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Effect of global change on maize production in the Argentinean Pampas

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ABSTRACT: We analyzed the direct effect of enhanced CO_2 concentration and the effect of expected climate change on the production of maize *Zea mays* L. in the Argentine Rolling Pampas. Maize yield was simulated using the CERES Maize model. Climate change scenarios for double CO_2 were generated by 3 widely used Global Circulation Models (GCMs). Simulation analysis indicated a decrease in maize yield between 20 and 25% according to the GCM chosen. The 3 GCMs predicted an increase in temperature and precipitation, mainly during summer months. Yield reduction was mainly the result of the shortening of the growing cycle. The direct effect of CO_2 enhancement did not compensate the reduction in yield associated with the shortening of the growing season. The proportional reduction in yield was higher under nitrogen stress condition than without nitrogen stress. Adaptive strategies may compensate for reduced yield. Sowing date needs to be moved forward 15 to 30 d to reach temperatures similar to the present. Modification of the grain filling duration coefficient in the crop model compensated yield reduction, suggesting that new cultivars may be a good way of offsetting the effects of global change

INTRODUCTION

The rapid increase of the CO_2 concentration in the atmosphere since the beginning of the century has been clearly documented (Schneider 1989). Increases in CO_2 concentration have large effects on the behavior of plants by decreasing stomatal conductance and increasing water use efficiency (Mooney et al. 1991). Field experiments have suggested that the increase in carbon fixation as a result of CO_2 fertilization is largely influenced by the availability of water and nutrients. Resource-limited sites such as tundra had a small response to CO_2 fertilization (Tissue & Oechel 1987). On the other hand, marshes where nutrients and water are abundant showed a larger increase in photosynthesis as a result of doubling CO_2 concentration (Ziska et al. 1990).

An increase in CO_2 concentration in the atmosphere also has an indirect effect upon vegetation through changes in climate. There is agreement among scientists that an increase in CO_2 and other greenhouse gases in the atmosphere will result in an increase in global temperature (Ramanathan 1988). Global Circulation Models, GCMs (Hansen et al. 1983, Manabe & Wetherald 1987, Wilson & Mitchell 1987), are excellent tools to explore geographical differences in the effects of CO_2 increases.

The direct and indirect effects of an increase in CO_2, which account for a large fraction of what is known as global change, may have profound effects upon vegetation. Studies have suggested that the location of major natural vegetation types as well as of major croplands may shift as a result of global change (Emanuel et al. 1985, Cramer & Solomon 1993, Leemans & Solomon 1993). Important changes are also predicted in the functioning of ecosystems (Hunt et al. 1991). There is increasing interest in evaluating the way global change could affect crops and their ability to supply

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food. Modelling the growth of key crops like maize *Zea mays* L. under changed atmospheric composition and climate is one of the priorities established in the operational plan of the Global Change and Terrestrial Ecosystems (GCTE) core project of the International Geosphere-Biosphere Programme (Steffen et al. 1992). Parry et al. (1990) pointed out 3 main issues that need to be addressed in considering the likely effects of global change on agriculture; first, the nature of the expected changes in climate; second, the estimated impacts of these changes on crops; and third, the range of appropriate responses to adapt to global change.

Argentina is one of the world's largest grain producers. Most of Argentina's grain is produced in the Pampas region (Fig. 1). This region covers approximately 34 million hectares of land of which one third is used for growing grain crops, and the rest for steer fattening and cow-calf operations based upon leys and natural grasslands respectively (Hall et al. 1992) (Fig 1) The Rolling Pampa is the most productive subregion of the Pampas and the area devoted to grain crops varies among years between 50 and 75 %. The Rolling Pampa subregion has a temperate humid climate and lacks a dry season. It has an annual rainfall of approximately 1000 mm and a mean annual temperature of 17 °C. The frost-free period is about 260 d. Soils in the region are mainly Mollisols (INTA 1990) developed on a deep mass of Pampean loess (Frenguelli 1925).

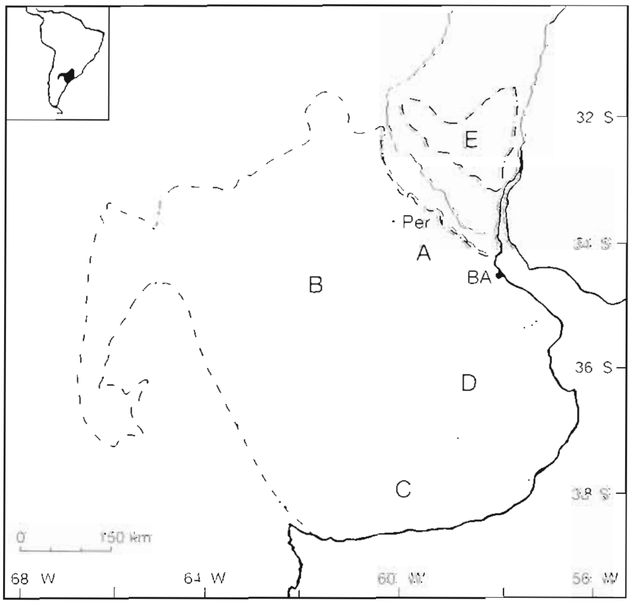

Fig. 1. Potential natural vegetation of the pampean grasslands A: Rolling Pampa; B: Inland Pampa; C: Southern Pampa, D: Flooding Pampa; E: Mesopotamic Pampa (– · –) Boundaries of the region; (·····) subregions. BA: Buenos Aires; Per: Pergamino Adapted from Leon (1991)

Maize is one of the region's most important crops with 2.3 million hectares (Hall et al. 1992). Its production is concentrated in the northeast of the Rolling Pampa. The average yield of maize in the region over the period 1980 to 1992 was 4.6 t ha^{-1} Maize is rotated with wheat and soybean crops.

The objective of this work was to assess the effect of global change upon the yield of maize in the Rolling Pampas of Argentina. To do this we used output data from 3 Global GCMs in conjunction with a crop model.

METHODOLOGY

We used output from 3 GCMs to obtain predictions of the rainfall and temperature patterns for the 'effective' double CO_2 scenario. The crop simulation model used this information to predict the effects of global change upon the behavior of maize. The effective doubling of CO_2 means an increase in greenhouse gases (CO_2, CH_4, N_2O, CFC) producing radiative forcing equivalent to a doubling of the CO_2 concentration. Taking into account the relative rate of increase of the different greenhouse gases, this radiative forcing would be reached at a CO_2 concentration of 555 ppm.

As input for the control runs we used weather data recorded by the National Meteorological Service for the town of Pergamino (Lat. 33° S, Long 60° W) which is a representative location for the climatic conditions of the Rolling Pampa (Fig. 1). We used daily data of precipitation and maximum and minimum temperature for 19 yr corresponding to the period 1960 to 1984. They represent the only available weather data for the intensive study area of Pergamino. Daily radiation was estimated from sunshine hour data and latitude (Fedes et al. 1978). The GCMs used were: (1) GISS, developed by the Goddard Institute for Space Studies (Hansen et al 1983), (2) GFDL, developed by the Geophysical Fluid Dynamics Laboratory of NOAA (Manabe & Wetherald 1987), and (3) UKMO, United Kingdom Meteorological Office (Wilson & Mitchell 1987). GCM output consisted of monthly changes in temperature, precipitation, and radiation. We calculated the climate change scenarios by adding or subtracting the change predicted by the models to the 19 yr weather record used for the control runs (Smith & Tirpak 1988). This procedure maintained the interannual and daily variability of the historic weather data. Adams et al. (1990) used the same procedure to study the effect of global change on agricultural systems.

The crop model chosen was the Crop Environment Response Synthesis Model (CERES Maize) (Jones & Kiniry 1986, Ritchie et al. 1989) which has been validated in several regions of the world and proved to represent crop behavior very well under contrasting conditions (Hodges et al. 1986). CERES Maize simulates the interaction between environmental factors and plant growth processes of the crop using soil and daily weather data. The main physiological processes simulated by the model are photosynthesis, respiration, phenology, leaf initiation and growth, stem growth, root growth, soil water extraction, evapotranspiration, nitrogen uptake, light interception, grain initiation, and grain growth. As input the model requires daily values of precipitation, maximum and minimum temperature, radiation, soil profile characteristics, planting density, planting date, latitude, and the genetic coefficients for the cultivar Adams et al. (1990) and Cooter (1990) used this model to analyze the effects of global change on agricultural systems in the USA.

The modelling experiments were performed for one of the major soil types of the Rolling Pampa, the Pergamino series. This is a typical Argiudoll with no physical constraints for agriculture. Argiudolls account for more than 85% of the Rolling Pampa soils (INTA 1990, Hall et al. 1992).

We performed runs for the baseline scenario and for the 3 double-CO_2 scenarios, accounting for both direct and indirect effects of CO_2. To simulate the direct effect of CO_2 we increased in the model the efficiency of transformation of light into dry matter by 6% (Kimball 1983, Cure & Acock 1986). We simulated modal cultural practices for the Rolling Pampa which are: sowing date around October 15, fallow duration 45 d, between-row distance 70 cm, and density 7 plants m^{-2} In the simulations we used the maize hybrid DAF12 (Dekalb). We selected this hybrid because it was widely used by farmers and because detailed information for model calibration was available (J H. Lemcoff unpubl.). The model adequately reproduced the growing season length and yield observed in a detailed field experiment (Lemcoff unpubl.).

Model runs were made assuming an initial soil water content equal to field capacity and a low nitrogen content in the soil (50 kg ha^{-1}). These are typical conditions for farms with continuous agriculture and without fertilization schedules. We assumed the incorporation of 800 kg ha^{-1} of standing dead material at the beginning of the fallow. We also analyzed the performance of maize without nitrogen stress for the GFDL double-CO_2 scenario.

A further analysis tested the sensitivity of the maize crop system to climate change. The purpose of this analysis was to assess model response to changes in temperature and precipitation. The experiment consisted in running the model for 3 temperature conditions (control, +2 °C, and +4 °C) and 3 precipitation conditions (control, +20%, −20%).

Finally, we explored some management strategies for adapting current crop systems to future environmental conditions. We analyzed the shift in the sowing date under the double-CO_2 scenario required to match present sowing temperature. In order to analyze the strategy of using new cultivars, we simulated potential new genetic material by modifying, within a biologically plausible range, 3 genetic coefficients related to developmental aspects of the cultivars in CERES Maize The modified coefficients were the juvenile phase coefficient, the photoperiodism coefficient, and the grain filling duration coefficient. The juvenile phase coefficient represents the time period, expressed in degree-days above a base of 8 °C, during which the plants are not responsive to changes in photoperiod. The photoperiodism coefficient corresponds to the extent to which development, expressed in days, is delayed for each hour increase in photoperiod above the longest period at which development proceeds at a maximum rate. The grain filling duration coefficient represents the duration from silking to maturity in degree-days above a base of 8 °C.

RESULTS

The GISS, GFDL and UKMO GCMs predicted an increase in temperature and precipitation for the region around Pergamino (Fig. 2) There was a good agreement among these GCMs regarding their predictions of mean annual temperature. The models predicted an increase in annual average temperature ranging between 4.2 and 5.2 °C, and agreed in predicting higher increases during summer than winter Annual precipitation projections were more variable, ranging from almost no change from present conditions, to a 30% increase. The 3 models agreed in predicting larger precipitation increases during spring and summer than during winter (Fig. 2).

The increase in temperature and precipitation predicted for a double-CO_2 scenario resulted in a decrease in the yield of maize for the Rolling Pampa (Fig 3A). This was mainly a result of the shortening of the growing period (Table 1). An increase in temperature triggered maturity stages faster in the climate change scenario than under present conditions. The duration of the sowing-maturity period was shortened by 26 d on average (Table 1). The direct effect of the increase in CO_2 was a small increase in yield that was not enough to compensate for the decrease resulting from the expected changes in climate (Fig 3A). Results of the crop model simulations were similar for the 3 climate change scenarios (Fig 4), in spite of the differences in total rainfall shown in Fig 2. The joint effects of the changes in CO_2 and climate resulted in a reduction in yield of between 20 and 25% depending on the scenario.

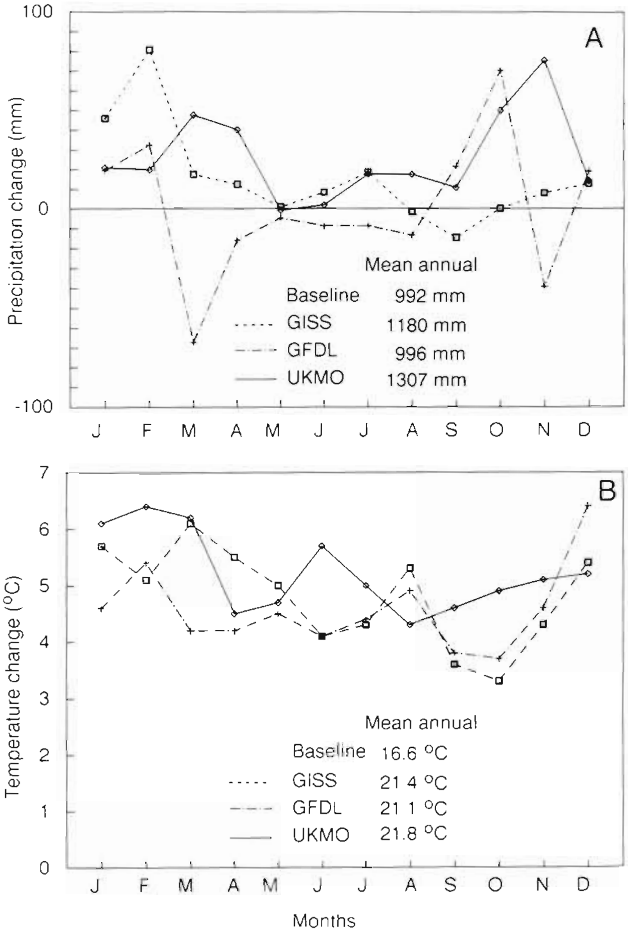

Fig. 2. Variations in (A) rainfall and (B) temperature as a result of climate change for the town of Pergamino as predicted by 3 Global Circulation Models (GCMs)

Nitrogen fertilization reduced the difference in yield between the control and the GFDL double-CO_2 scenario from 25 to 12 % and resulted in a greater direct effect of the CO_2 increase (Fig. 3B). These results agree with observations in which the responses to CO_2 fertilization were higher in environments not limited by water and nutrient than in those frequently limited by them (Bazzaz & Fajer 1992).

In the sensitivity analysis we observed a decrease in yield as a result of the increase in temperature (Table 2). This was accounted for by the decrease in the season length, which particularly affects the grain filling period. This period is critical since retranslocation is not quantitatively important in CERES Maize.

The simulated increases in precipitation did not result in increases in yield as we had expected. An explanation may be that with a shorter growing season and smaller plants, water availability did not limit production. The low water stress index in all 3 simulations supports this idea. An increase in precipitation increased the N stress index, as a result of higher N losses under conditions with high precipitation (Table 2).

DISCUSSION

The major effect of climate change as predicted by this modelling exercise is a decrease in yield resulting from the increase in temperature and the corresponding shortening of the growing period and particularly of the grain filling period. The decrease in yield occurred in spite of the increase in precipitation. Results from Adams et al. (1990), for sites in North America located at similar latitudes to Pergamino (Oklahoma and Texas), also showed that maize production decreased when precipitation increased. In contrast, a simulation analysis for the Southeastern USA region showed that yield and water availability were positively related (Cooter 1990).

Our exercise was limited to assessing the effects of changes in CO_2 and climate upon maize yield while maintaining all other variables constant. However, this does not necessarily represent what may actually happen following global change. Farmers will rapidly adapt to the new environmental conditions. Two possible adaptive strategies to cope with the expected climatic change are (1) a shift in the sowing date and (2) a change in cultivars.

One of the strategies suggested is to sow maize early so that the growing period occurs mostly during the cooler part of the year, resulting in a longer growing season. In the climate change scenarios, temperatures similar to those at which maize sowing occurs at present will be reached during July (Fig. 5). Alternatively maize could be sown late. In this way the hot months

Table 1. Mean and standard deviation values for season length, water stress index (0 to 1) in the vegetative phase, precipitation during the crop growing season and evapotranspiration; for baseline conditions and the 3 climate change scenarios

		Baseline	GISS	GFDL	UKMO
Season length (days)	Mean	126	102	101	99
	SD	8	4	4	3
Water stress	Mean	0.006	0.002	0	0
	SD	0.02	0.007	0	0
Precipitation (mm)	Mean	590	477	530	594
	SD	144	94	134	115
ET (mm)	Mean	483	380	366	367
	SD	20	25	23	27

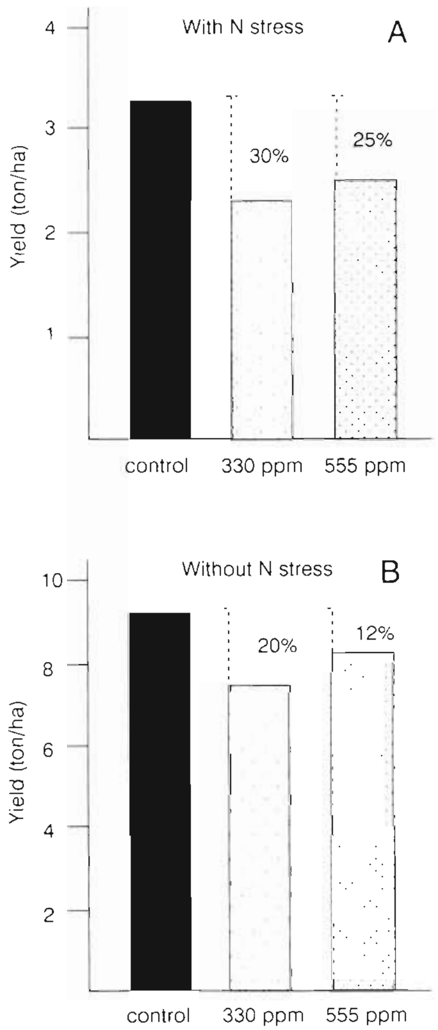

Fig. 3. Effect of climate change alone (330 ppm) and of climate change plus the direct effect of CO_2 enhancement (555 ppm) on maize yields (A) under nitrogen stress and (B) without nitrogen stress. Black bars: control; cross-hatched bars: GFDL climate change scenario with current CO_2 level (330 ppm) and enhanced CO_2 level (555 ppm)

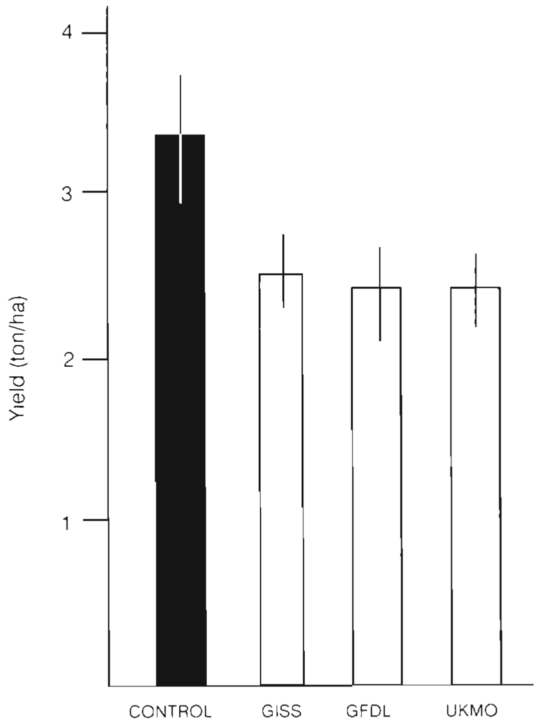

Fig. 4. Effect of changes in CO_2 concentrations and in climate as predicted by 3 GCMs (GISS, GFDL, and UKMO) upon maize yield in the Rolling Pampa. Plotted yields are average for 19 yr. Vertical bars are standard deviations

of midsummer are also avoided. Further analysis is needed to evaluate the photoperiodic constraints to modify sowing dates.

An alternative strategy may be to change the cultivar utilized. Results showed that a 20% increase in the coefficient related to the duration of the grain filling period would be enough to compensate the decrease in yield resulting from climate change (Fig. 6). Modifications of the other coefficients did not result in full yield compensation. Our analysis suggests that by modify-

Table 2. Effect of changes in temperature and precipitation under elevated CO_2 conditions upon average maize yield, season length, rainfall during crop growing season, nitrogen stress index, nitrogen losses, and evapotranspiration

Rainfall (%)	Temp. (°C)	Yield (t ha^{-1})	Season length (d)	Rainfall (mm)	N stress (veget.)	N losses (kg ha^{-1} d^{-1})	ET (mm)
-20	0	3.92	126	488	0.31	0.12	399
-20	+2	3.58	113	438	0.31	0.12	378
-20	+4	3.52	104	385	0.30	0.12	366
+0	0	3.77	126	611	0.34	0.17	397
+0	+2	3.38	113	547	0.33	0.17	376
+0	+4	3.35	104	482	0.32	0.17	364
+20	0	3.49	126	733	0.37	0.22	395
+20	+2	3.16	113	657	0.36	0.22	373
+20	+4	3.12	104	578	0.35	0.22	360

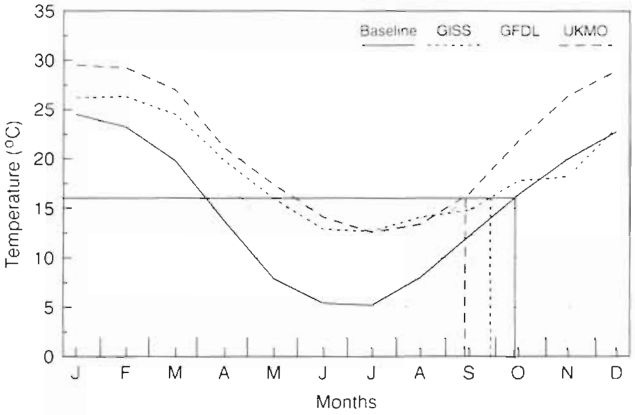

Fig. 5. Mean monthly temperatures for present conditions and for climate change scenarios as predicted by 3 GCMs (GISS, GFDL and UKMO). Vertical lines indicate the time when present sowing temperatures would be reached under each of the 3 climate change scenarios

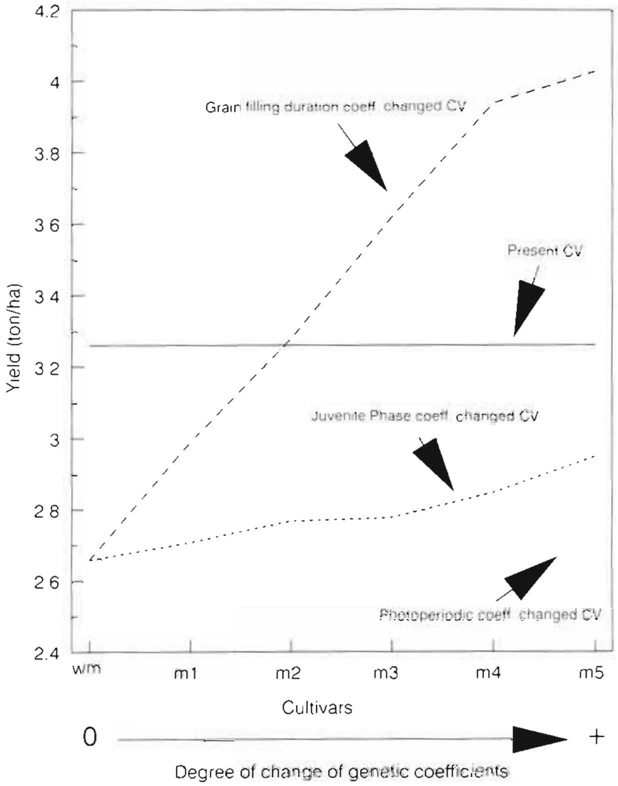

Fig. 6. Simulated yield of hypothetical cultivars in the double CO_2 scenario predicted by the GFDL model. Cultivars (m1 to m5) were generated by increasing, from 10 to 50 % (a biologically plausible range), the Juvenile Phase Coefficient, the Photoperiodic Coefficient and the Grain Filling Duration Coefficient of the DAF12 cultivar. wm: without modifications. Solid line: yield of DAF12 cultivars under present conditions

ing this physiological characteristic, yield under expected climate change conditions may be higher than yield under present conditions. Development of new cultivars adapted to the expected conditions may enable farmers in the Pampas to take advantage of the prolonged growing season and the higher precipitation. Leemans & Solomon (1993), using a different modelling approach, predicted that temperate maize will be largely replaced by tropical maize in this region. Cultivars with grain filling duration coefficients similar to those used for the hypothetical genotypes are available. However, we have not considered whether they can be easily adapted to the conditions of the Pergamino region (pests, diseases, photoperiod, etc.).

The overall result of this exercise is that maize production in the Rolling Pampa may decrease 25 % as a result of the predicted global change. This result leads to questions relevant to policy and technology development. How much time is required to produce new genotypes? Is it compatible with the expected rate of climate change? Are there other management practices which need to be adjusted to deal with global change conditions?

Our work focused on the core of the current maize producing area. There is a possibility that the response to global change may not be fully compensated towards the warmer boundaries of the present maize region. Leemans & Solomon (1993) predict that these changes in temperature and precipitation will determine a geographic displacement of the most suitable agroclimatic area for maize. In these circumstances, what will be the needs for irrigation or fertilization? Exploring these productive scenarios will help to improve adjustment of agricultural, social, and economic systems to global change.

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