Quantifying the Benefits of Supplemented Irrigation due to Less Volatile Yields: A Prospect Theory Approach Applied to Summer Crops in Uruguay.

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Abstract

The introduction of irrigation produces a significant increase in crop yields and a noticeable reduction in their annual variability. These two factors turn the implementation of irrigation into an attractive practice, with a direct impact on the economic profitability of crops (positive in levels and negative in dispersion). When irrigation is implemented on rain-fed summer crops to supplement natural precipitation, this effect is even more evident. The typical analysis involving the economic feasibility of supplemented irrigation is from the financial point of view. However, these methodologies fail to consider the benefits arising from income stability. Our study focuses on monetarily quantifying these benefits using Prospect Theory. We compare the certainty equivalent of the stochastic profit flows of a farmer applying supplemented irrigation to a crop rotation and using a cumulative Prospect Theory utility function, with that of a farmer who does not use irrigation and crops in a rain-fed system. We show an application to summer crops in Uruguay, and find that there is a relatively high value that the producer assigns to the lower volatility, which ranges between 20 to 32% of the total benefit he or she assigns to the use of irrigation. The scenarios where we change the productive orientation of the operation, the soil aptitude, the distance to the port, and the attitudes towards risk, in all cases, show a considerably high value attributed to the lower volatility. These results are useful for efforts and policies seeking to promote the adoption of this technology.

1. Introduction

The irrigated area in Uruguay has been steadily increasing in recent decades, from 52 thousand hectares in 1970 to more than 240 thousand in 2011 (MGAP-DIEA 2011), where rice has been traditionally the main crop. Furthermore, irrigated agriculture is observing a more dynamic behaviour in the recent years, mainly driven by other summer crops such as soybean, corn, sorghum and artificial pastures, whose area augmented 34% in the inter-census period between 2000 and 2011. It has to be noted that these summer crops, with Uruguayan climatologic conditions, are such that they can be commercially produced in rain-fed systems (i.e., no irrigation) in acceptable conditions. In fact, this is how they have been traditionally produced.

Nevertheless, when irrigation is introduced in these crops, a significant increase in the yields and an important reduction in their annual variability, are obtained. The combination of these factors makes the introduction of supplemented irrigation an attractive practice, with a direct impact on the economic profitability of the crops (positive in levels and negative in dispersion). Moreover, this practise is conceived as a measure to increase the resilience of the productive systems against weather changes, and thus, it is considered as a measure of adaptation to variability and climate change.

Besides the advantages as a strategy of intensification and stability, there are other advantages in terms of environmental sustainability. Irrigation allows for a more adjusted use of inputs relative to the actual crop requirements and a better exploiting of the crop productive potential, making a more efficient use of the inputs and therefore diminishing the losses of the system to the environment.

Despite that, irrigation can also produce negative environmental impacts, generally associated to the higher use (in absolute terms) of chemical inputs. For this reason, it is key that the use of irrigation technology be accompanied by best management practices. However, given the mentioned reduction of the yields variability, it is expected that in all cases the losses to the environment (higher or lower) will have a lower dispersion, which constitutes an important factor for environmental management.

The income variability generated by the exposition of productive systems to climate events, creates uncertainty that negatively affects farmers´ investment and production decisions. Thus, production practices that make farmers more resilient to variability and climate change have the double effect of being an adaptation tool, and at the same time, fostering a good business environment. The lower dispersion in the annual economic profitability induced by irrigation, implies a positive impact on the agent´s expectations. This promotes an economic environment that encourages investment, the adoption of technology and innovation, and the generation of an overall increase in production.

The use of supplemented irrigation in summer crops has been evaluated from several points of view, in particular, the economic and financial convenience of its adoption. In other words, to what extent does the net income increase after its adoption, using the typical methodologies of net present value and internal rate of return (Rosas et al. 2014; Tavakoli et al. 2010; Yuan, Fengmin and Puhai 2003; Marra and Woods 1990).

We argue that, at most, these evaluations consider partially the benefits of supplemented irrigation, because the reduction in variability of the expected income is not taken into account in these methodologies. They only consider the higher income on average that the practice generates. However, the stability of profits is valued by or provide utility to the producer, and thus if it is not considered, it implies that the benefits of its adoption are underestimated. In this document, we propose an approach in which the producer's decision process regarding the adoption of the irrigating practice, considers both the higher income flow on average and also its lower volatility. In particular, a production system that generates less volatile yields would be preferred. The method is based on cumulative Prospect Theory (PT) which is a model of decision-making under risk that incorporates features of the decision process such as risk aversion, loss aversion, a reference point for gains and losses, and a system for weighing the probabilities according to the individual´s perception of gains and losses (Kahneman and Tsversky, 1992).

The agricultural economics literature has paid scant attention to the evaluation of supplemented irrigation which consider both the higher mean and lower volatility of the income flow. The few studies that do so are Apland et al. (1980) and Pandey (1990). Apland et al. (1980) evaluate the economic feasibility of supplemented irrigation in the Corn Belt, with data from 1968 to 1975. They use a case study approach where they analyse the impact of risk aversion on the demand for supplemented irrigation by firms. Pandey (1990) uses stochastic dominance to identify risk-efficient irrigation schedules for winter wheat in central India, using the output of a crop simulation model. He also estimates quantitatively the benefits of the farmers due to risk reduction.

There is one recent study of supplemented irrigation for Uruguay by Gelós (2016), who focusing only in corn, evaluates the decision of implementing this technology considering the differential in both returns and risk. He employs an expected utility approach and uses the certainty equivalent to conclude about the most convenient technology in different scenarios.

Besides the use of cumulative Prospect Theory, our study also differentiates from other evaluations of supplemented irrigation, because we evaluate the adoption of the technology in the context of a rotation of crops and not for crops individually considered. Crop rotations are planned for at least two years, may include double-cropping within the same year, and are designed so that they result in better agronomic and environmental results than deciding the crops every year. In this way, we incorporate in our analysis the standard decision process carried out by the farmers. We highlight the importance of proposing analytical methodologies that not only evaluate the adoption of a given technology but also, that broadly consider all the benefits associated to it. That is, not just limiting to consider the higher income obtained on average, but also to consider the aspects associated to the embedded risk reduction.

This paper contributes to support private and public initiatives that promote the implementation of supplemented irrigation in summer crops, by providing empirical evidence of the economic convenience of its adoption.

The next section presents the methodology employed in the analysis, and it is followed by the data section. Then, results are shown and discussed, and the paper finishes with some concluding remarks.

2. Methodology

The objective of this study is to compare the value of the utility derived from the profits of an irrigated crop production versus the profits of a rain-fed crop production.

This paper is different to previous evaluations regarding the convenience to adopt supplemented irrigation, because it applies the concept of cumulative Prospect Theory. Although this theory was developed more than 30 years ago, there are still relatively few accepted applications in economics (Barberis 2013). Moreover and up to our knowledge, there is no previous application of Prospect Theory to the evaluation of the adoption of irrigation practices, and also, there are no precedent uses of this approach in Uruguay for the evaluation of decisions under uncertainty.

Prospect Theory is a model of decision-making under risk which arises partly from the critics of the Expected Utility Theory, as several experimental studies have demonstrated that the latter is systematically violated when people choose among risky gambles. Prospect Theory presents several characteristics that are interesting to us and are explained below.

Following Kahneman and Tsversky (1992), the pioneers of this theory, given a gamble that promises outcome x_i with probability p_i, people assign it a value of

$\sum_i \pi_i\,[w(p)]v(x_i)$. In this expression, π is a probability weighting function, p is the cumulative probability, $w(p)$ is the decision weight function which takes the form w^+ for the gains and w^- for the losses, and v is the value function.

This formulation reveals a fourfold pattern of risk attitudes that are modelled under Prospect Theory, say 1) reference dependence, 2) loss aversion, 3) diminishing sensitivity, and 4) probability weighting.

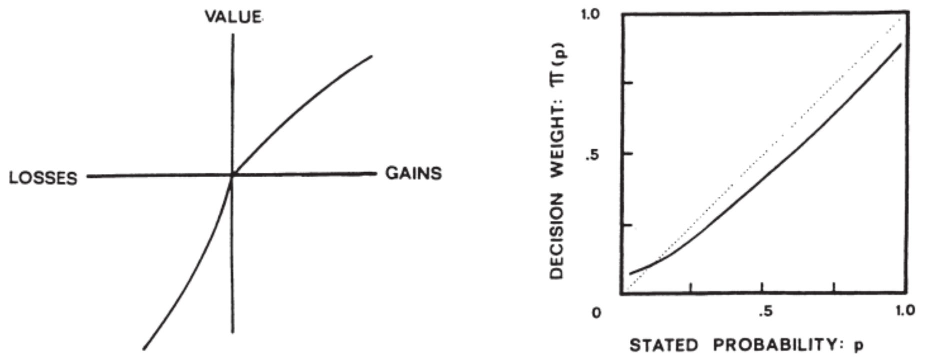
Firstly, utility is defined over gains and losses (instead of over final profits) with respect to a reference point. This is to say, subjects care about variations in wealth that are measured as deviations from the reference point, rather than changes in the absolute final or initial wealth, as Expected Utility does. It is sometimes unclear how to precisely define the reference point, and Kahneman and Tsversky offer little guidance about it, as Barberis (2013) states. In their 1979 publication, the authors emphasize the subjectivity and contextual nature of the reference point. Koszegui and Rabin (2006) propose using recent expectations about outcomes, but their proposal is still in need of more testing. Furthermore, their proposal contradicts the widely assumed reference points in Prospect Theory's such as the status quo or the individual's current assets (Bocquého, Jacquet and Reynaud 2014) which were stated in Kahneman and Tsversky (1979).

Secondly, the value function v has a kink at the origin, indicating a greater sensibility to losses than to gains, which is typically known as loss aversion. The origin is not necessarily zero, it is what divides gains from losses relative to the reference point. This implies that the value function decreases more rapidly as losses increase, than it does the increase of value when gains are higher.

Thirdly, the value function v is concave in the domain of gains and convex in the domain of losses. This is known as diminishing sensitivity. This determines an S-shaped utility function, as it is observed in figure 1 in the left panel. The concavity over gains captures the experimental findings that people tend to be risk averse over moderate probability gains. The convexity over losses is motivated by the fact that people tend to be risk-seeking over losses.

Finally, people weight outcomes by decision weights π_i or probability transformations, which are computed with the help of a weighting function $w(p)$. It is a non-linear probability transformation where small probabilities are given a bigger weight, i.e., $\pi(p) > p$ and almost all other events are underweighted, so that $\pi(p) < p$. This is also based on experiments and it is depicted in the right panel of figure 1.

Figure 1. Value function proposed by Kahneman and Tsversky (1979) and the probability weighting function.



Source: Handbook of the Economics of Finance, chapter 18, Barberis, N & Thaler, R. (2003)

The functional forms and the value of the parameters used in this paper, were taken from Kahneman & Tsversky (1992).

In particular, the value function takes the form:

$$v(x) = \begin{cases} x^a & x \geq 0 \\ -\lambda(-x)^a & x < 0 \end{cases} \qquad (2.1)$$

where λ is the coffiecient of loss aversion and α is the coefficient that determines the curvature of the value function for gains and losses. If λ is greater than 1, individuals are more sensitive to losses than gains because, given a loss, this parameter induce the value function to report the individual an even lower value. Parameter α is between 0 and 1; if α is less than 1, the value function exhibits risk aversion over gains and risk seeking over losses. The extreme case of α = 1 collapses to risk neutrality or linear utility.

The decision weighting functions are specified as:

$$w^{-}(p) = \frac{p^{\delta}}{\left(p^{\delta} + (1-p)^{\delta}\right)^{1/\delta}}$$
$$w^{+}(p) = \frac{p^{\gamma}}{\left(p^{\gamma} + (1-p)^{\gamma}\right)^{1/\gamma}} \qquad (2.2)$$

where, p is the cumulative probability, and δ and γ are the probability weights. If δ and γ are both set to 1, the weighting probability effect disappears.

It is interesting to analyse the sensitivity of results to changes on these parameters. For example, setting λ = 1 to see the effect of loss aversion, or setting $\gamma = \delta$ = 1 to see the effect of using the probability weights instead of standard probabilities. Also, by setting α = 1 the effect of using a linear value function can be evaluated. It has to be noted that by setting parameters appropriately, that is, the reference point equal to 0 and $\alpha = \lambda = \gamma = \delta = 1$, Prospect Theory has the Expected Utility approach, as a particular case.

In addition, gains are ranked from the lowest to the highest and the losses from the lowest loss to the highest loss. The cumulative probability p of any outcome x_i is obtained as the probability that a gain is higher than or equal to x_i. With m losses and n gains, the probability of obtaining a gain that is higher than or equal to the lowest possible gain is: $\frac{n}{(m+n)}$. In the same way, the probability of obtaining a loss that is higher or equal to the lowest loss is: $\frac{m}{(m+n)}$. In the same way, the probability of obtaining a gain that is higher or equal to the second smaller gain is: $\frac{(n-1)}{(m+n)}$. Therefore, the decision weights given to the smallest gain is: $\pi = w^{+}\left[\frac{n}{(m+n)}\right] - w^{+}\left[\frac{(n-1)}{(m+n)}\right]$. Similarly, the decision weights given to the second smallest gain is: $\pi = w^{+}\left[\frac{(n-1)}{(m+n)}\right] - w^{+}\left[\frac{(n-2)}{(m+n)}\right]$.

For the case of losses, the decision weight for the smallest loss is: $\pi = w^{-}\left[\frac{m}{(m+n)}\right] - w^{-}\left[\frac{(m-1)}{(m+n)}\right]$. Thus, under this formulation, the decision weight of any outcome equals the incremental value of the weighting function at each possible outcome.

In addition, an innovation exerted by Prospect Theory relative to other approaches that also deal with attitudes towards risk, lies on the transformation of the shape of the value function induced by the probability weighting functions, whose shapes can be modified by changes in the parameters. Therefore, under cumulative Prospect Theory, there are two sources of risk aversion. One is given by the curvature of the utility function (parameter $\alpha \in [0,1]$) and the other is given by the parameters of the probability weighting function (γ and δ). This is because for a given curvature of the value function, risk aversion is strengthened by overweighting small probabilities and underweighting middle to large probabilities. In particular if γ (δ) is:

1. ∈(0,1) then the weighting function $w(p)$ would have an inverted S-shape. This means that people overweight small probabilities (concave section) and underweight large ones (convex section).
2. Equal to 1, then $w(p) = p$ which implies linear probabilities and we are in the Expected Utility framework.
3. Greater than 1, then $w(p)$ will have an S-shape, with concavity for large probabilities and convexity for smaller and middle ones.

Finally, Kahneman & Tsversky, using experimental evidence, obtain the following parameter values that we adopt in this application: α = 0.88, λ = 2.25, γ = 0.61, and δ = 0.69.

After briefly presenting the Prospect Theory approach, we turn to the specifics of our application in supplemented irrigation. The type of problems we are dealing with are better presented when crop rotations (or sequences) are considered, both for irrigated and rain-fed systems, instead of considering the evaluation of individual crops. This has to do with the inter-annual complementarities between the crops (agronomic, economic and environmental) and also because it is the way that producers typically plan their crops. Given a crop rotation, we compute the profits of each irrigated crop, add them up to obtain the profit of the whole rotation, and then plug it in the utility function. The utility of the rain-fed rotation is computed analogously but considering a different crop mix in the rotation, different yields, volatilities, and production costs. The mentioned complementarities are taken into account directly in the yields, in their volatilities, and their production costs.

For both the rain-fed and irrigated systems, we consider a sequence of K crops, indexed by the subscript i. We generate the stochastic profit of the crop i in the rotation as $x_i = \tilde{P}_i \tilde{y}_i - P_R R_i - P_X X_i$. The stochasticity comes from the prices $\tilde{P}_i$ and the production per hectare $\tilde{y}_i$, which are unknown at the moment production decisions are taken. Yield of the i^{th} crop behaves as a density function $\tilde{y}_i = f(y_i)$, which takes values in the closed interval $[a, b]$, where a and b represent, respectively, the lowest and highest possible yield. Expected prices of crops behave according to a density function $h(P_i)$ with $P_i \in [0, +\infty]$. The price of the water for irrigation (in dollars per millimetre[1] per hectare), is P_R, and R_i is the quantity of water for irrigation that is applied to the crop i (in millimetres per hectare). This function is also valid for the rain-fed case, by simply taking $R_i = 0$. X_i y P_X are the quantities and prices of the remaining inputs that are part of the productive process, both deterministic and not random.

A risk averse individual, who receives an uncertain stream of profits, is willing to pay for an insurance that allows him to avoid that "risky bet", but which gives him or her the same level of utility than the risky bet. This value is called the *Risk Premium* (RP) and it is defined as the monetary amount that the individual is willing to pay to receive a certain amount of money (i.e., a quantity free of risk), but which leaves him or her

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[1] Note that 25.4 millimetres of rain are equivalent to 1 inch of rain.

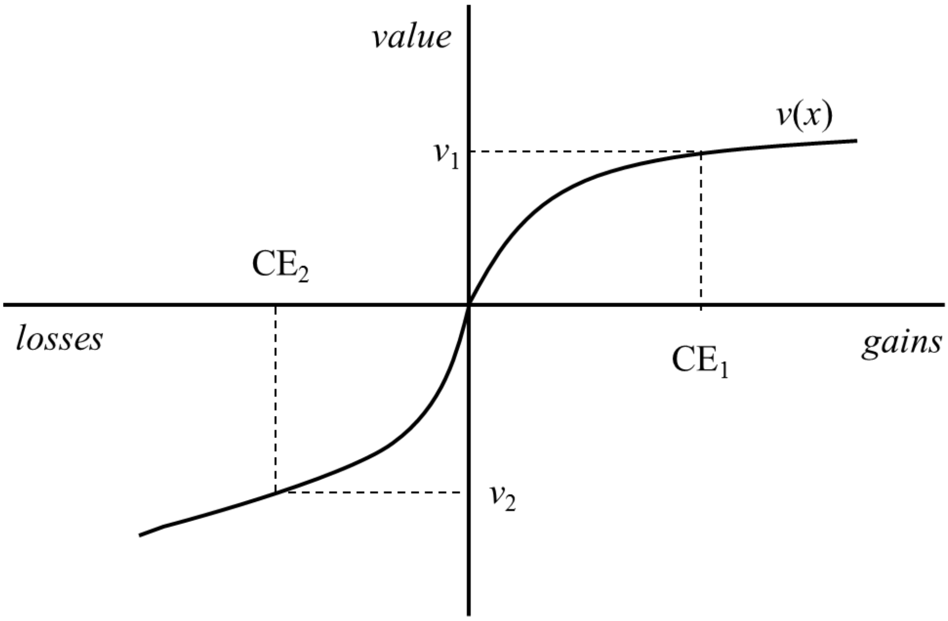
with the same utility level as the expected utility that the uncertain profits would report him or her.

The comparison of the value (or utility level) the irrigated production reports to the producer versus the rain-fed production, which is the focus of this study, arises from comparing the value of the utility function derived from each production system. As the first ones are higher on average and also less volatile, their utility will always be higher than the utility of the rain-fed system. In fact, one portion of this difference is due to the profits that are higher on average, and the remaining is due to the lower volatility. One key contribution of this analysis is to quantify each portion in monetary terms so as to be directly interpretable by the individual.

One avenue to implement this quantification is to rely on the *Certainty Equivalent* (CE). It is defined as the certain monetary amount (i.e., without uncertainty and in US dollars per hectare) which gives the individual the same utility level than the utility that comes from facing the risky stream of profits. It is calculated as the expected profits minus the risk premium: $CE = E(x) - RP$. This depends negatively on the risk aversion which implies that when risk aversion is higher, everything else equal, the RP that he or she is willing to pay is higher, and thus the CE is lower. One of the advantages of the CE is that it is expressed in the same monetary units as the profits.

To calculate the *certainty equivalent* we use the value function in equation (2.2) (Babcock 2015). As it can be seen in figure 2, when the value funcion equals v_1, certainty equivalent equals CE_1, using the value function over gains. Similarly, when total value equals v_2, certainty equivalent equals CE_2, using the value function over losses.

Figure 2. Value Function (equation 2.2) and certainty equivalent



Source: Based on Babcock (2015)

In the case of a risk neutral individual, the risk premium is equal to zero, so the utility that profits report is the same as the expected value of the profits, without a risk penalty. For agents who dislike risk, when they face a volatile stream of profits, their risk premium is higher than zero, so they will be willing to receive an amount, lower than the average of the profits, to get rid of the uncertainty but keeping the same level of utility.

In this paper, we expect to break down the *additional value* the producer receives for using an irrigated rotation with respect to a rain-fed one. In particular, we want compute the portion of that value that corresponds to profits that are *higher on average* and that one corresponding to the profits being of *lower volatility*.

In the first place, we calculate the certain equivalent for both the rotation with irrigation (CE_{wi}) and the rain-fed rotation (CE_{rf}). It is straightforward to compute by how much does the CE increases due to irrigation; we present the total additional value in percentage change with respect to the situation of the rain-fed rotation, that is, $(\frac{CE_{wi}}{CE_{rf}} - 1)$.

Secondly, the *total additional value* has two components. The value corresponding to profits that are *higher on average* are computed as the certain equivalent of an individual who faces a stream of profits whose average is equal to that of a producer who irrigates but with a coefficient of variation equal to that one of the producer with rain-fed systems. We denote this certainty equivalent as CE_{wi2}. The ratio $(\frac{CE_{wi2}}{CE_{rf}} - 1)$ represents the additional value for the producer that irrigates exclusively attributable to the higher average profits. In this result, the relative lower volatility does not play any role. It is important to highlight that this is precisely the value typically considered in evaluations of the convenience of investing in irrigation technology, and in the convenience of technology adoption in general, which usually is performed by the net present value and the internal rate of return.

Finally, the difference between both results is the value to the farmer attributable to the *lower volatility* of profits, which reduces to $\frac{(CE_{wi} - CE_{wi2})}{CE_{rf}}$.

3. Data

We seek to conduct the evaluation of the value of irrigation technology, in the context of representative production systems, applied at the farm level, and for crops which are appropriate to the use of supplemented irrigation. To this end, we construct a series of scenarios that are representative of typical conditions in Uruguay. We consider two types of soil aptitudes (medium and high) because they are relevant to determine the type of crop rotation that the producer can apply. Conditional on the soil aptitude, we select a set of rotations that are consistent with the best management practices of agricultural production, in particular, with the existing regulations of soil use and management implemented by the environmental and agricultural authorities. Soils in Uruguay are classified according to a productivity index (the CONEAT index) and we assume that a soil with high aptitude is one with a CONEAT index greater than 160. The geographical location is defined according to the distance to the port, which has a direct effect on the cost of the production through transportation costs; in particular, when they are relatively high, they may deter the farmer from producing export-oriented crops (such as soybeans). Farms within 150 kilometres from the Nueva Palmira Port (Uruguay) are considered close to the port. Then, irrigation technology is both used in farms with crops as the main (and possible the only) source of revenue, but also in farms where livestock production is completely integrated to the production of crops. We argue that the crop rotations each type of farms will optimally select are different. Finally, scenarios are different depending on crop prices; low prices are equivalent to the minimum registered around the years 2015-2016, medium prices are those expected in 2016 for 2017, and high prices are those observed in the 2016 harvest season (see table A1 in the Appendix for the detailed prices used for each crop). Table 1 shows the options we have in order to build the scenarios of agricultural production.

Table 1. Scenarios of agricultural production in Uruguay, by soil aptitude, geographical location, price, and main productive activity of the farm.

Productive system	Soil aptitude	Geographical location	Prices	Main production activity
With irrigation	High	Close to the port	Low	Crop only
Rain-fed	Medium	Far from the port	Medium	Crop & livestock

Table 2 shows the particular scenarios constructed for and discussed in this analysis. Other interesting scenarios are not presented here for reasons of space but are available from the authors upon request.

The criteria to determine which rotation to assign, given the combination of factors (environment, transportation costs, soil aptitude for agriculture, main production activity of the farm) is determined in general terms, by selecting crops whose transportation costs are low. Also, when soil aptitude is medium, sorghum is preferred to corn as its yields are more stable and has a lower probability of producing patches with ungrown plants[2]; however, in high aptitude soils, corn is preferred. When the distance to the port increases, the proportion of wheat in the rotations is reduced because it is a crop with the lowest relative price making the cost of transportation a relatively high portion of the total cost per ton produced. In the results section we present each selected scenario and explain the rotation attributed to each of them.

Table 2. Irrigated and non-irrigated crop rotations, according to the different scenarios of: soil aptitude, distance to the port, and productive activity.

Geographical location	Main production activity	High soil aptitude	Medium soil aptitude
		Rotations with irrigation	
Close to the port	Crops only	CCS1-CCM1[1]	CCS1-WS2-CCM1[3]
Far from the port	Crops only	CCS1-WS2-CCM1[2]	
		Rotations without irrigation (rain-fed)	
Close to the port	Crops only	CCS1-WS2-CCM1[1]	CCS1- WS2[3]
Far from the port	Crops only	CCS1 –WS2[2]	

Note 1: CC – Cover Crop; S1 – Soybean as 1st crop; S2 – Soybean as 2nd crop; M1 – Corn as 1st crop; M2 – Corn as 2nd crop; W – Wheat; SG1 – Sorghum as 1st crop.

Note 2: the scenario number is denoted with the superscript of each rotation.

The density functions of yields and prices, given by the functions $\tilde{y} = f(y)$ and $h(P)$, are generated using Monte Carlo simulations, whose details can be found in Rosas, Babcock and Hayes (2011) and Rosas, Ackermann and Buonomo (2014). The sources and necessary data to calibrate the parameters of these functions are explained below.

The non-irrigated yield density function of crop i, $\tilde{y}_i = f(y_i)$, arises from taking a time-series of annual observed non-irrigated yields (DIEA-MGAP), which we first detrend.

[2] It is relevant to consider that in medium soil aptitude conditions, the plant density of sorghum between 200 and 400 thousand plants per hectare is determinant for achieving good yields as it better competes with weeds due to that higher density. In addition, sorghum defines its yield in a period of approximately 60 days, as opposed to corn which has a lower density (50 thousand plants per hectare) and which defines its yield in a shorter period (20 days); this makes yields more volatile between years.

As a result, we obtain each observation as a proportion given by the deviation with respect to the trend evaluated at that year, yielding a series that oscillates around the trend. Secondly, we multiply the series by an average of the observed yields in the last four years of the series, implying that the series oscillates around that average. Then, we fit a non-parametric density function[3] to that series (DiNardo and Tobias 2001), which allows us to have a probabilistic representation of the behaviour of the rain-fed yields for crop *i*. Next, we obtain by Monte Carlo simulation 5000 random draws from such density function, building the random yield series faced by the farmer, and that is used to compute the non-irrigated profits of crop *i*. According to the rain-fed rotation, the appropriate crop yields are selected, combined in the whole profits of the rotation, and later plugged into the utility function.

The simulated crops are soybean as first and second crop (S1, S2), corn as first and second crop (M1, M2), sorghum as first crop (SG1) and wheat (W)[4]. Figure 3 illustrates the procedure for the particular case of soybean as first crop. The other crops are performed in a similar fashion. Panel 1 shows the observed historical time-series of yields from 1974 through 2014, and a cubic trend. Panel 2 is the detrended observed historical yields. Panel 3 illustrates the histogram of the detrended yields which oscillates around the mean of the last four years of the observed series.. Panel 4 shows the Monte Carlo simulation of 5000 random draws of the estimated non-parametric density function of yields.

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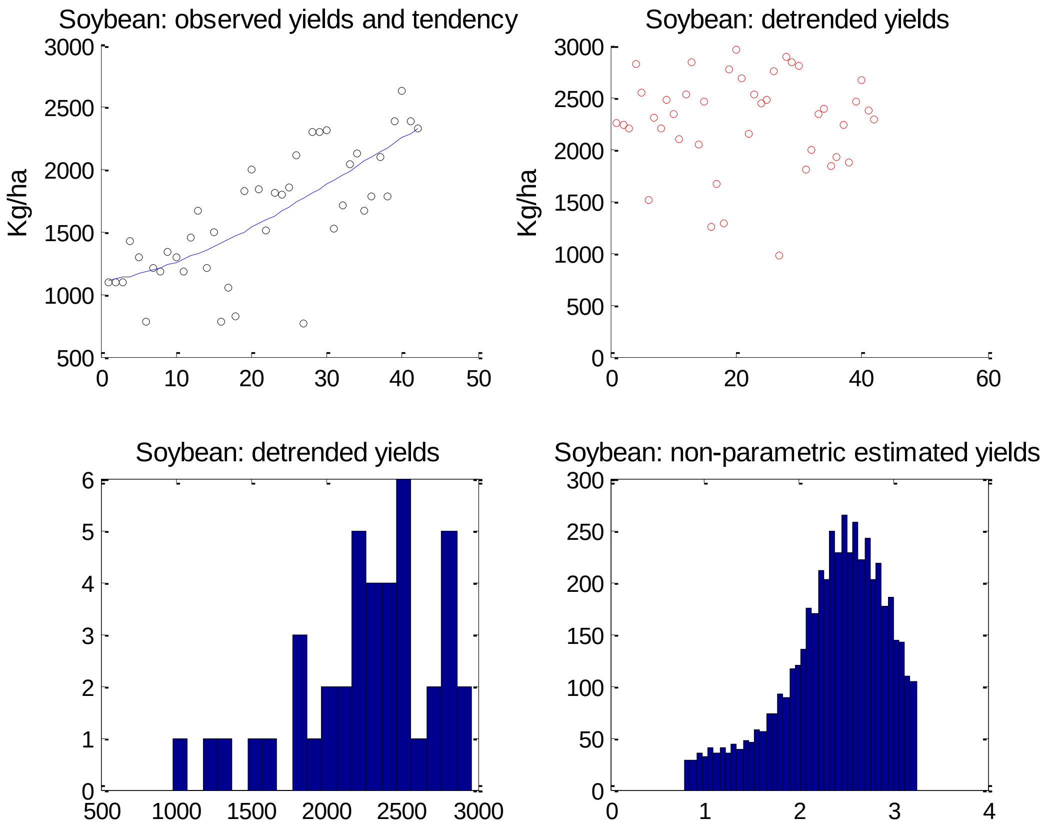
[3] We tried parametric methods, for example, fitting a *Beta*(*p*,*q*) distribution where we use the observed series to estimate its parameters *p* and *q*. However, the non-parametric methods proved to provide a better adjustment to the detrended yields, especially in the tails of the distributions.

[4] In the simulation, we also generated results for corn as second crop (M2) and sorghum as first and second crop (SG1, SG2); while not used in the scenarios presented here, they are available and will be used for the analysis of additional scenarios.

Figure 3. Steps to generate random draws of a non-parametric distribution of soybean yields.



Finally, in order to obtain the yield series that would be ultimately used in each scenario, we perform an adjustment in the support of the density function by purposedly changing the mean and width of the support so that it yields mean, standard deviation and coefficient of variation, are compareble to those registered in the scenario we seek to represent. We are required to do so because, although we generate a random series of yields for non-irrigated soybean as a first crop, historical data is at the aggregate country-level, so this transformation makes the yields behave according to the soil aptitude of the scenario and the other crops which precede and follow in the rotation. The information of the mean, standard deviation, minimum and maximum yields for each scenario, come from observed yields in commercial farms and were gathered by the authors (table 3). Note that, for instance in figure 3, the histogram of the detrended observed series oscillates around a different average than the non-parametric estimation; this occurs since the support of the latter was transformed to be adjusted to the case of no-irrigation in high aptitude.

Table 3. Average yields, standard deviation and variation coefficient.

	Soil Aptitude	Descriptive Statistic	S1	S2	M1	M2	SG1	W
		Mean kg/ha	4056	3879	10647	9518		3941
Irrigated	High	Standard dev.	197	291	894	1344		801
		CV %	5%	8%	8%	14%		20%
		Mean kg/ha	3781	3211	9102			3677
Irrigated	Medium	Standard dev.	224	311	1087			761
		CV %	6%	10%	12%			21%
		Mean kg/ha	2654	2315	5671		5123	3941
Rain-fed	High	Standard dev.	638	681	1327		611	801
		CV %	24%	29%	23%		12%	20%
		Mean kg/ha	2361	1924			4512	3319
Rain-fed	Medium	Standard dev.	541	732			815	844
		CV %	23%	38%			18%	25%

The random generation of irrigated yields is more challenging because we do not observe long enough historical time-series of irrigated crops as we do in rain-fed systems. However, we do observe several commercial farms, both crop only and crop-livestock oriented operations, applying irrigation in different geographical locations of the country and using different crop rotations. Furthermore, these farms match the scenarios we seek to represent in this study and cover a relatively large area over several years. For this reason, we use the minimum, maximum, mean, and the dispersion around the mean of these series of irrigated and non-irrigated crops to calibrate our scenarios. As these series are not sufficiently long so as to fit parametric or non-parametric densities, we take the draws of the rain-fed crop and then proceed to transform the support of the distribution so that it matches the observed mean, standard deviation and coefficient of variation of the corresponding irrigated crop.

Table 3 shows the average yields, standard deviation and coefficient of variation used in the calibration. As we mentioned above, these data come from rain-fed and irrigated systems in commercial farms gathered by the authors, which cover more than 350 thousand hectares during 10 years of rain-fed agricultural systems and more than 20 thousand hectares of crops during 8 years with irrigation.

The probability function $h(P_i)$, which depicts the unobserved expected random prices of each crop i at harvest time, we assume that behave according to a lognormal distribution. As the daily percentage change of the commodity prices can be approximated by a Normal distribution, in levels the variable is Lognormal (Hull 2009, p. 271). Based on data of historical time-series of the crop prices of interest taken from Index Mundi and the "Cámara Mercantil de Productos del País" (CMPP) in Uruguay, we compute the implicit volatility of such prices, which is one of the parameters of the lognormal distribution. The other parameter, the mean of each distribution, is the mean price for the corresponding scenario (low, medium, or high). In this application we use medium price levels, which are the current prices observed in 2016 cropping season. Table 4 shows medium price levels of the selected crops.[5]

Random prices are generated correlated with yields of the respective crops, and we use the Iman and Conover (1982) method to impose rank correlation between the random series.

Finally, data on costs of crops are obtained by the authors and correspond to those observed in commercial farms. We generate a vector of costs for each crop and

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[5] The presented results in this paper are calculated for medium prices, but in future extensions, it is possible to include high a low prices scenarios.

scenario-specific, both for irrigated and non-irrigated systems, which include input costs, farm hired labour, irrigation costs, post-harvest costs, cost of water, and the recovery value of the irrigation equipment in a 12 years lifetime. Table 4 shows a summary of costs per crop for the case of high soil aptitude and medium prices.[6]

Table 4. Costs and prices per crop, for irrigated and rain-fed systems.

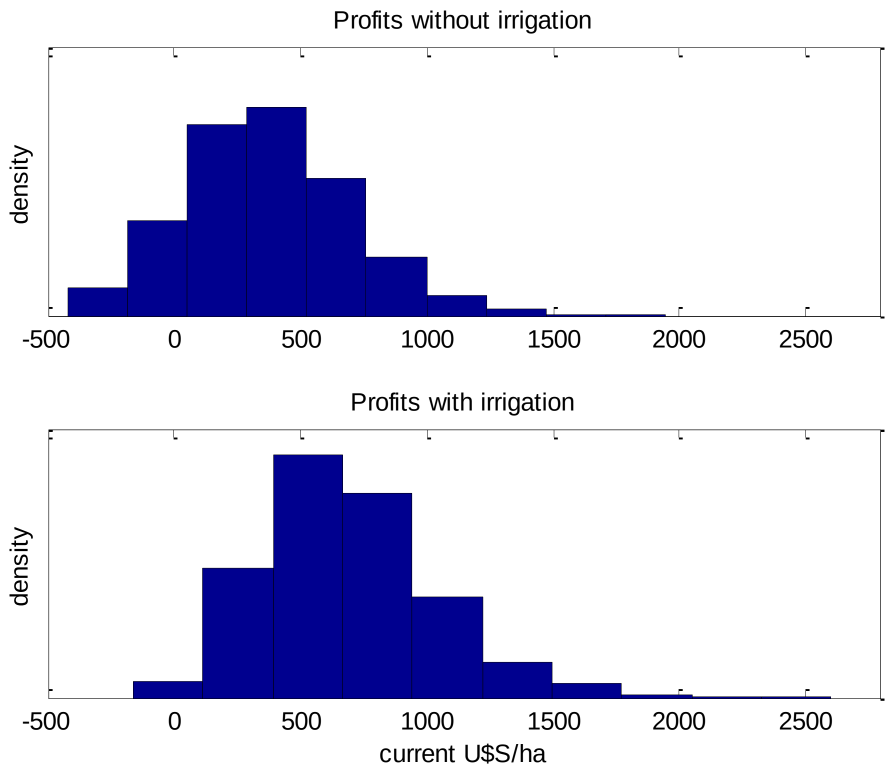
	Soil Aptitude	**Statistic**	**S1**	**S2**	**M1**	**SG1**	**W**
Irrigated	High	Total Cost	590	438	897	0	449
		Recovery cost irrigation equip.	106	106	106	106	106
		Price	361	361	162	141	166
		Inland freight	89	85	234	0	87
Rain-fed	High	Total Cost	446	318	600	382	433
		Recovery cost irrigation equip.	361	361	162	141	166
		Price	58	51	125	46	87

4. Results and discussion

Firstly, we present the results for the simulated scenario 1, consisting of a crop only oriented operation, close to the port (this is, with relatively low transportation costs), in a soil of high agricultural aptitude, and facing a medium price level. The results of the other scenarios are explained below, and although they are presented with less level of detail, they serve as a sensitivity analysis of our results. For each scenario we compare the situation of irrigated crops versus rain-fed crops.

[6] A more detailed breakdown of the costs of all crops, a description of them, as well as the values for other scenarios (medium soil aptitude, far from the port, and for low and high prices) is available from the authors.

Figure 4. Probability functions of the profits with and without irrigation, for the scenario 1 simulated.



The probability distributions of the profits with and without irrigation, obtained from the randomly generated yields and crop prices, using Monte Carlo simulations, are characterized by the properties exposed in the previous section, i.e., the profits with irrigation have a higher average and a lower dispersion than the profits without irrigation (see figure 4). In particular, the density function of the profits in the irrigated rotation has a coefficient of variation equal to 0.36 versus the 0.52 of the rain-fed rotation. Visually, the lower variability is perceived by noting that for the same interval of current U$S/ha of both panels, the density function of the irrigated rotation is more picked relative to that of the rain-fed, and is centred on a higher mean. These profits are used in the utility function to compute certainty equivalents.

Results are presented in the following way. On the one hand, the *total additional value* for the producer who uses irrigation versus the one not using it, is computed as the ratio of their certainty equivalents $\left(\frac{CE_{wi}}{CE_{fr}} - 1\right)$, therefore, it is expressed in percentage terms.

Then, we break this percentage down in the utility given to the producer due to the *higher mean profits* ($\frac{CE_{wi2}}{CE_{rf}} - 1$), also expressed in percentage terms, and the one corresponding to the utility due to the *lower volatility of profits*, which is the difference between these percentages, that is $\frac{(CE_{wi} - CE_{wi2})}{CE_{rf}}$.

Table 5 shows both results for *Scenario 1* (crop only, high soil aptitude, and close to the port) for different values of the parameters. The rotation with irrigation encompasses 2 years, CCS1-CCM1, this is: cover crop and soybean as first crop in the first year, and cover crop and corn as first crop in the second. In the rain-fed system, the rotation comprises 3 years, CS1-TS2-CCM1, with cover crop and soybean as first crop in the first year, later wheat and soybean as a second crop in the second year, and finally in the third year, cover crop plus corn as a first crop.

For an individual that is risk neutral (which is the same as to say that he has a linear value function: $\alpha = \lambda = \gamma = \delta = 1$), we found that the use of supplemented irrigation in his rotation reports a certainty equivalent 86% greater than the one of the rain-fed situation. This can be interpreted in the following way: the use of irrigation reports a value to the farmer 86% higher than not using this technology. In this situation, the whole difference (86%) corresponds to the average profits being higher with irrigation; that is, risk neutral individuals do not give value to facing profits with a lower volatility. This is reported in the second column of table 5.

Individuals will value the reduction in volatility of the profits with irrigation, as long as they are risk averse. Therefore, we start by setting the parameters of the cumulative prospect theory utility function as the ones empirically found by Kahneman and Tversky (which are $\alpha = 0.88$, $\lambda = 2.25$, $\gamma = 0.61$, and $\delta = 0.69$). This does not only imply introducing risk aversion through parameter α, but also loss aversion, weighting probabilities, and a reference point that determines perceived gains and losses. In particular, the reference point is set to be equal to 20% of the expected profits. With this set of parameters, the total value attributed to the use of irrigation is 130% relative to the production of rain-fed crops, due to both higher mean of profits and lower volatility. This is a consequence of the certainty equivalent, $CE = E(x) - RP$, being higher in the irrigated case not only because the expected profits $E(x)$ are higher but also because the risk premium (RP) is lower (the premium the irrigating farmer is willing to pay to avoid the risk is lower, because the risk or volatility is lower). Furthermore, this total additional value is composed by 75% due to profits that are higher on average and a 25% because these profits have lower volatility. In conclusion, the value attributed to lower volatility is relatively significant, considering in addition that this is a value rarely quantified, and only appreciated qualitatively.

In order to analyze the sensibility of the results to a different combination of the parameters of the utility function, we evaluate a situation where farmers only have loss aversion ($\lambda = 2.25$), presented in column 4 of table 5. The loss aversion is the perception of the agent that losses are given a higher negative value, relative to a gain of the same absolute value, which is given a relatively lower positive value. In this case, we find that the total additional value is composed by an 80% attributed to getting profits that are higher on average and the remaining 20% due to the profits having lower volatility.

Another combination of the parameters is one where we remove the effect of the probability weights ($\delta = \gamma = 1$), but leaving both risk and loss aversion. In this case, the value because of the lower volatility is 32% of the total additional value arising from using a rotation under irrigation (see column 5 of table5).

The results presented here show that when individuals are risk averse, regardless of the combination of the other parameters of the utility function, the value attributed to the lower volatility is considerable and does not present significant changes from one situation to another, ranging between 20 to 32%.

Table 5. Value attributed to the use of irrigation with respect to rain-fed systems, according to different values of the parameters.
***Scenario 1:* crop only - high soil aptitude - close to the port**

	Linear value function (risk neutral)	Kahneman &Tversky (1992)	Loss averse only	No weighting probabilities
Parameter values	$\alpha = 1.00$ $\lambda = 1.00$ $\gamma = 1.00$ $\delta = 1.00$	$\alpha = 0.88$ $\lambda = 2.25$ $\gamma = 0.61$ $\delta = 0.69$	$\alpha = 1.00$ $\lambda = 2.25$ $\gamma = 1.00$ $\delta = 1.00$	$\alpha = 0.88$ $\lambda = 2.25$ $\gamma = 1.00$ $\delta = 1.00$
Total additional value	0.86	1.30	1.10	1.31
Value for higher mean	0.86	0.97	0.88	0.89
Value for lower volatility	~0	0.33	0.22	0.41
$^{mean}/_{total}$	100%	75%	80%	68%
$^{volat}/_{total}$	~0%	25%	20%	32%

Next, we present the other two analyzed scenarios, comprising different configurations of productive systems due to geographical locations, soil aptitude, and main productive orientation of the operation. These are presented in Table 6.[7]

We run a *Scenario 2* consisting of a crop only production system, in a high soil aptitude, but located far from the port. The rotation that is suited for these characteristics and under irrigation consists of, 3 years and incorporates a winter crop instead of winter cover crops as the scenario 1. In particular, CCS1-WS2-CCM1, which is a cover crop in the winter followed by soybeans as first crop, winter wheat and corn as a second crop in the second year, and a cover crop plus corn as first crop in the third year. The rain-fed rotation lasts 2 years, CCS1-WS2, that is, a cover crop plus soybean as first crop in the first year, and in the second year a winter wheat followed by soybeans as second crop. In this case, the certainty equivalent of the risk averse producer that irrigates is between 60 to 73% higher relative to the one that follows a rain-fed system. This total additional value is such that between 11 to 25% corresponds to the value generated

[7] In scenarios 2 and 3, the reference point is set to be, respectively, 20% and 50% of the expected profits.

because the profits with irrigation are less volatile, and the remaining 89 to 75% is due to the higher profits on average.

Table 6. Value attributed to the use of irrigation with respect to rain-fed systems, according to different values of the parameters.

	Linear value function (risk neutral)	Kahneman &Tversky (1992)	Loss averse only	No weighting probabilities
Parameter values	$\alpha = 1.00$ $\lambda = 1.00$ $\gamma = 1.00$ $\delta = 1.00$	$\alpha = 0.88$ $\lambda = 2.25$ $\gamma = 0.61$ $\delta = 0.69$	$\alpha = 1.00$ $\lambda = 2.25$ $\gamma = 1.00$ $\delta = 1.00$	$\alpha = 0.88$ $\lambda = 2.25$ $\gamma = 1.00$ $\delta = 1.00$
Scenario 2: crop only – high soil aptitude – far from the port				
Total additional value	0.51	0.69	0.60	0.73
Value for higher mean	0.51	0.60	0.54	0.55
Value for lower volatility	~0	0.09	0.06	0.18
$mean/total$	100%	87%	89%	75%
$volat/total$	~0%	12%	11%	25%
Scenario 3: crop only – medium soil aptitude – close to the port				
Total additional value	0.53	0.53	0.57	0.64
Value for higher mean	0.53	0.24	0.20	0.21
Value for lower volatility	~0	0.29	0.37	0.43
$mean/total$	100%	45%	35%	33%
$volat/total$	~0%	55%	65%	67%

In *Scenario 3* we turn to a medium soil aptitude, with an agricultural system that is crop only, but its geographical location is close to the port. The rotation with irrigation also takes 3 years, CCS1-WS2-CCM1, so is the same as the scenario 2. The rain-fed rotation lasts 2 years, CCS1-WS2, and also is the same as that of the scenario 2. Results of this scenario are qualitatively similar to and thus consistent with those obtained in scenarios 1 and 2. In particular, the certainty equivalent of the irrigating systems is between 57 to 64% higher than those who follow a rain-fed system. The portion of the total additional value that corresponds to the lower volatility is as high as 55 to 67%, implying that the value given to the more stable profits is not only significant but also, it is even higher than that given by the higher mean of profits.

In conclusion, if we consider the results of the three scenarios proposed and the combination of parameters of the utility function, we find that the results are qualitatively similar and do not present too much variation between them, or in other words, in all cases, there is a relatively high value that the producer assigns to the lower volatility of profits obtained due to the use of irrigation, regardless of the productive orientation of the operation, soil aptitude, distance to the port, and attitudes toward risk. As expected, the proportion of this value in the total additional value increases as the individual is more risk averse. The higher risk aversion motivates the individual to increase the risk premium he or she is willing to pay to avoid the uncertainty inherent to the productive activity, but that increment is even higher for the rain-fed individual which has a higher risk, making his or her certainty equivalent to decrease sharply.

Importantly, and as it was stated before, these scenarios represent typical productive schemes found in the agricultural sector in Uruguay, so the results may be useful for promoting the adoption of this technology.

5. Conclusions

The introduction of irrigation produces a significant increase in crop yields as well as a noticeable reduction in their annual variability. The combination of these two factors turns the implementation of irrigation into an attractive practice, with a direct impact on the economic profitability of crops (positive in levels and negative in dispersion). This effect is even more evident when irrigation is implemented on rain-fed summer crops, to supplement the precipitation that falls naturally.

The typical analysis involving the economics of irrigation is from the financial point of view; that is, to what extent the higher revenues pay for the investment and additional costs. However, these methodologies fail to consider the benefits arising from the reduction in income variability.

Our study focuses on monetarily quantifying the benefit arising from the fact that yields are less volatile relative to those of rain-fed summer crops, a value to the farmer that is usually ignored. Although the value of the higher profits on average of the producer are easy to interpret, as they can be associated with the tangible benefit (even in monetary units), it is more difficult to conceptually assimilate the value of the lower uncertainty. This is translated, for instance, into a better general environment for business, taking risky decisions in an environment with more certainty, being more eager to invest in businesses to increase production, and so on, although it does not necessarily imply observing directly a higher flow of funds received.

Coming back to our initial argument, it is generally accepted that there exists a positive valuation of stable incomes, which is object of a wide literature in economics and finance. When economic agents, such as consumers, producers of goods or services, or investors, can perceive two amounts of money, equal in average, but one with more uncertainty than the other, they will prefer the more secure one. Behind this argument lies the fact that we suppose individuals dislike risk, or in other words, are risk averse. In particular, if an agricultural producer has the alternative to generate a flow of profits with a given volatility (rain-fed production) and another one with a lower volatility (irrigated production), he would prefer the latter even in the case they would have the same average value. This is to say, producers and economic agents in general, not only value the higher profits in average, but also assign an additional value in case they have a lower volatility.

We propose a Prospect Theory approach that simultaneously incorporates both effects. More precisely, we compare on the one hand, a representative crop producer who maximizes the utility of a stream of uncertain profits and uses supplemented irrigation technology, with on the other, a situation where everything else equal, the producer employs a rain-fed system. The comparison yields the overall value arising from both higher average and lower volatility. Then, we turn to decompose this value into the contribution of each source.

Prospect Theory features some key factors which tackle the main critics other treatments of decision-making under uncertainty (such as mean-variance analysis and expected utility) have. Experimental work has shown that people systematically violate behaviour depicted by these frameworks, having Kahneman and Tversky (1979) and Tversky and Kahneman (1992) as the main precursors. In particular, outcomes are modelled as gains and losses with respect to a reference point, and thus agents can be modelled as both risk averse and loss averse. Prospect Theory also incorporates the fact that agents tend to overestimate (underestimate) small (large) probabilities. Accounting for loss aversion and probability weighting may drive results and induce a different design of effective and efficient policies, contracts, and decision schemes regarding irrigation.

A key concept for our work is the certainty equivalent, i.e. the certain amount of money an individual is willing to receive which reports him or her the same level of utility than an uncertain bet or lottery. To quantify the premium associated with the less volatile yields of the irrigating farmer, we proceed in two steps. First, we compute the certainty equivalent of the stochastic profit flows of a farmer applying supplemented irrigation to a crop rotation and using a cumulative prospect theory utility function (CE_{wi}). We compare it with that of a farmer that, everything else equal, does not use irrigation (CE_{rf}). As risk averse individuals negatively value the higher variability of profits, the former will be higher. Their difference (CE_{wi} - CE_{rf}) provides us with the overall value from using irrigation (both from higher yields and lower volatility). In the second step, we decompose both effects by comparing CE_{wi} with another stochastic flow of profits which has the same average profit but the volatility of the farmer not applying irrigation (denoted as CE_{wi2}). The difference ($CE_{wi} - CE_{wi2}$) is exactly how much a farmer values the lower volatility induced by the use of irrigation.

We show an application for summer crops in Uruguay, where the irrigated area increased in 34% between 2000 and 2011due to supplemented irrigation in summer crops. The stochastic nature of profits arises from two correlated sources: expected yields (both irrigated and non-irrigated) and expected output prices. Crop yields are modelled as probability density functions, computed by fitting non-parametric density functions to observed time-series of yields obtained from Uruguayan official agricultural statistics. Random prices are assumed to be log-normally distributed and calibrated using expected reference prices for each crops. Production and investment costs are taken from private agronomy advisers and from official extension services. Random deviates are drawn from each density function by Monte Carlo simulations (assuring that prices are correlated with crop yield) and then plugged into the utility function. Profits with and without irrigation are computed for selected crop rotations and not for individual crops, as it is the standard way of conceiving the crop productive system.

We conduct sensitivity analyses by constructing scenarios of soil productivity levels, crop rotations (some for crop only and some serving crops integrated to livestock production), and distance to the port. Also, we explore the role of degrees of loss aversion, curvature of the value function, and probability weighting schemes.

In the context of this study, the contribution of the value function is to put in the same units the value (or the utility) of two flows of uncertain profits that have different average and different level of volatility or risk. This is particularly important because it allows evaluating situations where there is a tradeoff between the lower average and the lower risk. For example, if there are two flows of profits with different risk levels, to what extent can the average of the less risky decrease so that the agent continues preferring it?

In the particular case of this study, and for the level of prices we assumed in the scenarios, the rain-fed production generates a flow of uncertain profits both with a lower average and a higher volatility than those generated by the irrigated production. For this reason, the value function of the uncertain profits is necessarily higher. However, and in spite of that, in this study the concept of value function is used to monetarily quantify the value that the producer who irrigates receives for less volatile (or less risky) profits. This is, the producer who irrigates receives a higher value than the one who has a rain-fed system, and the concept of Prospect Theory is used to establish what proportion of such value corresponds to a higher benefit on average and what proportion corresponds to a lower volatility.

Results are presented firstly for scenario 1, which comprises a crop only operation, in high soil aptitude, close to the port with low transportation costs, and facing medium crop prices level. Producers with irrigation and with rain-fed systems use crop rotations that in both cases are the typically observed in those types of soils and productive systems. We find that a risk neutral individual, the use of supplemented irrigation in his or her rotation reports a certainty equivalent 86% higher than the one of the rain-fed situation. In this case, the whole difference (86%) corresponds to the average profits being higher with irrigation, that is, risk neutral individuals do not give value to facing profits with a lower volatility.

When individuals are risk averse, they give value to the reduction in volatility. We run different scenarios of risk aversion, including loss aversion only, no weighting probabilities, and the values that Kahneman and Tversky found empirically. In these cases, when we break down the total additional value and take it as the 100%, we find that, in all these scenarios, the value for lower volatility is around 25 to 32% whereas the value for higher mean is between 68 to 80%.

Furthermore, we run a scenario 2 consisting of a crop only system, in a high soil aptitude, but located far from the port. We find that the certainty equivalent of the risk averse producer that irrigates is between 60 to 73% higher relative to the one that follows a rain-fed system. This total additional value is such that between 11 to 25% corresponds to the value generated because the profits with irrigation are less volatile, and the remaining 89 to 75% is due to the higher profits on average.

In the last scenario we run, scenario number 3, we turn to a medium soil aptitude, with an agricultural system that is crop only, but is geographically close to the port. Results of this scenario are very similar to and thus consistent with those obtained in scenarios 1 and 2. In particular, certainty equivalent of the irrigating systems are between 57 to 64% than the corresponding rain-fed systems, which implies that the value given to the more stable profits is not only significant but also even higher than that given by the higher mean of profits.

In conclusion, independently from the geographic and particular characteristics, when individuals are risk averse, there exists a significant value that the producer assigns to the lower variability of the yields with irrigation, apart from the ones that he or she assigns for obtaining higher yields on average. As expected, the proportion of this value in the total additional value increases as the individual is more risk averse. The higher risk aversion motivates the individual to increase the risk premium he or she is willing to pay to avoid the uncertainty inherent to the productive activity, but that increment is even higher for the rain-fed individual which has a higher risk.

This work is a first approximation to the topic for the Uruguayan case and contributes to a literature of measuring the benefits of adopting technology in a decision-making environment under uncertainty. Also, it contributes to the increasing number of applications of Prospect Theory helping to understand how to use it and its main differences with other models of attitudes towards risk such as expected utility and mean-variance analysis. Moreover, this is a general methodology that can be applied to the adoption of other agricultural practices which induce a reduction in income volatility.

These scenarios represent typical productive schemes found in the agricultural sector in Uruguay, so the results may be useful as an input to support private efforts and public policies promoting supplemented irrigation as a practise to generate productive systems that are more resilient to variability and climate change. This is also applicable to other neighbour countries such as Argentina and Brazil which are conduction similar efforts of promoting adoption of supplemented irrigation in summer crops.

In further developments of this study, we extend our preliminary results by using other reference points, other combinations of utility parameters, and other production scenarios.

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Appendix

Table A1. Level of prices of each crop for each scenario

Level of prices	S1	S2	W	M1	M2	SG1	SG2
Medium	361	361	166	162	162	145	141
High	410	410	195	181	446	170	217
Low	283	283	141	133	133	120	153

Note: CC – Cover Crop, S1 –Soybean as first crop, S2 – Soybean as second crop, M1 – Corn as first crop, M2 – Corn as second crop, W – Wheat, SG1 – Sorghum as first crop.