# Dynamic adaptation of maize and wheat production to climate change

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# Dynamic adaptation of maize and wheat production to climate change

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**Abstract** Agriculture represents the main source of livelihood for small scale farmers, and a significant fraction of the gross domestic product in the case of intensive commercial agriculture. Because crop performance at the end of a growing season is strongly linked to the observed meteorological conditions, agricultural systems have been one of the main subjects of analysis to understand the impacts of both climatic variability and climatic change. As climate scientists make progress understanding the key elements of the atmosphere and provide with better projections of climate change scenarios, more effort is devoted to impact assessment and the evaluation of adaptation strategies to reduce vulnerability of crops and farmers. The objective of this work was to document the impacts of climate change on maize and wheat yields in Chile as well as to describe the dynamics of adaptation (i.e. changes in management decisions over time) that will take place, considering that farmers can "learn" from previous crop yield outcomes. Yield outcomes were obtained using a crop simulation model run under climate change scenarios based on HadCM3 projections. A simple decision model for a risk neutral farmer was used to investigate changes in optimum management decisions over time. Maize showed yield reductions in the order of 5% to 10%. Under irrigation, the best alternative for adaptation corresponded to adjustments in sowing dates. In the case of winter wheat significant yield reductions were observed for the no adaptation case. Because this crop showed positive responses to the increase of carbon dioxide, adaptation strategies were very effective counterbalancing the impacts of a warmer and drier environment. Dynamic adaptation was referred here to the introduction of small adjustments in management based on previous observed changes in productivity. This type of adaptation strategy

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outperformed prescriptive decisions based on historical or projected climate change scenarios, since it was sufficiently flexible to maintain near optimum economic performance over time, as climate varied from baseline to projected future conditions.

## 1 Introduction

Agriculture is one of the most susceptible systems to climate change since meteorological variables determine resource availability (i.e. solar radiation, water, carbon dioxide) and control fundamental processes involved in crop growth and development. Literature shows a wide variety of examples where researchers have addressed the effects of climate variability on crops (Carlson et al. 1996; Phillips et al. 1998; Podestá et al. 1999; Rubas et al. 2006) as well as the impacts of climate change on crop yields and resource capture (Kaiser et al. 1993; Rosenzweig and Parry 1994; Riha et al. 1996; Reilly et al. 2003; Parry et al. 2004). These studies have contributed to understand the degree of vulnerability of crops under variable climatic conditions.

Even though agricultural responses to climate change tend to be crop and location specific, there is ample evidence that most agricultural systems will be reshaped. In some cases, projected changes in productivity will force farmers to adopt different management practices, while in others the impacts of climate change will imply that current varieties (species) will no longer be a feasible economic alternative. Although there is still considerable uncertainty regarding to the magnitude of future climatic changes, it is necessary to assess the impacts that can be expected on agricultural production and evaluate alternatives of adaptation, for both scientific and policy making reasons.

As new insights about the relationship between climate change and crop productivity are generated, more attention is given to the identification of specific changes in current management practices to either reduce negative consequences or take advantage of future favorable conditions. Agricultural adaptation, defined as "the adjustment in agricultural systems in response to actual or expected climatic stimuli or their effects, to moderate harm or exploit beneficial opportunities" (IPCC 2001) becomes a key element in climate change policy that must be studied in depth.

Researchers have performed impact assessments and alternatives evaluation following a wide variety of methodologies. Some examples are historical analogs, Ricardian analysis and empirical relationships (Tao et al. 2006; Mendelsohn and Dinar 1999; Polsky and Easterling 2001; Webb et al. 2008). However, the most common approach corresponds to the use of crop simulation models to estimate the potential impacts of projected climatic conditions on agricultural systems. In this framework, daily meteorological variables consistent with current climatic conditions and climate change projections are generated. Then these time series, in conjunction with soil parameters, are used as input variables for crop simulation models that represent the dynamics of plant growth and development. Finally the results of these simulations (i.e. yields, length of the growing period, total water and nutrient uptake, etc.) for both, current and future climatic conditions are compared. Impacts of climate change are then expressed as absolute or relative changes in crop productivity and resource use. Because crop models allow the representation of different agricultural management practices, adaptation strategies are explored simulating the results of a set of alternatives and cultivars, choosing the ones that would maximize productivity or any other economic index under projected climatic conditions.

Although this approximation does answer relevant questions about potential changes in crop growth and development (impacts), and what changes must farmers introduce to cope with new climatic conditions (adaptation), it does not provide insights on how the transition from optimum management at present time to optimum management in the future will occur. Additionally it overlooks the possibility of relevant intermediate strategies that can outperform the former ones because (a) climate changes smoothly between the two stages and (b) farmers involved can act as rational decision makers.

Two previous studies have documented the effects of time lags on farmer's adoption of adaptation strategies. Using crop simulation models, Schneider et al. (2000), compared the performance of farmers, who practice no adaptation, perfect adaptation, and 20 year-lagged adaptation. In this way authors represented the typical delay that is observed in any adoption of technological innovation, and the effects of natural variability which would mask farmer's capacity to detect climate change. A rather similar approach was followed by Easterling et al. (2003), in which the adoption of adaptation strategies was represented by a logistic curve (i.e. an s-shape curve that models farmer's incorporation of technological innovation over time). As expected, logistic adaptation tend to be less effective than climatically optimized adaptation strategies ("clairvoyant farmer"), but has the advantage of introducing realism in climate change impact assessment.

Although these two examples partially capture the dynamics of adaptation, they still can be regarded as prescriptive assessments, since the rules of technological adoption are exogenous and set by the researchers to analyze specific situations. The manner in which adaptation is internalized by farmers in response to previous observed yield variations is a subject that needs to be explored.

The objective of this work is to document impacts of climate change on maize and wheat yields in Chile as well as to describe the dynamics of adaptation (i.e. changes in management decisions over time) that will take place, considering that farmers can "learn" from previous crop yield outcomes. Since the level of severity of climate change is the major driver of yield reduction, our hypothesis is that the use of time series of previous yields helps farmers to internalize the impacts of climate change, and enable them to make small adjustments in crop management that are more effective than prescriptive strategies based on projected climate change scenarios. We also explored different yield record lengths to isolate the effects of natural variability from climate change on yield trends.

## 2 Methods and procedures

Two different locations were selected to perform this study whose main climatic features are presented in Table 1. The first location, Curicó (34.6° S), shows a typical Mediterranean climate. Total annual precipitation is around 700 mm, being concentrated in the austral fall and winter (May to September). Mean maximum temperature varies from 14°C in July to 30°C in January, whereas mean minimum temperature shows a range from 2°C to 10°C. In this location, irrigation plays a fundamental role, allowing farmers to obtain high yields, both in annual as well as in perennial crops. This region was selected to analyze the impacts of climate change and the dynamics of adaptation over time on maize and spring wheat, both grown

**Table 1** Mean values (1971–2000) of maximum temperature, minimum temperature, precipitation, and HadCM3 climate change projections for different periods

| Maximum temperature (°C) | | | | | Minimum temperature (°C) | | | | Precipitation (mm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Present | Δ (2020) | Δ (2050) | Δ (2080) | Present | Δ (2020) | Δ (2050) | Δ (2080) | Present | R (2020) | R (2050) | R (2080) |
| Curicó | | | | | | | | | | | | |
| Jan | 30.1 | 1.79 | 4.26 | 6.24 | 12.3 | 1.84 | 3.21 | 4.38 | 1.8 | 1.01 | 0.56 | 0.51 |
| Feb | 29.6 | 0.68 | 3.25 | 6.20 | 11.6 | 1.69 | 3.00 | 5.39 | 2.8 | 1.54 | 1.28 | 1.14 |
| Mar | 26.4 | 1.83 | 2.96 | 5.65 | 9.8 | 1.54 | 2.65 | 5.26 | 10.2 | 0.71 | 0.73 | 0.76 |
| Apr | 21.1 | 0.90 | 2.84 | 4.83 | 7.2 | 1.66 | 2.71 | 3.98 | 28.1 | 1.28 | 1.06 | 0.79 |
| May | 16.6 | 0.78 | 2.23 | 3.76 | 5.3 | 1.38 | 2.14 | 3.22 | 49.4 | 1.02 | 0.71 | 0.73 |
| Jun | 13.8 | 0.41 | 1.82 | 3.17 | 4.8 | 0.60 | 1.18 | 1.98 | 67.7 | 1.04 | 0.81 | 0.71 |
| Jul | 12.6 | 0.92 | 2.01 | 3.18 | 3.6 | 0.26 | 0.92 | 1.65 | 116.8 | 0.89 | 0.84 | 0.71 |
| Aug | 15 | 1.23 | 2.39 | 4.23 | 4.2 | 0.90 | 1.49 | 2.22 | 78.7 | 1.19 | 0.92 | 0.63 |
| Sep | 18 | 1.23 | 2.16 | 4.40 | 5.8 | 0.70 | 1.05 | 2.20 | 38.1 | 0.80 | 0.64 | 0.48 |
| Oct | 21.6 | 1.05 | 2.82 | 5.15 | 8 | 0.47 | 1.66 | 2.41 | 21.8 | 0.89 | 0.75 | 0.55 |
| Nov | 25.4 | 1.51 | 4.83 | 7.49 | 9.7 | 1.08 | 1.86 | 3.71 | 12.4 | 0.99 | 0.44 | 0.40 |
| Dec | 28.7 | 1.70 | 4.83 | 6.29 | 11.7 | 1.37 | 3.11 | 4.81 | 1.8 | 1.03 | 0.59 | 0.74 |
| Temuco | | | | | | | | | | | | |
| Jan | 24.5 | 2.36 | 4.83 | 6.85 | 8.8 | 1.44 | 2.85 | 3.96 | 27.1 | 0.93 | 0.69 | 0.66 |
| Feb | 25.9 | 1.70 | 3.73 | 6.76 | 8.9 | 1.80 | 2.94 | 5.39 | 32.1 | 1.09 | 1.07 | 0.93 |
| Mar | 23.1 | 2.38 | 3.62 | 5.90 | 7.8 | 1.69 | 2.47 | 5.14 | 52.4 | 0.70 | 0.62 | 0.86 |
| Apr | 18.8 | 1.04 | 2.88 | 4.23 | 6.3 | 1.44 | 2.30 | 3.49 | 61.8 | 1.17 | 0.94 | 0.74 |
| May | 15.3 | 0.68 | 2.27 | 3.27 | 5.8 | 1.06 | 1.72 | 2.44 | 107.1 | 1.10 | 0.77 | 0.75 |
| Jun | 12.7 | 0.52 | 1.65 | 2.66 | 4.9 | 0.52 | 1.18 | 1.94 | 153.0 | 1.00 | 0.91 | 0.72 |
| Jul | 12.3 | 1.06 | 1.67 | 2.70 | 3.8 | 0.20 | 0.78 | 1.64 | 120.3 | 0.87 | 0.90 | 0.84 |
| Aug | 13.9 | 1.26 | 2.11 | 3.41 | 3.8 | 0.99 | 1.63 | 2.30 | 114.8 | 1.09 | 0.93 | 0.69 |
| Sep | 15.9 | 0.83 | 1.63 | 3.53 | 4.1 | 0.66 | 0.84 | 2.10 | 52.2 | 1.01 | 0.76 | 0.71 |
| Oct | 18.3 | 0.85 | 2.09 | 3.49 | 6 | 0.38 | 1.36 | 2.11 | 72.6 | 0.83 | 0.78 | 0.61 |
| Nov | 19.9 | 0.89 | 2.91 | 4.85 | 7.3 | 0.89 | 1.33 | 2.97 | 72.4 | 1.12 | 0.63 | 0.63 |
| Dec | 22.5 | 1.81 | 5.17 | 7.74 | 8.4 | 1.12 | 2.20 | 3.89 | 49.4 | 0.95 | 0.64 | 0.67 |

Δ( ) corresponds to the difference between period ( ) and current climatic conditions. R( ) corresponds to the ratio of precipitation for period ( ) and current climatic conditions (Present)

under irrigated conditions. The soil corresponds to a typical sandy loam soil with 1.1 meter depth, bulk density in the order of 1.2 g/cm$^3$, and good drainage conditions. Volumetric soil water content at field capacity and permanent wilting point were 0.32 and 0.18 respectively.

The second simulation experiment was set in the location of Temuco, located at 38.5° S. This region shows a warm temperate climate with abundant precipitation (higher than 900 mm). Winter wheat is the most important crop and it is grown under rain fed conditions. Even though rainfall shows strong seasonality, the amount received in summer reaches 110 mm, and is usually sufficient to allow wheat to reach maturity. Mean maximum temperatures vary from 12°C to 24°C during the year, and minimum temperatures range from 1°C in mid winter to 7°C in summer. Because of these characteristics, the occurrence of killing frosts is more frequent than in the previous location. Temuco region is characterized by the presence of volcanic soils (Dystrandepts). We selected a soil unit with 0.85 m depth and bulk density of 0.92, the soil showed moderate acidity (pH 5.8). Volumetric soil water content at field capacity and permanent wilting point were 0.48 and 0.27, respectively.

### 2.1 Climate change scenarios

We used the results of HadCM3 global circulation model, run under the new A1FI SRES emission scenarios. Although HadCM3 showed bias when comparing model outputs to current climatic conditions in both regions, it performs reasonably well reproducing the seasonality on mean monthly temperature and precipitation. For this reason, we used relative changes in temperature and precipitation instead of absolute values projected for each month. The results for the periods denominated "2020", "2050", and "2080" were used to generate the correspondent climatologies. Atmospheric levels of carbon dioxide were modified from current values, assuming a 1% increase per year. Table 1 shows the projections made by HadCM3 for the regions under study.

Because HadCM3 outputs are grid point estimates at monthly time scales, it was necessary to adapt a downscaling procedure to generate daily weather data consistent with current and future climate conditions at each location. Daily data from the nearest meteorological station was collected and used to fit a weather generator algorithm (Richardson 1981; Wilks and Wilby 1999). The main features of this stochastic model are the following.

Precipitation is divided into an occurrence and intensity process. Sequences of days with or without precipitation are obtained by a two state first order Markov chain. If current simulated day corresponds to a "wet" day, the correspondent amount of precipitation is generated using a log-normal distribution. Other relevant meteorological variables such as maximum temperature, minimum temperature, dew point temperature, and wind speed are obtained using a multivariate autoregressive model. To ensure a more realistic representation of day to day variability, the parameters of the autoregressive module were conditioned on precipitation status (i.e. different mean and variances were used depending on whether the current simulated day is dry or not). Solar radiation data was generated as a function of differences between maximum and minimum temperature (Meza and Varas 2000).

The parameters of the weather generator were assumed stationary within a month and were modified to represent different climatic periods according to the results of HadCM3. For each climatic period ("Present", "2020", "2050", and "2080") 75 independent time series of daily meteorological variables were generated. These series represent 75 possible growing seasons or years in each period.

### 2.2 Crop yield simulation

We used DSSAT v 4.0 (Jones et al. 2003) to simulate crop yields as a function of current as well as future climatological conditions. We simulated irrigated maize and spring wheat in the location of Curicó. Winter wheat performance was evaluated in the location of Temuco as an example of rain fed agriculture. We evaluated the performance of maize and wheat cultivars that are frequently used by farmers of Chile, their correspondent crop model parameters (i.e. genetic coefficients) were obtained from a calibration experiment carried out between 2004 and 2006 at the experimental station of the Pontificia Universidad Católica de Chile. Table 2 shows the parameters of each crop and cultivar.

To test management strategies and identify possibilities of adaptation, we evaluated a wide range of treatments. In the case of maize, we used two hybrids (one

**Table 2** Parameters of wheat and maize cultivars used in this experiment

| Crop | Cultivar | P1V (P1) | P1D (P2) | P5 | G1 | G2 | G3 | PHINT |
|---|---|---|---|---|---|---|---|---|
| Spring wheat | Halcón | 0.0 | 25.0 | 500.0 | 18.0 | 23.0 | 0.20 | 90.0 |
| Winter wheat | Swindy | 40.0 | 10.0 | 800.0 | 25.0 | 25.0 | 1.50 | 90.0 |
| Maize | DK-440 | 145.0 | 0.0 | 580.0 | | 1000.0 | 7.58 | 46.0 |
| Maize | DK-647 | 210.0 | 0.0 | 600.0 | | 900.0 | 8.80 | 46.0 |

Genetic coefficients P1V, P1D, and G1 apply only for wheat cultivars, while P1 and P2 are specific for maize (see Wilkens et al. 2004 for details about genetic coefficients in DSSAT).

classified as early maturing and the other regarded as long maturing), ten different sowing dates spaced by 15 days (between early August to mid December), and five different nitrogen levels (250, 300, 350, 400, 450 kg N/ha). For winter and spring wheat, treatments were composed by a combination of ten sowing dates (May to September) and five nitrogen levels (200, 250, 300, 350, and 400 kg N/ha).

To analyze the dynamics of adaptation we must consider a continuous sequence of 100 years or growing seasons. Even though there are results of general circulation models that represent transient climate changes, it would have been necessary to repeat the downscaling procedure for each simulated year, increasing the number of synthetic series of meteorological variables considerably. In this case we used a simple approximation to mimic the climate change trend. We randomly sampled 25 yield outcomes of each of the four climatological periods, and we combined them to get one realization or likely path of yield changes from current conditions to future ones. Because climate parameters do not change abruptly between climatological periods spaced by 30 years, this solution is good approximation in comparison to a linear trend. The sampling procedure was repeated 30 times to get estimates of mean and variances of yield changes and to better represent the variability of optimum management strategies.

Crop productivities were translated into gross margin (dollars per hectare) multiplying yield times the correspondent grain price and subtracting nitrogen use times unit cost of nitrogen and then subtracting fixed costs. Grain prices and nitrogen cost were regarded as fixed for the period of evaluation. For the region under study at year 2006, nitrogen cost was equal to 0.95 US$/kg, maize price was 0.17 US$/kg and wheat price was 0.2 US$/kg. We assumed that farmers behave as rational decision makers, with an objective function of maximizing expected gross margin at the end of the growing season.

In the case of dynamic adaptation, we set an experiment to analyze the effects of different periods of evaluation on the ability of farmers to introduce adaptation strategies in winter wheat production as climate changes progressively. A similar approach was followed by Schneider et al. (2000) but these authors addressed a related question, which is the comparison of a so called “dull farmer”, “clairvoyant farmer”, and a “realistic farmer”. The later was introduced to study the impacts of a 20-year lagged adaptation mimicking the masking effect of climate variability. Here, the evaluation period does introduce a lag in the time of adaptation as a consequence of the representation of a farmer that makes informed decisions on which alternatives should be implemented as climate changes form current conditions to projected ones.

Because decision making requires full knowledge of consequences associated to each decision (i.e. sowing date, nitrogen level, and or variety), the results of all treatments and growing season are available to the farmer only when looking backwards in time as they had actually occurred. In that sense, the farmer will be able to detect which management strategy starts to outperform the others as the time progresses. Alternative selection is done comparing previous expected gross margin results over $k$ years ($k = 1, 5, 10, 15, 20, 25$), choosing the one that maximizes this value and implementing it for the upcoming growing season. To evaluate if this dynamical (or time dependent) adaptation strategy produces better results than prescriptive solutions, we calculated average gross margin over 100 years where climate change was occurring and expressed the values obtained following dynamical strategies of adaptation relative to the average income of a prescriptive optimum alternatives for years 2000 and 2080 (M_2000 and M_2080, respectively).

## 3 Results and discussion

### 3.1 Changes in crop productivity

Optimum management strategies for each crop and region corresponded to combinations of alternatives that maximize expected gross margin at each time period. The use of current management practices in future periods generated yield and gross margin changes as a consequence of climate change. A summary of these results by crop and location are presented in Table 3 and Fig. 1.

In the case of maize at Curicó, long maturing hybrids under irrigation allow farmers to obtain fairly high levels of productivity. As a consequence, there is a significant demand for nutrients which requires nitrogen fertilization to be set at 450 kg/ha. Because long maturing hybrids express their yield potential when the growing season is sufficiently long, better results were obtained with early sowing dates. In this case, sowing date depends on the occurrence of late frosts, being mid October the earliest sowing date that minimizes the loses associated to frost damages.

Considering a projected climate scenario composed by an increase of carbon dioxide and a warmer regime, it is likely to observe negative impacts on maize yields. Typical responses of the crop are a reduction of the growing cycle, and a reduction of grain number and a reduction grain unit weight (Parry 1990). Even tough it is expected that higher atmospheric concentration of carbon dioxide can be beneficial for crops in general, Maize has a photosynthetic system of the type C4 (i.e. the method of $CO_2$ uptake forms a four-carbon molecule instead of the two three-carbon molecules of the Calvin cycle) being less affected by increases in $CO_2$ in the future climate scenarios. As a result, the negative impacts of higher temperatures tend to

**Table 3** Optimum alternatives for current climatological conditions and for HadCM3 climate change projections for different crops and locations

| Crop | Location | Period | Variety | Sowing Date | Nitrogen (kg/ha) |
|---|---|---|---|---|---|
| Maize | Curicó (Irrigated) | Present | Long Maturing | 15-Oct | 450 |
| | | 2080 | Long Maturing | **01-Sep** | 450 |
| Spring wheat | Curicó (Irrigated) | Present | – | 01-Jul | 250 |
| | | 2080 | – | 01-Jul | 250 |
| Winter wheat | Temuco (Rainfed) | Present | – | 01-Aug | 350 |
| | | 2080 | – | **01-Jun** | 350 |

Bold values illustrate changes in management between these two time periods.

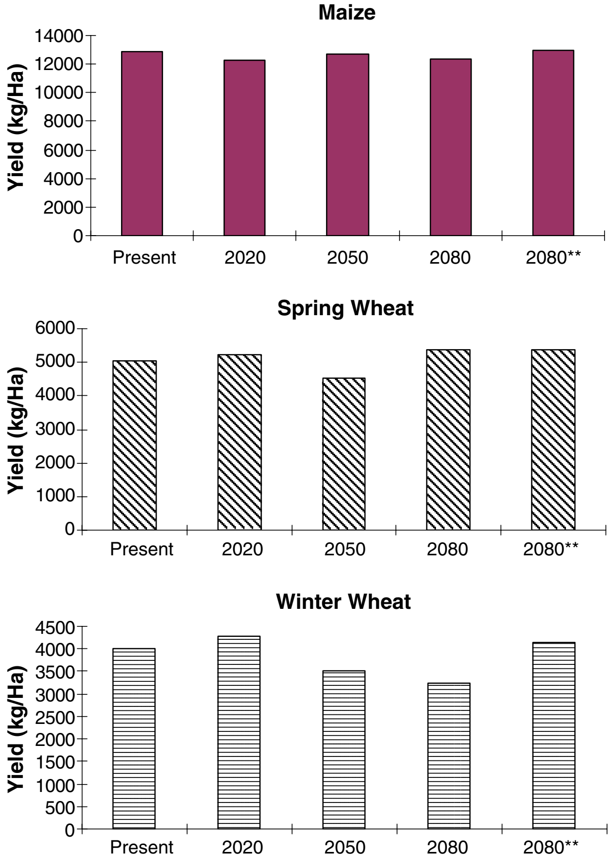



**Fig. 1** Yield impacts on different agricultural systems of HadCM3 climate change projections using current management and comparison with best management in the future (2080**)

prevail over the fertilizing effect of $CO_2$ (Goudriaan and Unsworth 1990). Moreover, apparently the carbon assimilation rate does not change even under an increase of light intensity (Wolf and Van Diepen 1994). In this study, future climate scenarios affect maize productivity and reduced yields between 5% and 10%. These reductions represented an economic loss of almost 100 dollars per hectare.

However, in a warmer environment, temperature limitations of late winter and early spring are reduced, so it is possible to sow earlier in the season and compensate the effects of climate change. When this measure of adaptation is taken, maize reached the same levels of productivity as the ones observed under current climatic conditions (Fig. 1a).

For the case of spring wheat at Curicó, the best economic outcomes are achieved when sowing is carried out in mid July and nitrogen fertilization is around 250 kg/ha. As climate changes, becoming warmer and drier, yields can be maintained following the same management practices, thanks to the access to irrigation and because wheat shows a positive response to increases in $CO_2$ concentration (Fuhrer 2003). Simulations of yields for year"2050" showed a reduction of more than 10% on wheat productivity, which resulted in net economic losses of almost 125 dollars per hectare. Later on, the increase in carbon dioxide counterbalanced changes in temperature and other meteorological variables, allowing wheat to recover and even experience increases on productivity (Fig. 1b). Optimum management strategies were identical when comparing current climatic conditions and the ones that will prevail by year 2080.

The last case corresponded to winter wheat at Temuco. In this type of agricultural system, crop growth depends on soil moisture and ultimately on seasonal rainfall. Optimum management corresponded to 350 kg N/ha and sowing dates on early August (i.e. mid austral winter). Without adaptation, the impacts of climate change were very significant and consistent with results reported for similar agroecosystems (Tubiello et al. 2000). Following current management practices, new climatic conditions produced yield reductions up to 20%. The economic impacts of these reductions represented almost 200 USD/ha.

As in the case of maize, the use of early sowing dates is a very effective strategy of adaptation. Winter wheat under future climatic conditions can be sown on late autumn early winter. The weather conditions experienced during the growing season and the increase in $CO_2$ allowed winter wheat to recover and express the yield potential observed at present time.

Apparently, only maize and winter wheat show a potential for adaptation. If a set of management practices is regarded as the optimum in two different periods, and if climate does not change in an abrupt manner, it was possible to identify the moment when one strategy outperformed the other and consequently when it would be advisable to switch.

Figure 2 shows the evolution of maize and winter wheat yields following two different management strategies, one regarded as optimum for current climatic conditions (M_2000) and the management that maximized gross margin under future climatic conditions (M_2080). A 10 year running mean filter was applied to reduce year to year variability and facilitate the identification of periods when M_2080 outperformed M_2000.

For the case of maize, even tough strategies did not show clear dominance over the other in the first years, after year 30 the M_2080 strategy was clearly the one that produced better yield results. In this case it is likely that, if HadCM3 results capture the magnitude of climate change, adaptation could occur early.

Winter wheat producers in Temuco, on the other hand, saw how M_2000 strategy was the best for a longer period. To assess the optimum moment to switch from M_2000 to M_2080 in this case, we calculated average gross margin over 100 years for different opportunities in a prescriptive manner. Figure 3 shows average gross margin for different periods of adaptation (i.e. the average results of a farmer that adopted M_2080 from that particular year until the end of the series). Maximum values were observed when M_2080 strategy is adopted from year 50. Switching from M_2000 to M_2080 strategy before or after year 50 was inefficient and produced economic losses (measured as opportunity costs).

## 3.2 Dynamic adaptation

In the previous subsection we have shown that at least in the cases of maize and winter wheat, there are alternatives for adaptation. For the case of winter wheat we have performed an assessment about the optimum moment to introduce management practices that were optimal for future climate conditions.

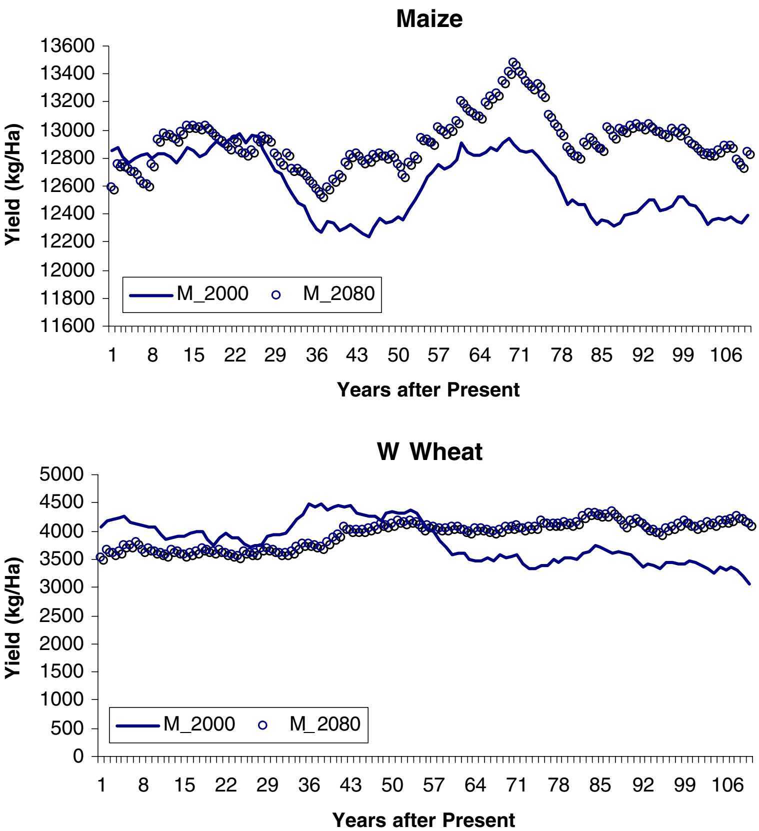
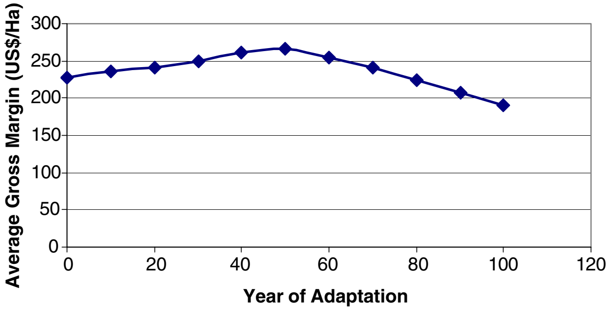



**Fig. 2** Evolution of maize and winter wheat yields using current (M_2000) and future (M_2080) management strategies

It is interesting however, to analyze if these optimum management practices (M_2000 and M_2080) are valid for the whole period, or if new strategies can be identified as a consequence of smooth transitions from current to future climatic conditions.

The introduction of changes in current management practices will be done as soon as the farmer is convinced that climatic conditions are affecting crop productivity for

**Fig. 3** Average gross margin over 100 years as a function of the year of adaptation for a farmer growing winter wheat



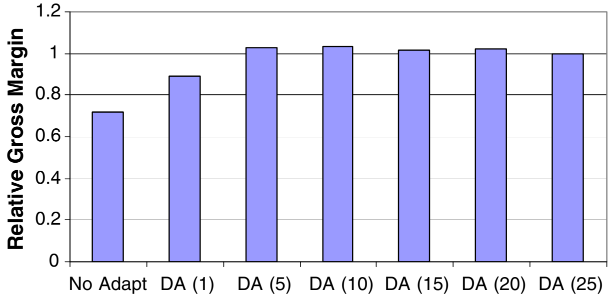



**Fig. 4** Relative gross margin obtained by for winter wheat producers after 100 years for various dynamical adaptation strategies based on $k$ years of evaluation (DA($k$))

relatively long periods of time. Because year to year variability in crop yields, as a response of weather conditions during the correspondent growing season, is a natural phenomenon, farmers must collect sufficient evidence that climate is affecting crop productivity and that different management practices are justified. Clearly, if farmers base their decisions on very short periods of evaluation, it is more likely that the selection of alternatives will be more influenced by climate variability than climate change. On the other hand, if farmers are skeptical and require the accumulation of several years of yield data, climate change impacts will be masked and they will miss opportunities for adaptation.

Figure 4 shows the results of this experiment for dynamical adaptation based on different periods of evaluation (DA($k$)). As a baseline for comparison, the no adaptation case has also been included.

Adaptation strategies based on crop performance of the previous growing season are strongly affected by climate variability, and produce slightly better results than the no adaptation case. Figure 5 illustrates the sensitivity of adaptation decisions on the evaluation period, comparing changes in sowing date for two different dynamical adaptation strategies. As more yield data is incorporated, represented by DM(10), alternative selection showed smaller variability, allowing robust adaptation strategies to emerge and improving the economic performance of farmers substantially.

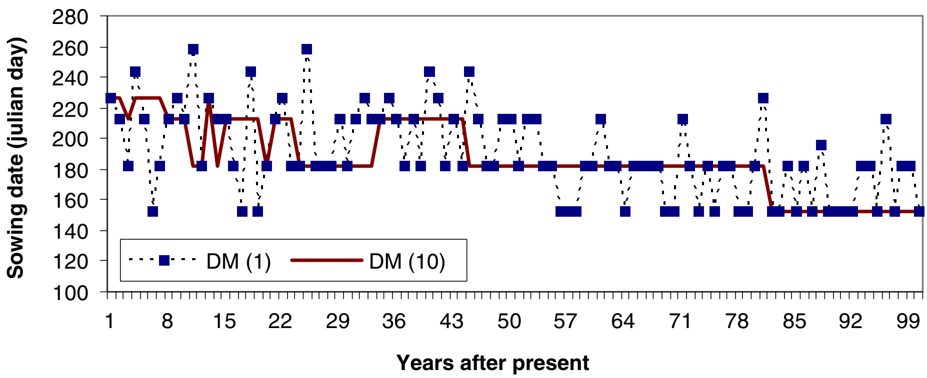



**Fig. 5** Influence of the length of evaluation period on the selection of alternatives for winter wheat climate change adaptation

In this experiment there were no differences between evaluation periods of 5 and 10 years. Results achieved in those cases were slightly better than prescriptive optimum switch (3% additional gain in average gross margin). Observed results showed a slight deterioration, when evaluation period extended beyond 15 years. This feature suggests that, for the climate change scenario represented here, when farmers decide to collect large amounts of yield data to evaluate the impacts of climate change, the adoption of different alternatives to face new conditions is delayed. Thus it is likely that these farmers will experience yield as well as economic reductions in the long run.

Because of the nature of the assumptions made there are some limitations in this study. Among them, the most important relates to the invariance of product price and fertilizer cost. For a rational decision maker in a production function with diminishing returns, the optimum fertilization amount is set at the level where marginal income equals marginal cost. For the adaptation strategies simulated here, any change in nitrogen cost and/or maize (wheat) prices can modify the economically optimum level of fertilizer and also the economic value of climate change impacts. A more realistic analysis should include economic scenarios (usually driven by international markets) to translate the effects of climate change on product prices and input costs. In this work the analysis of the dynamics of adaptation is focused on changes in sowing dates. In general, this type of adaptation strategy is less sensible to price/cost relationships, thus the conclusions obtained are applicable for a wide variety of economic scenarios.

The second major limitation of this study corresponds to the identification of adaptation strategies. Simplifying adaptation, representing only changes in agronomic management (fertilization, plant density, sowing dates) neglects other possibilities that arise from the introduction of new genetic material and the development of new cultivars. Meza et al. (2008) showed that hypothetically new cultivars (i.e. cultivars with longer maturing periods than the ones currently used) can take advantage of the new climate scenarios in Mediterranean regions with access to irrigation. The authors also demonstrated that new emerging adaptation alternatives like double cropping are a very effective manner to cope with climate change. In this modeling example, there are potentially 50 different alternatives to evaluate (ten sowing dates and five nitrogen levels). There is a clear relationship between the number of alternatives available and the adaptation success. In a constrained system it is less likely that adaptation can occur effectively. We have represented adaptation in a simple manner to facilitate the analysis of the dynamics of adaptation, and show that previous observed yields can be used by farmers as a manner to identify the best moment to adopt adaptation strategies.

## 4 Concluding remarks

Future climate conditions will almost certainly produce important changes in agricultural systems across the globe. For this reason, it is necessary to perform complete assessments about changes in crop growth and development (impacts) under different climate scenarios as well as to evaluate realistic ways by which agricultural systems can adapt. As long as climate change does not produce severe shocks in the agricultural system, it is likely that agricultural practices can be modified and negative effect can be partially or even totally avoided.

In this study we have shown that winter wheat and maize can be affected by climate change in Chile, and that there are simple adaptation strategies available. Maize showed yield reductions in the order of 5% to 10%. Under irrigation, the best alternative for adaptation corresponded to adjustments in sowing dates. In the case of winter wheat significant yield reductions were observed for the no adaptation case. Because this crop showed positive responses to the increase of carbon dioxide, adaptation strategies were very effective counterbalancing the impacts of a warmer and drier environment.

The introduction of changes in current management practices will be done as soon as the farmer is convinced that climatic conditions are affecting crop productivity for relatively long periods of time. Dynamic adaptation allows farmers to select alternatives based on a collection of previous evidence of yield impacts and alternative performance. This work has shown that results obtained are comparable and sometimes higher than prescriptive adaptation strategies, especially if no abrupt changes in climate are detected.

If the number of management alternatives increases, more flexibility is added to the system and more possibilities for adaptation can be evaluated. Combinations of sowing dates and fertilization rates are two simple ways to cope with climate change. Because our work focuses on agricultural practices, we certainly can not conclude that the alternatives evaluated are the only ones available. Seed companies and plant breeders have shown a tremendous ability to generate new crop varieties replacing existing ones in less than one decade. Some of them will probably show better responses to the future climatic environment. Therefore it is likely that the set of alternatives will be increased with a direct impact on adaptation capabilities.

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