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Adaptation Measures for Maize and Soybean in Southeastern South America[1]

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1. Introduction

Climate change is already affecting agricultural systems in several regions of the world. The Intergovernmental Panel on Climate Change's Third Assessment Report (IPCC, 2001) includes a list of cases (including agroecosystems) in which there is sufficient scientific evidence of such an effect. Southeastern South America (SESA) is one of the world's zones where significant changes in climate and crop production have been detected during the last part of the 20th century. These changes were characterized by increases in precipitation (up to 50% in some areas), decreases in maximum temperature, especially during spring and summer; and increases in minimum temperature during almost all the year (Castañeda and Barros, 1994; Barros et al., 2000; Pinto et al., 2002; Bidegain et al., 2005; Magrin et al., 2005). In Argentina, changes in climate contributed to the increase in rainfed yields. Magrin et al. (2005) in comparing the period from 1950 to 1970 with 1971 to 1999 observed that increases in rainfed yields attributable to

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changes in climate (isolated by using crop simulation models with the same production technology) were 38% in soybean and 18% in maize.
Also, land use has been changing during the past few years. Encouraged by more favorable climatic and economic conditions, farmers in the region devoted more lands to agriculture, especially remarkable being the expansion of soybean crops. In Argentina, the area devoted to soybeans increased by 133% [6 to 14 million hectares (Mha)] between 1995 and 2003 (SAGPyA, 2005). This trend has also been observed in Brazil, where even in traditional soybean areas as Rio Grande do Sul, lands devoted to soybean increased by 38% during the past five years (IBGE–LSPA, 2005). More recently, Uruguay is also facing a huge expansion of this crop (from 12,000 ha in 2,000 up to 278,000 ha in 2004) (MGAP-DIEA, 2005).

In spite of the increases in economic benefits in the short term, the abrupt expansion of soybean crops all over the region could have negative consequences in the medium and long term. This trend to soybean monoculture has yet to provoke reductions in soil organic matter (Garcia, 2003), soil compaction in superficial layers (Diaz-Zorita et al., 2002), and noticeable increase in the use of herbicides like glyphosate (e.g., in Argentina, 28 Ml in 1997 and 100 Ml in 2002) (Joensen and Ho, 2004).

According to future projections, soybean-planted area in South America would increase from 38 Mha in 2003/2004 to 59 Mha in 2019/2020. Thus, total production of Argentina, Brazil, Bolivia, and Paraguay will rise 85% (172 million tons), representing 57% of world production (Maarten Dros, 2004).

Considering the great importance of agriculture for the region, the assessment of potential impacts of climate change on crop production is necessary. For this purpose, crop simulation models are the classical tool and have been used at different spatial scales: from global (Rosenzweig and Parry, 1994) to country or regional levels around the world. One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions, as well as crop management. Crop models, in general, integrate current knowledge from various disciplines, including agrometeorology, soil physics, soil chemistry, crop physiology, plant breeding, and agronomy, into a set of mathematical equations to predict growth, development, and yield (Hoogenboom, 2000). However, there are still some issues related to climate variability and climatic change that are not fully understood or missing in crop models and that give some uncertainty about future projections such as the impact of increasing CO_2, ozone, or flooding, as well as the interaction with pests, weeds, and diseases.

Future changes to crop yields and production were also assessed for our region by means of crop models using climatic projections from general circulation models (GCMs) available during the 1990s. According to climate change scenarios projected by GCMs and considering CO_2 effects, during the 21st century, soybean production in the Pampas region of Argentina could range between reductions of 22% and increases of 3%, 18%, and 21% under UKMO (Wilson and Mitchell, 1987), GFDL (Manabe and Wetherald, 1987), GISS (Hansen et al., 1989), and MPI-DS, a down-scaling from MPI model (Magrin et al., 1998) scenarios, respectively. It is important to remark that reductions in soybean production are only expected under UKMO, which project for the main production area a huge increase in mean temperature (7ºC) without changes in precipitation during the most sensitive period for the crop (December-January-February). Inversely maize production is expected to reduce under most GCM projections, results for the overall pampas region were –8%, –16%, –8%, and +2% under UKMO, GFDL, GISS, and MPI-DS, respectively (Magrin and Travasso, 2002). Although an earlier study for the main maize production zone estimated reductions ranging between 20% and 25% according to UKMO, GFDL, and GISS projections (Paruelo and Sala, 1993). For Brazil (de Siqueira et al., 2000) 16% reduction in maize yields and 27% increase in soybean yields were reported under GISS scenario when considering CO_2 effects. Finally, without considering CO_2 effects, reductions of 14% and 25% in maize yields were reported for Uruguay with increases of 2ºC and 4ºC in mean temperature, respectively (Sawchik, 2001). Evidently, the magnitude of the impacts is dependent on the GCM considered.

Regardless of the level of uncertainty of climate and crop model projections, it seems likely that future climatic conditions would be more favorable for soybeans than for maize in the SESA zone. This issue could seriously threaten the system's sustainability if current practices are not reconsidered. Agricultural production systems will require effective adaptive strategies to overcome these expected pressures in the immediate future.

In view of these antecedents in the present work, we assess the impacts of future scenarios, based on HadCM3 projections under different SRES scenarios and time periods, as well as the adaptation measures that could reduce potential negative impacts of climate change on maize and soybean production in the Pampas region of southeast South America by means of crop simulation models.

2. Methodology

2.1 Study area

The study area, ranges from 25.4ºS up to 38.7ºS and from 48.5ºW up to 65ºW, and includes the states of Rio Grande do Sul in Brazil, Uruguay, and the Pampas region in Argentina (Figure 1). In the Pampas region of Argentina, arable lands cover approximately 34 Mha. Mean annual precipitation varies from 600 mm in the southwest to more than 1200 mm at the northeast. Mean annual temperature displays a north-south gradient from 13.5 to 18.5°C . Mollisol is the dominant soil order over the area, and Argiudols and Haplustols are the most representative soils of the region. In general, the soils, which were developed from aeolian sediments, display a gradient in texture, being coarser at the southwest and finer at the northeast. In Uruguay, the total area covered by agricultural systems is approximately 1.5 Mha. Precipitation is evenly distributed (long term means show small peaks in spring and fall), and the mean annual rainfall ranges from 1050 mm in the southwest and west to 1450 mm in the north, whereas mean annual temperature varies from 18.2ºC in the north to 16.8°C in the south and southeast. Most of the soils in the study region of Uruguay are classified as Mollisols, and their predominant characteristics are high organic matter content, existence of a clayey layer (Bt horizon) at variable depth, and light or moderate acidity (pH = 5.5–6.5) in the surface horizons. In Rio Grande do Sul, cultivated area attains some 7 Mha. This region is characterized by subtropical humid conditions with rainfall evenly distributed along the year. Mean annual rainfall in Passo Fundo attains 1788 mm and mean annual temperature 17.5ºC, with mean monthly values ranging from 12.7ºC in the coldest month up to 22ºC in the warmest one. The predominant soils in the region are Oxisols with clay texture.

We selected six sites in the region representing areas with contrasting environmental conditions (from the humid subtropics in Brazil through the humid and semiarid Pampas): Azul (AZ, 36.78ºS; 59.85°W), Pergamino (PE, 33.90ºS; 60.58°W), Santa Rosa (SR, 36.62ºS; 64.28°W) and Tres Arroyos (TA, 38.37ºS; 60.27°W) in Argentina; La Estanzuela (LE, 34.33ºS; 57.68°W) in Uruguay, and Passo Fundo (PF, 28.26ºS; 52.41°W) in Brazil (see Figure 1)

2.2 Climatic scenarios

Future climatic scenarios were based on the runs of a GCM developed by the Hadley Center (HadCM3). HadCM3 (Johns et al., 2003) appears to be more confident than other GCMs to reproduce local conditions in Southeast South America (Camilloni and Bidegain, 2005). Model runs were obtained for two IPCC socioeconomic scenarios for future greenhouse gas emissions identified as A2 and B2 in the Special Report on Emissions Scenarios (SRES) . GCM projections were obtained for the six sites in the region. The spatial resolution of the HadCM3 climate scenarios is 2º latitude by 2° longitude. Once the grid cell containing each one of the six sites was identified, monthly climatic values (maximum and minimum temperature and precipitation) for three 30-year-time periods (centered in 2020, 2050, and 2080) were extracted and the monthly rate of change of each variable was obtained by comparison with the GCM climatology (base period 1960–1990). Then, these coefficients of change were applied to the observed data (1971–2000) to obtain the future climatic scenario on a daily basis.

2.3 Crop models

Crop simulation models included in DSSAT (Tsuji et al., 1994) were used in each of the six sites to assess the expected impacts of climate scenarios on crops yields, as well as to evaluate the impact of some adaptive measures. The crop models that integrate DSSAT (including CERES for maize and CROPGRO for soybean) are detailed biological simulation models of crop growth and development that operate on a daily time step. The models simulate dry matter production as a function of climate conditions, soil properties, and management practices. The dry matter produced on any given day is partitioned between the plant organs that are growing at that time. Crop development in DSSAT models is driven by the accumulation of daily thermal time or degree days. Also these models are able to simulate crop growth considering variable CO_2 concentrations. The inputs required to run the models are daily weather variables, management information (planting date, fertilizer use, irrigation, etc.), cultivar characteristics, and soil profile data. Output from the models includes final grain yield, total biomass, and biomass partitioning between the different plant components at harvest, among others.

These models have been exhaustively tested in the region at the plot and at the field level with rather low estimation errors (Guevara and Meira, 1995; Meira and Guevara, 1995; Travasso and Magrin, 2001; Sawchik, 2001; de Siqueira et al., 2000). Then, they were used to assess the impacts of interannual climate variability and climate change in the agricultural sector (Magrin et al., 1997, 1998; Travasso et al., 1999; Magrin and Travasso, 2002; de Siqueira et al, 2000; Sawchik, 2001).

Agronomic model inputs used in our study, including initial water and nitrogen content in the soil profile, date of planting, plant density, sowing depth, date and rate of fertilizer application and cultivars, were defined according to the typical conditions and farmer practices in each site. Climatic inputs for the crop simulation models included observed daily maximum and minimum temperatures, precipitation, and solar radiation corresponding to the period 1971–2000 and the climate change scenarios obtained as described above. Crop models were run under rainfed and irrigated (water and nutrients nonlimiting) conditions for different CO_2 concentrations: 330 ppm (current) and those corresponding to each SRES scenario (417, 532, 698 ppm for A2, and 408, 478, 559 ppm for B2 in 2020, 2050, and 2080, respectively).

Adaptive management practices included in the analyses were planting dates and supplementary irrigation for maize and soybeans, as well as nitrogen rates for maize. In each site, planting dates were tested by anticipating/delaying the actual ones. Supplementary irrigation was added during the reproductive period, starting 20 days before flowering at a rate of 20 mm every 20 days. Incremental nitrogen rates were also tested for maize in all sites.

3. Results

3.1. Changes in climate

SRES A2 scenario, which assumes higher CO_2 concentration than SRES B2, leads to larger increases in temperature and precipitation, particularly for 2050 and 2080 (Table 1 and Figure 2). Increases in mean temperature for the warm semester (October–March) ranged from 0.8ºC to 4.1ºC in SRES A2 and from 0.7ºC to 2.9ºC under SRES B2 depending on site and time period (Table1).

Considering precipitation changes (Figure 2) the general pattern shows a trend to increase during the warm semester (October–March), representing up to 253 mm and 172 mm for SRES A2 and B2 respectively and to decrease during the coldest months (May-Aug) representing up to 46 mm and 34 mm for SRES A2 and B2, respectively.

3.2 Crops yields

Irrigated maize yields decreased in almost all sites and scenarios when the direct effects of CO_2 were not considered (Figure 3). Yield reductions were larger for the latter time periods, and were stronger under SRES A2 (up to -23%). We found a significant correlation between maize yield changes and temperature increases during the crop growing season ($R^2 = 0.74$), resulting in a reduction of 5% in yields per ºC of temperature increase.

Irrigated soybean yields were less affected and varied between –8% and 5% (Figure 3). The relation between yield changes and temperature increases was weaker ($R^2 = 0.4$) and the yield reduction was smaller (decreases of 1.8% in yields per ºC of temperature increase) than in maize.

When the direct CO_2 effects were considered under irrigated conditions, the obtained maize yields were higher but the increase was insufficient to offset the temperature effects (Figure 4). In contrast, huge increases in soybean yields were detected under both SRES scenarios (up to 43% and 38% for A2 and B2, respectively).

Under rainfed conditions and without considering the direct CO_2 effects, maize yield changes ranged between -9 % and 9% for SRES A2, and -12 % and 3% for SRES B2. Rainfed soybean yield changes varied between -22% and 10.5% for SRES A2 and between -18 and 0.5 for SRES B2 (Figure 4). When the direct effect of CO_2 on crops was taken into account, grain yield increased for both crops but a greater impact was observed in soybean (up to 62.5 %).

Under A2 scenario irrigated and rainfed soybean yields and rainfed maize yields were higher than current climate yields: the direct effects of the high concentration of CO_2 and the higher Spring-Summer precipitation more than compensated for the negative effect of increased temperature. As expected, the changes in crop yield under B2 scenario were in the same direction of those under the A2 scenario but smaller in magnitude.

The differences in crop behavior can be attributed to the interaction between temperature and CO_2 effects. In soybean (a C3 plant) CO_2 effects on photosynthesis are greater than in maize (a C4 plant) (Derner et al., 2003). The soybean simulation model used in our research assumes some 40% increase of the photosynthesis efficiency at a CO_2 concentration of 660 ppm, while the corresponding value for maize is only about 10%. Consequently, the obtained yields in irrigated maize crops are more dependent on the effect of temperature. On the other hand, the effect of CO_2 on stomatal resistance is known to be higher in C4 than in C3 plants (Kimball et al, 2003), contributing to higher water use efficiency in rainfed maize.

3.2.1 Crop phenology

Projected increases in temperature led to shortening crops growing seasons (Figure 4). For both crops the worst situation was found with highest temperature increases (A2, 2080). Impacts were much more important in maize, since the most affected phases were planting-flowering and flowering-maturity. Under A2 scenario and in 2080 maize crops growing season was reduced on average 27 days. In soybean the worst scenario resulted in growing seasons that were only 2 – 7 days shorter, mostly due to reductions in the planting-flowering period. The stronger shortening of the crop growing season observed in maize is coincident with the greater reductions in grain yields.

3.3. Adaptive measures

3.3.1 Considering CO_2 effects

3.3.1.1 Planting dates in maize. In general, earlier planting dates led to increased maize yields under both SRES scenarios, especially for 2050 and 2080, although there were differences among sites (Figure 5). Earlier planting dates contributed to longer planting-flowering periods (Table 2) and earlier maturity dates. This measure would allow maize crops to develop under more favorable thermal conditions, increasing the duration of the vegetative phase, which, in turn, would benefit the obtained grain number and hence the crop grain yield. An additional possible advantage of earlier planting dates relates to the anticipation of crop maturity and therefore the harvest. Under current planting dates, maize crops are usually harvested during March–April or later, depending on the region. Future climate scenarios project important increases in rainfall for these months (see Figure 2), which could lead to excess water episodes that could constrain harvest-provoking yield losses. This issue is not taken into account by the CERES model, and therefore, the impact of earlier sowing dates could be even higher under the climate conditions predicted by the HadCM3 GCM.

3.3.1.2 Nitrogen fertilization. Changes in nitrogen rates for the optimal planting dates resulted in increased maize yields only in two out of the six sites: Passo Fundo and Santa Rosa. In these sites, nitrogen rates should increase by 20 and 45 kg N/ha, respectively, probably due to the more favorable environmental future conditions allowing crop's response to increases in N.

3.3.1.3 Summary of changes with adaptation measures. Considering optimal planting dates and nitrogen rates, mean yield increases under SRES A2 could attain 14%, 23%, and 31% for 2020, 2050, and 2080, while under SRES B2, these figures would be 11%, 15%, and 21%.

3.3.1.4 Planting dates in soybean. Even if soybeans were less affected than maize by temperature increases, changing planting dates resulted in higher yields. In three out of the six sites evaluated, planting dates should be anticipated (AZ, SR, and PF), while in the others, the best option under future conditions will be to delay them (Figure 7).

3.3.1.5 Summary of changes with adaptation measures. Considering optimal planting dates mean yield increases under SRES A2 could attain 35%, 52%, and 63% for 2020, 2050, and 2080, whereas under SRES B2, these figures would be 24%, 38%, and 47%.

According to these results, soybean crops would greatly benefit under the enhanced CO_2 environment and the climatic conditions projected by HadCM3 for 2020, 2050, and 2080 under SRES A2 and B2 scenarios. However, crop responses to CO_2 enrichment under field conditions are yet not fully understood. The positive effect of increasing CO_2 on photosynthesis and water use efficiency had been demonstrated for several crops (Kimball et al., 2003). Notwithstanding, recent works (Long et al., 2005; Morgan et al., 2005) are critical of the way in which CO_2 effects on crop production are simulated, as it is based on studies carried out under controlled or semicontrolled conditions, and this could lead to overestimate the effects, in particular, for soybeans, in which photosynthetic efficiency was assumed to be higher than 30%. In the same way, Leakey et al. (2006) reported that under field conditions, maize crops growing under ample water and nutrients showed lack of response to increased CO_2. Also there is uncertainty about the response of crops to environments slowly enriched with CO_2 because of the likely acclimation (Ainsworth and Long, 2005). Research of the past few years had suggested that the initial stimulation of photosynthesis observed when plants grow at elevated CO_2 may be counterbalanced by a long-term decline in the level and activity of photosynthetic enzymes, as the plants acclimate to their environment, an event referred to as "downregulation.” Acclimation to CO_2 enrichment is not included in crop models used in our study.

3.3.2. Without considering CO_2 effects

3.3.2.1 Maize. Without considering CO_2 effects, yields decreased between 1% and 5% under future scenarios.

Optimal planting dates and N rates were the same as mentioned above, but yield response was different. Changes in maize yields were positive under all scenarios and time periods only in PF, SR, and AZ. Inversely, in TA, we obtained a generalized yield decrease, whereas in PE and LE we found both positive and negative changes depending on the scenario (Figure 8). Mean changes for the six sites ranged between 4% (B2 2020) and 12% (A2 2050 and 2080).

These results suggest that without CO_2 fertilization simple measures as changes in planting dates or N rates will not be sufficient in some places. When supplementary irrigation was applied, an overall yield increase was observed with changes close to 20% under all scenarios (Figure 8).

3.3.2.2 Soybean. Without adaptation measures, soybean yields decreased under all scenarios (1–12%). Changing planting dates led to a weak increase in yields (2–9%) only for 2020 and 2050 (Figure 8), but the addition of supplementary irrigation strongly reverted this situation, increasing yields between 30% (A2 2080) and 43% (A2 2020) (Figure 9).

Certainly, with rather simple adaptation measures, the soybean crop will be benefited in the future, even if CO_2 effects are not considered. The important expansion of this crop observed in the study area during the past few years could continue, putting at risk the sustainability of the agricultural systems.

Soybean is a high-nutrient extractive crop with a low level of crop residues, so the monoculture leads to negative N and C balances. Experiences in Argentina have shown that for a crop yielding 4000 kg/ha, some 120 kg N/ha/year and 950 kg C/ha/year are lost from the system (Garcia, 2003).

The expansion of soybean monoculture raises concern, and there is a need to carry out those management practices that tend to preserve the natural resources, for example, adequate crop rotations. Grasses as cover crops and a higher proportion of corn and wheat in the rotation could help to improve soil carbon (C) and N balances, among other benefits. Crop-pasture rotations, which used to be the main rotation in the Pampas, are another possibility to improve soil organic matter balances and, thus, soil C and N (García, 2004). In the same way in Uruguay, traditional rotations included 3–4 years of crops and 3–4 years of pastures, but the recent expansion of agriculture and, in particular, the soybean crop, led to decreases in the pasture component, increasing the agricultural system's vulnerability. In southern Brazil, Costamilan and Bertagnolli (2004) recommend a three year's crop rotation, including the sequence oats/soybean, wheat/soybean, and spring vetch/maize.

There are other alternative measures, which could help sustain not only the environment, but also the livelihood of farmers in the region, which are related to the destination of crop production. Assuming that the trend to increase agriculture and hence crop production will continue in the future, regardless of climate change, Oliverio and Lopez (2005) analyzed two possible scenarios to estimate Argentina's crop production in 2015. In the first one, they extrapolated the actual trend in planted areas (with increasing importance of oilseeds, specially soybean) and in the second one, they proposed a maximum ratio of 2.5:1 between oilseeds and cereals, promoting the so-called transformation in origin as a way to contribute to both the sustainability of agricultural systems and economic returns. Transformation in origin means that part of the production (for example, of maize) remains at the place where it was produced and is used to feed animals or for local industry, adding value to the primary product, instead of the traditional approach in which it is sold as a commodity, which, in some cases, implies important costs of transportation to ports and fiscal retentions, among others. Assuming that half of the maize production is transformed in origin, economic benefits could be more than duplicated.

4. Conclusions and Final Comments

Future climate scenarios based on the runs of HadCM3 suggest that mean temperatures for the entire study region would increase an average of 0.9, 2.1, and 3.4^{o}C by 2020, 2050, and 2080, respectively, for SRES A2. Corresponding figures for SRES B2 are 0.8, 1.7, and 2.6ºC. Precipitation projections show a trend to increase during the warm semester (October–March), which encompasses the growing seasons of both maize and soybeans and to decrease during the coldest months (May–August). Changes in precipitation were stronger in the climate model runs for the 2050 and 2080 time periods.

The expected increased temperature would result in shorter growing seasons and consequently in lower maize grain yields. However, under CO_2 enrichment, this negative impact could be greatly mitigated by adjusting the crop sowing time to earlier dates. When CO_2 was not considered, changes in planting dates or nitrogen rates were not enough to overcome actual yield levels, but a moderate supplementary irrigation during reproductive growth led to significant yield increases (up to 20%).

Soybean will be certainly the most benefited crop under future conditions. Assuming that the effect of CO_2 will effectively occur, yield increases could attain more than 60% only by modifying planting dates. Notwithstanding, without considering CO_2 effects, adaptation measures should also include supplementary irrigation.

Sustainability is an ineludible objective for the agricultural ecosystems of the 21st century. Adaptation measures should thus promote adequate nutrient supply, crop rotations, soil organic matter balances, crop and soil management practices, as well as weeds, pests, and disease control to sustain the environment and the welfare of farmers in the region.

Finally, regarding crop models, the simulation of the impact of CO_2 enrichment on crop production, the interaction with weeds, pests and diseases, and excess water/flooding should be improved to ensure accurate yield estimations under future conditions.

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Table 1. *Projected Changes in Mean Temperature (ºC) for the Warm Semester (October–March) According to HadCM3 under SRES A2 y B2 Scenarios for 2020, 2050, and 2080*

Mean Temperature (October–March)						
	HadCM3 A2			**HadCM3 B2**		
	2020	2050	2080	2020	2050	2080
SR	0.9	2.1	3.4	0.7	1.7	2.5
TR	0.8	1.9	3.1	0.7	1.6	2.4
AZ	0.8	1.9	3.1	0.7	1.6	2.4
PE	0.9	2.1	3.4	0.8	1.7	2.7
LE	0.8	2.0	3.2	0.8	1.5	2.6
PF	0.9	2.4	4.1	0.9	1.8	2.9
Mean	**0.9**	**2.1**	**3.4**	**0.8**	**1.7**	**2.6**

Table 2: *Length (days) of planting-flowering (P-F) and flowering-maturity (F-M) periods for maize at current planting date, and 20 and 40 days before under SRES A2 scenario for the years 2020, 2050, and 2080*

	Current				**Twenty days before**			**Forty days before**		
	1971–2000	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
P-F	86	82	77	73	91	85	81	101	94	88
F-M	59	54	50	46	53	49	46	53	50	47

Note: Values for 1971–2000 are also shown.

Figure 1: Study area and sites involved in the work

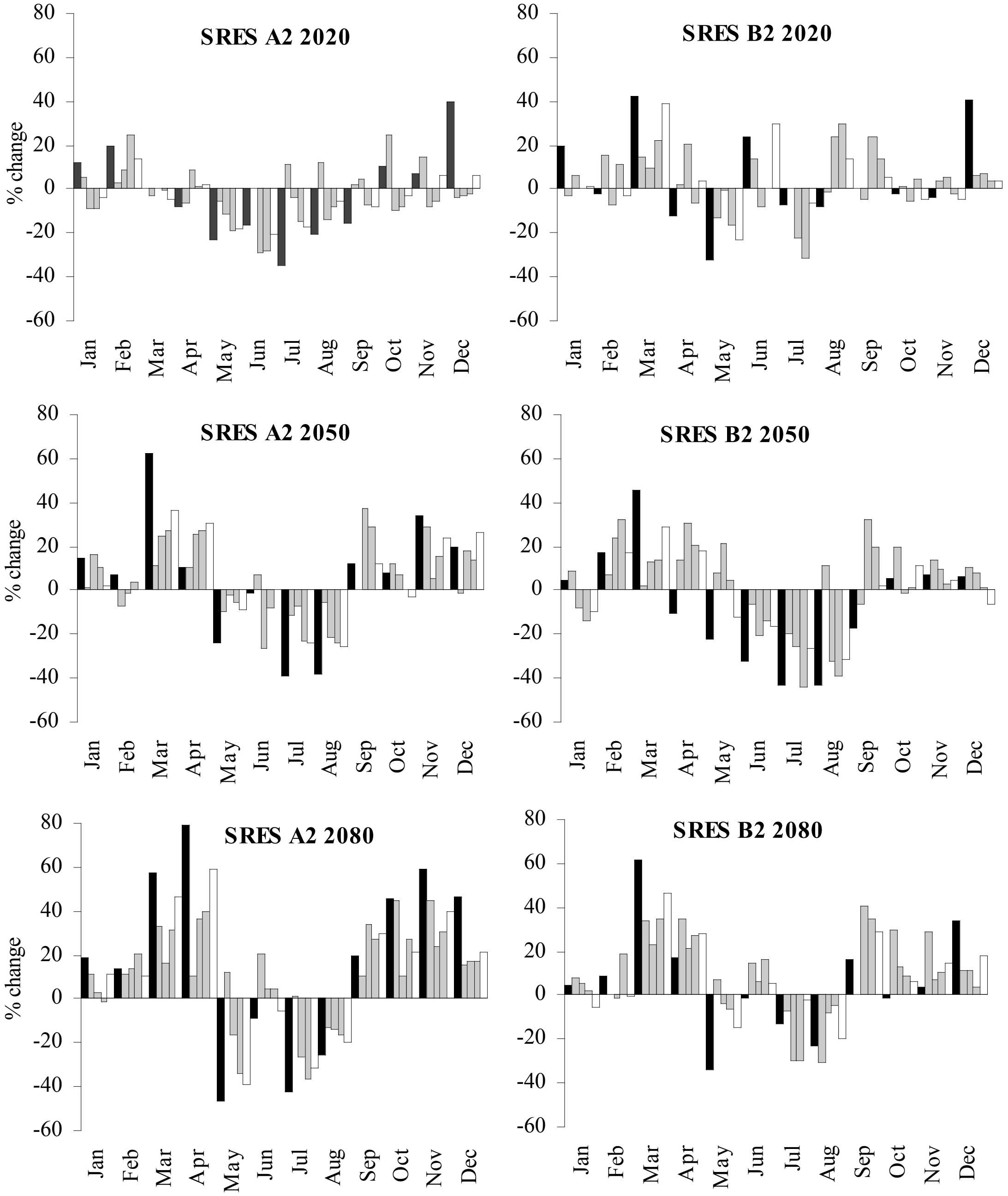
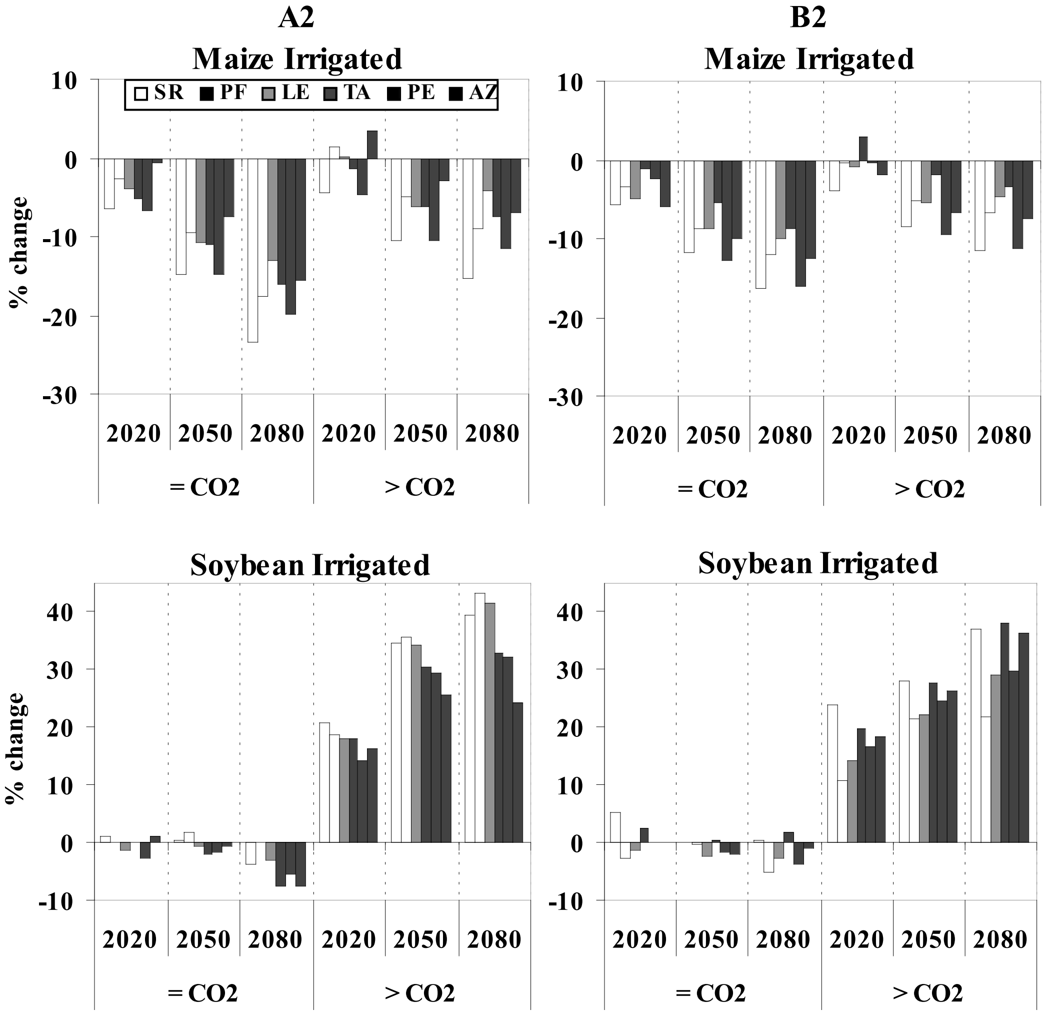


Figure 2. Changes in monthly precipitation (%) projected by HadCM3 under SRES A2 and B2 for 2020, 2050, and 2080.



A2

Maize Irrigated

B2

Maize Irrigated

Soybean Irrigated

Soybean Irrigated

Figure 3: Changes in irrigated maize and soybean yields (%) under different scenarios and CO_2 concentrations.

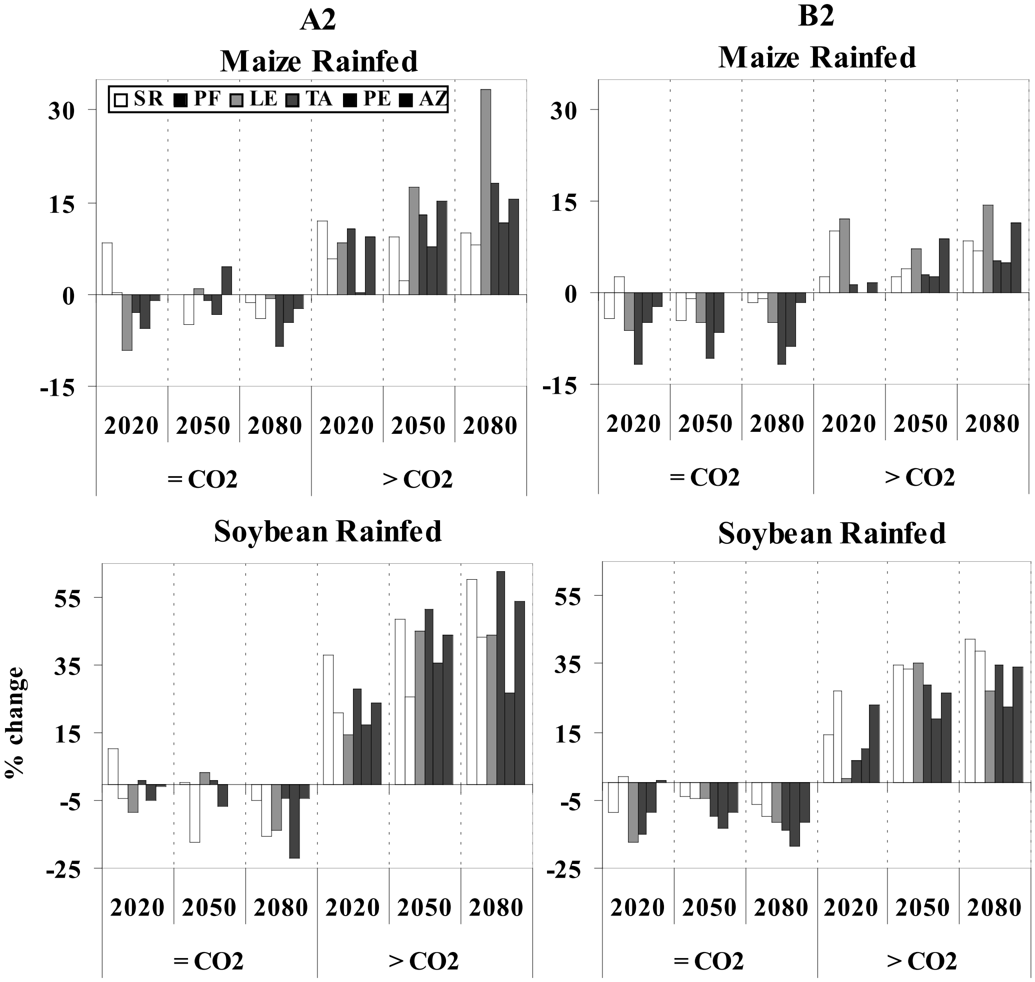


Figure 4: Changes in rainfed maize and soybean yields (%) under different scenarios and CO_2 concentrations.

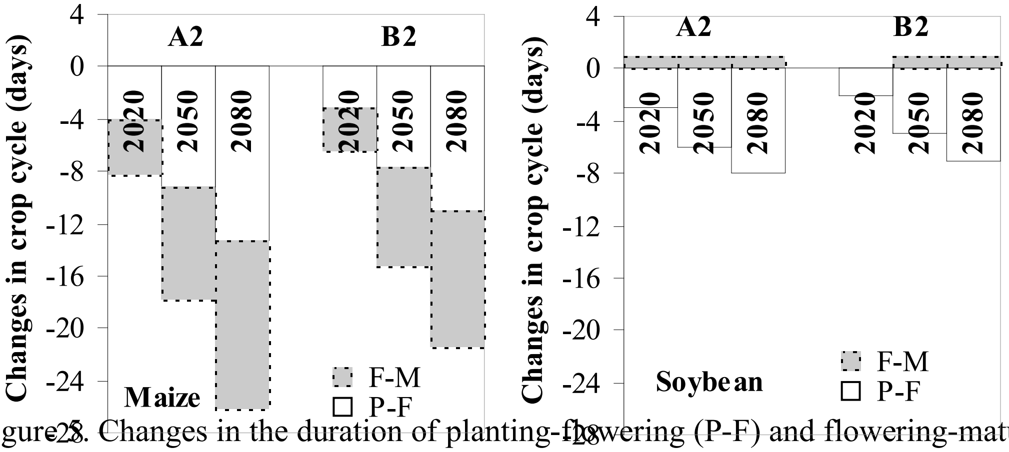


Figure 5. Changes in the duration of planting-flowering (P-F) and flowering-maturity (F-M) periods, expressed as mean values for the six sites, for maize and soybean crops under different SRES scenarios and time periods.

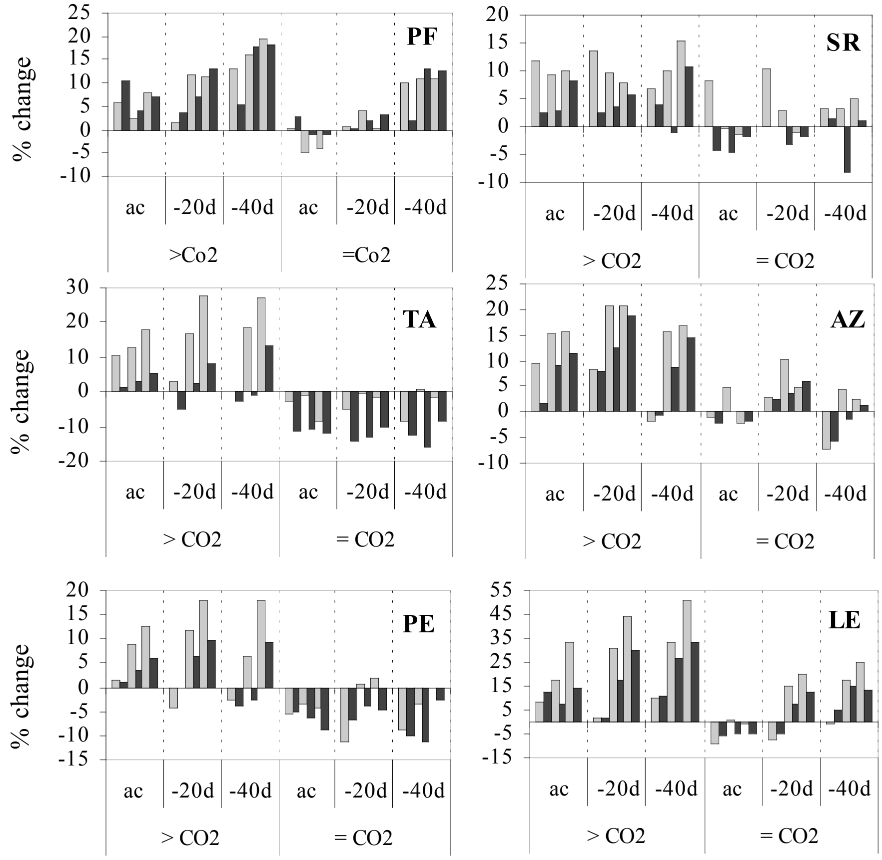


Figure 6. Maize: yield changes (%) for different planting dates (ac = current, –20 and –40 days) in the six sites under different scenarios (A2 in grey, B2 in black for 2020, 2050, 2080) and CO_2 concentrations.

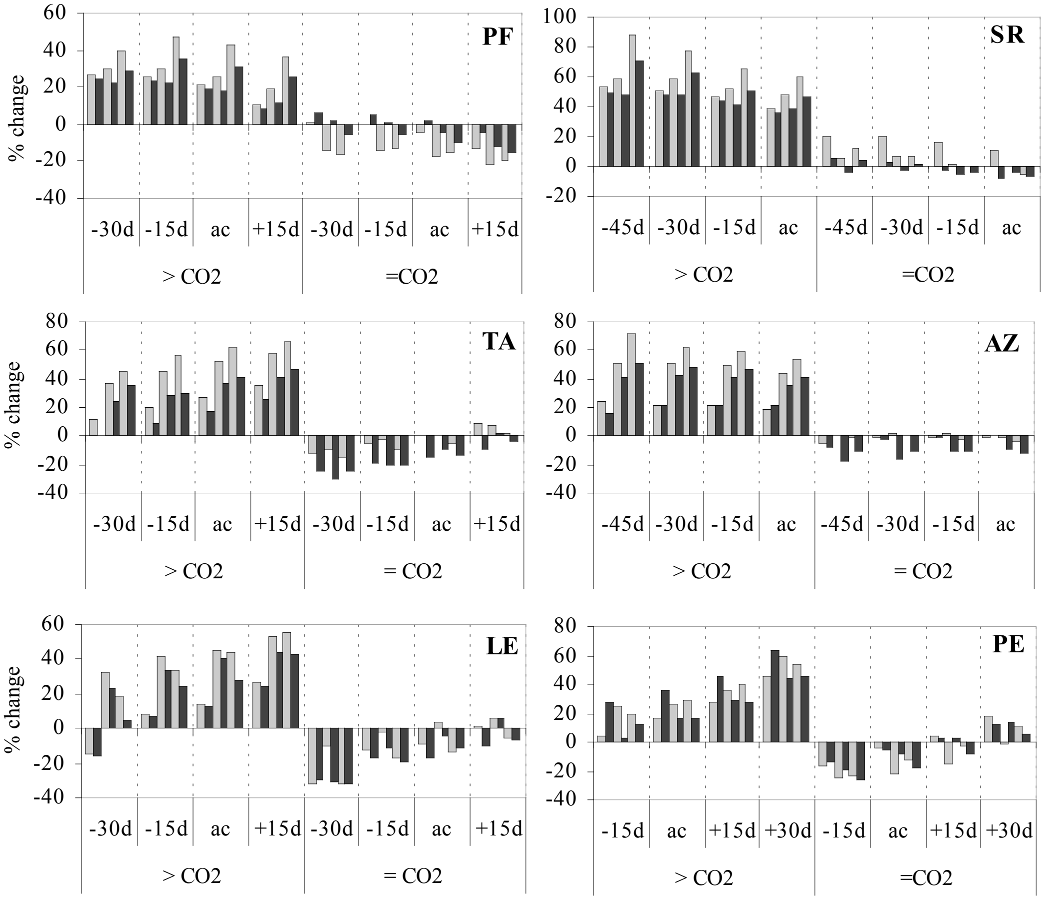


Figure 7. Soybean: yield changes (%) for different planting dates (ac = current, ± 15, 30 days) in the six sites under different scenarios (A2 in grey, B2 in black for 2020, 2050, 2080), and CO_2 concentrations.

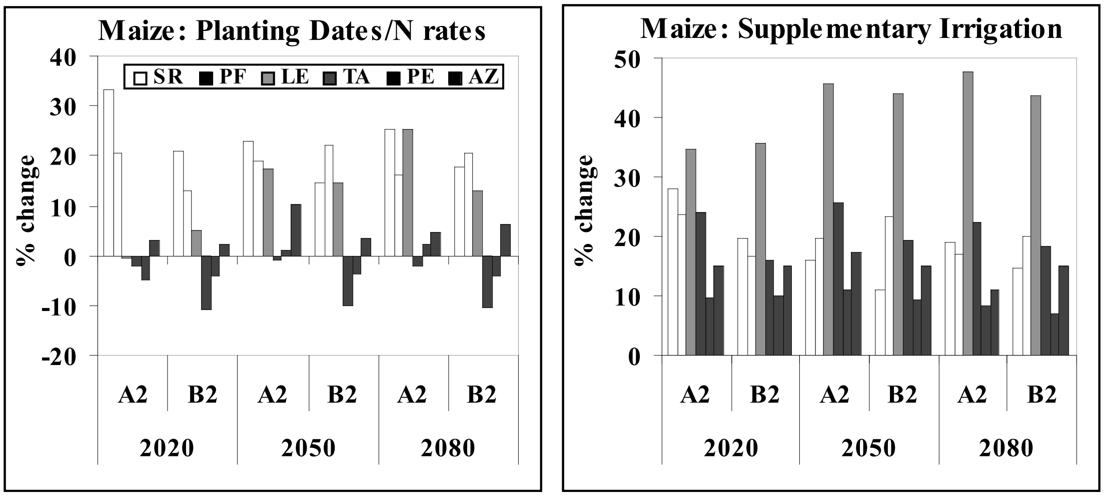


Figure 8: Adaptation measures for maize. Yield change (%) under optimal planting dates/nitrogen rates and supplementary irrigation for the six sites without considering CO_2 effects.

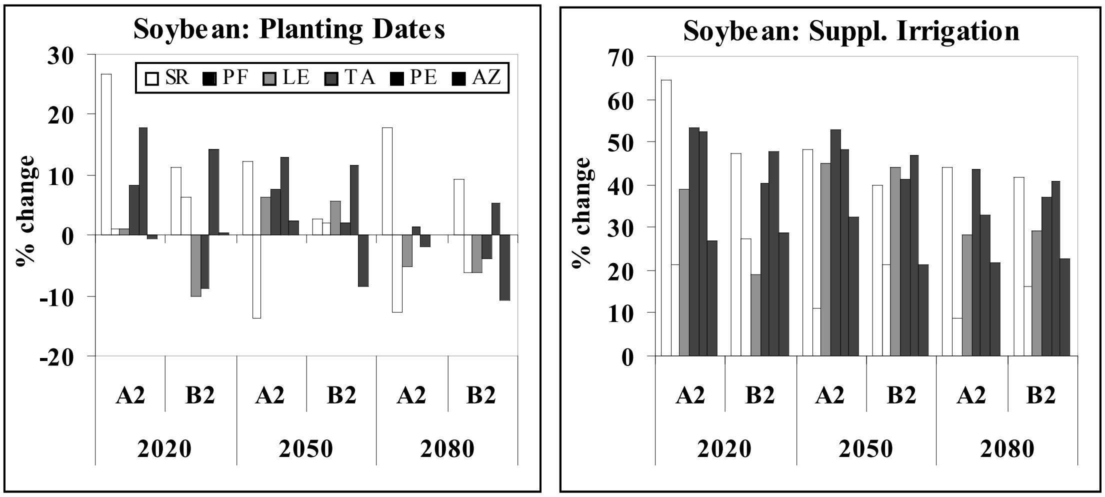


Figure 9: Adaptation measures for soybean. Yield changes (%) under optimal planting dates and supplementary irrigation for the six sites without considering CO_2 effects