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Objective Functions in Agricultural Decision-Making: A Comparison of the Effects of Expected Utility, Regret-Adjusted Expected Utility, and Prospect Theory Maximization

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ABSTRACT

Simulated outcomes of agricultural production decisions in the Argentine Pampas were used to examine objective functions with greater psychological plausibility than expected utility (EU) maximization, in particular, regret-adjusted expected utility and prospect theory value maximization. For each objective function, we provide the distribution of production enterprises on a hypothetical 600 ha farm optimal for either land owners or tenants (owners are subject to an optimization constraint that reflects a crop-rotation regimen). We provide an explicit functional form for each objective function, propose an equivalent, but more mathematically-tractable formulation for the prospect theory value-function maximization, and explore a broad parameter space. Optimal enterprise allocation differs for the three objective functions and for different parameter values, especially for land tenants, whose enterprise allocation is less constrained. The effects of regret are minor compared to the effects of loss aversion and gain-loss reference point of prospect theory. Our results demonstrate in a non-laboratory decision context that psychologically plausible deviations from EU maximization matter. They can be used to explain observed land allocation decisions inconsistent with EU maximization and to identify segments of decision makers who differ in decision objectives or optimization constraints as the result of socioeconomic/demographic or psychological differences.

1. INTRODUCTION

1.1 Historical evolution of theories of rational choice

The objective function or choice criterion that decision makers seek to optimize has been the object of theoretical and empirical investigation for centuries (Machina 1987; Starmer 2000; Schoemaker 1982). The first candidate, introduced in the mid-17th century, was the maximization of expected monetary values. This concept soon encountered problems because it conflicted with the intuition of educated decision makers, as in the so-called St. Petersburg paradox, where people pay only a small amount of money for a game of infinite mathematical expectation. To resolve the St. Petersburg paradox, Bernoulli (1954/1738) proposed that people maximize the expected utility of wealth rather than expected monetary value, postulating that money and wealth have diminishing returns. The work by von Neumann and Morgenstern (1944, 1947) provided an explicit formulation of expected utility (EU) and an axiomatic foundation. Subsequent extensions and variations are described by Schoemaker (1982). The EU utility model has been central in the analysis of choice under risk and uncertainty. It has been successful not only because of its compelling axiomatic foundation and ability to describe economic choices, but also because of its mathematical tractability (Woodward 1998).

Despite its obvious strengths, EU maximization as the (sole) objective of risky choice has encountered some opposition in recent years. There is both experimental and real-world evidence that individuals often do not behave in a manner consistent with EU theory (Camerer 2000; McFadden 1999), including the classical demonstrations referred to as the Allais (1953) and Ellsberg (1961) paradoxes. A central assumption of EU theory is that the utility of decision outcomes is determined entirely by the final wealth they generate regardless of context, i.e., that it is an absolute or reference-independent construct. Yet, decision-makers' evaluation of outcomes appears to be influenced by a variety of relative comparisons (Kahneman 2003). In one such comparison, decision-makers contrast the outcome of their decision to what might have happened had they made a different choice. When, for the same state of the world, the expected outcome of an action compares unfavorably with the expected outcome of a different (counterfactual) action, decision-makers experience regret. Regret theory, independently introduced by Loomes and Sugden (1982) and Bell (1982), introduces the effect of anticipated regret as a correction to classical utility theory. It formalizes the process by which decision-makers experience regret about their action if their realized outcome is worse than the counterfactual outcome, or rejoice if their realized outcome is better. Consistent with a negativity effect found in many judgment domains (Weber 1994), feelings of regret are stronger than feelings of rejoicement. Since people anticipate experiences of regret, they choose such that their course of action minimizes anticipated post-decisional regret. That is, regret theory predicts that people act not to maximize expected utility but to maximize an expected utility that has been modified by consideration of anticipated regret. Minimization of anticipated decision regret is a goal frequently observed, even if it results in lower material profitability (Markman et al. 1993).

Prospect theory (Kahneman Tversky 1979) and its modification, cumulative prospect theory (Tversky Kahneman 1992; Fennema Wakker 1997) currently have become the most prominent alternatives to EU theory. Prospect theory formalizes another relative comparison observed when decision makers evaluate the utility of decision outcomes. Its value function *v* is defined in terms of relative gains or losses, that is positive or negative deviations from a reference point. Value therefore is determined by changes in wealth, rather than reference-independent states of wealth as in utility theory (Kahneman 2003). Furthermore, the value function for losses is steeper than the value function for gains, resulting in a sharp kink at the reference point. This feature of the value function models the phenomenon of loss aversion, i.e., the observation that the negative experience or disutility of a loss of a given magnitude is larger than the positive experience or utility of a gain of the same magnitude. Empirical studies have consistently confirmed loss aversion as an important aspect of human choice behavior (Schmidt Zank 2005; Camerer 2005). Rabin (1998) emphasized the growing importance of loss aversion as a psychological finding which should be integrated into economic analysis. In particular, loss aversion is the most important explanation for phenomena such as the endowment effect (Thaler 1980), the status quo bias (Samuelson Zeckhauser 1988; Johnson Goldstein 2003), and the equity premium puzzle (Benartzi Thaler 1995). In another deviation from EU theory, prospect theory predicts that risk attitudes depend on how a problem is framed, in particular, that risk-averse behavior will predominate if outcomes are perceived to be gains (with a concave value function), but that risk-seeking behavior will predominate if outcomes are perceived to be losses (with a convex value function). Finally, prospect theory differs from EU theory in the way it handles probability information, although this is not relevant to the work presented here.

1.2 Objective functions considered in this study

In this paper we compare and contrast the objective functions or choice criteria associated with EU, regret-adjusted utility, and prospect theories. Formulations of these three objective functions are applied to a real-world optimization problem in agricultural management. EU maximization is a widely used criterion in agricultural economics, and thus is a useful benchmark against which to compare the results of other objective functions. Given the increasing evidence that affective processes play an important and often decisive role in many decision situations (e.g., Damasio 1995; Loewenstein et al. 2001) and the fact that the feeling of regret probably has important learning functions, we explore the implications of introducing a regret correction to expected utility. Finally, we consider prospect theory for its ability to resolve the Allais and Ellsberg paradoxes and to accommodate other phenomena inconsistent with EU theory, including real-world choice behavior in diverse contexts (Camerer 2000). Prospect theory has received limited attention in the agricultural economics or agricultural decision-making literature. Collins et al. (2001) used prospect theory to re-interpret changing risk preferences in grass seed growers, and Reusser et al. (2004) used it as one of their models when examining how uncertainty propagated throughout an agent-based model. Eggert and Martinsson (2004) elicit the risk preferences of commercial fishers and find them more consistent with prospect theory than EU. We argue that as proven and mathematically tractable alternatives to the EU model become available, agricultural and resource economists along with other economists should begin to consider alternative objective functions and to explore how they might improve analysis and insight (Woodward, 1998).

1.3 Objectives and contributions

The main objective of this paper is to examine the nature and magnitude of differences in the agricultural production decisions identified as "optimal" by maximization of the objective functions associated with EU, regret, and prospect theory. Most studies comparing these choice models have focused on (often hypothetical) monetary lottery choices in laboratory studies. It is important to determine the extent to which these choice theories make different prescriptions for or predictions of behavior in more complex, real-world contexts and to understand the nature of these differences. Much is at stake, since those deviations matter a great deal in terms of what we need from agriculture, such as rural incomes, food security, export earnings and agro-environmental amenities.

The paper makes three types of contributions. (1) We provide explicit functional forms for objective functions for which accepted forms do not exist (e.g., for regret theory). For functions that are incompatible with widely used optimization tools, we develop equivalent but more tractable formulations. For instance, the discontinuity in the derivative of prospect theory's value function provides a problem for the GAMS optimization software (Gill et al., 2000) widely used by economists. Although other algorithms can handle such discontinuities, they tend to get unstable solutions and users are warned to verify results. Whether explicit functional forms for objective functions do not exist or are in need of improvement, it is important for the decision analytic community to agree on common formulations in order to allow for the replication and comparison of results. We hope that our paper will contribute to such standardization. (2) It provides a mechanism to explain observed land allocation decisions that are inconsistent with EU maximization with reference to alternative objective functions. (3) Its identification of the agricultural production decisions that are optimal with respect to the three objective functions (for a broad range of plausible parameter values for each function) will allow researchers to identify different segments of decision makers who might differ in objective functions or optimization constraints as the result of socioeconomic/demographic or psychological differences.

1.4 A case study: agricultural production decisions in the Argentine Pampas

Our case study targets agricultural production in the Pampas of central eastern Argentina. We focus on agricultural decision-making in the Pampas for several reasons. (1) In non-centrally planned economies like Argentina, agricultural production decisions are overwhelmingly made by individual decision-makers (farmers, professional farm managers, technical advisors). The ability to predict optimal decisions at the individual level and to model differences in (presumably optimal) observed decisions as resulting from either differences in objective functions or in parameter values within the same objective function, therefore, has much utility. (2) Agricultural production involves a variety of real-world decisions, with important economic consequences and thus is a useful test bed for the exploration of the implications of alternative choice theories and their objective functions. (3) The annual cycle of agricultural production provides rich opportunities (i.e., ready replications and variations) for the study of real-world decisions. (4) The collection of agricultural statistics is common and institutionalized in many countries therefore data about agricultural production decisions are more available and more reliable than decisions in other sectors. (5) The scale of production systems in the Argentine Pampas and available technology are very similar to those of other important production regions (e.g., the American Corn Belt), which makes our results applicable to a broader set of regions.

2. OBJECTIVE FUNCTIONS CONSIDERED

2.1 EU maximization

We define a risky prospect $q = (p_1, w_1; ....; p_n, w_n)$ as the ensemble of possible wealth/outcomes w_i with associated probabilities p_i that are non-negative and add up to one. A common formulation (Hardaker et al. 2004, p. 104) states that a decision-maker evaluates the expected utility of prospect q as

$$EU(q) = \sum_i p_i u(w_i) \quad . \qquad (1)$$

The real-valued utility function $u(\cdot)$ is given by Pratt (1964) as:

$$u(w) \propto \begin{cases} \frac{w^{1-r}}{1-r} & if \; r \neq 1 \\ \ln w & f \; r = 1 \end{cases} \quad , \qquad (2)$$

where r is the coefficient of constant relative risk aversion (CRRA). CRRA implies that preferences among risky prospects are unchanged if all payoffs are multiplied by a positive constant (Hardaker et al., 2004). The curvature of the utility function, defined by parameter r, captures all information concerning risk attitude.

2.2 Regret-corrected expected utility maximization

A formulation for the expected value of the utility of outcomes corrected by anticipated regret was presented by Braun and Muermann (2004), who called this function Regret-Theoretical Expected Utility (RTEU). Their formulation is applicable to continuous states of the world, whereas our application provides discrete states of the world corresponding to different cropping cycles. The discrete form of RTEU for risky prospect q (defined in the same way as for expected utility) can be written as

$$RTEU(q) = \sum_{i=1}^{n} p_i \left\{ u(w_i) - k \; g(\Delta u_i) \right\} \quad . \qquad (3)$$

This expression depends not just on possible outcomes/wealth w_i, but also contains an additively separable regret function that is increasing in the difference between the utilities of the realized and unrealized outcomes. The correction to utility due to anticipated regret is captured by the difference

$$\Delta u_i = u(w^{\max}) - u(w_i) \quad , \qquad (4)$$

where $w^{\max}$ is the maximum outcome that could have been realized in state of the world i, under a counterfactual action. The difference Δu_i must be ≥ 0. Factor k, initially introduced by Loomes and Sugden (1982) and subsequently used by Braun and Muermann (2004), weights the effect of regret.

The regret function $g(\cdot)$ in Eq. 3 needs to increase as a function of Δu_i. To obtain a more specific functional form for $g(\cdot)$, Braun and Muermann (2004) proposed three desirable properties for it:

$$g(0) = 0 \quad , \qquad (5a)$$

$$g'(\Delta u) > 0 \qquad \forall \Delta u \quad , \text{ and} \qquad (5b)$$

$$g''(\Delta u) > 0 \qquad \forall \Delta u \quad , \qquad (5c)$$

where g' and g'' indicate, respectively, the first and second derivatives $d/d\Delta u$. The first condition (Eq. 5a) states that when the difference with respect to the optimum value is null there is no regret. The second condition (Eq. 5b) states that $g(\cdot)$ ought to be an increasing function, implying that when the difference between the counterfactual option and the chosen option increases, regret also must increase.

Although the first two requirements seem reasonable, we see no compelling arguments for the third condition (Eq. 5c). Furthermore, Laciana et al. (2005) showed that this condition cannot apply if regret theory is to produce the pattern of preferences described by the Allais (1953) paradox. To do so, Laciana et al. (1995) show that function $g(\cdot)$ must instead satisfy the condition

$$g''(\Delta u) < 0 \qquad \forall \Delta u \quad . \tag{5d}$$

Laciana et al. (2005) propose the following explicit form for function $g(\cdot)$ that satisfies the first two conditions posed by Braun and Muermann (2004) and the modified third condition.[1]

$$g(\Delta u) = 1 - \beta^{\Delta u} \quad , \tag{6}$$

where parameter β ($0 \le \beta < 1$) must be fitted from experimental results and describes the decision maker's sensitivity to the magnitude of Δu_i, with a more differentiated response for larger values of β.

2.3 Prospect theory's value maximization

In prospect theory (Kahneman Tversky 1979), the subjective value of a prospect is defined as:

$$V(q) = \sum_i \Omega\,(p_i)\, v\,(\Delta w_i) \quad , \tag{7}$$

where Δw_i represents the difference between outcome w_i and a reference point w_{ref}, a free parameter, that separates perceived gains from perceived losses. The value of this difference is defined by

$$v(\Delta w) = h(\Delta w) \left| \Delta w \right|^{\alpha} \tag{8}$$

Function $h(\Delta w)$ is the step function

$$h(\Delta w) = \begin{cases} 1 & if \quad \Delta w \ge 0 \\ -\lambda & if \quad \Delta w < 0 \end{cases} \tag{9}$$

where λ is a parameter ($\lambda > 1$) that reflects the degree of loss aversion. The exponent α in Eq. 8 ranges between 0 and 1 and describes the nonlinearity of the value function, therefore accounting for the degree of risk aversion (concavity) in the gain region and risk seeking (convexity) in the loss region.

The evaluation of risky prospects is based on subjective probability weights that do not always correspond to the objective probabilities. Tversky and Kahneman (1992) propose the nonlinear function $\Omega\,(p)$

$$\Omega\,(p) = \frac{p^{\gamma}}{\left(p^{\gamma} + (1-p)^{\gamma}\right)^{1/\gamma}} \tag{10}$$

to model the subjective weight of event probabilities, which overweights objective probabilities below 0.3 or so and underweights larger probabilities. The value of $\Omega\,(p)$ depends on positive parameter γ, that must be empirically estimated.

3. CASE STUDY DETAILS

In this paper, we identify agricultural production decisions that are optimal under different objective functions. The set of decisions examined are related to the production of cereals and oilseeds in the Pampas region of central-eastern Argentina, one of the most important agricultural regions

[1] The function proposed by Laciana et al. was intended to reproduce specifically the pattern of preferences presented by Allais (1953).

in the world (Hall et al. 1992). In this section, we first describe the production systems in this region. We then define a set of cropping enterprises that encompasses a realistic range of management options and initial soil conditions for the typical crops in the region, namely maize, soybean, and a wheat-soybean doublecrop. Next we describe how yields and economic returns are simulated for each cropping enterprise using historical climate data, biophysical models, and realistic cost estimates. These results are used as input to different optimization procedures, described in Section 4.

3.1 The area of study

The climate, soils, and cropping systems of the Argentine Pampas have been characterized by Hall et al. (1992). In particular, we focus on the region near Pergamino (33º 56' S, 60º 33' W), the most productive subregion of the Pampas (Paruelo & Sala 1993). Two characteristics of agricultural production in the study region have implications for the optimization described below. First, agriculture in the Pampas is market-oriented and technology-intensive. As a consequence, a broad spectrum of agronomic management options exists and can be explored in the optimization process. Second, a considerable proportion of the area currently farmed is not owned by the farmers exploiting it. Very short land leases (usually one year) provide incentives for tenants to maximize short-term profits via highly-profitable crops. In contrast, land owners tend to rotate crops to steward long-term sustainability of production and soil quality. Given the differences in decision-making goals and constraints between land owners and tenants, we model the two groups separately.

3.2 Crop enterprises

We defined 64 different cropping enterprises that reflect a realistic range of cultivation options for the study area. Each enterprise involves the combination of (a) a given crop (maize, full-cycle soybean and wheat soybean), (b) various agronomic decisions (cultivar/hybrid, planting date, fertilization options), and (c) a set of initial conditions (water and nitrogen in the soil at planting) that result from previous production decisions. That is, several enterprises may be associated with the same crop, although involving different management options. Management variables and their simulated levels for each cropping enterprise defined are listed in Table 1.

3.3 Simulation of yields: agronomic models

Yields for each enterprise were simulated using the crop models in the Decision Support System for Agrotechnology Transfer package (Jones et al. 1998): Generic-CERES (Ritchie et al. 1998) for maize and wheat, and CROPGRO (Boote et al. 1998) for soybean. These models have been calibrated and validated under field conditions in several production environments including the Pampas (Guevara et al. 1999; Meira et al. 1999; Mercau et al. 2001). The information required to run the DSSAT models includes: (i) daily weather data (maximum and minimum temperature, precipitation, solar radiation), (ii) "genetic coefficients" that describe physiological processes and developmental differences among crop hybrids or varieties, (iii) a description of crop management, and (iv) soil parameters, including soil moisture and N content at the beginning of simulations. Historical (1931-2001) daily weather data for Pergamino provided information re category (i). Genetic coefficients, the management options that defined the enterprises, and likely ranges of initial soil conditions were provided by Asociación Argentina de Consorcios Regionales de Experimentación Agrícola (AACREA), a non-profit farmers' group (similar in goals to the US Agricultural

Table 1. Management variables and their simulated levels for each cropping enterprise defined. The 64 different enterprises are the result of combining different levels of each variable considered. For instance, the 24 enterprises involving maize result from combing one genotype, two planting dates, three doses of N fertilizer, one row spacing, two levels of initial soil water, and two levels of initial soil N, and (1 x 2 x 2 x 2 x 3 x 1 = 24).

Management variables	Crop		
	Maize	**Soybean**	**Wheat - Soybean**
Genotype	DK 752	N 3901	Scorpion (wheat)
		DM 4800	DM 4800 (soy)
Planting date	15 Sep	25 Oct	10 Jun[1]
	15 Oct	15 Nov	10 Jul[1]
Fertilizer added ($kg\ N\ ha^{-1}$)	50	0	40 (wheat)
	75		60 (wheat)
	100		80 (wheat)
Row spacing (m)	0.70	0.35	0.19 (wheat)
	0.70	0.52	0.52 (soy)
Available soil water at planting (%)	80	80	70
	100	100	90
Available soil N at planting ($kg\ N\ ha^{-1}$)	50	50	40
	70		60
Number of enterprises	24	16	24

Extension Services) that partnered with us in this study.

Simulations assumed no irrigation, a very infrequent practice in the Pampas. For each enterprise, 70 simulated yields were obtained (one for each cropping cycle in the 1931-2001 historical record used).

3.4 Simulation of economic outcomes

Economic outcomes were simulated for a hypothetical 600-hectare farm, the median size of AACREA farms in the Pergamino region. We computed net economic returns per hectare π_{ij} for year i and enterprise j as the difference between income and costs:

$$\pi_{ij} = Y_{ij}P_j - (F_j + V_{ij} + S_i + T_i) \quad . \qquad (11)$$

Gross income per hectare $(Y_{ij}P_j)$ were the product of simulated yield for a year and enterprise (Y_{ij}) and a constant output price for each crop (P_j). 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). After deducting export taxes charged by the Argentine government, these prices were 78.9, 166.0, and 112.0 US \$ ton^{-1} for maize, soybean and wheat, respectively.

Four different kinds of costs were involved in the computation of net returns per hectare:

(i) *Fixed costs* (F_j) for enterprise j are independent of yield. For land owners, fixed costs included: (a) crop production inputs (e.g., fertilizer, seed, field labors), and (b) farmer's salary, health insurance, and a fixed fiscal contribution. For land tenants, fixed costs also included (c) land rental (assumed to be 232.5 \$ ha^{-1}, equivalent to the price of 1.4 tons of soybean) and (d) management costs (12 \$ ha^{-1}).

(ii) *Variable costs* (V_{ij}) are a function of yield on year i for enterprise j. These costs included: (a) harvesting costs, estimated as 8% of gross income $(Y_{ij}\ P_j)$, (b) transportation costs (about 10 \$ ton^{-1}), (c) sales tax and commissions, estimated as 8% of gross income. Variable costs were the same for land owners and tenants.

(iii) *Structural costs* (S_i) are applicable only to land owners and covered: (a) maintenance of farm infrastructure, (b) real estate taxes, and (c) management and technical advice. Structural costs are independent of farm activities or enterprise yields. For the sake of simplicity, however, they were approximated following a criterion used by AACREA: they were a percentage (23%, 18%, and 20% for maize, soybean and wheat-soybean respectively) of income per ha after subtracting variable costs $(Y_{ij}P_j - V_{ij})$. Because structural costs are incurred even if part of the farm is not cultivated, an implicit but not unreasonable assumption, given the high costs of land around Pergamino, is that the entire 600-ha area of the hypothetical farm is cultivated.

(iv) *Income tax* (T_i) applies equally to land owners and tenants and was computed as follows:

$$T_i = \begin{cases} b(\bar{\pi} - a) + c & if \quad \bar{\pi} \geq a \\ c & if \quad \bar{\pi} < a, \end{cases} \qquad (12)$$

where a is a threshold income above which farmers pay an average tax rate $b = 0.32$. Below a, farmers pay a minimum tax assumed to be 59.33 \$ ha^{-1}. To simplify calculations, an average annual income $\bar{\pi}$ of 177.5 \$ ha^{-1} (57.6 \$ ha^{-1}) was assumed for owners (tenants).

4. OPTIMIZATION PROCEDURE

A whole farm production model was used to identify optimal decisions for the objective functions associated with EU, regret, and prospect theories. The choice variable in the optimization is the vector $\vec{x} = (x_1, ..., x_{64})$ that includes the area in the 600-hectare hypothetical farm allocated to each of the 64 alternative cropping enterprises considered. Different land amounts allocated to the 64 enterprises were considered by the optimization of each objective function. The optimization was performed using algorithm MINO5 in the GAMS software package (Gill et al., 2000).

4.1 Wealth and income

For comparability, all objective functions are expressed in terms of a decision-maker's wealth, either in an absolute sense (for EU and regret-adjusted EU), or as a difference from a specified reference level (in prospect theory). The total wealth of a decision-maker in year i is

$$w_i = w_0 + \pi_i \quad , \tag{13}$$

where w_0 is the decision-maker's initial wealth (i.e., prior to production decisions for year i) and π_i is the farm-wide income during year i, after deducting costs. Farm-wide income π_i is calculated as:

$$\pi_i = \sum_{j=1}^{m} x_j \pi_{ij} \quad , \tag{14}$$

where π_{ij} is the net margin for year i and enterprise j (Eq. 11) and x_j is the amount of land allocated to enterprise j (i.e., a component of the land allocation vector $\vec{x}$).

4.2 Expected Utility Optimization

The expected utility (Eq. 1) of final wealth can be expressed as:

$$EU(\vec{x}) = \sum_{i=1}^{n} p_i \, u\left[w_i\left(\vec{x}\right)\right] \quad , \tag{15}$$

where p_i is the probability of a given climate scenario for year i. A climate scenario is defined as the climate conditions over an entire production cycle. We assume that all climate scenarios in the historical record have the same probability, i.e. $p_i = 1/n$, where n is the number of cropping cycles in the historical climate data (in this case, 70 years). Therefore, we can write

$$EU(\vec{x}) = \frac{1}{n} \sum_{i=1}^{n} u\left[w_i\left(\vec{x}\right)\right] \quad . \tag{16}$$

The next step is the optimization

$$\max_x EU(\vec{x}) = EU(\vec{x}^*) \quad , \tag{17}$$

where $\vec{x}^* = (x_1^*, ..., x_{64}^*)$ indicates the proportion of land allocated to each enterprise that maximizes the value of EU.

4.3 Regret-corrected Utility Optimization

The goal is to obtain the decision vector $\vec{x}^*$ that maximizes the function $RTEU\left(\vec{x}\right)$ given by Eq. 3:

$$\max_x RTEU(\vec{x}) = RTEU(\vec{x}^*) \quad . \tag{18}$$

This maximization is performed in the same way as for expected utility.

4.4 Prospect Theory Value Optimization

In prospect theory, value is defined by changes in wealth rather than reference-independent states of wealth. Outcomes w_i are evaluated as gains or losses with respect to a reference value w_{ref}:

$$\Delta w_i = w_i - w_{ref} \quad . \tag{19}$$

One plausible reference value of wealth that determines whether a farmer thinks of another wealth level as a gain or a loss is the income w_r that a farmer could achieve with minimal effort (e.g., by renting his/her land) added to the decision-maker's initial wealth :

$$w_{ref} = w_0 + w_r \quad . \tag{20}$$

Combining Eqs. 13 and 19 with Eq. 20 we obtain:

$$\Delta w_i = \pi_i - w_r \quad . \tag{21}$$

The total value function for prospect theory (Eq. 7) then can be rewritten as:

$$V\left(\vec{x}\right) = \sum_{i=1}^{n} \Omega\left(p_i\right) v\left[\Delta w_i\left(\vec{x}\right)\right] \quad . \tag{22}$$

As for previous objective functions, all climate scenarios are assumed to have the same probability (i.e., $p_i = 1/n$), therefore $\Omega(p_i)$ is independent of i. Rewriting Eq. 22, we obtain

$$V(\vec{x}) = \Omega\left(\frac{1}{n}\right)\sum_{i=1}^{n} v\left[\Delta w_i(\vec{x})\right] , \qquad (23)$$

which indicates that the constant $\Omega\left(1/n\right)$ is irrelevant for the optimization; thus one needs not worry about the functional form of Ω. The optimization is performed in a way analogous to Eq. 16:

$$\max_x V(\vec{x}) = V(\vec{x}^*) \ . \qquad (24)$$

Optimizing the value function with the GAMS software (Gill et al., 2000) available to us was problematic because of the discontinuity of function $h(\cdot)$ (defined in Eq. 9) at $\Delta w_i = 0$ (where prospect theory's value function has a sharp kink and is not differentiable). To address the problem, we used a continuous function $\tilde{h}(\cdot)$ that is numerically equivalent to $h(\cdot)$:

$$\tilde{h}(x) = 1/2\left[1 - \lambda + (1+\lambda)\tanh(\rho x)\right] \qquad (25)$$

where ρ is an arbitrary parameter such that $\rho > 1$; large values of ρ (we used $\rho = 10$) reproduce function $h(\cdot)$ more closely. Justification for this approximation can be found in Laciana and Weber (2005).

4.5 Optimization constraints

As previously mentioned, allocation of land to cropping enterprises differs for land owners and tenants in the Pergamino region. Land owners tend to adhere to a rotation of crops that offers advantages for soil conservation and control of pests and diseases. In contrast, land tenants seek high profits during short leases (usually one year) and thus usually select enterprises with the greatest economic returns. The clear differences in enterprise allocation between land tenure regimes suggest that we explore optimal decisions separately for land owners and tenants.

With three major cropping systems (maize, soybean, and a wheat-soybean double crop) the rotation advocated by AACREA allocates about 33.3% of the land to each of these cropping systems in a given year. To allow owners some flexibility in land allocation, we introduced two constraints in the optimization procedure: land assigned to a crop could be no less than 25%, or more than 45% of the farm area. These constraints did not apply to land tenants, who could allocate the entire farmed area to a single crop. The lack of allocation constraints is consistent with the observed increase in mono-cropping of soybean that has occurred in the Pampas in the last few years (Satorre 2005).

4.6 Parameter space explored for each objective function

As discussed in Section 2, each objective function has a set of parameters. In some cases, the value of a given parameter characterizes a personality characteristic (e.g., degree of risk aversion or loss aversion) that may vary among decision-makers. In other cases, there are no widely accepted values for a parameter, therefore a broad range of plausible values must be considered. In this section, we describe and justify the central (or nominal) parameter values; the full set of values explored is listed in Table 2

Table 2. Range of parameters considered for each objective function.

Objective Function	Parameter	Land owners		Land tenants	
		Nominal value	**Values explored**	**Nominal value**	**Values explored**
Expected Utility	Initial wealth (w_0)	1400 \$ ha^{-1}	700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400	1000 \$ ha^{-1}	700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600
	Risk aversion coefficient (r)	1	-0.5, 0, 0.5, 1, 2, 3, 4	1	-0.5, 0, 0.5, 1, 2, 3, 4
Regret-corrected Utility	k	-	0.155, 0.3595, 0.564	Same as for land owners	
	β	-	0, 0.0005, 0.005, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9	Same as for land owners	
Prospect Theory Value Function	Reference wealth (w_r)	232.5 \$ ha^{-1}	100, 175, 232.5, 325, 400, 500	20 \$ ha^{-1}	5, 10, 20, 30, 40, 50, 60, 70, 80
	Risk aversion (α)	0.88	0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.88, 0.9, 1	Same as for land owners	
	Loss aversion (λ)	2.25	1, 2.25, 3, 3.5, 4, 4.5, 5, 5.5, 6	Same as for land owners	

4.6.1 Expected Utility.

The expected utility function has two parameters: (i) the decision maker's initial wealth w_0 and (ii) the risk-aversion coefficient r. Initial wealth w_0 is defined as liquid assets. For land owners, this quantity was estimated as 40% of the value of the farm land. The definition is based on the assumption that a farmer will not sacrifice future income potential by selling crop land, but can borrow up to 40% of his/her land value. The 1994-2003 average value of land for Pergamino was 3541 \$ ha^{-1} (http://www.mlb.com.ar/nota_arre3.asp), making w_0 equal to 1400 \$ ha^{-1} (3541 \$ ha^{-1} x 0.4). For land tenants, we assumed a w_0 value of 1000 \$ ha^{-1}, the liquid assets required to finance two complete cropping cycles (i.e., in case of a total loss in one cycle, the farmer still has capital to fund a second cycle). For the risk-aversion coefficient r, we followed Anderson and Dillon's (1992) classification: 0.5 is hardly risk averse; 1.0, somewhat risk averse (normal); 2.0, rather risk averse; 3.0, very risk averse; and 4.0, extremely risk averse. We also included risk-seeking behavior and risk indifference by also considering r values of –0.5 and 0.0. The range of r values was the same for owners and tenants.

4.6.2 Regret-corrected Expected Utility.

The regret-corrected expected utility has the same parameters as the EU model (w_0 and r), and for which we used the same ranges. It also has two other parameters: a factor k that weighs the regret, and parameter β associated with the regret function $g(\cdot)$ (see Eq. 6). Appropriate bounds for k and β were derived by Laciana et al. (2005) to ensure that regret theory reproduce the pattern of preferences described by the Allais paradox. These ranges are $0.155 \le k \le 0.564$ and $0 \le \beta < 0.9$. With the exception of w_0, all parameter values were the same for owners and tenants.

4.6.3 Prospect Theory Value Function.

The value function is defined by (i) a reference wealth w_r that separates outcomes perceived as gains and losses, (ii) a risk aversion parameter α, and (iii) a loss aversion parameter λ that quantifies the relative impact of gains and losses. For land owners, w_r was estimated as the income easily-achieved by renting the land instead of farming it. This value of w_r was estimated to be 232.5 \$ ha^{-1} (a rental fee of 1.4 ton ha^{-1} of soybean times a price of 166 \$ ton^{-1}). For land tenants, w_r was estimated as the income obtained by placing the tenant's initial wealth (w_0 = 1000 \$ ha^{-1}, as described for EU) in a bank for six months (the duration of a cropping season) at an annual interest of 4% (representative of current rates in Argentina). The nominal w_r value, then, was 20 \$ ha^{-1}. For the risk-aversion parameter α and the loss-aversion parameter λ, we used the values of 0.88 and 2.25, respectively, that were estimated by Tversky and Kahneman (1992) for both owners and tenants, but also explored other values (Table 2).

5. RESULTS

This section describes the land allocations (i.e., the proportion of land assigned to different enterprises) identified as optimal for each objective function. The cropping enterprises selected during the optimization procedure (only seven out of 64 possible enterprises) are shown in Table 3. The table also shows the mean economic returns (profit after subtracting all costs) and their standard deviation (S.D.) over the 70 simulated cropping cycles.

Table 3. Cropping enterprises selected during the optimization procedure (only seven out of 64 possible enterprises were selected). The combination of management variables that define each enterprise is shown. The table also shows the mean economic returns (profit after subtracting all costs) and their standard deviation (S.D.) over the 70 simulated cropping cycles. Results are presented both for land owners and tenants. For the wheat-soybean double crop, the superscripts a and b indicate values for wheat and soybean, respectively.

Enterprise ID	Enterprise management						Economic returns for owners ($ ha^{-1})		Economic returns for tenants ($ ha^{-1})	
	Genotype	Planting date	Fertilizer added (kg N ha^{-1})	Row spacing (m)	Available soil water at planting (%)	Available soil N at planting (kg N ha^{-1})	Mean	S.D.	Mean	S.D.
Maize										
Ma21	DK752	Sep 15	100	0.70	100	70	113.2	106.8	6.8	157.7
Ma23	DK752	Oct 15	75	0.70	100	70	116.5	84.1	5.8	128.6
Ma24	DK752	Oct 15	100	0.70	100	70	116.3	90.1	9.8	135.8
Full-cycle soybean										
Soy14	DM4800	Oct 25	0	0.52	100	50	188.1	60.7	69.4	89.0
Wheat-Soybean										
SW19	Scorpion[a] & DM4800[b]	Jun 10	40	0.19[a] 0.52[b]	90	60	162.1	83.4	62.3	121.7
SW20	Scorpion[a] & DM4800[b]	Jun 10	60	0.19[a] 0.52[b]	90	60	167.3	84.7	72.3	122.5
SW21	Scorpion[a] & DM4800[b]	Jun 10	80	0.19[a] 0.52[b]	90	60	168.8	85.0	77.6	122.0

5.1 EU Maximization

5.1.1 Land owners

The enterprise allocation that maximized expected utility for land owners was constant for the full range of initial wealth and risk aversion values explored (Fig. 1). The maximum area allowed for one crop by the optimization constraints defined for owners (45% of total land) was allocated to full-cycle soybean Soy14, the enterprise with the highest average economic returns (188.1 \$ ha^{-1}, Table 3). Conversely, the minimum area required by constraints (25%) was for maize, the crop with lowest average profits. Ma23, the enterprise with the highest average profits for this crop (116.5 \$ ha^{-1}) was selected; another maize enterprise, Ma22, had similar mean profits but a higher dispersion of outcomes (implying higher risk) and thus was not picked. The remainder of the area (30%) was allocated to the wheat-soy enterprise SW21, which had average profits between those of full-cycle soy and maize (168.8 \$ ha^{-1}). The stability of results for all parameter combinations illustrates the importance of constraints associated with maintaining a crop rotation: these constraints clearly override any financial or personality characteristics of a decision-maker.

5.1.2 Land tenants

For land tenants, only two enterprises (full-cycle soybean Soy14 and wheat-soybean SW21) were involved in the maximization of expected utility. Because of the markedly lower economic margins of maize enterprises (due to the combination of rental costs for tenants and low maize prices) and the lack of constraints requiring a minimum area for maize, the optimization did not select any enterprise involving this crop. Relative proportions of the selected enterprises depended on the combination of parameters.

Figure 1. Land allocation (as proportion of the hypothetical 600-ha farm) that maximizes expected utility for land owners. The selected combination of enterprises is constant for all initial wealth w_0 and risk aversion r.

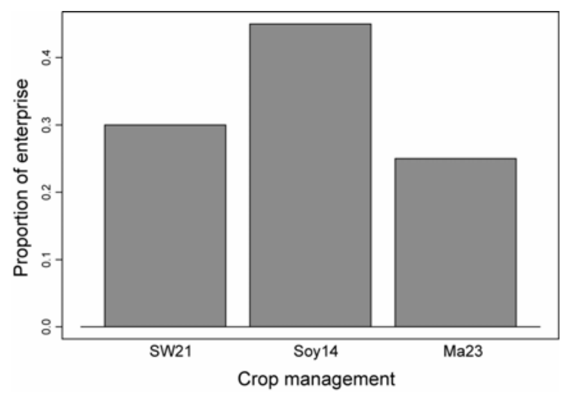
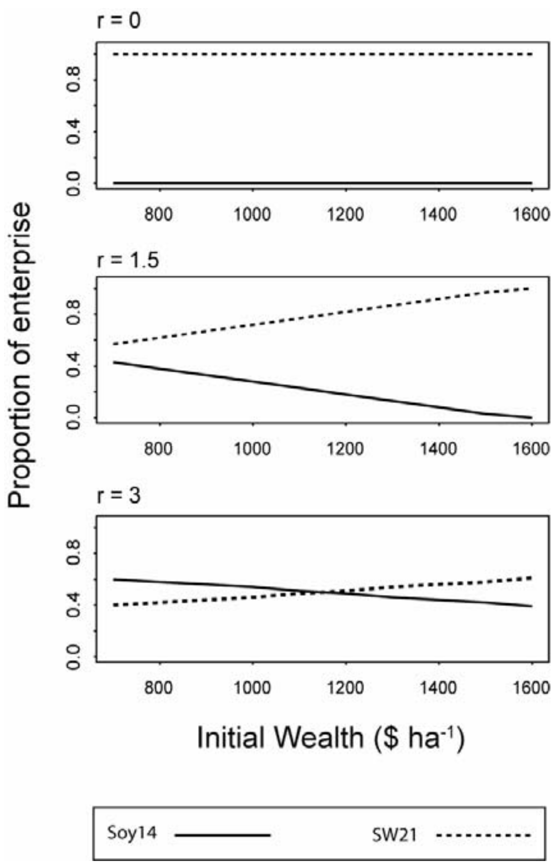


Fig. 2 has three panels with increasingly higher levels of risk aversion r (from top to bottom). In each panel, the optimal allocation of land is shown as a function of initial wealth w_0. For a risk-neutral decision-maker ($r = 0$; Fig. 2, upper panel), the optimal action was to allocate the entire area to the double crop enterprise SW21; this result is constant for the entire range of values considered for w_0. Because the decision-maker is risk-neutral, the selection of SW21 was based only on its higher mean profit relative to Soy14 (77.6 \$ ha^{-1} vs. 69.4 \$ ha^{-1}), and ignored the higher risks associated with the considerably larger dispersion of profits for this enterprise (122.0 \$ ha^{-1} vs. 89.0 \$ ha^{-1} for Soy14). When moderate amounts of risk aversion are considered (r=1.5; Fig. 2, middle panel), the optimal action involved diversification of enterprises for most values of w_0. For low w_0, diversification is highest: 60% of the land was allocated to SW21 and 40% to Soy14. As w_0 increases (and, thus, decision makers can afford higher financial

Figure 2. Land allocation (as proportion of the hypothetical 600-ha farm) that maximizes expected utility for land tenants. The three panels show the results for risk neutrality (r=0, upper panel), moderate risk aversion (r=1.5, middle panel), and pronounced risk aversion (r=3.0, bottom panel), in each case plotted as a function of initial wealth w_0.



risks), the proportion of land assigned to SW21 increased until this enterprise occupied the entire area, resembling results for risk-neutrality. Even with CRRA, absolute risk aversion declines with rising wealth. Finally, for a highly risk-averse decision-maker (r=3.0; Fig. 2, bottom panel), the optimal land allocation was fairly conservative, as crop diversification (comparable proportions of SW21 and Soy14) prevailed throughout the w_0 range. However, there was a minor effect of w_0: for initial wealth below 1100 $ ha^{-1}, Soy14 (less profitable, but also less risky) occupied a slightly higher area than SW21 (more profitable but riskier). This allocation was reversed for higher w_0 values.

5.2 *Regret-Adjusted Expected Utility Maximization*

5.2.1 Land owners

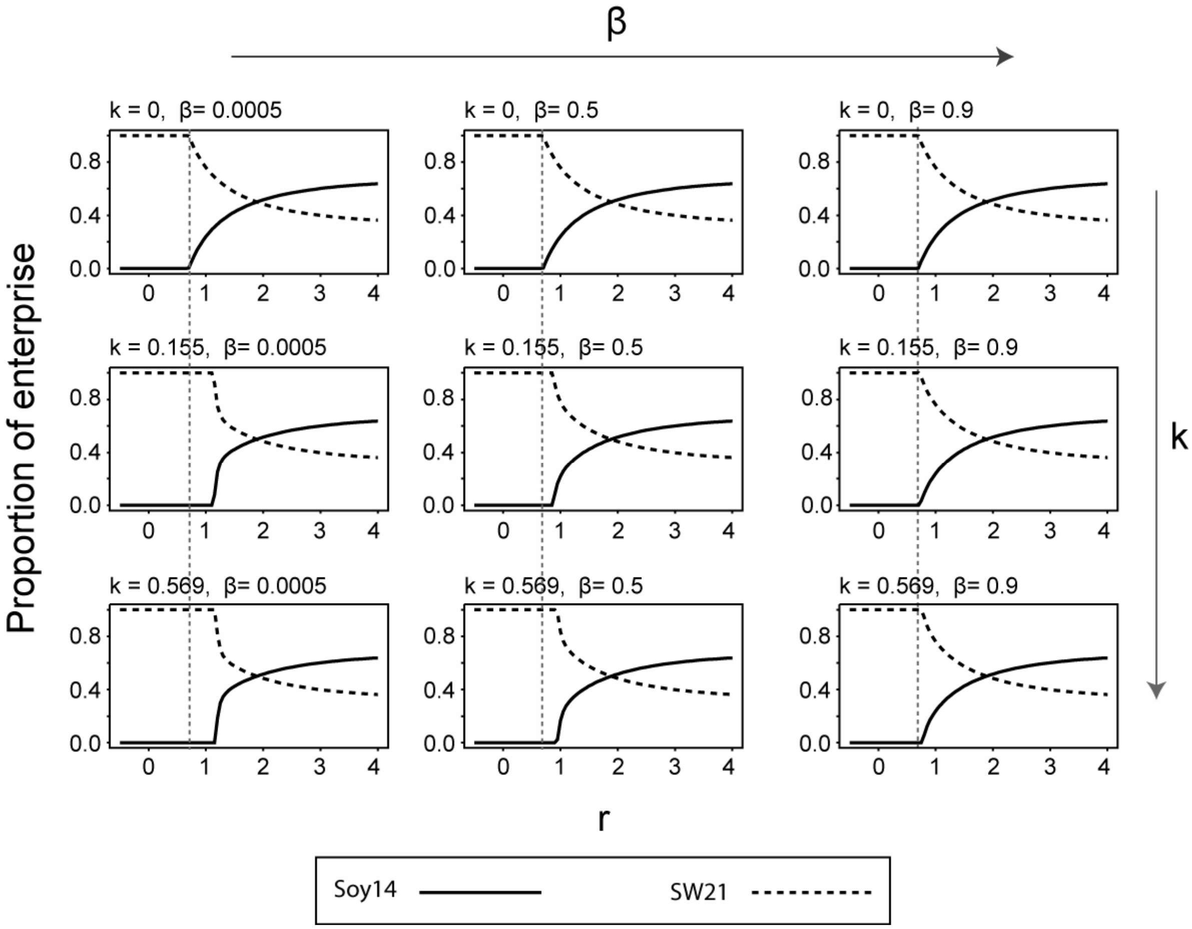
The enterprise allocation that maximized regret-adjusted expected utility was the same as that for EU (Fig. 1). That is, no effects of anticipated regret were noticeable for any combination of parameter values. The lack of discernible regret effects is again due to the strong constraints imposed on optimal solutions by the owners' modeled adherence to crop rotation.

5.2.2 Land tenants

The same two enterprises involved in the maximization of EU for tenants also maximized regret-adjusted expected utility: full-cycle soybean (Soy14) and wheat-soybean (SW21). As for EU, the optimal proportions of these enterprises varied with the combination of parameters. Fig. 3 shows a matrix of panels combining selected values of regret parameters k (increasing from top to bottom) and β (increasing from left to right). In each panel, the optimal allocation of land is shown as a function of risk aversion r.

In the first row of Fig. 3, there was no regret effect (as k = 0), thus results coincided with those for EU. This row can be used as a reference to understand the effects of anticipated regret. A dashed vertical line in each panel indicates the r value at which the optimal action switched from a monoculture of SW21 to an enterprise diversification that also included Soy14 when no regret existed. In the top row of Fig. 3, this switch occurred

Figure 3. Land allocation (as proportion of the hypothetical 600-ha farm) that maximizes regret-corrected expected utility for land tenants. The different panels correspond to combinations of regret parameters k (increasing for top to bottom) and β (increasing from left to right). In each panel, the optimal allocation of land is shown as a function of the risk aversion coefficient r.



for r slightly below 1. As we move down the columns of Fig. 3, parameter k increases indicating progressively higher degrees of anticipated regret. That is, the decision-maker gives increasing importance to the fact that a better option can exist. To avoid anticipated regret, the decision-maker becomes more risk-seeking. This result is illustrated by a displacement in the location of the switch towards enterprise diversification, which occurred at higher r values (above 1.0) than when regret did not exist. This displacement is most noticeable for lower β values, for which any kind of deviation (Δu) from optimal outcomes results in considerable regret (left column of Fig. 3).

As we move along the columns of Fig. 3, increases in β indicate higher sensitivity in the experience of regret to the magnitude of Δu (as implied by the functional form of $g(\cdot)$ in Eq. 6). For instance, if we focus on the center row of Fig. 3, we see that for a constant k value, the switch to enterprise diversification occurred at lower r values as β increased. That is, β has an effect opposite to that of k. For high β values

(Fig. 3, right column), the effects of regret were mostly unnoticeable and results seemed to coincide with those for EU (because regret only becomes noticeable for large values of Δu). A preliminary conclusion is that, at least for the combination of parameters explored, anticipated regret seemed to be a second-order effect and did not change substantially the results based on expected utility theory.

5.3 *Prospect theory*

5.3.1 Land owners

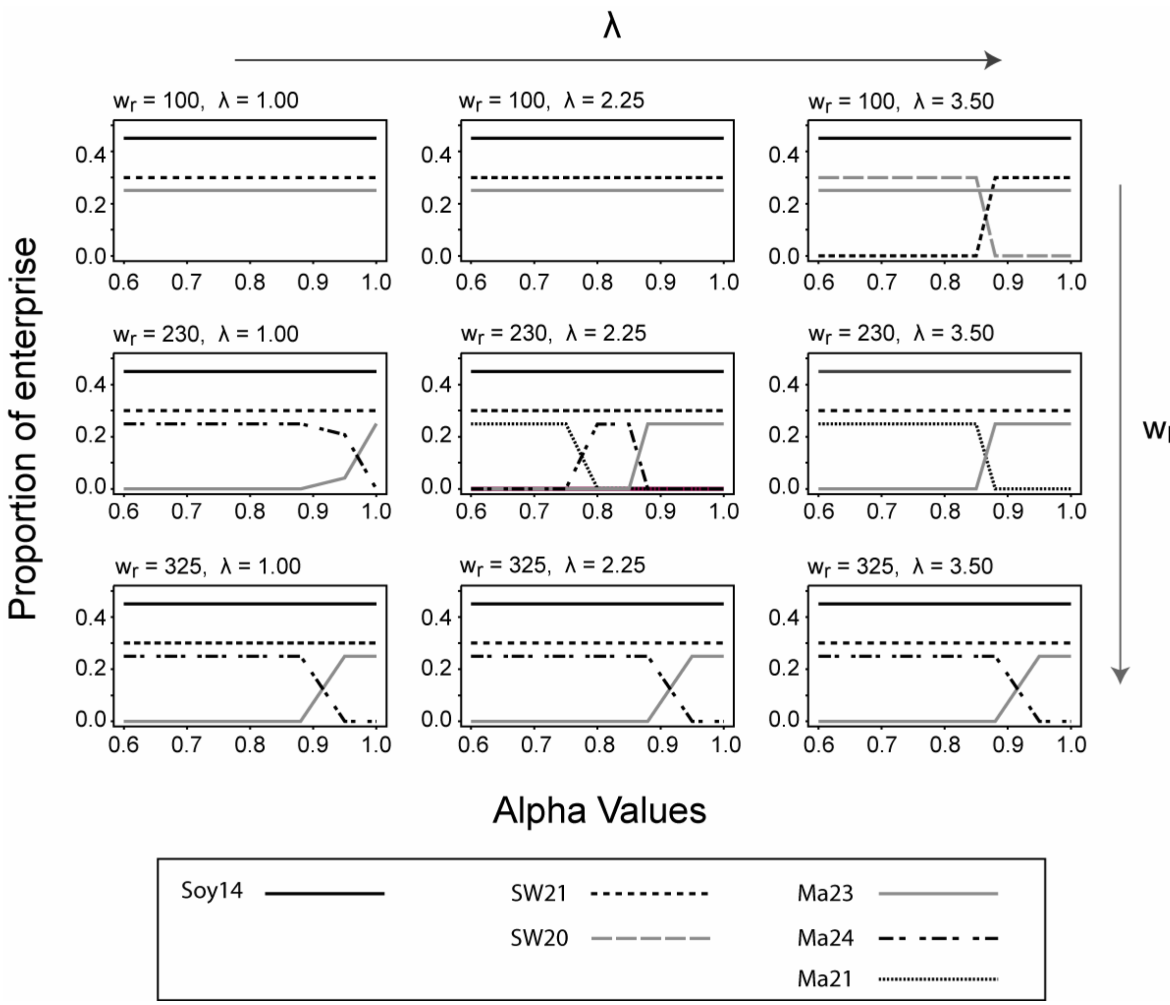
The land allocation that maximized prospect theory's value included, for all parameter combinations, full-cycle soybean Soy14 as the enterprise with the largest area. Conversely, enterprises involving maize (three different ones were selected: Ma21, Ma23, and Ma24) occupied the smallest area. The wheat-soy double crop (in most cases, enterprise SW21, but also SW20) occupied the remaining area. These results are consistent with the relative average profitability of each crop. Fig. 4 shows a matrix of panels combining different values of prospect theory parameters w_r (reference wealth, increasing from top to bottom) and λ (loss aversion parameter, increasing from left to right). In each panel, the optimal allocation of land is shown as a function of risk preference parameter α.

To interpret results in Fig. 4, one must understand interactions among prospect theory's parameters. In particular, we focus on risk preference α and reference wealth w_r, as their interaction may produce apparently counterintuitive results. The effect of risk preference parameter α depends on whether the decision-maker perceives to be operating in the economic gains or losses domains. In the gains domain, the value function is concave (as for expected utility), and higher α values indicate *lower* risk aversion. Conversely, in the domain of losses, the value function is convex thus higher α values indicate *higher* risk aversion. In turn, the likelihood of being in the domain of gains or losses is partly a function of w_r. Fig. 5 displays histograms of the difference $(\pi_{ij} - w_r)$ between economic profits and w_r for three maize enterprises (Ma21, Ma23, and Ma24) and three w_r values (100, 230, and 325 \$ ha^{-1}). As w_r increases, the proportion of negative differences (i.e., economic outcomes perceived as losses) for an enterprise is higher. Indeed, when w_r=325 \$ ha^{-1} (bottom row of histograms), outcomes for all three maize enterprises are negative.

The top left panel of Fig. 4 (w_r=100 \$ ha^{-1} and λ=1.00) serves as a reference to discuss the consequences of varying prospect theory's parameters. In this panel, the optimal enterprise allocation was the same as that for EU maximization for land owners: 45% of Soy14, 30% of SW21, and 25% of Ma23 (see Fig. 1). The similarity with EU results is due to two facts. First, because λ=1.00, there is no loss aversion (i.e., gains and losses are valued equally by the decision-maker). Second, because w_r is low, most of the outcomes are positive (gains).

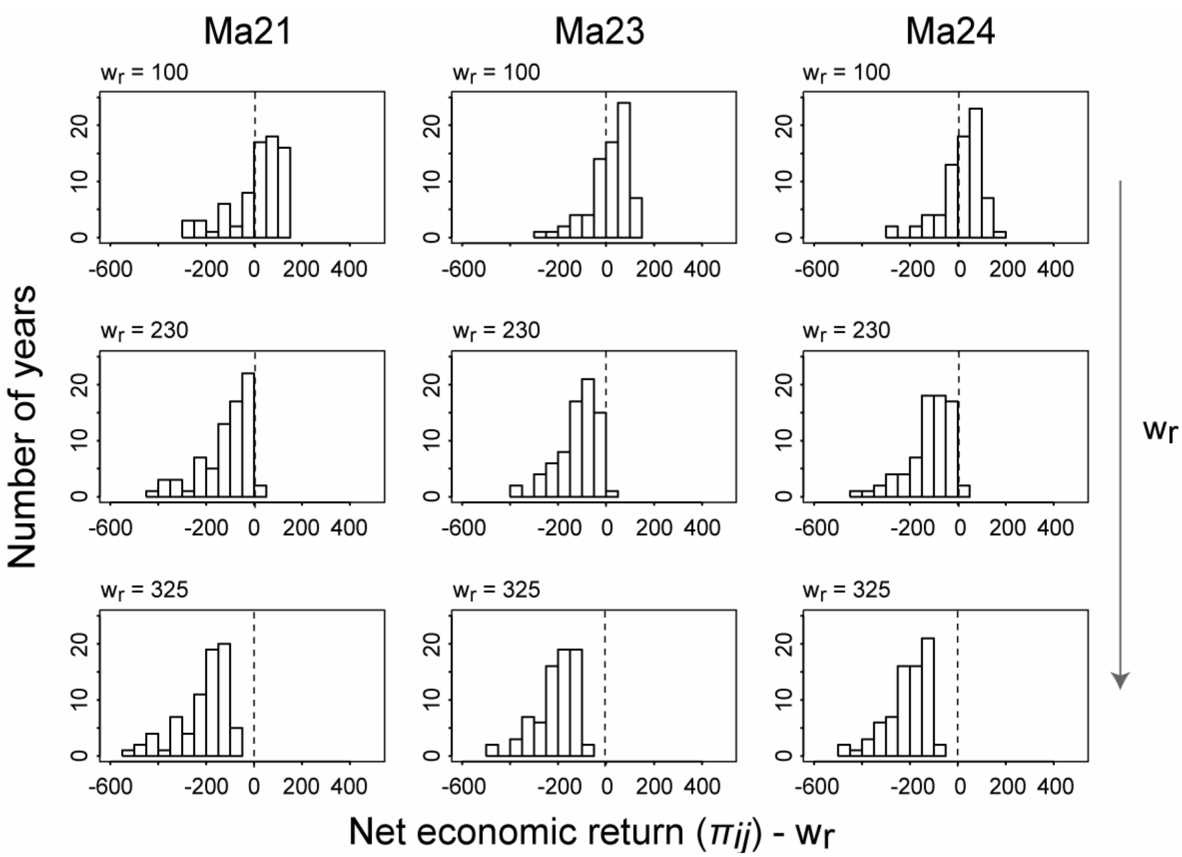
In the top middle panel of Fig. 4, λ has increased to its nominal value of 2.25, indicating that losses of a given magnitude have more than twice as much impact as gains of the same magnitude. The reason that this increase in loss aversion has no impact on the optimal land allocation is that reference wealth is low (w_r=100 \$ ha^{-1}), which means that the economic profits for the various enterprises are mostly higher than w_r and are thus perceived as gains. With few losses, degree of loss aversion cannot be expected to have much impact on land allocation.

Figure 4. Land allocation (as proportion of the hypothetical 600-ha farm) that maximizes prospect theory's value function for land owners. The different panels correspond to combinations of w_r (reference wealth, increasing from top to bottom) and λ (loss aversion parameter, increasing from left to right). In each panel, the optimal allocation of land is shown as a function of the risk preference coefficient α .



Moving now to the top right panel of Fig. 4, loss aversion increases to λ=3.50. In this panel, there is a switch between two of the wheat-soybean enterprises (SW21 and SW20) as a function of α values. Below the nominal α value of 0.88, SW20 is chosen whereas, above 0.88, SW21 is the selected enterprise. Again, because w_r is low (100 \$ ha^{-1}), most outcomes will be perceived as gains, thus lower α values imply higher risk aversion and a choice of SW20 over SW21 is a more conservative strategy. Although the statistics of outcomes are fairly similar for both enterprises (Table 3), the proportion of negative outcomes (data not shown) is lower for SW20 than for SW21, making it a more attractive choice when losses are valued more than three times higher than gains. In contrast, for higher α values risk aversion decreases, and the decision-maker selects the

Figure 5. Histograms of the difference between net economic returns and prospect theory's reference wealth $(\pi_{ij} - w_r)$ for land owners. Results are shown for three maize-related enterprises (Ma21, Ma23, and Ma24), and different reference wealth values (in \$ ha^{-1}). The histograms display the simulated outcomes for 70 cropping cycles.



enterprise with higher economic returns (SW21) even though it is riskier.

As we move down the rows of Fig. 4 to higher reference levels w_r, the main effect is a switch between maize enterprises (mostly Ma23 and Ma24, but Ma21 also appears). For $\alpha < 0.88$, Ma24 tends to prevail; for $\alpha > 0.88$, Ma23 is selected. The gross margin of both maize enterprises is similar but the variability of Ma24 (90.1 \$ ha^{-1}) is higher than the corresponding value for Ma23 (84.1 \$ ha^{-1}). As w_r values increase, maize outcomes come to be encoded mostly as losses and low values of α are associated with risk-seeking behavior. In contrast, as α increases, the decision-maker becomes more risk-averse and the less risky Ma23 option is selected.

5.3.2 Land tenants

The land allocation that maximized prospect theory's value function for tenants involved two enterprises: full-cycle soybean (Soy14) and wheat-soybean (SW21). As in previous cases, the specific proportions of these enterprises depended on the combination of parameters.

The top left panel of Fig. 6 (w_r =10 \$ ha^{-1} and λ =1.00) can be used as a reference to discuss the consequences of varying prospect theory's parameters. In this panel, there is no loss aversion. Also, a low level of reference wealth puts more outcomes into the domain of gains, where low α values make a decision-maker more risk-averse. As a result, a diversified land allocation including two enterprises (Soy14 and SW21) is selected. As α increases and the decision-maker becomes less risk-averse, the allocation switches towards an increasingly higher proportion of SW21 (until mono-culture is reached), where SW21 has a higher margin but also is riskier.

As we move along the top row of Fig. 6, loss aversion increases and we see a mixture of the two dominating enterprises in the central and right top panels. Nevertheless, there is a higher proportion of Soy14 which, despite having lower average profit than SW21, shows lower variability of outcomes.

If we move down the left column of Fig. 6, the switch from diversification to a monoculture of SW21 begins at progressively lower values of α. This is due to the fact that as w_r increases, an increasing proportion of outcomes are perceived as a loss where α denotes risk-seeking. Risk-seeking to neutral decision-makers choose the riskier option (SW21) in search of higher profitability, and thus enterprise selection in the bottom-left panel is identical to that of risk-neutral EU maximizers (top panel in Fig. 2).

This pattern is also apparent in the middle bottom panel of Fig. 6, where we now also have loss-aversion (λ = 2.25). Its high reference wealth (w_r = 80 \$ ha^{-1}) implies that a high proportion of outcomes are perceived as losses. For low α values, the decision-maker is more risk-seeking and thus selects riskier enterprises in search of higher profits to get out of the domain of losses. As α increases, risk seeking decreases and the selected allocation becomes diversified as loss aversion now takes effect, with a higher proportion of the less variable enterprise Soy14.

When loss aversion is even stronger, as in the right panels of Fig. 6 (λ = 3.50), it starts to take over and dictates diversification across the whole range of α, and even more so for higher levels of reference wealth, as more outcomes are in the domain of losses and hence subject to loss aversion.

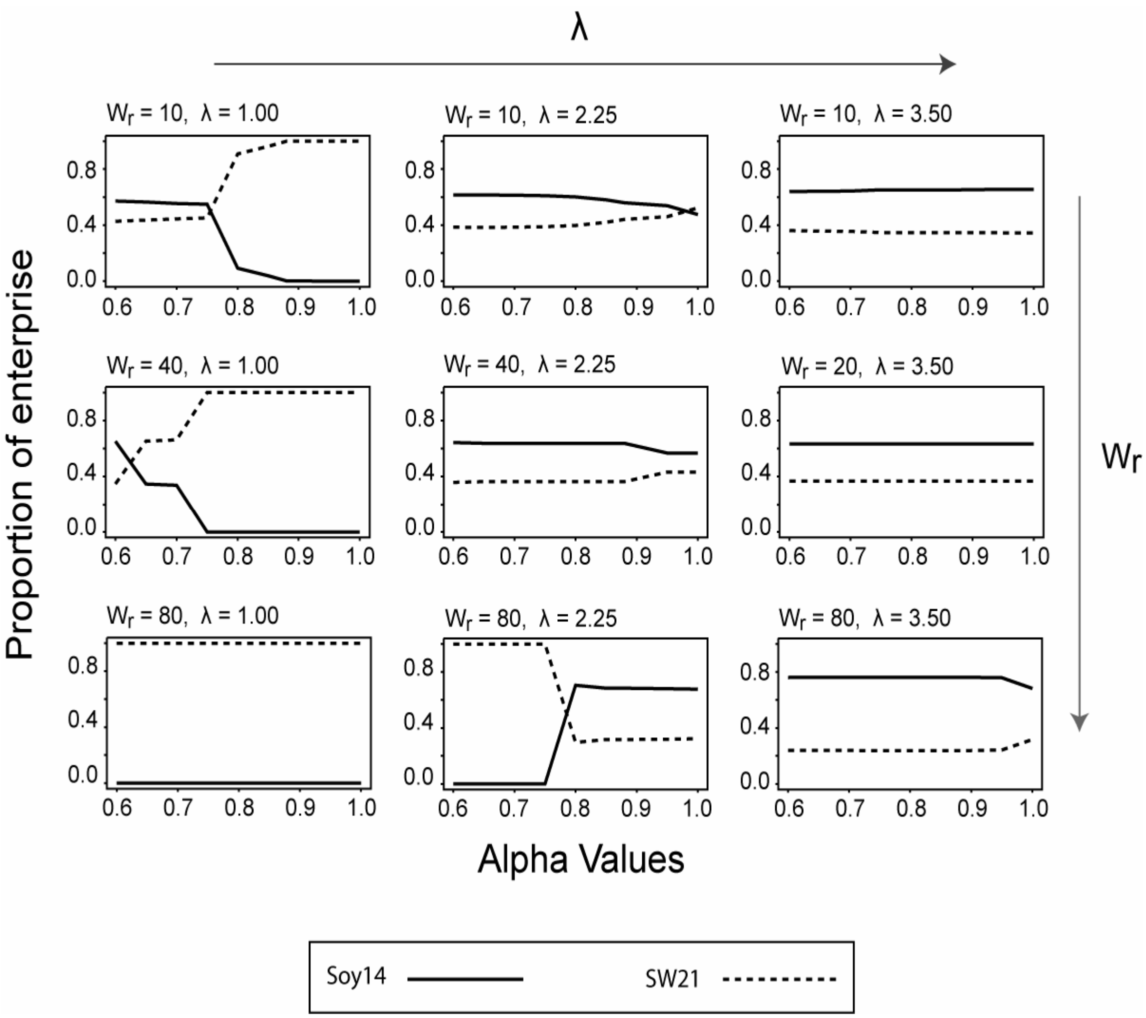
6. DISCUSSION

Our results demonstrate in a non-laboratory decision context that psychologically plausible deviations from EU maximization matter. The optimal allocations for land owners dictated by some parameter combinations of prospect theory (namely the allocation of some land to SW20, Ma24 or Ma 21; see Fig. 4) for example, are not predicted by any parameter combination in either EU or regret-adjusted EU maximization. As another example, prospect-theory value maximization allows tenants to allocate a much greater proportion of land to Soy14 than EU maximization (compare Figs. 6 and 2). Given that an increasing trend towards a monoculture of soybean has been observed on the part of tenants in the Argentina Pampas (Satorre 2005), prospect-theory value maximization seems to be a plausible explanation.

Another general observation about our results is that deviations from behavior predicted by EU maximization as the result of anticipated regret minimization are far less pronounced than deviations as the result of loss aversion and of different risk attitudes in the domain of gains and losses, embodied in prospect theory. For land owners, whose choices are constrained by the crop rotation regimen that is in their long-range interest, EU and RTEU optimization predict the same land allocation. For tenants, the main effect of minimizing anticipated regret is to delay diversification at lower levels of risk aversion.

Optimization of any utility or value function reflects a tradeoff between the expected profits of an enterprise and its risk or dispersion of outcomes. It is interesting to see that different objective functions shape the nature of this tradeoff in different ways. In particular, more risk-averse land allocation is encouraged by the individual difference parameter r, reflecting degree of risk-aversion, and by lower initial wealth w_0 in both EU and RTEU optimization. In contrast, in prospect-theory value optimization, such behavior is encouraged by a lower reference wealth (that divides the perception of returns

Figure 6. Land allocation (as proportion of the hypothetical 600-ha farm) that maximizes prospect theory's value function for land tenants. The different panels correspond to combinations of w_r (reference wealth in \$ ha^{-1}, increasing from top to bottom) and λ (loss aversion parameter, increasing from left to right). In each panel, the optimal allocation of land is shown as a function of the risk preference coefficient α .



into gains vs. losses) and much more by the individual difference parameter λ, reflecting degree of loss aversion, than by individual difference parameter α, reflecting risk preference, and equivalent to EU's r. Similarly, less risk-averse land allocation is encouraged by different processes and parameters under the three objective functions. For EU maximization, both parameters r (less risk aversion) and w_0 (greater initial wealth) are deciding factors (top panel and right end of middle panel of Fig. 2). In RTEU optimization, greater weight placed on anticipated regret (parameter k) also encourages greater risk taking at lower levels of risk-aversion (left side of bottom left panel in Fig. 3). In prospect-theory value optimization, on the other hand, less risk-averse land allocations come about when the decision-maker has no loss aversion but a low reference value, resulting in most outcomes being perceived as losses for which choices are either risk-seeking or at best risk-neutral (bottom left panel of Fig. 6).

6.1 Relevance of results

We envision three main applications of the work presented here. First, an improved understanding of individual differences in preferences and objective functions allows for the development of agronomic advice tailored to the personality characteristics of different types of farmers. Such advice will be more effective than the common "one size fits all" technical recommendations. Second, knowledge of individual preferences may be helpful to guide the framing and to assess the acceptability of regional or national policies of agricultural sustainability (for example, policies that encourage crop diversification). Finally, an understanding of production decisions in agriculture may contribute to comprehension of a range of related issues, such as adoption of technological innovations and adaptation to climate change.

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REFERENCES

Allais, P.M. 1953. Le comportement de l'homme rationnel devant le risque: Critique des postulats et axiomes de l'école americaine. Econometrica **21** 503-546.

Anderson, J.R., J.L. Dillon. 1992. Risk analysis in dryland farming systems. Farm Systems Management Series, No. 2. Rome, FAO.

Bell, D.E. 1982. Regret in decision making under uncertainty. Operations Research **30** 961–981.

Benartzi, S., R.H. Thaler. 1995. Myopic loss aversion and the equity premium puzzle. Quarterly Journal of Economics **110** 73-92.

Bernoulli, D. 1954/1738. Exposition of a new theory on the measurement of risk. Econometrica **22(1)** 23-36 (Translation of D. Bernoulli, 1738, *Specimen theoriae novae de mensura sortis,* Papers of the Imperial Academy of Science of Saint Petersburg **5** 175-192).

Boote, K.J., J.W. Jones. 1998. Simulation of crop growth: CROPGRO model. R. M. Peart, R. B. Curry, eds. *Agricultural*

Systems Modeling and Simulation, Marcel Dekker, pp. 651 – 692.

Braun M., A. Muermann. 2004. The impact of regret on the demand for insurance, Journal of Risk and Insurance, **71** 737-767.

Camerer, C. 2000. Prospect Theory in the wild. D. Kahneman, A. Tversky , eds. *Choice, Values, and Frames,* Cambridge University Press, New York, pp. 288-300.

Camerer, C. 2005. Three cheers—psychological, theoretical, empirical—for loss aversion. Journal of Marketing Research **42** 129-133.

Collins, A., W.N. Musser, R. Mason. 2001. Prospect theory and risk preferences of Oregon seed producers. American Journal of Agricultural Economics **73(2)** 429-435.

Damasio, A. 1995. Descartes' error: Emotion, Reason, and the Human Brain. Avon Books, New York.

Eggert, H., P. Martinsson. 2004. Are Commercial Fishers Risk Lovers? *Land Economics* 80(4): 550-560.

Ellsberg, D. 1961. Risk, ambiguity and Savage axioms. Quarterly Journal of Economics **75(4)** 643-79.

Fennema, H.P., P.P. Wakker. 1997. Original and cumulative prospect theory: A discussion of empirical differences. Journal of Behavioral Decision Making **10 (1)** 53-64.

Gill, P.E., W. Murray, B.A. Murtagh, M.A. Saunders, M. Wright. 2000. GAMS/MINOS, In: GAMS-The Solver Manuals. GAMS Development Corporation.

Hall, A.J., C.M. Rebella, C.M. Ghersa, J.P.H. Culot. 1992. Field crops systems of the Pampas. Pearson, C.J. (ed.). *Field Crops Systems: Ecosystems of the World,* vol. 18. Elsevier, Amsterdam, pp. 413–449.

Hardaker, J.B., R.B. M. Huirne, J.R. Anderson, G. Lien. 2004. *Coping with risk in agriculture.* CABI Publishing, Cambridge, Massachussets. 332 p.

Johnson, E.J., D. Goldstein. 2003. Do defaults save lives? Science **302** 1338-1339.

Jones, J., G. Tsuji, G. Hoogenboom, L. Hunt, P. Thornton, P. Wilkens, D. Imamura, W. Bowen, U. Singh. 1998. Decision support system for agrotechnology transfer. Tsuji, G., Hoogenboom, G., Thornton, P. (eds.). *Understanding Options for Agricultural Production*, Kluwer, Dordrecht, pp. 157–177.

Kahneman, D., A. Tversky. 1979. Prospect Theory: an analysis of decision under risk. Econometrica **47** 263-292.

Kahneman, D.A. 2003. Perspective on judgment and choice: mapping bounded rationality. American Psychologist **58** 697-720.

Laciana, C.E., E.U. Weber. 2005. A reformalization of the Prospect Theory value function with a well-defined first derivative. Under review, Operations Research.

Laciana, C.E., E.U. Weber, X.I. González. 2005. A parameterization of Regret Theory based on the Allais paradox. Under review, Journal of Risk and Uncertainty.

Loewenstein, G.F., E.U. Weber, C.K. Hsee, E. Welch. 2001. Risk as feelings. Psychological Bulletin **127** 267-286.

Loomes, G., R. Sugden. 1982. Regret theory: an alternative theory of rational choice under uncertainty. The Economic Journal **92** 805-824.

Machina, M.J. 1994. Review of: Generalized Expected Utility Theory: The Rank Dependent Model (Norwell, Mass., Kluwer Academic). Journal of Economic Literature **32** 1237-1238.

Markman, K.D., I. Gavanski, S.J. Sherman, M.N. McMullen. 1993. The mental simulation of better and worse possible worlds. Journal of Experimental Social Psychology **29** 87-109.

McFadden, D. 1999. Rationality for economists? Journal of Risk and Uncertainty **19** 73-105.

Paruelo, J., O. Sala. 1993. Effect of global change on Argentine maize. Climate Research **3** 161–167.

Pratt, J.W. 1964. Risk aversion in the small and in the large. Econometrica **32** 122-136.

Rabin, M. 1998. Psychology and economics. Journal of Economic Literature **36** 11-46.

Reusser, D.E., M. Hare, C. Pahl-Wostl. 2004. Relating Choice of Agent Rationality to Agent Model Uncertainty - an experimental study. Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds.). *Complexity and Integrated Resources Management.* Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, iEMSs: Manno, 2004.

Ritchie, J., V. Singh, D. Godwin, W. Bowen. 1998. Cereal growth, development and yield. In: Tsuji, G., G. Hoogenboom, P. Thornton (eds.). *Understanding Options for Agricultural Production,* Kluwer Academic Publishers, Dordrecht, pp. 79–98.

Satorre, E.H., 2005. Cambios tecnológicos en la agricultura actual. Ciencia Hoy **15** 24 - 31.

Samuelson, W.F., R.J. Zeckhauser. 1988. Status Quo Bias in Decision Making. Journal of Risk and Uncertainty **1** 7-59.

Schmidt, U., H. Zank. 2005. What is loss aversion? Journal of Risk and Uncertainty **30** 157-167.

Schoemaker, P.J.H. 1982. The expected utility model: its variants, purposes, evidence and limitations. Journal of Economic Literature **20** 529-563.

Starmer, C. 2000. Developments in non-expected utility theory: the hunt for a descriptive theory of choice under risk. Journal of Economic Literature **18** 332-382.

Thaler, R.H. 1980. Toward a Positive Theory of Consumer Choice. Journal of Economic Behavior and Organization **1** 39-60.

Tversky, A., D. Kahneman. 1992 Advances in prospect theory, cumulative representation of uncertainty. Journal of Risk and Uncertainty **5** 297-323.

von Neumann, J., O. Morgenstern. 1944. *Theory of Games and Economic Behavior*. Princeton University Press, Princeton.

Weber, E.U. 1994. From subjective probabilities to decision weights: The effect of asymmetric loss functions on the evaluation of uncertain outcomes and events. Psychological Bulletin **115** 228-242.

Woodward, R.T. 1998. Should agricultural and resource economists care that the subjective expected utility hypothesis is false? Meeting of the American Agricultural Economics Association, August 2-5, 1998, Salt Lake City, Utah. http://agecon2.tamu.edu/people/faculty/woodward-richard/paps/AAEA98-Uncertainty.pdf. (23 January 2006).