

Climate and Complexity in Agricultural Production Systems of the Argentine Pampas

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1. Introduction

Agriculture plays a central role in world food production and food security (Falcon & Naylor 2005), and is one of the most vulnerable sectors of society to climate variability and change (Parry & Carter 1989; Meinke et al. 2006). Managed agroecosystems combine the complexity, multiplicity of scales, and feedbacks of biophysical interactions in natural ecosystems with the additional intricacies of human decisions (Dalgaard et al. 2003). Agricultural production involves real-world decisions with important economic consequences, and thus is a useful test bed to explore linkages between agroecosystems, uncertain decadal climate trajectories, and land use changes over periods of a few decades, a scale relevant to resource management, and to infrastructure and investment planning.

Our focus is on crop production systems in the region of central eastern Argentina known as the Pampas, one of the most important agricultural regions of the world. The climate of the Pampas shows marked inter-decadal variability, consistent with reports for southern South America (Giorgi 2002; Mauget 2007). A steady increase in annual precipitation has been observed since the 1960s (Castañeda & Barros 1994; Rusticucci & Penalba 2000; Boulanger et al. 2005; Magrín et al. 2005). The increase in precipitation has not been uniform throughout the seasonal cycle: increases have been concentrated in the late spring-summer timeframe, whereas the winter has seen little or no increase, and even some negative trends. The inter-decadal climate variability has been reflected in changes

in the streamflows of major rivers of the region (Berbery et al. 2006). The increased precipitation has partly contributed to major changes in land use patterns in the Pampas (Viglizzo et al. 1995, 1997; Satorre 2005). In many places, continuous cropping has widely replaced ecologically-sound agriculture-pasture rotations.

Climate variability and change must be assessed within the specific economic, institutional, land tenure, and technological contexts in which they take place. Argentine agriculture has undergone major changes since the early 1990s (Schnepf et al. 2001; Satorre 2005). *Economic drivers* favored expansion of the area dedicated to agriculture. Structural economic changes fostered investment in technology (larger farming machinery, increased use of fertilizers and biocides). *Institutional factors* such as creation of governmental and stakeholder institutions for agricultural research and extension enhanced technology diffusion. Evolving *land tenure regimes* also played a role. As in the U.S. (Carolan 2005), almost half of the area cropped in the Pampas is not owned by farmers cultivating it. As land becomes more commodified, competition among farmers for rental land increases. Short leases (usually one year) and cash-rent arrangements prevail. Such contracts provide strong incentives to maximize short-term profits via agriculture and may discourage sustainable practices (Carolan 2005; Lichtenberg 2007; Myyrä et al. 2007). Finally, *technological innovations* such as a wheat/soybean double crop, no-tillage planting (Senigagliesi et al. 1997; Martínez-Ghersa & Ghersa 2005), and

genetically-modified, herbicide-tolerant soybeans (Trigo & Cap 2003; Kesan & Gallo 2005; Qaim & Traxler 2005; Traxler 2006) played a major role in land-use changes in the Pampas.

The expansion of soybean in the Pampas and the rest of Argentina has been nothing but impressive: introduced in the early 1970s, the soybean area (production) reached 5.1 Mha (11 Mtons) in 1990 and exploded to 14.0 Mha (38 Mtons) in 2005, displacing other crops, pastures, and forests. Nevertheless, potential conflicts are arising. While Argentina enjoys the economic benefits of soybean exports (\approx \$4.5 B in the first half of 2006; 20% of all exports), worries are growing about “soybean monoculture,” i.e. the abandonment of ecologically-sound crop rotations (Leteinturier et al. 2006). Clearly, a system in which over half of the agricultural area is dedicated to a single crop is highly brittle to shocks or surprises such as price fluctuations or climate anomalies.

Agricultural production systems that evolved partly in response to increased rainfall may not be viable if (as is entirely possible) climate reverts to a drier epoch. However, there is much uncertainty about projected paths of future climate, particularly on regional scales and short time horizons (25-30 years hence). This paper describes a preliminary exploration of plausible climate scenarios and their potential impacts on agricultural systems and their economic sustainability (an important component of overall sustainability).

2. The study region

Our geographic focus is the region of central-eastern Argentina known as the Pampas, one of the main cereal and oilseed producing regions in the world (Hall et al. 1992; Morello & Solbrig 1997; Satorre 2005). We have selected two specific locations with different climatic, ecological and social characteristics: Pergamino (Buenos Aires province, 33°56'S, 60°33'W) and Pilar (Córdoba province, 31°41'S, 63°53'W) respectively represent near-optimal and relatively marginal agricultural conditions. Pergamino is in the most productive subregion of the Pampas (Paruelo & Sala 1993). In contrast, Pilar is in the northern, semi-arid end of the Pampas (Dardanelli et al. 1997). Characteristic crop rotations in both sites include maize, soybean, and a wheat-soybean doublecrop (wheat followed by

short-cycle soybean). Precipitation in the two study sites has varied significantly over past decades. Median rainfall for Oct-Mar (spring-summer) in Pergamino increased about 12% between 1931-50 and 1975-94; Pilar rainfall showed a much higher increase of 33% between the same periods.

The two target regions have different agricultural history and traditions. Farming in Pergamino has been a major activity since the late 19th century. In contrast, agriculture became widespread in Pilar only about 2-3 decades ago, partly in response to climatic amelioration and technological developments (Boulanger et al. 2005; Magrín et al. 2005). Pilar producers came to agriculture from other sectors (industry, business) and most likely have risk perceptions and decision-making approaches quite different from farmers in Pergamino. Contrasting ecological and cultural conditions between sites let us explore differences in vulnerability to climate, risk perceptions, and scope for adaptive management.

3. Approach

The main goal of this work is to improve understanding of linkages between agricultural ecosystems, climate variability and change, and decision-making under risk and uncertainty over scales of a few decades. To assess how current agricultural systems might respond to inter-decadal climate change we followed four main steps. First, we used historical climate data to define a set of plausible and interesting climate scenarios 25 years from present. Second, to downscale regional scenarios and quantify uncertainty due to non-linear crop response to weather sequences, we used semi-parametric weather generators to produce multiple realizations of daily weather consistent with the proposed decadal scenarios. Third, we used the synthetic daily weather series and crop growth models to monitor the temporal evolution of outcomes (yields, economic returns) and risk metrics in current production systems given a plausible trajectory of precipitation decrease. Finally, we explored adaptive responses based on perception of the rainfall decrease and adjustment of current production alternatives. In the next paragraphs we present a brief description and preliminary results from each of these steps.

3.1 Definition of plausible climate trajectories

Substantial progress in global and regional modeling at medium to high spatial resolution provides the opportunity of using atmospheric-ocean global general circulation models (AOGCMs) to generate regional projections of temperature and precipitation (Tebaldi et al. 2006). There are concerns, however, that global climate models still are not capable of simulating regional climate for short time horizons (25-30 years into the future) to desirable levels of accuracy (Rosenzweig et al. 2004; Tebaldi et al. 2006). Temperature and precipitation trajectories at the end of the 21st century have been studied for South America by Boulanger et al. (2006, 2007): whereas they found consistency in predicted temperature changes, there was considerable divergence among models in precipitation projections. Lack of consistency in AOGCM projections requires that we explore alternative approaches to the definition of plausible climate scenarios.

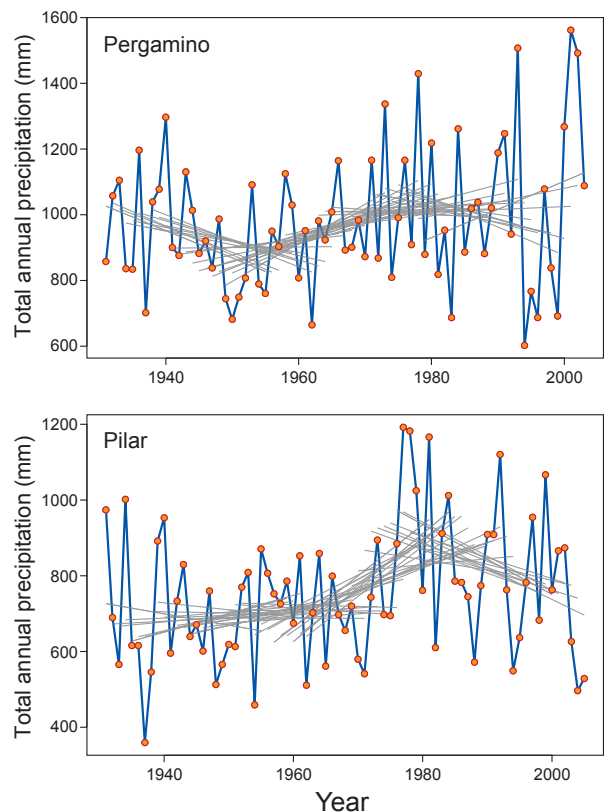
The procedure we used to define plausible climate scenarios was based on exploration of historical climate records for each location. The underlying assumption was that trends in climatic variables that had occurred in the past might be observed again in the future.

We computed annual precipitation totals using historical data for Pergamino (1931-2004) and Pilar (1931-2005). Then, trends were fitted to precipitation totals over a series of overlapping 25-year windows shifted by one year. For example, the first window for Pilar encompassed the period 1931-1955, the second window corresponded to 1932-1956, and so forth. Linear trends for each window were fitted using both ordinary least squares regression and a robust regression that minimized the impact of outliers. Both procedures yielded mostly similar results; for brevity we show results only for the ordinary regression. Figure 1 shows the annual precipitation totals and the trends fitted for each window at both study locations. Various patterns are apparent: (a) a decrease in precipitation in Pergamino between 1931 (first year of the climate records for both locations) and the 1950s (although in Pilar this decreasing trend is not so consistent), (b) a marked increase in precipitation between the end of the 1950's and the early 1990's at both locations and, (c) a considerable decreasing trend in precipitation in Pilar over the last

15 years (in Pergamino the decreasing trend was not so consistent).

The trends estimated from historical data (i.e., the slopes of fitted lines in Figure 1) were used to project plausible trajectories of annual precipitation totals 25 years into the future (2005-2029 and 2006-2030 for Pergamino and Pilar respectively; Figure 2). Although the projected trends show a wide range of plausible scenarios, here we focus only on a possible future decrease in annual precipitation. Various reasons justify this choice. First, agriculture in the Argentine Pampas is largely rainfed, so production is highly sensitive to lack of precipitation. Second, recent awareness of the impacts of precipitation changes on land use and production systems in the Pampas (see Introduction) has heightened stakeholders' concerns about a possible return to a drier epoch. Finally, some of the likely effects of increased rainfall (e.g., flooding, higher incidence of

Figure 1. Total annual precipitation for Pergamino (1931-2004) and Pilar (1931-2005). The grey lines indicate the linear trends (fitted by ordinary least squares regression) to overlapping 25-year windows.



diseases) are not captured by currently used process models.

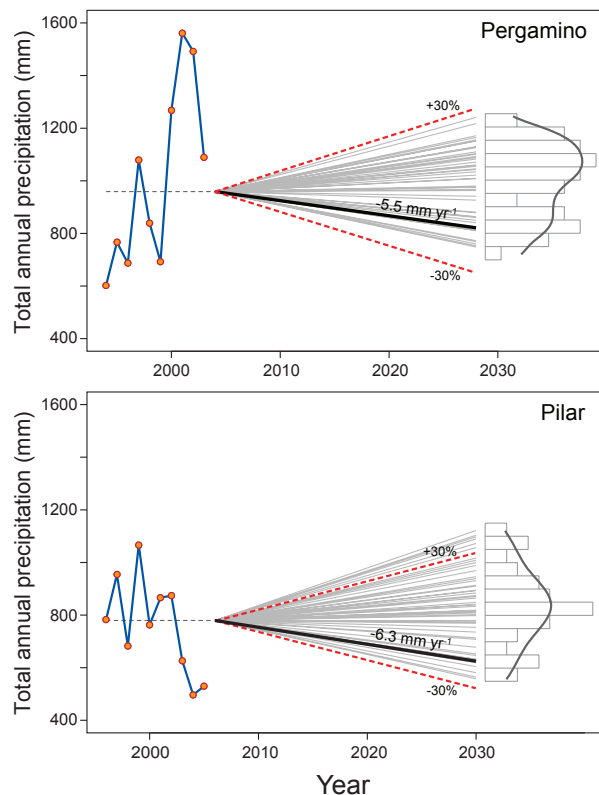
To select a plausible decreasing precipitation trend for Pilar, we averaged the slopes estimated for the ten most recent 25-yr windows: the average trend (indicated on Figure 2, lower panel) has a value of $-6.3 \text{ mm year}^{-1}$. In Pergamino, in contrast, the recent evolution of precipitation is less consistent than in Pilar: both positive and negative trends are observed. For this reason, we estimated the average increasing trend for Pergamino between the 1950s and 1990s and reversed its sign. That is, we assumed that Pergamino precipitation could decrease at a rate comparable with previously observed increases. The resulting trend was $-5.5 \text{ mm year}^{-1}$ (Figure 2, upper panel). The starting point for projected rainfall trajectories was the median annual precipitation of 1995-2004 for Pergamino and 1996-2005 for Pilar: 980 mm and 775 mm respectively.

3.2 Temporal downscaling of selected rainfall trajectories

The second stage of this work involved the temporal disaggregation of selected climate trajectories (specified as changes in annual precipitation totals) into daily synthetic (simulated) series of weather variables required by crop simulation models (maximum and minimum temperature, total daily precipitation and solar radiation). We coupled a semi-parametric (or hybrid) method for the generation of daily weather sequences (Apippattanavis et al. in press) and a biased re-sampling algorithm that replicates an observed low-frequency trend or simulates a hypothetical climate trajectory.

The semi-parametric approach to stochastic weather generation proposed by Apippattanavis et al. (in press) has two main components: (a) a Markov chain for generating the precipitation state (i.e., no rain, rain, or heavy rain), and (b) a k-Nearest Neighbor (k-NN) bootstrap re-sampler (Rajagopalan & Lall 1999) for generating the multivariate weather variables. The Markov chain correctly describes the spell statistics, whereas the k-NN bootstrap captures the distributional and lag-dependence statistics of the weather variables. Plausible climate trajectories can be easily incorporated into the weather generator framework (Yates et al. 2003; Clark et al. 2004). Resampling of the historical

Figure 2. The grey lines indicate all linear trends (fitted by ordinary least squares regression) to overlapping 25-year windows of historical annual precipitation totals. The left sides of the figures show precipitation totals for the 10 most recent years of available data (1995-2004 for Pergamino; 1996-2005 for Pilar). The median totals for these periods (980 mm for Pergamino, 775 mm for Pilar) were used as the point of departure for projections based on estimated trends. The two decreasing trends selected for further analysis are indicated by a thick black line. Histograms of projected precipitation totals 25 years into the future are shown on the right side of each panel. An empirical density was fit to the histogram to facilitate visualization of the distribution of trends.



record is biased according to the trend one wishes to reproduce or simulate. Each historical year is weighted according to its “closeness” (in terms of the conditioning variables) to the scenario for which weather sequences are to be generated. The result of this step was 100 equally-likely sequences (each 25 years long) of simulated daily weather at each location, each sequence being consistent with the decadal trends considered. Figure 3 displays

boxplots of simulated annual precipitation totals for Pilar.

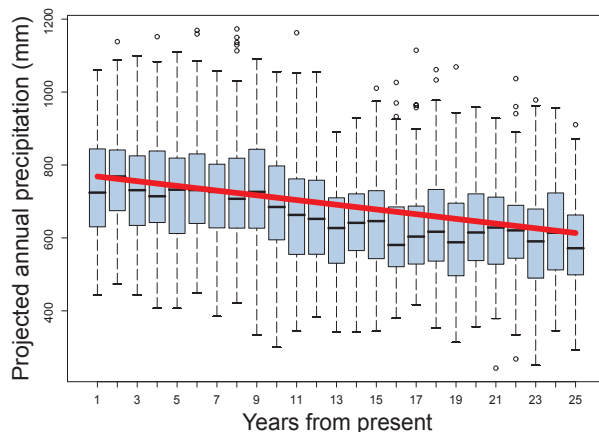
3.3 Simulation of crop yields and economic returns

Dynamic, process-level models help explore potential impacts of decadal climate variability and the scope for adaptive management of agricultural systems on decadal scales. These models simulate crop growth and development as a function of daily weather, soil type, and crop genetic characteristics (Boote et al. 1996). We used models in the Decision Support System for Agrotechnology Transfer (DSSAT, Jones et al. 1998, 2003) to simulate yields for the three main crops in the region: Generic-CERES (Ritchie et al., 1998) for maize and wheat, and CROPGRO (Boote et al. 1998) for soybean. DSSAT models have been calibrated and validated in many production environments, including the Pampas (Guevara et al 1999; Meira et al. 1999; Mercau et al. 2001, 2006). As these models simulate realistic outcomes of management practices (e.g., genotype used, planting date, fertilization amount), they allow exploration of a large portion of the

potential adaptation space. In consultation with local experts we chose, for each crop, a management that is typical or most representative of current practices at each location. The representative managements for each crop and location are listed in Table 1.

We computed net economic returns per hectare as the difference between income and costs. Gross income per hectare was the product of simulated yields and a constant output price for each crop. Assumed output prices were the median of 2000-2005 prices during the month when most of the harvest is marketed (April, May, and January for maize, soybean, and wheat, respectively). Costs calculations were based on a representative 600-ha farm and included fixed, variable, and structural expenses, and income tax; details are available elsewhere (Messina et al. 1999; Ferreyra et al. 2001; Letson et al. 2005). The probability of negative economic returns (PNER) was used to quantify changes in economic risks to production associated with climate trends. Using the 100 realizations for each year in the 25-yr simulated sequences, we computed PNER as the proportion of realizations for each year in which economic profits were negative.

Figure 3. Boxplots of projected annual precipitation totals in Pilar. Each box-and-whiskers plot shows the distribution of precipitation totals for the 100 realizations corresponding to each year in the sequence. The line in the center of the box represents the median of the 100 realizations, the box encloses the central 50% of the distribution, and the whiskers indicate the range of the data. The thick line overlaid to the boxplots indicates the proposed decreasing trend (-6.6 mm year⁻¹).



4. Results

4.1 Impacts of decadal climate trends on current production systems

A first group of simulations involved the assumption of a naïve farmer who does not adapt to changing conditions: the current representative management for each crop was used without modification in all years in the simulated sequences. Additionally, a constant economic context (crop prices and input costs) was assumed for the entire sequence, providing an “all else being equal” situation which helps isolate the effects of changing climate from impacts that may be quite similar, but result from quite different factors that are sometimes closely interconnected (Parry 1985). Yields and economic returns were simulated using the typical management defined for each location, and the 100 realizations of daily climate in the 25-yr sequence.

The proposed decreasing trend in precipitation leads to different yield impacts at each location: simulated yields for all crops increase slightly in Pergamino, whereas they decrease markedly in Pilar (Table 2). At the end of the 25-yr projected

Table 1. Agronomic managements typical or representative of current production systems for each crop and region considered.

| Crop | Pergamino | | | Pilar | | |
|---------------------|-----------|---------------------|--|-----------|---------------------|--|
| | Cultivar | Planting Date | Fertilization (kg N ha ⁻¹) | Cultivar | Planting Date | Fertilization (kg N ha ⁻¹) |
| Full-cycle soybean | DM-4800 | 1 Nov | 0 | DM-4800 | 1 Nov | 0 |
| Maize | DK-682 | 15 Sep | 40 | DK-682 | 20 Oct | 80 |
| Wheat | Escorpion | 10 Jun | 30 | Escorpion | 20 May | 40 |
| Short-cycle soybean | DM-4800 | After wheat harvest | 0 | DM-4800 | After wheat harvest | 0 |

sequence, Pergamino yields of full-cycle soybean, maize, and short-cycle soybean (planted after wheat) increase on average 6.6, 4.5, and 1.0 % respectively. The moderate yield increases may be related to higher radiation levels (as the number of rainy days decreases along the simulated sequence) and decreases in minimum temperatures associated with more dry days (the weather generator keeps the correlation between climatic variables). Wheat yields in Pergamino decrease slightly (-6.3%). In Pilar, in contrast, simulated yields show a steep fall: average decreases are 27.7, 25.0 and 38.5% for full-cycle soybean, maize, and double-crop soybean, respectively. In contrast, simulated yields for wheat (a winter crop) decline much less—about 7%—than for summer crops, because precipitation decreases are projected to occur mostly during the wet period in late spring-summer.

Patterns for economic returns are similar to those discussed for yields (Figure 4). In Pergamino, economic returns for all crops increase slightly, whereas Pilar returns show a marked decrease. Starting with returns fairly similar to those in Pergamino, by the end of the 25-yr sequence Pilar economic returns decrease to about 50% of the initial values. The most dramatic decrease is for maize, which reaches average profits close to zero in Pilar. For the economic context for which returns were calculated (consistent with recent conditions), full-cycle soybean showed the highest economic profits in both locations, and maize was the less profitable crop.

For Pergamino, PNER for all crops is always close to 0 (i.e., risk is very low) and does not change

noticeably with decreasing precipitation (Figure 5). Conversely, increases in PNER are much higher in Pilar: or maize in Pilar, the PNER grows almost fourfold throughout the 25-yr sequence, from 0.11 to 0.40. The risk increase also is very high for full-cycle soybean: PNER rises from 0.00 to 0.23. The chance of negative profits for the double-wheat-soybean double crop rises from 0.12 to 0.30.

4.2 Adaptation of crop management to decadal climate trends

A second group of simulations was based on the assumption of a “clairvoyant” farmer who is perfectly aware of fluctuating climate and adapts her crop management accordingly in order to mitigate potential impacts of a precipitation decrease. This case represents the opposite of the “no change in management” situation explored in the previous section.

To explore the outcomes of adapting to the varying climate, we defined alternative managements for each crop and location. Two managements were explored for full-cycle-soybean (defined by planting dates on 1 November and 10 December). Three alternative maize managements were based on different fertilization rates (0, 40, and 80 kg N ha⁻¹). The two management schemes for wheat also were defined by differences in fertilization amounts (40, and 80 kg N ha⁻¹ in Pergamino; 0, and 30 kg N ha⁻¹ in Pilar). Yields and economic returns were simulated for each of the alternative managements and locations using the 100 realizations of daily climate in the 25-yr sequence. Then, the optimal actions (defined as the proportion of land allocated

Table 2. Crop yields (averaged over the 100 realizations for each year) on years 1 and 25 (i.e., at the beginning and the end) of the simulated sequence and yield trends.

| Crop | Pergamino | | | Pilar | | |
|---------------------|--|---|--|--|---|--|
| | Avg. Yield Year 1 (kg ha ⁻¹) | Avg. Yield Year 25 (kg ha ⁻¹) | Avg. Yield Trend (kg ha ⁻¹ yr ⁻¹) | Avg. Yield Year 1 (kg ha ⁻¹) | Avg. Yield Year 25 (kg ha ⁻¹) | Avg. Yield Trend (kg ha ⁻¹ yr ⁻¹) |
| Full-cycle soybean | 3270 | 3488 | + 6.1 | 2853 | 2070 | - 31.7 |
| Maize | 7463 | 7799 | + 35.1 | 6485 | 4858 | - 76.4 |
| Wheat | 3170 | 2969 | - 9.9 | 1597 | 1575 | - 4.6 |
| Short-cycle soybean | 1294 | 1307 | + 9.1 | 1491 | 917 | - 19.8 |

to each crop and management) to follow in response to precipitation decrease were selected.

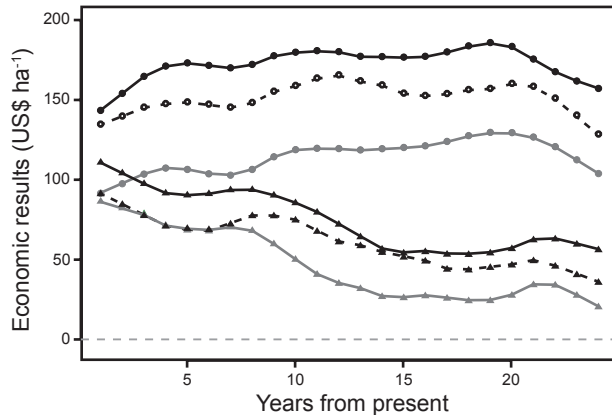
“Best” or “optimal” agricultural practices adopted as part of adaptation to a changing context often involve strong assumptions about decision-makers: that they are fully rational, know the outcomes of all alternative actions, and seek to maximize their expected utility (EU, von Neumann and Morgenstern 1944) of their actions. Despite its obvious strengths, EU maximization as the (sole) objective of risky choice has encountered some opposition in recent years (Gintis 2000; Janssen & Jager 2000; Camerer 2005). Prospect theory (PT) (Kahneman and Tversky 1979) and cumulative prospect theory (Tversky and Kahneman 1992; Fennema and Wakker 1997) currently has become the most prominent alternative to EU theory. Two major characteristics of PT include: (a) the utility of decision outcomes is defined in terms of *relative* gains or losses, that is, positive or negative deviations in income from a reference point such as the status quo, and (b) individuals exhibit strong “loss aversion” (the psychological impact of economic losses is larger than the perceived benefit of gains of comparable magnitude). Empirical studies have consistently confirmed loss aversion as an important aspect of human choice behavior which should be integrated into economic analysis (Rabin 1998; Camerer 2005; Schmidt and Zank 2005).

“Optimal” actions to adapt to the proposed climate trend were selected by maximization of PT’s value function. Details on the objective

function and the optimization procedure for a similar case can be found in Podestá et al. (in press). Optimal management was determined for a series of overlapping two-year windows along the 25-year sequence of decreasing rainfall. This assumes the farmer is aware of the likely range of expected climate conditions, defined on one hand by a window’s position in the sequence (i.e., windows towards the end of the sequence are drier) and, on the other hand, by the natural variability contained in the 200 realizations of simulated weather in each 2-yr window.

For both locations, optimal adaptive actions involved allocating 100% of land to full-cycle soybean throughout the entire 25 years of decreasing rainfall. Although always considered, none of the other crops appeared in the optimal adaptation solutions. That is, if relative commodity prices and input costs remain similar to current conditions (as assumed for simplicity in these simulations) soybean may continue to have higher economic profitability than other crops, even in a context of decreasing rainfall. In Pergamino, optimal management of full-cycle soybean was constant for the entire simulated sequence: early planting on 10 November. In Pilar, in contrast, about ten years into the simulated sequence, the optimal management switched from early planting on 10 November to late planting on 1 December. The shift may reflect the fact that Pilar has much drier winters than Pergamino and thus crop success is highly dependent on spring and summer rainfall. As overall precipitation decreases, a delay

Figure 4. Temporal evolution of economic returns (averaged over the 100 realizations for each year in the sequence) in Pergamino (circles) and Pilar (triangles). The dark line corresponds to full-cycle soybean, the dashed line indicates the wheat-soybean double crop, and the grey line is for maize. The lines have been smoothed to facilitate visualization of trends.

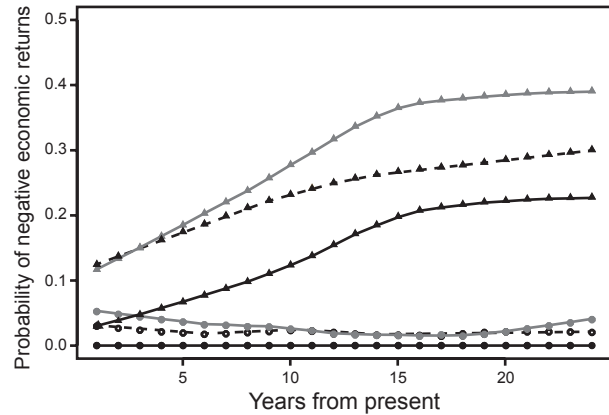


in plating may be required to accumulate soil water. Results are illustrated in Figure 6.

5. Discussion

This paper describes an exploration of plausible climate scenarios 25 years into the future and their potential impacts on agricultural systems in the Argentine Pampas. Decadal climate variability, together with changes in the economic, institutional, land tenure, and technological contexts, has contributed to major changes in land use patterns in the Pampas. Although there is considerable uncertainty about projected paths of future climate, particularly on regional scales and short time horizons, there is growing concern among stakeholders in the Pampas that agricultural production systems that evolved partly in response to increased rainfall may not be viable if (as is entirely possible) climate reverts to a drier epoch. Two locations in the Pampas, Pergamino and Pilar, representing respectively climatically optimal and marginal conditions, were selected for detailed analyses. Contrasting conditions between sites let us explore differences in vulnerability to climate and scope for adaptive management. Two decreasing linear trends consistent with previously experienced fluctuations, -5.5 and -6.3 mm year⁻¹ for Pergamino and Pilar respectively, were chosen for detailed analysis. Nevertheless, future studies

Figure 5. Temporal evolution of the probability of negative economic returns (a metric of production risk) in Pergamino (circles) and Pilar (triangles). The dark line corresponds to full-cycle soybean, the dashed line indicates the wheat-soybean double crop, and the grey line is for maize. The lines have been smoothed to facilitate visualization of trends.

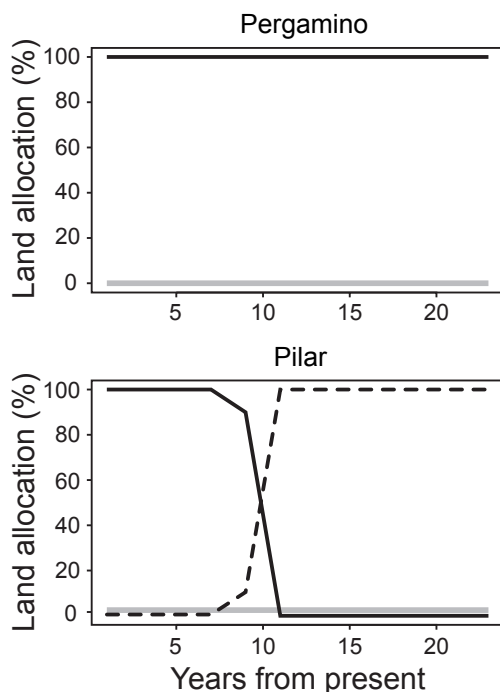


also might explore the potential impacts (both negative and positive) of increasing precipitation, such as a higher likelihood of floods and reduced drought stresses.

There have been two equally unrealistic extremes in modeling farmers' adaptation to climate variability and change: a naïve farmer who does not notice a changing context and makes decisions as always, and a "clairvoyant" farmer who tracks fluctuating climate precisely and follows the best adaptation strategies (Schneider et al. 2000). In reality, farmers are neither naïve nor clairvoyant (Risbey et al. 1999; Smit & Skinner 2002). Nevertheless, we simulated these two unrealistic but useful extreme situations, as they help bound the range of possible outcomes.

In the case of no adaptation, our results show differential responses to plausible decadal precipitation variability between optimal and marginal locations: whereas in Pergamino crop yields and economic returns do not change noticeably (or even increase slightly) with decreasing precipitation, the more marginal Pilar experiences a clear decrease of yields and profits. If precipitations decrease as projected, Pilar also might experience much higher probabilities of negative economic results. Pilar farmers growing maize, who currently experience economic losses once every nine or ten years, might in the future lose money in four out of ten years. Other possible risk metrics such as the

Figure 6. Allocation of land (in percentage) to each crop and management considered as part of adaptation to a changing climate context. The black line corresponds to early planting full-cycle soybean (which is always the optimal allocation in Pergamino). The dashed line corresponds to late-planting full-cycle soybean and becomes the optimal action in Pilar by years 10-12 of the sequence. The grey line indicates all other crops and managements considered in the optimization; allocated land was always null for these.



probability of consecutive negative returns can be explored. The increased rate of economic failure may endanger the future viability of continuous agriculture in climatically marginal regions such as Pilar, where farmers already may operate near the limits of profitability and have a slender buffer against hardship.

In a second step, we allowed farmers to adapt their agronomic management in response to fluctuating climate using currently available technology or know-how. In both locations, optimal adaptive actions involved allocating 100% of land to full-cycle soybean, regardless of decreasing precipitation. This finding probably reflects the strong effect of current relative commodity prices and input costs on soybean profitability: at present soybean not only yields higher economic profits, but also requires

lower initial investments and less management effort (e.g., genetically modified varieties tolerant to herbicides simplify considerably weed controls) than other crops. This result is consistent with the recent expansion of soybean in Argentina at the expense of other crops and cattle. Nevertheless, it may be useful to explore the robustness of our results to changes in relative prices and input costs for different crops. For example, higher global demand for bioethanol in the near future might increase prices of maize (a possible source of this biofuel), possibly changing the optimal adaptation strategies found here.

Adaptation can be complicated because a noisy background of shorter-scale variability and climate surprises both may mask lower-frequency fluctuations and delay adaptive responses (Schneider et al. 2000; Streets & Glantz 2000). Conversely, false detection of trends may induce maladaptation. For simplicity, we assumed here that farmers tracked precisely the decrease in precipitation and responded accordingly. Future work, however, should explore realistic and psychologically plausible ways in which farmers use personal information about the climate recently experienced to form their expectations of climate conditions for the following few years.

Agricultural production decisions are mostly made by individuals, thus strategies to deal with climate risks must be grounded on a firm understanding of human decision-making under uncertainty. The typical assumption in agricultural economics is that farmers are maximizers of expected utility. Nevertheless, different assumptions about what decision makers are trying to achieve (i.e., their objective functions) may change what actions are considered as “optimal” for a given climate context. We used a psychologically more realistic objective function: prospect theory’s value function. Prospect theory is one of the leading current descriptive models of decision making under uncertainty. However, so far it has received relatively limited attention in the agricultural economics or agricultural decision-making literature. We argue that, as it is a proven and mathematically tractable alternative to the EU model, agricultural and resource economists should begin to consider prospect theory.

Future studies should consider realistic adaptation trajectories that involve not only changes in currently available genotypes or management actions, but also technological innovations. For

instance, it is relevant to explore whether crop breeding can keep pace with projected yield decreases associated with lower rainfall. For Pilar, average projected yield decreases for maize are $\approx 76 \text{ kg ha}^{-1} \text{ year}^{-1}$. Crop breeding, in contrast, has produced recent average yield increases $100\text{-}250 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Eyh rabide et al. 1992; Eyh rabide et al. 2001; Luque et al. 2006). Projected decreases in full-cycle soybean yields in Pilar are $\approx 32 \text{ kg ha}^{-1} \text{ year}^{-1}$. This projection compares unfavorably with recent breeding increases of $12\text{-}16 \text{ kg ha}^{-1} \text{ year}^{-1}$ (Santos et al. 2006). Further, it would be critical to assess whether such rates of yield increase could be maintained in drier environments.

Forthcoming advances in agricultural technology may affect not only the sector's productivity, but also its vulnerability to changes in climate (McKenney et al. 1992). Therefore, it is important to anticipate the technological changes that may shape agriculture over the next decades. One of the most anticipated developments in agricultural biotechnology is the introduction of genes to enhance drought tolerance in plants (Babu et al. 2003; Masle et al. 2005). In the next decade, seed companies expect to introduce transgenic solutions to improve drought tolerance in maize (www.pioneer.com/pipeline/spec_sheets/drought.pdf). Maize is the main alternative to soybean in the Pampas and its yields are very sensitive to drought-related stresses. Availability of drought-tolerant maize may allow cropping in a marginal area that becomes even drier. Rotations including drought-tolerant maize would be more attractive in a drier climate and partially alleviate concerns about soybean mono-cropping.

In the next few decades, complex interactions between decadal climate variability, technological innovations and other drivers may force agricultural stakeholders and policy-makers to face unavoidable tradeoffs between productivity, stability, and sustainability in agroecosystems of the Pampas (Viglizzo & Roberto 1998). The growing tension between multiple and conflicting objectives, coupled with incomplete and uncertain information about expected climate trajectories and other valid societal concerns offer opportunities for salient scientific knowledge to inform decision-making and policy.

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