasing at a similar magnitude (34%). A 20% increase in irrigation efficiency (*Yd_IrrEff*) partially offsets the impact of the *Yd_lessW* scenario, with a 17.3% decrease in total land and a 17.9% decrease in irrigated land, compared with the baseline.

Regarding the economic impacts of climate change, Fig. 3a shows that the overall effect on the weighted regional expected income is negative, varying from − 24.0% in the *Yd_lessW* scenario to − 17% in the *YdChg* scenario. As expected, the improvement in irrigation efficiency counterbalances the impact of the water scarcity scenario, diminishing the impact from − 24 to − 20%, compared with the baseline. Figure 3b presents the regional variation of labour use between the

**Table 2** Scenario characterisation

| Name of scenario | Effects | Key assumption[c] |
|---|---|---|
| YdChg[a] | Crop yield decrease | 30% decrease in rain-fed crops/10% decrease in irrigated crops |
| Yd_lessW[b] | Crop yield decrease + water availability shock | Previous assumptions<br>30% decrease in water availability for irrigation |
| Yd_IrrEff | Crop yield decrease + water availability shock + improvement of irrigation efficiency | Previous assumptions<br>20% improvement in irrigation efficiency |

[a] Scenario based on literature on national crop yield responses to climatic scenario A2

[b] Scenario based on precipitation changes under RCP8.5 in Central Chile

[c] All prices are the same and are fixed in all scenarios

baseline and scenarios of climate change effects. Labour use is also more negatively affected by scenario *Yd_lessW* than it is by scenario *YdChg*, which is explained by the decrease in crop activities with higher labour requirements under a water scarcity scenario. The latter also explains the higher counterbalanced impact of the improvement of water efficiency on the regional labour, diminishing the impact from − 27 to − 16%, compared with the baseline.

Despite these regional effects, it is crucial to highlight the high levels of heterogeneity across households. Figure 4a shows the percentage change of agricultural income compared with the baseline for each household type under the three scenarios. This panel shows that under the *YdChg* scenario, the major changes in agricultural income would occur in the poorest farm households ('Smallholder farm'). Because of the higher share of rain-fed crops, the effects of less water availability or increased efficiency in irrigation techniques do not have major impacts, other than those observed in the scenario of yield changes.

Within the other three farm households, the impacts of each scenario vary depending on the features of each household. Figure 4a shows that in the *YdChg* scenario, all households undergo similar changes in agricultural income, varying from − 19.4% in 'Medium-mixed-farm' households to − 13.7% in 'Large-SpringCrop-farm' households. By contrast, within the water-limiting scenario (*Yd_lessW*), differences in the impact of climate change on agricultural income are more evident. These impacts vary between − 37.9% for the farm household type 'Medium-Grain' and − 20.9% for the farm household type 'Medium-mixed-farm'. The combination of yield impact and reduced water availability for irrigated crops significantly affects the agricultural income of 'Medium-Grain'

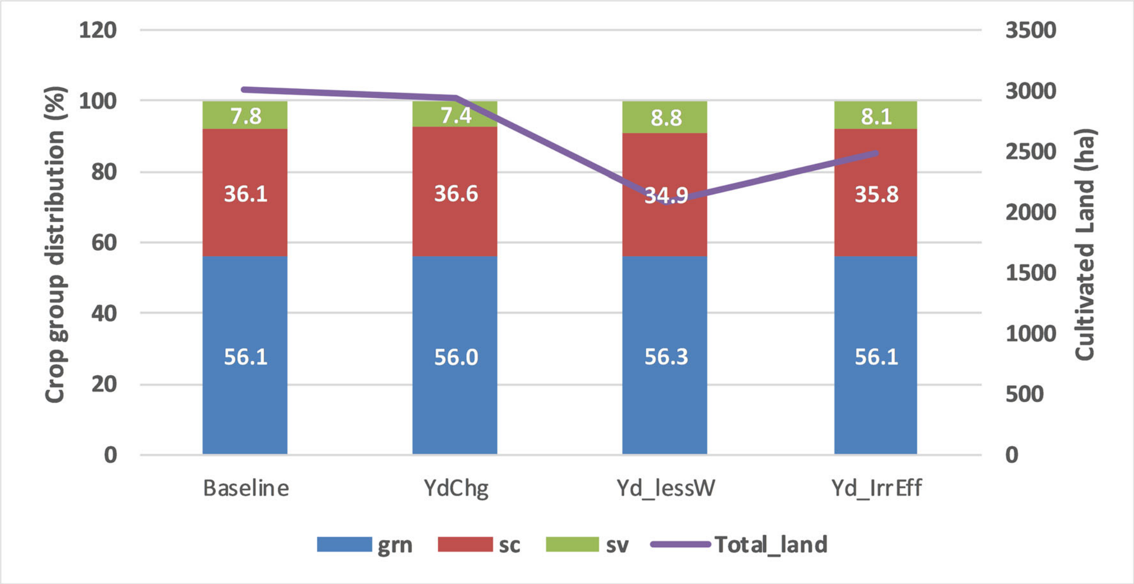

**Fig. 2** Regional crop distribution and cultivated land change; grn: group of grains; sc: group of spring crops; group of spring vegetables

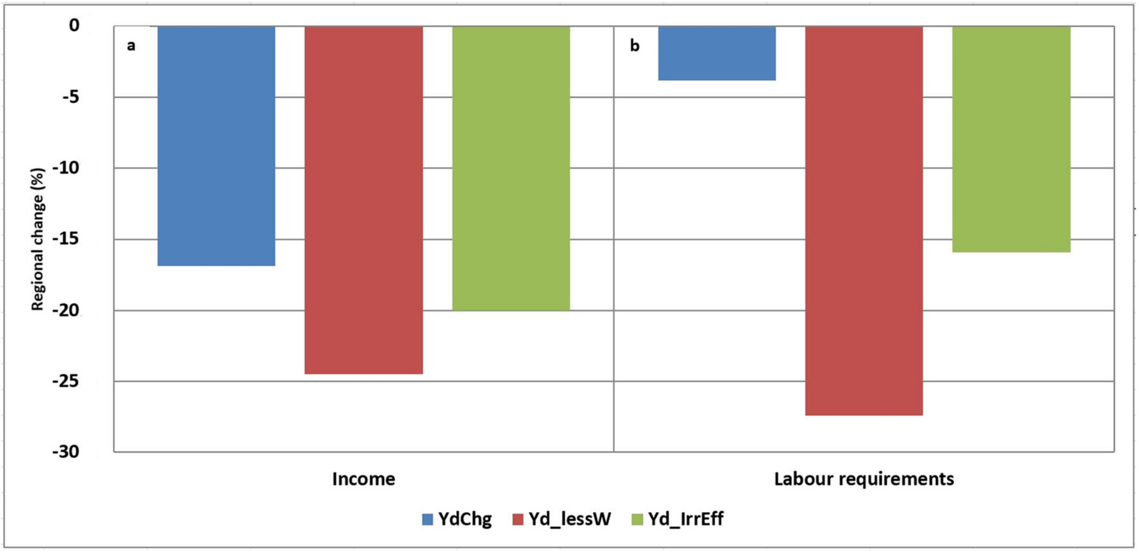

**Fig. 3** **a** Regional income change compared with the baseline. **b** Regional labour requirement change (%) compared with the baseline; YdChg: Crop yield change scenario; Yd_lessW: Crop yield change plus water availability shock scenario; Yd_IrrEff: Crop yield decrease plus water availability shock plus improvement of irrigation efficiency scenario

and 'Large-SpringCrop-farm' households, mainly due to their high dependence on water-intensive crops.

Figure 4a also shows that an increase in irrigation efficiency (*Yd_IrrEff*) has major impacts on some households (particularly 'Medium-Grain' and 'Large-SpringCrop-farm') and must be considered a crucial adaptation measure for likely climate impacts. However, this modelling framework suggests that adaptation measures that improve irrigation efficiency are not equally beneficial for all. This phenomenon can be observed in 'Smallholder farm', which largely depends on rain-fed agriculture, and in 'Medium-mixed-farm', where the high diversification of crops and the growth of high-value crops are one of their main features.

Figure 4b shows the percentage change of expected household incomes compared with those of the baseline for each household type within the three scenarios. Unlike agricultural income, household expected income is specified as the income received from all activities, including agricultural income, non-farm wages, and off-agricultural farm incomes (see Online Resource 2). Although in most households, there are no significant changes compared with their agricultural incomes, the 'Medium-Grain' households under the water scarcity scenario counterbalance the impact from −37.8% of agricultural income to −24.6% of household income. This is explained by the increase in the participation in off-farm activities such as hiring out labour, which is a consequence of the decline in crop productivity.

Labour requirement changes are different among households. Contrary to the large effects of climate change on the income of 'Smallholder farm', in this case, the labour

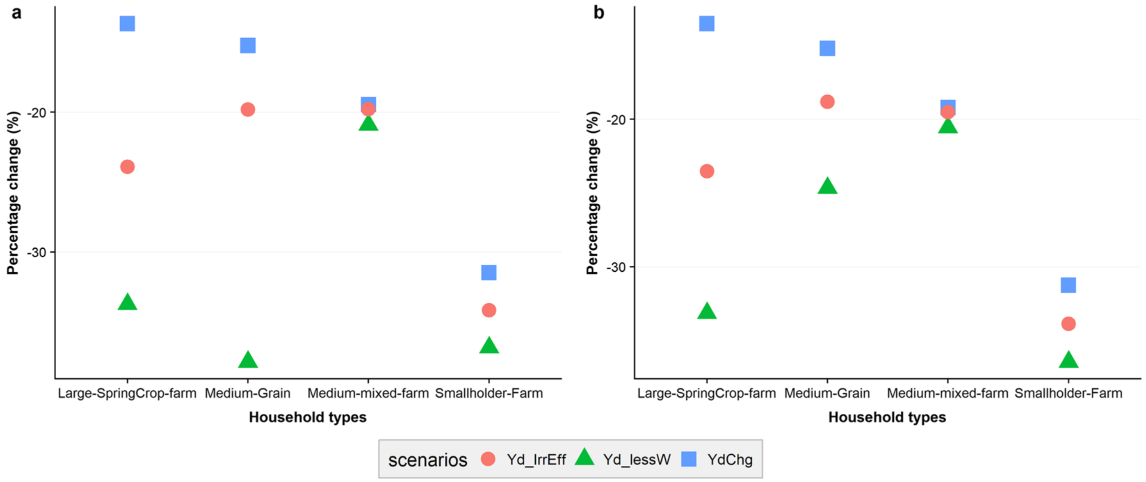

**Fig. 4** **a** Agricultural income changes compared with the baseline by household type. **b** Farm household expected income changes compared with the baseline by household type; YdChg: Crop yield change scenario; Yd_lessW: Crop yield change plus water availability shock scenario; Yd_IrrEff: Crop yield decrease plus water availability shock plus improvement of irrigation efficiency scenario

requirement changes are insignificant mainly because they tend to use mostly family labour. The other three farm households present heterogeneous responses regarding their labour requirement changes. Figure 5 shows that although 'Medium-Grain' undergoes minimal changes in its labour requirements in a *YdChg* scenario, a shock on both yields and water availability will majorly impact it. Family labour represents a critical share of the total labour of 'Medium-Grain' households, which is mainly distributed among grains. When these crops are hit hard by climate change, the labour requirements decrease, but (as shown in Fig. 4b) this household can counterbalance the impacts on income by participating in off-farm activities.

## Discussion

This study highlights the relevance of accounting for farm households' heterogeneity and its relationship with adaptation strategies, the role of off-farm labour, and the vulnerability of the poorest farmers as key elements to define adaptation policies in dualistic agricultural regions.

Our results show that most of the farm households are highly vulnerable to risks related to water availability for irrigation, particularly those highly dependent on specific irrigated crops (i.e., maize, rice). These results are in line with other studies in irrigated, arid, and semi-arid regions, where a further demand increase of water is anticipated (Bobojonov and Aw-Hassan 2014; Esteve et al. 2015; Roco et al. 2016). When looking at the different household types, households' heterogeneity arises as one of the main issues of this study, specifically for the adaptation scenario of improvement in irrigation efficiency.

Households' heterogeneity has not been addressed in current adaptation plans, which have neither fully accounted for farm households' specific features nor linked their adaptation needs with national adaptation initiatives. Currently, adaptation plans have tended to overemphasise technological and infrastructural measures while often overlooking different farm household needs and their autonomous adaptation strategies (Agrawal and Perrin 2009; Olsson et al. 2014; Perch 2011). Our findings could shed lights on this omission. For instance, for those households growing water-intensive crops, the adaptation policy will counterbalance the effects of a water scarcity. However, this policy does not act as a significant buffer for the impact of water scarcity in farm households with a high diversification of crops or for small-scale farmers that mainly depend on rain-fed crops.

The uneven effect of improvement in irrigation efficiency reveals the lack of access by small households to a well-established irrigation system. Thus, policies aimed to close this gap should consider not only technological and infrastructural measures, but also the institutional dimension represented, for example, by water rights to avoid unwanted effects of this policy on other water users (Rockström et al. 2010). The unequal effect of the adaptation policy also highlights the diversification of crops as a relevant factor for coping with climate change (Aerts et al. 2008; Fraser et al. 2005; Tonhasca and Byrne 1994) and provides a concrete example of a strategy for supporting efforts to cope with water scarcity in semi-arid regions (Aleksandrova et al. 2016). This finding shows that crop diversification enhances farm household resilience and may lead to inexpensive adaptation alternatives compared to technological and infrastructural measures. Diversification is a key aspect of cost-effective smart-adaptation strategies in regions under high water stress (Gassert et al. 2013).

Our results suggest that farm households with a high level of family labour counterbalanced the impact of climate change on income by participating in off-farm activities, reducing negative impacts by nearly 13%. Off-farm activities are adaptive responses to climate change, particularly for those households with a large family size (Barnett and O'Neill 2012; Karfakis et al. 2012). This

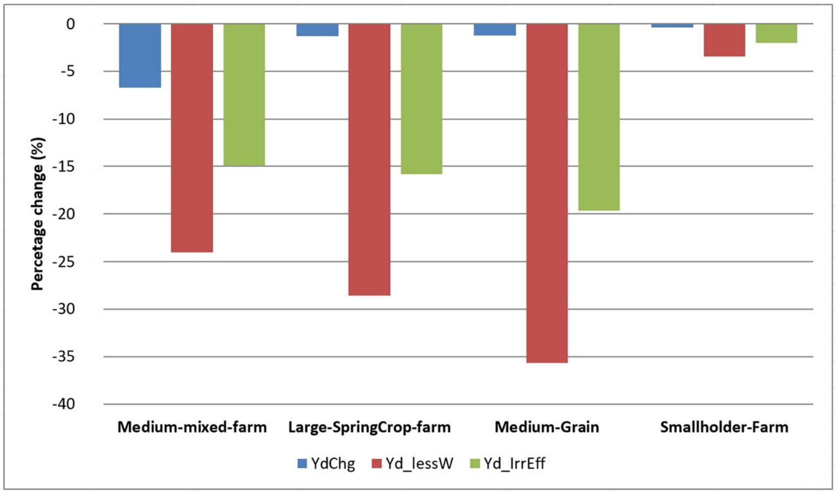

**Fig. 5** Labour requirement changes by household compared with the baseline; YdChg: Crop yield change scenario; Yd_lessW: Crop yield change plus water availability shock scenario; Yd_IrrEff: Crop yield decrease plus water availability shock plus improvement of irrigation efficiency scenario

finding highlights what the latest IPCC report already recognised that off-farm income and employment opportunities are key to enhancing farmer's adaptive capacity (Gbetibouo et al. 2010; Dasgupta et al. 2014). The implementation of this adaptive response raises the question as to whether a resource scarcity due to climate change could increase the migration of rural households as a means to diversify their income (Davis and Lopez-Carr 2010).

Finally, as expected and reported in previous research (Bellon et al. 2011; Fernández et al. 2016; Morton 2007; Ponce et al. 2017), our results show that the poorest farmers will face the largest decrease in the farm household expected income, under all the scenarios analysed.

## Conclusions and policy implications

The principal message of this study is associated with the vulnerability of farm-households in dual agricultural regions with water stress conditions. Climate change will impose distributional consequences on those regions mainly due to their intrinsic heterogeneity, in which, the poorest farm households will face the largest economic impacts.

The vulnerability of farm households is commonly associated with expected climate-driven physical changes such as, for example, imbalances in water for irrigation. However, vulnerability is also associated with productive and socio-economic features which determine the agents' adaptive capacity. Thus, policy-makers involved in the development of adaptation strategies must be able to see beyond the climate-driven physical changes, considering also the heterogeneity of the exposed farm households.

As much as improving water use remains as one of the major focal points of agricultural adaptation strategies, especially in dry regions, inexpensive measures such as crop diversification and off-farm employment opportunities should not be underestimated. These are coping mechanism crucial for the development of smart-adaptation strategies in regions under high water stress.

This modelling framework entails limitations that need to be considered. Because of the static condition of the framework, this model does not consider the evolutionary pattern of the endogenous variables which determine the final economic impact of climate change. On the other hand, as the model decisions are driven by relative agricultural profits (crops and labour), our results are restricted to agricultural land allocation, thus not considering other sectors, such us forestry or livestock, with land use competition with agriculture. Additionally, it is important to highlight that although massive changes in agricultural land allocation will drive changes in LUC, mainly through relative profits with other sectors, this issue is beyond the scope of this study, as this research is household-based, and it is not based on a multi-sector model. Despite these limitations, the directions of our conclusions remain, meaning that farm household heterogeneity determines for the effectiveness of adaptation policies in regions characterised by dualistic agricultural sectors.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest.

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