# Climate Change and Adaptation

EARTHSCAN CLIMATE

EDITED BY Neil Leary, James Adejuwon, Vicente Barros, Ian Burton, Jyoti Kulkarni and Rodel Lasco

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# Maize and Soybean Cultivation in Southeastern South America: Adapting to Climate Change

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## Introduction

Several important changes in climate and crop production trends have been detected in Southeastern South America since the late 20th century. The climatic changes are characterized by increases in precipitation (up to 50 per cent in some areas); decreases in maximum temperature, especially during spring and summer; and increases in minimum temperature during most of the year (Castañeda and Barros, 1994; Barros et al, 2000; Pinto et al, 2002; Bidegain et al, 2005; Magrin et al, 2005). In response to the favourable climate trends, a subsequent significant increase in crop production, especially in the yield of rain-fed crops, has been noted. Magrin et al (2005), in comparing the period from 1950 to 1970 with that from 1971 to 1999, calculated a 38 per cent increase in soybean yields and an 18 per cent increase in maize yields attributable to the changes in climate (isolated by using crop simulation models with the same production technology).

Added to the influence of changing temperature and precipitation, changes in land use over the past few years have further contributed towards the increase in crop yields. Encouraged by favourable climatic and economic conditions, farmers in the region have begun to devote more and more land to agriculture, especially soybean farming. The recent expansion of soybean cultivation is particularly remarkable, with an increase of 133 per cent (from 6 to 14 million hectares, Mha) in the area devoted to this crop between 1995 and 2003 in Argentina alone (SAGPyA, 2005). A similar trend has also been observed in Brazil, where, in the traditional soybean growing areas such as Rio Grande do Sul, lands devoted to soybean have increased by 38 per cent over the past five years (IBGE-LSPA, 2005). More recently, a huge expansion of this crop has also been observed in Uruguay,



with an increase in cultivated area from 12,000ha in 2000 to 278,000ha in 2004 (MGAP-DIEA, 2005).

According to future projections, the total area under soybean cultivation in South America is expected to grow from 38Mha in 2003/2004 to 59Mha in 2019/2020. Thus an increase of 85 per cent (172 million tons) in the total production of Argentina, Brazil, Bolivia and Paraguay is expected (Maarten Dros, 2004).

Some previous studies have used crop production models[1] based on climate scenarios from general circulation models (GCMs) to assess future changes in crop yields specifically for the southeastern South America region. According to model projections, when $CO_2$ enrichment effects on crop growth stimulation are accounted for, soybean production in the Pampas region of Argentina during the 21st century could range between a reduction of 22 per cent and increases of 3 per cent, 18 per cent and 21 per cent under the UKMO (Wilson and Mitchell, 1987), GFDL (Manabe and Wetherald, 1987), GISS (Hansen et al, 1989) and MPI-DS (Magrin et al, 1998) scenarios respectively.[2] Maize production, on the other hand, is expected to decline under most GCM scenarios; results for the overall Pampas region were -8 per cent, -16 per cent, -8 per cent and +2 per cent under the UKMO, GFDL, GISS and MPI-DS respectively (Magrin and Travasso, 2002), although an earlier study for the main maize production zone estimated reductions of between 20 per cent and 25 per cent based on UKMO, GFDL and GISS projections (Paruelo and Sala, 1993). For Brazil (de Siqueira et al, 2000), a 16 per cent reduction in maize yields and a 27 per cent increase in soybean yields were reported under the GISS scenario when $CO_2$ effects are taken into consideration. Finally, for Uruguay, reductions of 14 per cent and 25 per cent in maize yields have been reported for increases of 2°C and 4°C in mean temperature respectively (Sawchik, 2001), although in this case $CO_2$ effects were not considered.

Some degree of uncertainty is invariably associated with such crop model projections, largely because the interactions between various climatic and non-climatic elements and their impacts on crop production are not fully understood. However, regardless of the level of uncertainty, it appears that future climate conditions will probably be more favourable for soybeans than for maize in southeastern South America. Therefore, based on the current trend, a further expansion of soybean growing areas in this region can be anticipated.

Such large-scale expansion of soybean farming, with a subsequent decline in maize production, could have significant negative consequences in the medium and long term. Potential ecological implications of this trend in soybean monoculture could include reductions in soil organic matter (García, 2003), soil compaction in superficial layers (Diaz-Zorita et al, 2002) and a noticeable increase in the use of herbicides like glyphosate (for example, in Argentina, use was 28Ml in 1997 and 100Ml in 2002) (Joensen and Ho, 2004). Such impacts could seriously threaten the system's sustainability if current practices are not reconsidered. Effective adaptation strategies to sustain the viability of agricultural production systems in this region have therefore also become a critical necessity for the immediate future.

Keeping these findings in mind, our specific objective in this study was to assess the impacts of future climate scenarios (based on the latest GCM projections – HadCM3 – under different SRES scenarios and time periods) on crop production systems in southeastern South America, specifically the Pampas region in Argentina, Uruguay and the states of Rio Grande do Sul in Brazil (Figure 19.1).[3] Six sites in this region were selected representing areas with contrasting environmental conditions (from the humid subtropics in Brazil to the humid and semiarid Pampas), namely Azul, Pergamino, Santa Rosa and Tres Arroyos in Argentina; La Estanzuela in Uruguay; and Passo Fundo in Brazil (see Figure 19.1).

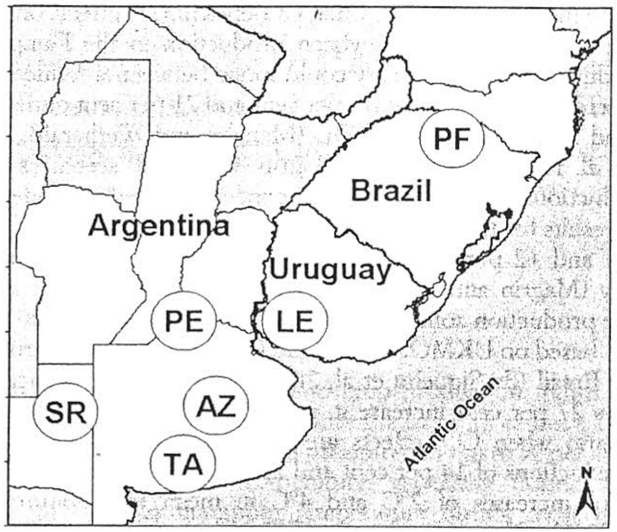


**Figure 19.1** *Study area and study sites*

*Note:* AZ = Azul; PE = Pergamino; SR = Santa Rosa; TA = Tres Arroyos; LE = La Estanzuela; PF = Passo Fundo.

Crop simulation models were used to examine the influence of increasing temperature and precipitation on future crop yields. The effect of $CO_2$ enrichment was also assessed since some studies have shown that increased $CO_2$ concentration in the atmosphere promotes plant growth by boosting photosynthetic activity and increasing water use efficiency (see Kimball et al, 2003). The crop yield results generated were next used in the same crop models to evaluate potential adaptation measures that could help reduce the negative impacts of climate change on maize and soybean production in this region. This study thus played an important role not only in determining the vulnerability of agriculture in this region, but also in identifying strategies that can potentially address this vulnerability.



## Future Climate Scenarios in Southeastern South America

Future climatic scenarios for each of the six study sites were determined with the help of the HadCM3 (Johns et al, 2003) GCM model, which was found to reproduce local conditions in this region with greater confidence than other GCMs (Camilloni and Bidegain, 2005). Model runs were conducted for the two socioeconomic scenarios, A2 and B2, from the IPCC Special Report on Emissions Scenarios (SRES). Monthly values for the variables maximum temperature, minimum temperature and precipitation were obtained from the model results for three 30-year time periods (centred on 2020, 2050 and 2080), and the monthly rate of change of each variable was obtained by comparison with the baseline period 1960–1990. These coefficients of change were next applied to the observed data (1971–2000) to obtain the future climatic scenario on a daily basis.

It was observed that larger increases in temperature and precipitation, particularly for 2050 and 2080, could be expected for the SRES A2 scenario (which assumes a higher $CO_2$ concentration) than for the SRES B2 scenario (Table 19.1 and Figure 19.2). Increases in mean temperature for the warm semester (October–March) ranged from 0.8°C to 4.1°C under SRES A2 and from 0.7°C to 2.9°C under SRES B2, depending on site and time period (Table 19.1).

**Table 19.1** *Projected changes in mean temperature (°C) for the warm semester (October–March) according to HadCM3 under SRES A2 and B2 scenarios for 2020, 2050, and 2080*

| | Mean temperature changes (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** |

*Note:* AZ = Azul; PE = Pergamino; SR = Santa Rosa; TA = Tres Arroyos; LE = La Estanzuela; PF = Passo Fundo.

With respect to precipitation (Figure 19.2), the general pattern showed an increasing trend during the warm semester (October–March), with up to 253mm and 172mm rainfall increases for SRES A2 and B2 respectively. A decreasing trend was observed for the coldest months (May–August), with up to 46mm and 34mm reductions in rainfall for SRES A2 and B2 respectively.

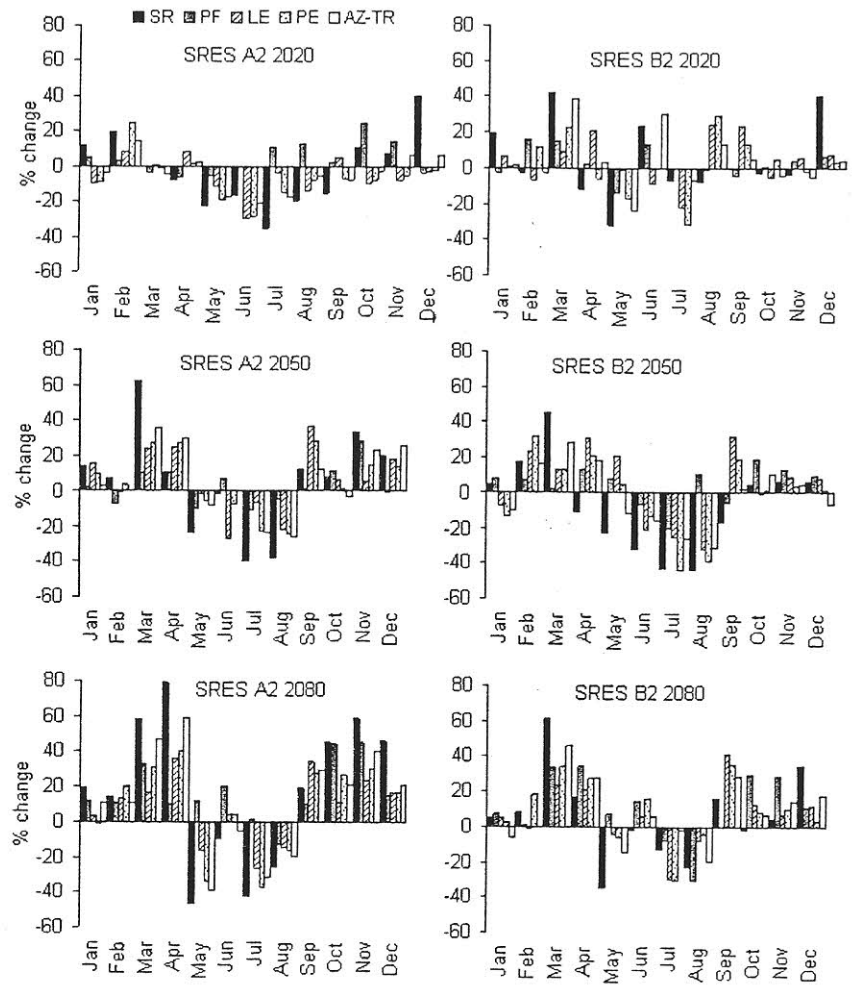


**Figure 19.2** *Changes in monthly precipitation (%) projected by HadCM3 under SRES A2 and B2 for 2020, 2050 and 2080*

## Impact on Crop Production

The expected impacts of these climate scenarios on crop yields in each of the six study sites were next assessed using crop simulation models included in the Decision Support System for Agrotechnology Transfer (DSSAT) computer program[4] (Tsuji et al, 1994). The crop models in 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. They simulate dry matter production as a function of climate conditions, soil properties



and management practices. These models are also able to simulate crop growth for variable atmospheric $CO_2$ concentrations. The inputs required to run the models are daily weather variables, crop and soil management information (planting date, fertilizer use, irrigation and so on), 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 previously been exhaustively tested in the study region at the plot and field levels with relatively low estimation errors (Guevara and Meira, 1995; Meira and Guevara, 1995; Travasso and Magrin, 2001; Sawchik, 2001; de Siqueira et al, 2000). Subsequently, they have also been used to assess the impacts of interannual climate variability and climate change in the agricultural sector of this region (Magrin et al, 1997 and 1998; Travasso et al, 1999; Magrin and Travasso, 2002; de Siqueira et al, 2000; Sawchik, 2001).

Agronomic model inputs used in our study included initial water and nitrogen content in the soil profile, date of planting, plant density, sowing depth, date and rate of fertilizer application, and cultivars. 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 from the HadCM3 runs described above. Crop models were run under rain-fed and irrigated (water and nutrients non-limiting) conditions for different atmospheric $CO_2$ concentrations: 330ppm (current) and those corresponding to each SRES scenario (417, 532 and 698ppm for A2, and 408, 478 and 559ppm for B2 in 2020, 2050 and 2080 respectively).

### Changes in crop yields

The results show a decrease in irrigated maize yields at almost all sites and under all scenarios in comparison to the baseline (1971–2000) when the direct effects of $CO_2$ on crop growth were not considered (Figure 19.3). Yield reductions were larger for the later time periods, and were stronger under SRES A2 (up to –23 per cent) than under B2. A significant correlation was observed between changes in maize yield and temperature increases during the crop growing season ($R^2 = 0.74$), resulting in a reduction of 5 per cent in yields per °C temperature increase.

Under the same conditions, irrigated soybean yields were, however, less affected, with yield changes varying between –8 per cent and +5 per cent (Figure 19.3). The correlation between yield changes and temperature increases was weaker ($R^2 = 0.4$) than in the case of maize and therefore the yield reduction was also smaller (a decrease of 1.8 per cent per °C temperature increase).

When the direct $CO_2$ effects on crop growth were considered, maize yields under irrigated conditions were somewhat higher than those obtained in the absence of $CO_2$ effects, but the increase was insufficient to offset the negative temperature effects (Figure 19.3). In contrast, huge increases in irrigated soybean yields were detected under both SRES scenarios (of up to 43 per cent and 38 per cent for A2 and B2 respectively).

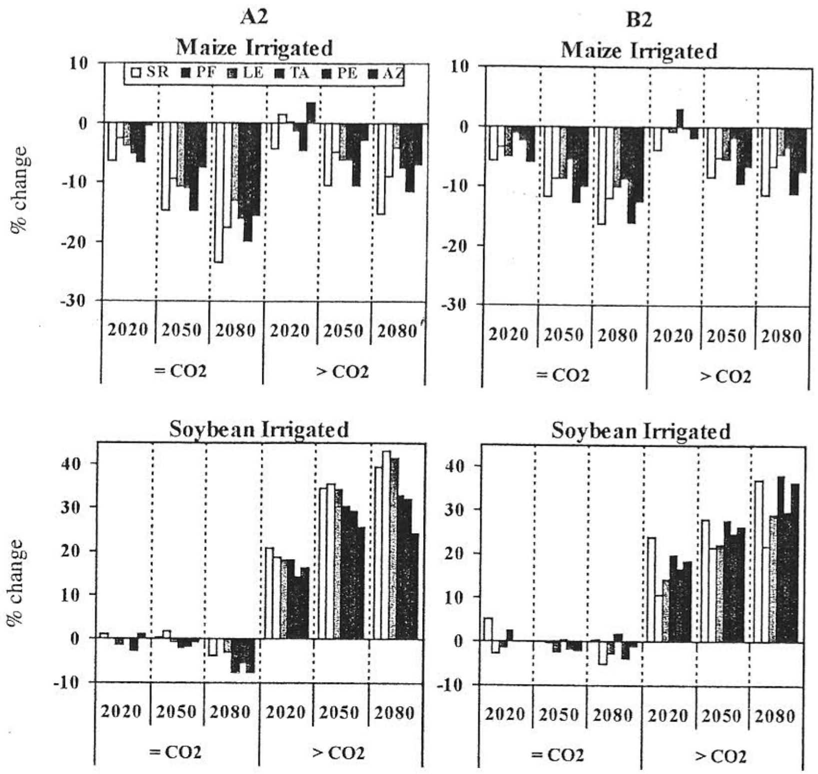


**Figure 19.3** *Changes in irrigated maize and soybean yields (%) under different scenarios and $CO_2$ concentrations*

Under rain-fed conditions and without considering the direct $CO_2$ effects, maize yield changes ranged between –9 per cent and +9 per cent for SRES A2, and –12 per cent and 3 per cent for SRES B2. Rain-fed soybean yield changes varied between –22 per cent and 10.5 per cent for SRES A2, and between –18 per cent and 0.5 per cent for SRES B2 (Figure 19.4). When the direct effect of $CO_2$ on crop growth was taken into account, grain yields increased for both crops but once again a greater impact was observed on soybean yields (up to 62.5 per cent increase).

Thus, under the A2 scenario, when the direct effects of $CO_2$ were considered, irrigated and rain-fed soybean yields and rain-fed maize yields were higher than current climate yields: the direct effects of high $CO_2$ concentration and the higher spring and summer precipitation more than compensated for the negative effect of increased temperature. As expected, the changes in crop yield under the B2 scenario were in the same direction as those under the A2 scenario but smaller in magnitude.



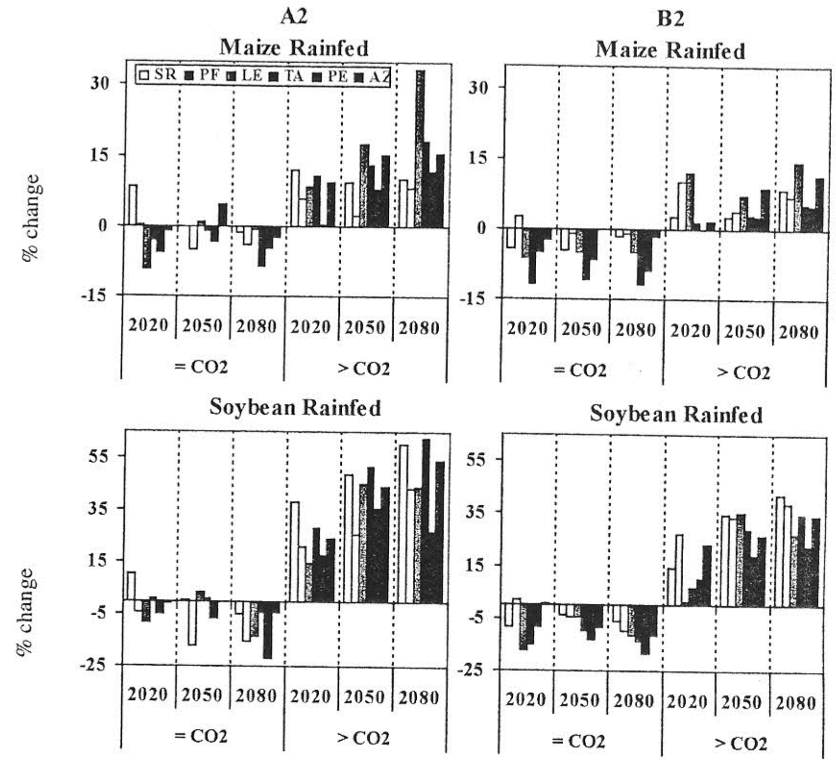


**Figure 19.4** *Changes in rain-fed maize and soybean yields (%) under different scenarios and $CO_2$ concentrations*

The differences in the response between soybean and maize can be attributed to the differences in the influence of temperature and $CO_2$ concentration on crop growth. In soybean (a C3 plant) $CO_2$ effects on photosynthesis are greater than in the case of maize (a C4 plant) (Derner et al, 2003).[5] The soybean simulation model used in our research assumes about a 40 per cent increase in photosynthesis efficiency at a $CO_2$ concentration of 660ppm, while the corresponding value for maize is only about 10 per cent. Consequently, the effect of temperature is more dominant in irrigated maize crops than the effect of $CO_2$ concentration, which explains the obtained yields. 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), which contributes to a higher water use efficiency in rain-fed maize and explains the increase in yield, especially when the direct effects of $CO_2$ are not considered.

## Changes in crop phenology

The projected increases in temperature were also observed to lead to a shortening of the crop growing seasons (Figure 19.5). For both soybean and maize, the worst impacts were observed with the highest temperature increases (A2, 2080). Impacts were much more severe in the case of maize, since the most affected phases were planting–flowering and flowering–maturity. Under the A2 scenario, in 2080 the maize crop growing season was reduced on an average by 27 days. In the case of soybean the worst case scenario resulted in growing seasons that were only 2–7 days shorter, mostly due to reductions in the planting–flowering period. The bigger shortening of the crop growing season observed in maize is coincident with the greater reductions in grain yields.

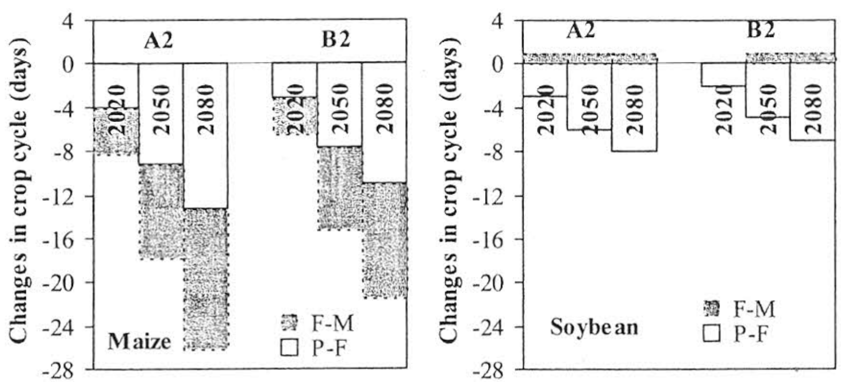


**Figure 19.5** *Changes in the duration of planting–flowering (P–F) and flowering–maturity (F–M) periods, expressed as mean values for the six sites, for maize and soybean crops under different SRES scenarios and time periods*

## Assessment of Potential Adaptive Measures

The DSSAT crop models used to assess crop yield vulnerability to changes in temperature and precipitation were also capable of evaluating climate adaptation measures. We therefore used the same crop models to examine the impact of several adaptive management practices on crop yields, which include changing planting dates, supplementary irrigation and increasing nitrogen application rates. At each site, alternate planting dates were tested for maize and soybean by advancing/delaying planting from the actual dates. Supplementary irrigation was added to both crops during the reproductive period, beginning 20 days before flowering at a rate of 20mm every 20 days. Incremental nitrogen application rates were tested in all sites for maize only



since nitrogen application is not a current practice for soybean in this region. These measures were tested both in the presence and absence of $CO_2$ enrichment effects.

## Considering $CO_2$ effects

### *Changing planting dates for maize*

On average, earlier planting dates were observed to lead to increased maize yields under both SRES scenarios, especially for 2050 and 2080, although there were differences between individual sites (Figure 19.6). Earlier planting dates contributed to longer planting–flowering periods (Table 19.2) and earlier maturity dates. This measure thus allows maize crops to develop under more favourable thermal conditions, increasing the duration of the vegetative phase, which in turn increases grain yield. An additional possible advantage of earlier planting dates relates to the corresponding earlier crop maturity dates and therefore the earlier harvest period. 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 19.2), which could lead to excess water episodes that could, in turn, affect harvest and cause yield losses. The CERES model is unable to account for this effect and therefore the impact of earlier sowing dates could possibly be even higher under the climate conditions predicted by the HadCM3 GCM.

**Table 19.2** *Length (days) of planting–flowering (P–F) and flowering–maturity (F–M) periods for maize at current planting date and 20 and 40 days earlier under SRES A2 scenario for 2020, 2050 and 2080*

| | Current | | | | 20 days before | | | 40 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 |

### *Changing planting dates in soybean*

Even though soybean yields were less affected by temperature increases than maize, changing planting dates did result in higher yields. In three of the six sites evaluated (Azul, Santa Rosa and Passo Fundo), earlier planting dates were found to be beneficial, while in the others, delayed planting dates were found to be the best option under future conditions (Figure 19.7).

### *Effects of nitrogen fertilization (maize only)*

Changes in nitrogen application rates along with optimal planting dates resulted in increased maize yields in only two of the six study sites (Passo Fundo and Santa Rosa). At these sites increases in nitrogen application rates of

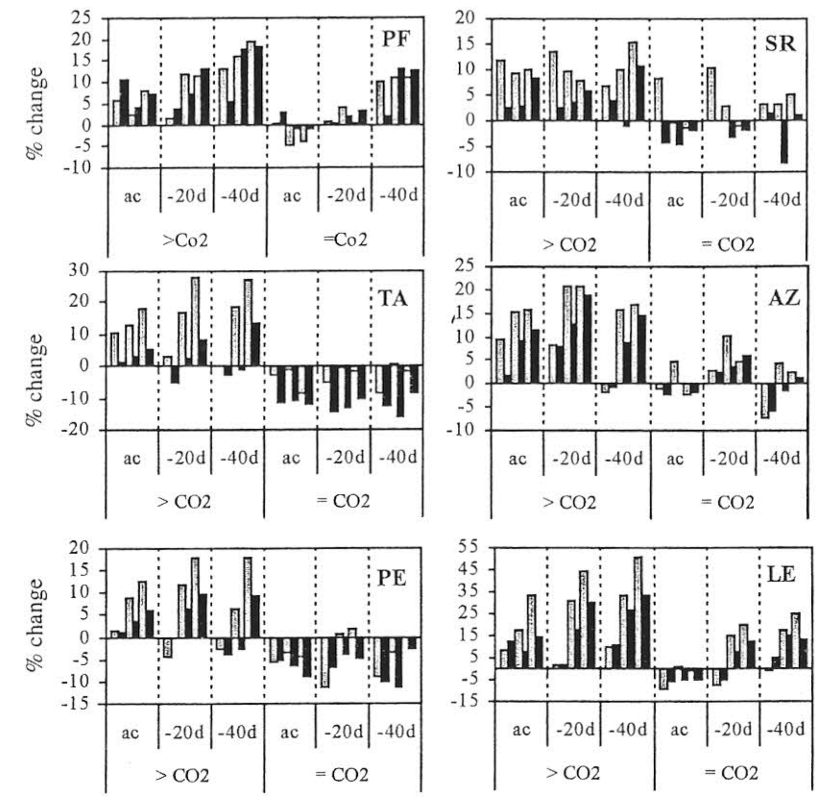


**Figure 19.6** *Maize: yield changes (%) for different planting dates (ac = current, -20 and -40 days) in the six sites under different scenarios (A2 in grey, B2 in black for 2020, 2050 and 2080) and $CO_2$ concentrations*

20 and 45kg N/ha respectively were found to be optimum for encouraging increased yields, possibly due to the more favourable future environmental conditions allowing a positive crop response to increases in nitrogen.

Therefore, in the case of maize, given optimal planting dates and nitrogen application rates, mean yield increases of 14 per cent, 23 per cent and 31 per cent for 2020, 2050 and 2080 respectively are possible under the SRES A2 scenario and mean yield increases of 11 per cent, 15 per cent and 21 per cent are possible under the SRES B2 scenario. For soybean, when optimal planting dates are considered, mean yield increases of 35 per cent, 52 per cent and 63 per cent for 2020, 2050 and 2080 respectively are possible under the SRES A2 scenario, while under the SRES B2 scenario mean yield increases of 24 per



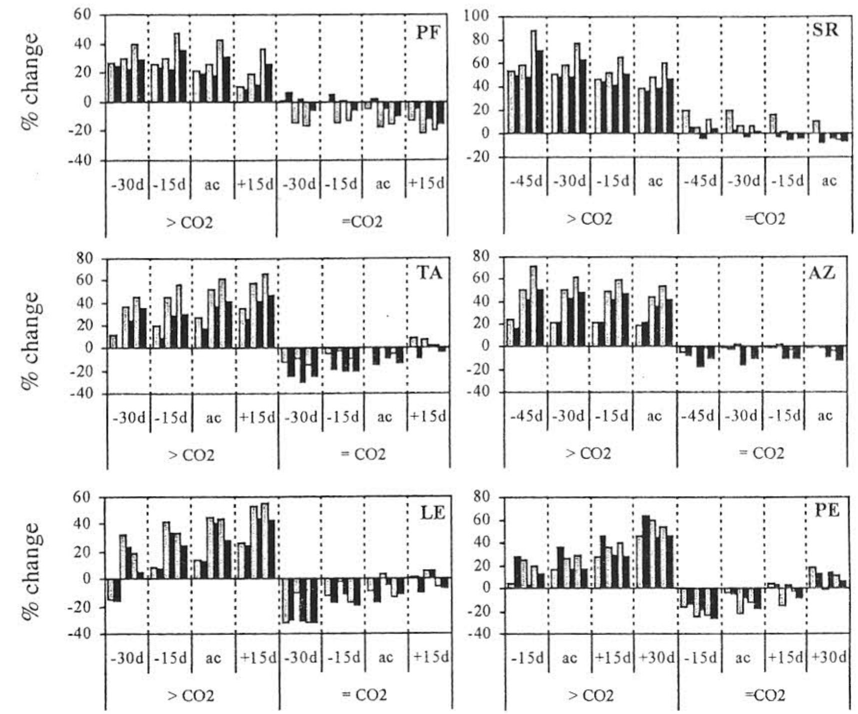


**Figure 19.7** *Soybean: yield changes (%) for different planting dates (ac = current, ± 15, 30 days) in the six sites under different scenarios (A2 in grey, B2 in black for 2020, 2050 and 2080) and $CO_2$ concentrations*

cent, 38 per cent and 47 per cent are possible for the same time periods.

## Without considering $CO_2$ effects

### *Maize*

When $CO_2$ effects were not taken into consideration, yields decreased between 1 per cent and 5 per cent under future scenarios in the absence of adaptation measures. Under optimal planting dates and nitrogen application rates, the overall yield response was higher but differed from the case where $CO_2$ effects were considered, even though the adaptation measures were exactly the same. In this case, changes in maize yields were positive under all scenarios and time periods only in Passo Fundo, Santa Rosa and Azul. Conversely, in Tres Arroyos, a generalized yield decrease was obtained, while in Pergamino and La Estanzuela both positive and negative changes were found depending on the scenario (Figure 19.8). Mean changes for the six sites ranged between 4 per cent (B2 2020) and 12 per cent (A2 2050 and 2080).

These results suggest that without $CO_2$ fertilization simple measures such

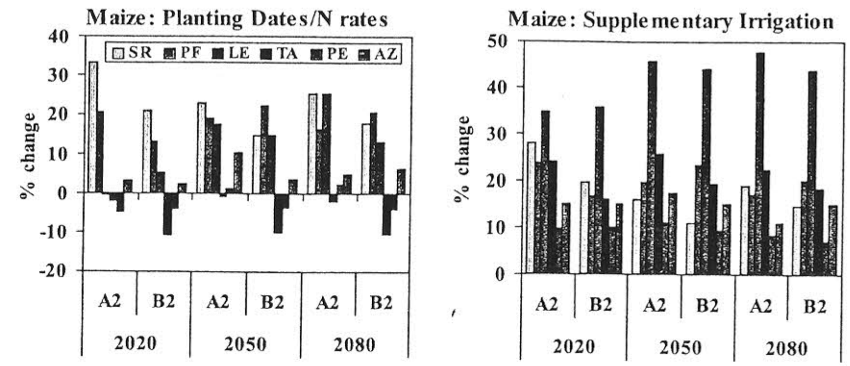


**Figure 19.8** *Adaptation measures for maize: Yield change (%) under optimal planting dates/nitrogen rates and supplementary irrigation for the six sites without considering $CO_2$ effects*

as changes in planting dates or nitrogen rates will not be sufficient in some places. When supplementary irrigation was applied, an overall yield increase was observed with changes close to 20 per cent under all scenarios (Figure 19.8).

### Soybean

In the absence of adaptation measures, soybean yields decreased under all scenarios (1–12 per cent). Changing planting dates led to a modest increase in yields (2–9 per cent) only for 2020 and 2050 (Figure 19.9), but the addition of supplementary irrigation strongly reverted this situation, increasing yields

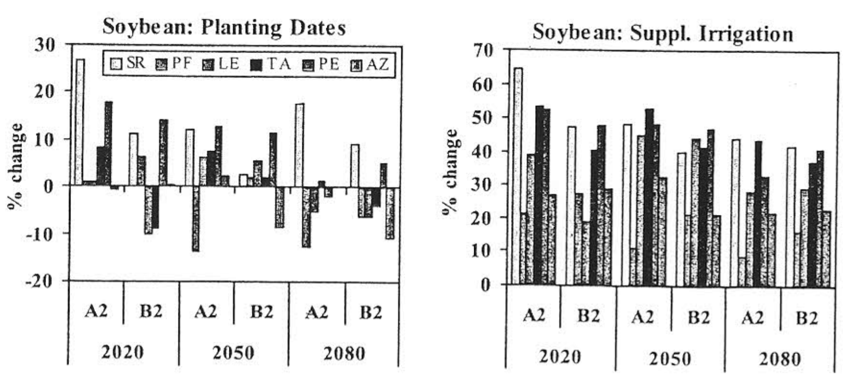


**Figure 19.9** *Adaptation measures for soybean: Yield changes (%) under optimal planting dates and supplementary irrigation for the six sites without considering $CO_2$ effects*



between 30 per cent (A2 2080) and 43 per cent (A2 2020) (Figure 19.9).

From these results it is obvious that soybean crops would benefit much more in comparison to maize from the application of simple adaptation measures under the projected future climate conditions. This is true even when $CO_2$ effects are not taken into consideration. However, the positive crop responses to $CO_2$ enrichment must be treated with caution since such responses have yet to be fully understood under field conditions. Though the positive effect of increasing atmospheric $CO_2$ concentration on photosynthesis and water use efficiency has been demonstrated for several crops (Kimball et al, 2003), such simulation studies have also been criticized by some scientists (Long et al, 2005; Morgan et al, 2005) on the grounds that they are carried out under controlled or semi-controlled conditions, which could lead to an overestimation of the effects, in particular, for soybeans, where photosynthetic efficiency was assumed to be higher than 30 per cent in model simulations. Similarly, Leakey et al (2006) have reported that under field conditions, maize crops growing under ample water and nutrient conditions showed a lack of response to increased $CO_2$. In addition, there is also uncertainty about the response of crops to environments slowly enriched with $CO_2$ (as would happen in the case of climate change) because of the likely acclimation (Ainsworth and Long, 2005). Past research has suggested that the initial stimulation of photosynthesis observed when plants grow at elevated $CO_2$ concentrations may be counterbalanced by a long-term decline in the level and activity of photosynthetic enzymes as the plants acclimate to their environment, a phenomenon referred to as 'down-regulation' (Ainsworth and Long, 2005). Acclimation to $CO_2$ enrichment is not included in the crop models used in our study.

Irrespective of the uncertainties, the climatic changes so far have proven to be favourable to the expansion of soybean cultivation in the study area, as is obvious from current trends. However, the present high growth rate of soybean cropping and its possible continuation in the future, provided continued favourable climatic conditions, is raising important concerns with respect to its impacts on the long-term sustainability of agriculture in the region. The ecological impacts that could potentially affect the growth trends in soybean farming are discussed in greater detail in the following section.

## Ecological Impacts of Soybean Cultivation

The significant growth of agricultural production in southeastern South America, especially of soybean, is unfortunately occurring at the expense of the local environment in the region. It has been observed that the large scale expansion of agriculture in Argentina has created negative soil nutrient balances (nutrient removal exceeding nutrient application) and although crop fertilization is a common practice, only 37 per cent of nutrients extracted are actually replenished (García et al, 2005).

Soybean is a highly nutrient extractive crop with a low level of crop residues, and the current trend of extensive soybean monoculture not only creates a deficit in soil nitrogen content (nitrogen fertilization is not a current practice for this crop) but also leads to negative soil carbon balances because of low carbon (C) inputs to the soil. Experiences in Argentina have shown that for a crop yielding 4000kg/ha, some 120kg N/ha/year and 950kg C/ha/year are lost from the system (García, 2003).

Modern agricultural technologies such as direct seeding and herbicide resistant soybeans (Pengue, 2001) have also contributed to the ecological degradation in the region by further encouraging intensive soybean monoculture. The direct seeding technology was initially introduced to address issues of serious soil erosion and the subsequent loss of soil fertility since it requires no tillage and allows residues from the previous crop to remain on the ground. Although this technique has successfully reduced the rate of erosion, other problems have cropped up from the further intensification of agriculture it encourages, namely the emergence of new diseases and pests, a marked reduction in the levels of nitrogen and phosphates in the soil, and, most recently, the emergence of herbicide-resistant weeds.[6] In the Pampas, there are already several types of weeds that are suspected of being tolerant to the recommended doses of glyphosate herbicide. Some of these now require a doubling of the application, leading to increased herbicide use. This further endangers the environment since herbicide run-off from the farms is already affecting adjacent ecosystems, for example, aquatic ecosystems.

In order to address these issues several alternatives have been suggested, one option being the use of fertilizers to restore soil carbon and nitrogen balances. Other potential measures to improve soil nutrient levels include the use of grasses as cover crops and crop rotation using a higher proportion of corn and wheat in the rotation. The traditional method of crop–pasture rotations is also recommended for correcting soil organic matter balances and thus restoring soil carbon and nitrogen levels (García, 2004). Such crop–pasture rotations were previously the primary crop rotation method in the Pampas region of Argentina (García, 2004). Similarly in Uruguay, traditional rotations included 3–4 years of crops alternating with 3–4 years of pasture. The recent expansion of soybean cultivation has unfortunately led to a decrease in the pasture component of this system. For southern Brazil, Costamilan and Bertagnolli (2004) recommend a three-year crop rotation, including the sequence oats/soybean, wheat/soybean and spring vetch/maize. Besides restoring soil nutrient levels, rotating crop varieties also helps to reduce the incidence of diseases, pests and weeds by breaking their cycle.

A somewhat innovative option for maintaining the viability of agriculture in the region is the 'transformation in origin' approach, promoted by Oliverio and Lopez (2005). The transformation in origin approach suggests the cultivation of a mix of oilseeds (for example, soybean) and cereals (for example, maize) with a part of the production (for example, of maize) remaining at the place where it was cultivated. This is either used as animal feed or in local industry. This practice adds value to the primary product, as opposed to 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 other things. Additionally, the cultivation of a mix of oilseeds and cereals under



this method also ensures that the nutrient content of the soil is better maintained. In order to test this approach, Oliverio and Lopez (2005) analysed two possible scenarios to estimate Argentina's crop production in 2015, assuming that the trend of increasing agricultural production will continue, regardless of climate change. In the first case, they extrapolated the actual trend in planted areas (with increasing importance of oilseeds, especially soybean), and in the second, they proposed a maximum ratio of 2.5:1 between oilseeds and cereals to test the transformation in origin method. They found that even if half the cereal portion of the crop yield (for example, maize) were to be transformed in origin, economic benefits could be more than doubled.

The future outlook for agricultural expansion in southeastern South America will therefore depend not only on future climatic conditions in the region but also on the viability of crop production systems, especially the maintenance of soil nutrient content. Although important remedial strategies have been suggested in studies, further research in this area could help to identify options that effectively address the combined implications of crop responses to future climatic conditions and the ecological impacts of intensive agriculture, specifically soybean cultivation, for the long-term sustainability of farming in the region.

## Conclusion

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

These climatic changes are likely to have important implications for agriculture in the region according to crop model results. In the case of maize, the increased temperatures would result in shorter growing seasons and consequently in lower grain yields. However, if the effect of $CO_2$ enrichment is accounted for, this negative impact could be greatly diminished by adjusting the crop sowing time to earlier dates. When the effect of $CO_2$ enrichment was not considered, changes in planting dates or nitrogen application rates were not enough to improve yield, but moderate supplementary irrigation during the reproductive growth phase did lead to significant yield increases (of up to 20 per cent).

The crop that would benefit the most under future climate conditions was found to be soybean. Assuming the effect of $CO_2$ enrichment, yield increases of greater than 60 per cent could be obtained simply by modifying planting dates. In the absence of $CO_2$ effects, supplementary irrigation was found to be necessary to ensure yield increases and increases of about 30–40 per cent were still possible.

The positive impact of the future climate on soybean production, nonetheless, has important implications for the local environments. A rapid expansion of soybean farming is already underway in this region, a trend that is only expected to strengthen in the future. However, intensive soybean cultivation tends to drain the soil of critical nutrients such as nitrogen and carbon. Additionally, the use of modern technological tools such as direct seeding and herbicide resistant seeds have generated further problems of new diseases and pests, a reduction in soil nutrient levels and the emergence of herbicide resistant weeds. Contamination of aquatic ecosystems with herbicide run-off from farms is also an issue.

Given the inevitability of continued large-scale expansion in soybean cultivation, the timely implementation of appropriate adaptive measures to tackle its harmful impacts becomes critical. Adaptation measures should thus promote adequate nutrient supply, crop and soil management practices, as well as weed, pest and disease control to sustain the environment and the welfare of farmers in the region. Suggested strategies include the traditional methods of crop rotation, crop–pasture rotation, mixed cropping, the use of grasses as cover crops and transformation in origin, in addition to the more common method of fertilizer application. A failure to initiate timely adaptive responses in the commercial farming sector in southeastern South America could translate into significant economic and ecological losses that could negate the benefits arising out of the new climatic conditions.

Finally, the further improvement of crop models is also important in order to better understand the impact of $CO_2$ enrichment on crop production, the interaction with weeds, pests and diseases, and the impact of excess water/flooding. This would ensure better accuracy in determining yield estimations under future conditions and help to identify more effective adaptation strategies.

## Notes

1 Such models estimate agricultural production as a function of weather and soil conditions, as well as crop management by integrating current knowledge from various disciplines to predict growth, development and yield (Hoogenboom, 2000).

2 United Kingdom Meteorological Office (UKMO); Goddard Institute of Space Studies (GISS); Geophysical Fluid Dynamics Laboratory (GFDL); and Max Plank Institute – Downscaling model (MPI-DS).

It is important to note that reductions in soybean production are only expected under UKMO, which projects for the main production area a huge increase in mean temperature (7°C) without changes in precipitation during the most sensitive period for the crop (December–February).

3 In the Pampas region of Argentina, arable lands cover approximately 34Mha and mean annual precipitation varies from 600mm in the southwest to more than 1200mm in the northeast. Mean annual temperature displays a north–south gradient from 13.5 to 18.5°C. In Uruguay, the total area under agriculture is approximately 1.5Mha, precipitation is more or less evenly distributed, and the mean annual rainfall ranges from 1050mm in the southwest and west to 1450mm in the north. Mean annual temperature varies from 18.2°C in the north to 16.8°C in the south and southeast. In Rio Grande do Sul, cultivated area covers about 7Mha. This region is characterized by subtropical humid conditions with rainfall evenly distributed throughout the year. Mean annual rainfall in Passo Fundo is 1788mm and mean annual temperature is 17.5°C.



4 DSSAT is a microcomputer software program combining crop soil and weather data bases and programs with crop models and application programs to simulate multi-year outcomes of crop management strategies. It allows users to ask 'what if' questions and is capable of simulating results in a mater of minutes (www.icasa.net/dssat/).

5 C3 plants produce a three-carbon compound in the photosynthetic process and include most trees and common crops like rice, wheat, barley, soybeans, potatoes and vegetables. C4 plants produce a four-carbon compound in the photosynthetic process and include grasses and crops like maize, sugar cane, sorghum and millet. Under increased atmospheric concentrations of $CO_2$, C3 plants have been shown to be more responsive than C4 plants (see IPCC, 2001)

6 Intensive monoculture is associated with several known issues: due to the absence of rotation with other crop varieties or pasture, the cycle of diseases, pests and weeds cannot be broken, which then necessitates the intensive application of chemical pesticides, herbicides and so forth, which, in turn, can eventually result in the development of resistance to these chemicals over successive crop cycles. Monocropping also depletes soil nutrient levels that otherwise would have been restored under the traditional methods of crop rotation or mixed cropping.

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