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Assessing the Impact of Agricultural Intensification on Water Pollution: An Integrated Model Assessment of the San Salvador Basin in Uruguay

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Selected Paper prepared for presentation at the 2021 Agricultural & Applied Economics Association Annual Meeting, Austin, TX, August 1 – August 3

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ABSTRACT

This research integrates for the first time in a South American basin, the San Salvador basin located in Uruguay, a biophysical model which simulates water quality and crop yields with an economic model to measure the economic benefits of agricultural intensification and well as the tradeoff between economic benefits and water quality in the period between the years 2000 and 2019. More specifically, using two different agricultural rotations we study the economic and environmental impact of agricultural intensification through nine (3x3) different scenarios in terms of irrigated area (rotation 1, rotation 2 or both) and fertilization (low, base, high) relative to a baseline scenario where production is held under rainfed agriculture. Following Rosas et al. (2017), we quantify economic benefits of the simulated yields by computing the certainty equivalent of the proposed scenarios. On the other hand, we measure the tradeoff between economic benefits and environmental variables in each scenario by computing the ratio between the variation of the certainty equivalent and the variation in the simulated phosphorus and nitrates concentration. Economic results indicate that irrigation could improve yearly economic benefits for a risk-neutral planner up to 73 additional dollars per hectare while a very risk averse planner could value those benefits in 189 dollars per hectare due to a reduction in the risk premium cause by less volatile yields. In contrast, water quality would suffer an increase of 7.06 and 4.84 percentage points for phosphorus and nitrates respectively.

FUNDED BY:

Agencia Nacional de Investigación e Innovación (ANII), Uruguay. Fondo Sectorial Innovagro (FSA_PI_2018_1_148628)

1. Introduction

According to the United Nations Development Program, the quantity and quality of water resources are key to achieve many of the millennium development goals. Both water quantity and quality are being increasingly threatened in Uruguay by the intensification of agricultural production, endangering the sustainable development of the agricultural sector and urban areas (MVOTMA, 2018). Therefore, the generation of relevant information for the design and monitoring of water and agricultural policies is required to sustainably manage the resource.

The sustainable availability of quantity and quality of water interacts in complex ways with economic decisions made by economic agents. In this line, it both affects and is affected by their choices. These decisions have effects on the functioning of ecosystems and ecosystem services, while the later affect the choices available to individuals. Thus, an analysis of these interactions and feedbacks requires a combination of model frameworks which simultaneously consider economic and biophysical elements. The assessment of these phenomena has been typically carried out independently through different types of models, which may be roughly grouped into economic models on one side, and biophysical models on the other (Plantinga, 2015; Kling et al, 2017). Economic models can assess changes in land use and practices when other (endogenous) economic variables change, but taking biophysical variables as given (exogenous). Biophysical models, on the other hand, assess changes in (endogenous) biophysical variables by considering the economic factors that drive land use as exogenous. More recently, however, and under the recognition of the necessity of capturing the interactions and feedbacks of the different components of the socioecological systems, there has been a strong interest and progress towards the development and use of integrated assessment models (IAMs), which make more holistic assessments and help to avoid unintended consequences.

IAMs encompass three different and interconnected systems that link human decisions, modeled by economic models, with biophysical processes, modeled by biophysical models. Firstly, decision systems determine outcomes such as agricultural land use, management practices or environmental policies. Decisions from the first system influence a second system defined by biophysical processes, which encompass natural variables related with water quality, soil health, crop production or climate. Lastly, natural outputs determine value systems that determine the market value of different goods as well as the nonmarket valuation of ecological services. Decisions taken at the first system depend on value systems (Kling et al., 2017). These models could have different complexity levels according to different assumptions regarding spatial and temporal interdependence in biophysical and economic variables, which make more challenging to find optimal solutions of land allocation or environmental practices.

In the IAMs literature, the relationship between practices of to agricultural intensification, economic benefits and water quality has been analyzed in two different ways. A first group, explore a large set of combination of agricultural practices in order to find those that are optimal (i.e., Rabotyagov et al., 2010; Rabotyagov et al., 2014; Pastori et al., 2017). The second reduce the analysis to a comparison between a set of proposed scenarios (Lee et al., 2012; Corona et al., 2019; Liu et al., 2019; Griffin et al., 2019; Lupi et al., 2019, etc.), which helps to find near-exact solutions for these problems, since it assesses a large number of possible policy combinations. It can be convenient, however, when we aim at comparing a limited number of policies due to different reasons, such as policy or computational feasibility.

This study applies an IAM which integrates results from the Soil and Water Assessment Model (SWAT) with an economic model based on expected utility theory, to evaluate agriculture intensification scenarios of irrigation and fertilization practices in the San Salvador River basin in Uruguay. Results of economic benefits and water quality are benchmarked against a baseline scenario with no irrigation.

2. The Model

2.1 Model Setting

The problem is framed from the perspective of benevolent catchment manager, who's objective is to choose among different agricultural practices by aggregating and assessing their economic and environmental effects in each production unit considered. Economic results in each unit are measured and ranked by applying the expected utility theory, which compares and aggregates welfare through a utility function $U(\pi_i)$ whose only input is the profits of the *i-th* unit.

In each production unit, per-hectare profits are computed as revenues minus costs of the crops (activities) in unit I (equation 1). Revenues (equation 2) are the product of crop j yield (measured in tons per hectare) and price (in dollars per ton) aggregated over the crops in unit *i*. Costs are the sum over the J crops in unit i, of a fixed quantity C_{ij} encompassing all input costs other than fertilizer and irrigation, plus the fertilizer level times its price and the applied water times its price (equation 3).

$$\pi_i = Revenue_i - Costs_i \quad (1)$$

$$Revenue_i = \sum_{j=1}^{J} Yield_{ij} \times Price_j \tag{2}$$

$$Costs_i = \sum_{j=1}^{J} C_{ij} + Price_{Fert} \times Fert_{ij} + Price_{Water} \times Water_{ij} \tag{3}$$

Profits are uncertain since they are affected by random variables in the revenue equation (crop yield) and in the cost equation (quantity of water needed for irrigation). In our model, these variables depend on irrigation and fertilization practices as well as on climate conditions. We assume that prices of both inputs and outputs are exogenous. The uncertainty of profits can be interpreted as a problem where the catchment manager faces a lottery on the benefits of each unit of production.

In expected utility theory, the price at which the catchment manager is willing to sell this lottery in each unit of production i can be operationalized by using the concept of certainty equivalent (equation 4), which equals the lottery expected profits ($\mathrm{E}(\pi_i)$) minus the risk premium (RP). This premium represents how much money an agent is willing to pay to avoid the lottery risk. Hence, a higher certainty equivalent can arise as a result of higher expected profits or lower risk premium[1]. This certainty equivalent is applied over a continuous, concave, and monotone utility function of profits whose first and second derivatives can be used to get the absolute risk aversion level of the catchment manager (equation 5). Assuming risk exposure is a crucial component in the model since it has observed implications in the farmers' decisions (Apland et al., 1980, Pandey, 1980; Chavas and Shi, 2015).

$$U(CE_i) = E\big(U(\pi_i)\big) \rightarrow CE_i = U^{-1}\Big(E\big(U(\pi_i)\big)\Big) = E(\pi_i) - RP \tag{4}$$

$$\frac{U''(\pi_i)}{U'(\pi_i)} = \alpha \tag{5}$$

In equation 6, for each unit i and outcome *t*, we assume that the utility of the lottery can be represented with an exponential utility function. Under this assumption, the certainty equivalent can be derived as in equation 7.

$$U(\pi_i) = -\sum_{t=1}^{T} e^{-\alpha \pi_{it}} \tag{6}$$

[1] The risk premium is defined as the maximum amount of money that a risk averse agent is willing to pay to avoid the lottery.

$$CE_i = log\left[\left(n^{-1}\sum_{t=1}^{T} e^{-\alpha\pi_{it}}\right)^{-1/\alpha}\right] \quad (7)$$

Finally, in equation (8), the catchment manager decides on the economic convenience of each scenario by computing the sum of these certainty equivalents weighted by the size of each production unit *i* (has_i).

$$CE = \frac{\sum_i^I CE_i \times has_i}{\sum_i^I has_i} \quad (8)$$

To assess the environmental impact on water quality of each scenario, simulated phosphorus (P) and nitrates (NO3) daily concentration levels are computed as in equation (9) and compared to the environmental threshold (TP and TN) defined by the national environmental regulator. If P or NO3 levels are higher than this threshold, the indicator variables INO3 and IP take the value of 1, and 0 otherwise. Thus, by adding up the indicator variables and dividing by the number of simulated days (T), as in equation (10), we get the proportion of time in which environmental regulations are violated (i.e., the threshold is exceeded).

$$IP_t = \begin{cases} 1 & if \quad P_t < TP_t \\ 0 & if \quad P_t \geq TP_t \end{cases}$$

$$INO3_t = \begin{cases} 1 & if \quad N_t < TN_t \\ 0 & if \quad N_t \geq TN_t \end{cases} \quad (9)$$

$$PropP = \frac{\sum_{t=1}^T IP_t}{T}$$

$$PropNO3 = \frac{\sum_{t=1}^T INO3_t}{T} \quad (10)$$

Finally, as shown in equations (11) and (12), the tradeoffs between economic benefits and water pollution are assessed by computing four different indices. Equation (11) relates the change of the aggregated certainty equivalent relative to the baseline scenario of no irrigation, to the change in the mean concentration of P and NO3.

Equation (12) relates the same variation in aggregated certainty equivalent to the change in the median concentration levels of P and NO3.

$$\zeta = \frac{\Delta CE}{\Delta P_{mean}}$$

$$\eta = \frac{\Delta CE}{\Delta NO3_{mean}} \tag{11}$$

$$\kappa = \frac{\Delta CE}{\Delta P_{median}}$$

$$\lambda = \frac{\Delta CE}{\Delta NO3_{median}} \tag{12}$$

Hence, using equations (11) and (12), we measure by how much economic benefits (CE) change when P or NO3 mean or median concentration deteriorate in 1 percentage point. We choose to report these cost-effectiveness ratios with respect to both the mean and median, in order to account for nutrient concentration variability and especially the presence of extreme values caused by daily extreme nutrient concentrations caused by low precipitation levels, low stream flown, and high nutrient export levels to the basin.

2.2 Model Data and Calibration

The SWAT biophysical models a river basin scale model, based on Geographic Information Systems (GIS) input data (Neitsch et al., 2015). It simulates biophysical processes (like plant growth, evapotranspiration, leaching, etc.) on sub-basin units, which are named as "Hydrological Response Units" (HRU). Each HRU is unique and homogeneous in terms of land use, soil and slope. The model reports water quality results for a number of spatially distributed modeled streams in the basin. This model has been widely used to analyze the impact on water pollution caused by land use and management practices (Gassman et al., 2007). In recent years, Uruguayan authorities and researchers have made significant efforts in order to implement this model in a number of relevant basins (Mer et al., 2020).

Our economic model includes not only purely economic variables, such as prices and costs, but also biophysical variables such as yields as well as phosphorus and nitrates concentrations in the catchment. The latter variables are obtained from a calibrated SWAT model (SWAT+ version), which simulates their output for a given land use and set of practices. This enables us to integrate purely biophysical processes into our economic assessment.

More specifically, in equations (1)-(2) we input crop yield, fertilizer quantities, and irrigated water variables from the SWAT model to, conditional on output prices and production costs, evaluate and rank a set of agricultural practices scenarios in the river basin. We use a weighted average of the certainty equivalent, as seen in equation (8), to conduct the evaluation.

Furthermore, nutrient concentrations and environmental standard compliance (equation 10) are assessed by using the SWAT model NO3 and P simulated concentrations at the basin's outlet. These values are also used to calculate the cost effectiveness ratios in equations (11) and (12).

We obtain economic data (see Annex) from different sources. Crop prices come from the *Camara Mercantil de Productos del País*, a chamber of agricultural exporters, which reports prices (dollars per ton) for all the simulated crops. Prices are adjusted by an estimated transportation fee of 10 dollars per ton to reach the relevant markets. Input-cost information were collected from different sources. Crop-specific production costs (C_{ij}) were collected from a private firm that operates within the basin whereas irrigation water cost was assumed to be 0.65 dollars per millimeter (dollars per mm) based on expert judgment from the *Instituto Nacional de Investigación Agropecuaria* (INIA).

Finally, the negative exponential utility function is calibrated at six uniformly distributed absolute risk aversion parameters within the range of 0 to 0.035 in order to quantify economic profits at different levels of risk aversion, consistent with reported parameters in the literature (Hardaker et al., 2004a; Hardaker et al., 2004b; Babcock et al., 1993).

3. Study Area and Proposed Scenarios

The San Salvador River basin belongs to a prominent agricultural area in the southwest region of Uruguay. It accounts for only 1.4% of the country area (about 240,000 hectares) but produces 21% of the wheat, 17% of the corn, 9% of the soybean and 14% of the sorghum of the country (Sigmaplus, 2017). While it presents high inter-annual rainfall volatility, the majority of the area is under rain-fed crop production. Supplemented irrigation of crops is an attractive technology for farmers in the basin, since it can potentially increase crop yields and simultaneously reduce yield volatility (Failde et al., 2013; Rosas et al., 2014; Rosas et al., 2017; Sigmaplus, 2017; Montoya et al., 2017; Montoya et al., 2019). However, intensification of crop production is a problem of increasing concern in the basin because it increases the pressure on water resources (Baker, 2003). More specifically, in recent years (2014-2019), environmental authorities have found that nitrogen concentration at the basin outlet is higher than the recommended level (1 mg/L) while phosphorus concentration at some monitoring stations within the basin are also above the regulation's threshold value (0.025 mg/L).

Since water pollution in this basin is mainly explained by nonpoint sources (MVOTMA, 2020), encompassing more than 90% of nitrates and phosphorus discharges, modeling fertilization, irrigation and other crop practices are key to understand and reduce nutrient discharges.

We propose to evaluate the economic and environmental impact of different irrigation and fertilization scenarios relative to a baseline rainfed scenario. Nine (3x3) scenarios are constructed by means of three irrigation levels and three fertilization levels.

Six of the most frequent crop rotations in the basin were used to model land use in the SWAT biophysical model (see Table 1). Only in rotations 1 and 6 the use of irrigation is considered to be technically feasible. Rotations encompass main crops (such as corn, soybean, wheat or barley) and cover crops (oats), whose main role is to maintain the quality of the soils by avoiding soil erosion and the consequent loss of nutrients.

Rotation	Year 1		Year 2		Year 3	
Rotation 1	Oats	Corn	Oats	Soybean		
Rotation 2	Oats	Soybean	Oats	Soybean	Oats	Corn
Rotation 3	Pasture	Soybean	Oats	Soybean		
Rotation 4	Wheat	Soybean 2	Oats	Soybean		
Rotation 5	Barley	Soybean 2	Wheat	Soybean 2		
Rotation 6	Wheat	Soybean 2	Oats	Corn	Oats	Soybean

Table 1: San Salvador Basin Rotations[2]

The application of irrigation on each HRU was simulated using an automatic routine of the SWAT model, which applies water to the plants when a given water stress threshold is reached. Water stress in an HRU is measured by an index that relates evapotranspiration (ET) with potential evapotranspiration (PET) as shown in equation (13). In this equation, 1 represents the maximum water stress level (evapotranspiration is equal to its potential) while 0 means there is no deficit. Aligned with the literature as well as technical recommendation from the modelers, the threshold was set to 0.8, meaning that at least 80% of the water demand is ensured (Montoya et al, 2017; Montoya and Otero, 2019). This unlimited water source simulation routing gives us an opportunity to estimate the potential benefits of irrigation in the basin.

$$Stress = 1 - \frac{ET}{PET} \tag{13}$$

[2] For each year, the first crop is set according to its planting date. See Annex 7.1 for more detail on crop operation dates.

Additionally, fertilization practices in irrigated farms were simulated at three different levels: high, medium and low, where the medium level is consistent with actual practices in irrigated fields. Fertilization practices include the application of urea, diammonium phosphate and urea 46-00-00[3]. Application rates in rainfed crops are 200, 150 and 46 kg/ha respectively. Application rates are 275, 190 and 53 kg/ha in the medium irrigation scenario. Then, high and low fertilization scenarios are built by considering 50% increments or reductions from these rates. Therefore, high fertilization scenarios imply rates that are, respectively, 56.3%, 40% and 22.8% higher than the rainfed scenario in urea, diammonium phosphate and urea 46-00-00. Rates are 37.5%, 26.7% and 15.2% higher in the medium scenario, while the low fertilization scenarios assume rates 18.8%, 13.3% and 7.6% higher, respectively.

Finally, as seen in Table 2, by combining irrigation and fertilization practices for the two considered irrigated rotations, we get the nine irrigation scenarios plus the baseline scenario of rainfed crop practices. When both rotations are irrigated, 25% of the basin area is covered by irrigated crops, while that percentage is only 18.9% and 6.3% when irrigation is applied to rotation 1 and 6, respectively. These scenarios aim at exploring the effect of agricultural intensification on economic benefits and water quality by increasing the irrigated area and fertilizer application rates.

Scenario	Irrigated Rotations	Fertilization	Irrigated Area (%)
1	1 and 6	High	25.30%
2	1 and 6	Medium	25.30%
3	1 and 6	Low	25.30%
4	1	High	18.90%
5	1	Medium	18.90%
6	1	Low	18.90%
7	6	High	6.30%
8	6	Medium	6.30%
9	6	Low	6.30%
10	None	Rainfed	0%

Table 2: Irrigation and Fertilization Scenarios

5. Results

[3] The difference between standard urea and urea 46-00-00 is that standard urea contains N and NH_3 while urea 46-00-00 only contains N.

This section presents the model results, which can be decomposed in three different parts: economic results (5.1), environmental or water quality results (5.2) and cost-effectiveness analysis (5.3).

5.1. Economic Results

Simulated Profits. Table 3 presents the results in the treated area, which covers rotations 1 and 6, for each of the proposed scenarios. It shows mean yearly net profits per hectare (dollars per ha) and their percentage change relative to the rainfed scenario. Results show that irrigation increases mean yearly net profits per hectare in the period 2000-2019. Profits are higher when the increase in fertilization with respect to the rainfed scenario is low, as marginal fertilization costs in medium and high fertilization scenarios exceed the marginal revenue generated by yield improvements.

In the rainfed crop scenario, yearly net mean profits reach 257 dollars per ha. Applying irrigation to rotation 6, which comprises approximately 25% of the total treated area (6.3% of the basin area) increase the net mean profits by up to 6.3% under a low fertilization level. When irrigation is applied to rotation 1, which comprises 75% of the total treated area, the net mean profit increases up to 22.3%. This figure is expected as the area treated under rotation 1 is approximately three times that of rotation 6. Lastly, when irrigation is applied in both rotations (25.3% of the basin area), net mean profits increase by 28% relative to the baseline.

Scenario	Irrigated Rotations	Fertilization	Net Profit Mean $/ha	Variation	% Basin Irrigated	% Treated Area
1	1 y 6	High	$ 305.96	18.95 %	25.3 %	100 %
2	1 y 6	Medium	$ 320.23	24.50 %	25.3 %	100 %
3	1 y 6	Low	$ 330.83	28.62 %	25.3 %	100 %
4	1	High	$ 297.21	15.55 %	18.9 %	74.70 %
5	1	Medium	$ 307.22	19.44 %	18.9 %	74.70 %
6	1	Low	$ 314.69	22.33 %	18.9 %	74.70 %
7	6	High	$ 266.00	3.41 %	6.3 %	24.90 %
8	6	Medium	$ 270.27	5.07 %	6.3 %	24.90 %
9	6	Low	$ 273.43	6.30 %	6.3 %	24.90 %
10	None	Rainfed	$ 257.22	-	0 %	0 %

Table 3: Simulation Results of Mean Net Annual Profits (dollars per ha)

The difference between mean annual profits under rainfed crops and irrigated can be also observed in Figure 1, which depicts simulated profits per year for the whole basin for the period (2000-2019). Additionally, it can be seen that scenarios with full irrigation coverage (1, 2 and 3) achieve better results than those with partial coverage (4, 5, 6, 7, 8 and 9). Dry years, such as 2001, 2009 or 2012 explain much of this difference between profits (see precipitations in annex). This is an expected result, as irrigation reduces water stress suffered by the plants in drier years, preventing significant yield losses.

Figure 1: Mean Profit per Hectare per Scenario (2000-2019).

Figure 2 also displays the evolution of annual profits per hectare for each rotation and scenario. For rotation 1, irrigation is applied under scenarios 1 to 6 whereas scenarios 7 to 10 imply no irrigation. Rotation 6 is treated with irrigation in scenarios 1 to 3 as well as 7 to 9. Although not identical, these two groups (irrigation or rainfed scenarios) mean profits remain similar for a given rotation, making it difficult to distinguish their respective time series plotted in Figure 2. Within each group, profit differences can be explained by fertilization levels as well as externalities from the hrus in the remaining rotation[4]. Conversely, while relative results among scenarios remain similar to those of Figure 1, there are some differences between results per rotation. Rotation 1 has a lower year-to-year variation than rotation 6 since it has a different crop mix and length. In particular, higher profits in rotation 1 can be explained by the higher frequency of the two main crops (corn and soybean) in a given year.

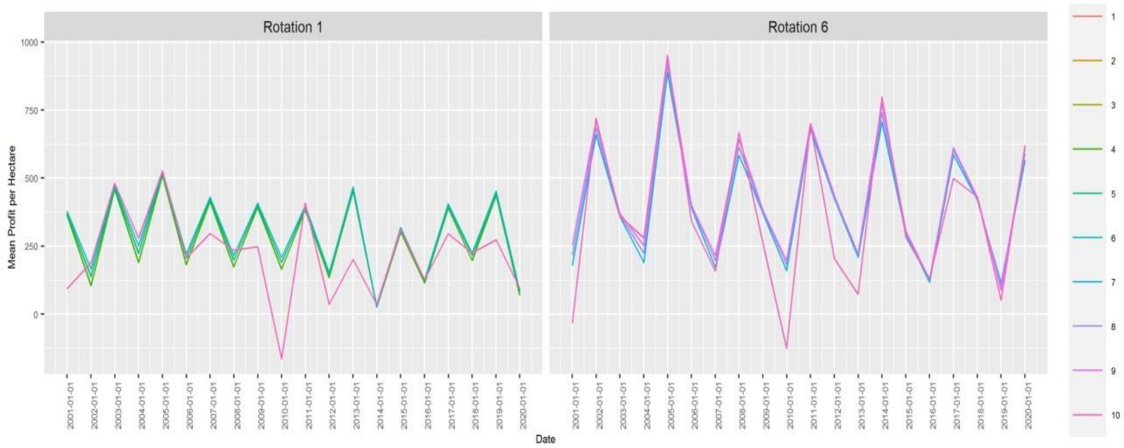

Figure 2: Mean Profit per Hectare per Scenario and Rotation (2000-2019).

Figure 3 shows profit dispersion across HRU's per year, and per scenario. Similar to Figure 1, there are salient differences between irrigation and rainfed profits in dry years 2001, 2009 and 2012. Rainfed production units tend to suffer more those years, since a large number of them experience losses. On the other hand, although the large majority of the production units achieve higher profits with irrigation, a small number[5] of them experience significant losses. Those losses are explained by increasing variable costs from irrigated water which are not compensated by yields improvements during dry years. Therefore, although irrigation remains convenient for a large portion of production units, not all of them are responsive to irrigation. Large irrigation costs in these units explain the presence of significant losses of more than 500 dollars in dry years. On the other hand, in spite of experiencing lower median profits, due to the absence of irrigation costs, losses of rainfed production units remain limited in dry years.

[5] For example, in scenario one, approximately 7% of units experience losses.

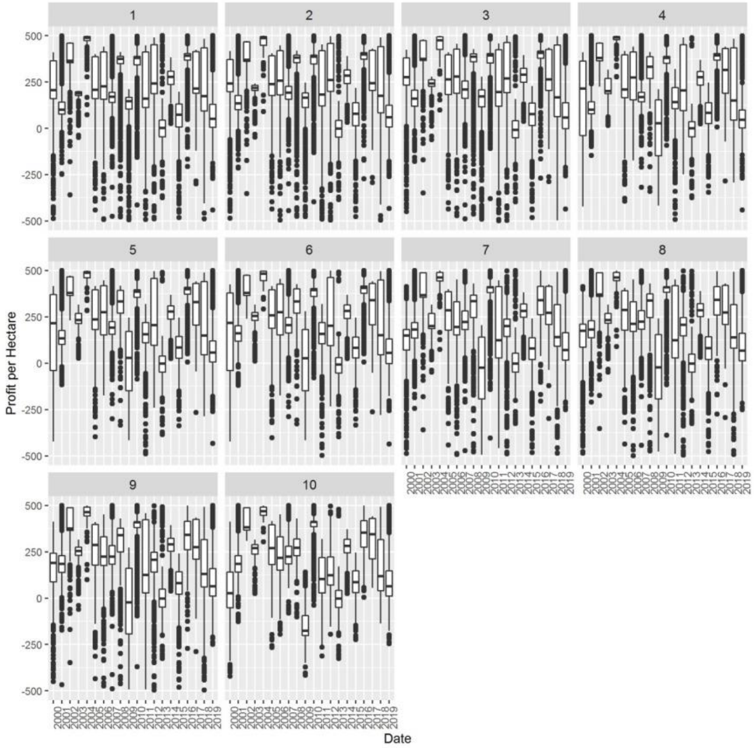

Figure 3: Profit per Hectare Dispersion (for each HRU) by Year and Scenario.

Simulated Certainty Equivalent. Previous results about mean profits per hectare for the whole simulated period, showed in Table 3, are the particular case where the mean certainty equivalent of equation (8) is calibrated for a risk-neutral agent (ARA parameter equal to zero). In this case, the basin central planner would value a certainty equivalent equal to the expected value of the profits. However, as risk aversion increases, it is important to account for and quantify changes in economic benefits of irrigation and fertilization practices, and how do they change for different levels of risk aversion.

Certainty equivalent results, calculated according to parameters of risk aversion reported in section 2.2 are displayed in Table 4Table 4. Values range from negative to positive figures. The worst case implies an extremely risk averse basin planner (ARA equal to 0.035) in the rainfed crop scenario, which would pay 74 dollars per hectare to sell the lottery. On the other end is a moderately risk averse planner (ARA equal to 0.007) in scenario 3 (both rotations are irrigated with low increases in fertilizer application) who would only sell his lottery for 242 dollars per hectare.

As expected, certainty equivalent values decrease with higher levels of risk aversion. As stated in equation (4), this reflects the fact that risk averse individuals would pay higher risk premiums to get rid of the lottery. On the other hand, at the same level of risk aversion, scenarios with irrigation on both rotations reduce significantly the risk premium as certainty equivalent values increase with respect to rainfed certainty equivalent. The magnitude of this difference grows as the individual becomes more risk averse. Particularly, when the ARA parameter equals 0.021, 0.028 or 0.035, the rainfed agriculture scenario has a negative certainty equivalent which becomes positive in scenarios (1, 2, 3, 4, 5 and 6) where irrigation is applied to the majority of the area. Hence, even when considering extreme risk averse basin planners, production would be possible in most of the irrigation scenarios.

Under all risk preference levels, the most preferred scenarios imply the irrigation of both rotations. Instead, preferred fertilization levels will depend on risk aversion levels. A moderately risk averse planner (ARA equal to 0.007, 0.014 and 0.021) would prefer practices with lower fertilization increases whereas a more risk averse planner (ARA equal to 0.028 and 0.035) would prefer fertilization practices based on medium increases. This change in preferences show how more risk averse agents value the effect of fertilizer on uncertainty reduction via yield stabilization.

Conversely, on the rainfed practices scenario, certainty equivalents are only positive when risk aversion levels are moderate. This implies that, even when expected benefits under rainfed agriculture are of 257 dollars per hectare, a risk averse planner could decide not to produce due to high risk premiums. This risk premium is determined by the higher volatility of profits with respect to irrigation scenarios. Particularly, volatility is exacerbated in dry years where crop yields are affected by hydric stress.

	Absolute Risk Aversion Coefficient					
Scenario	0	0.007	0.014	0.021	0.028	0.035
1	$ 305.96	$ 219.99	$ 172.03	$ 143.78	$ 125.13	$ 111.92
2	$ 320.23	$ 234.89	$ 184.52	$ 153.48	$ 132.78	$ 118.23
3	$ 330.83	$ 242.61	$ 188.58	$ 154.60	$ 132.03	$ 116.34
4	$ 297.22	$ 188.89	$ 130.41	$ 96.67	$ 74.99	$ 60.00
5	$ 307.22	$ 200.10	$ 139.77	$ 103.98	$ 80.93	$ 65.12
6	$ 314.67	$ 206.22	$ 143.50	$ 105.90	$ 81.82	$ 65.45
7	$ 266.00	$ 155.56	$ 72.78	$ 24.72	-$ 3.39	-$ 21.34
8	$ 270.27	$ 159.25	$ 75.91	$ 27.11	-$ 1.66	-$ 20.16
9	$ 273.43	$ 160.85	$ 76.23	$ 26.30	-$ 3.32	-$ 22.39
10	$ 257.22	$ 124.35	$ 30.99	-$ 22.59	-$ 53.74	-$ 73.50

Table 4: Certainty Equivalent by Scenario and Risk Aversion Level.

The difference between certainty equivalent values between each irrigated agriculture scenario and the rainfed agriculture scenario can be observed in Table 5. In the most extreme case, where ARA equals 0.035, the difference between the certainty equivalent in rainfed agriculture and the irrigated agriculture (scenario 2) is of 191 dollars per hectare.

Moreover, previous observations about the potential risk-reducing benefits of irrigation are verified in the same table. While irrigation could induce improvements up to 73 dollars per hectare via higher expected profits, improvements due to risk premium reductions could be even greater. For example, in scenario two where improvements via expected profits are valued in 63 dollars per hectare, an extreme risk averse planner could value improvements from risk premium reduction as high as 128 dollars per hectare (difference between total CE increase of 191 dollars per hectare and CE increase for a risk neutral agent of 63 dollars per hectare). Hence, in this scenario, economic benefits via risk premium reductions could account for approximately two thirds of the total benefits.

	Absolute Risk Aversion Coefficient					
Scenario	**0**	**0.007**	**0.014**	**0.021**	**0.028**	**0.035**
1	\$ 48.74	\$ 95.63	\$ 141.04	\$ 166.37	\$ 178.87	\$ 185.42
2	\$ 63.01	\$ 110.53	\$ 153.53	\$ 176.07	\$ 186.52	\$ 191.73
3	\$ 73.61	\$ 118.26	\$ 157.59	\$ 177.19	\$ 185.77	\$ 189.84
4	\$ 40.00	\$ 64.54	\$ 99.42	\$ 119.27	\$ 128.73	\$ 133.49
5	\$ 50.00	\$ 75.75	\$ 108.78	\$ 126.57	\$ 134.66	\$ 138.62
6	\$ 57.45	\$ 81.87	\$ 112.51	\$ 128.50	\$ 135.56	\$ 138.95
7	\$ 8.78	\$ 31.21	\$ 41.79	\$ 47.31	\$ 50.35	\$ 52.16
8	\$ 13.05	\$ 34.90	\$ 44.92	\$ 49.70	\$ 52.08	\$ 53.34
9	\$ 16.21	\$ 36.50	\$ 45.24	\$ 48.89	\$ 50.42	\$ 51.10

Table 5: Certainty Equivalent Increase, per Scenario and Risk Aversion Level.

Relative to Rainfed Agriculture Scenario.

Finally, when observing certainty equivalents at the unit level for each scenario and risk aversion parameter (see annex), most of the results are positive. In cases where certainty equivalents are negative, this result is explained by recorded losses due to low yield, excessive irrigation or both. However, in the non-rainfed scenario an upward shift in the boxes with respect to the rainfed agriculture scenario is observed, which shows that most of the units experienced growth in their certainty equivalent values. The same result is clearly observed on the density functions plotted in Figure 8 and Figure 9 in the annex, which show a shift towards higher values.

5.2 Environmental Results

In Table 6, environmental results in terms of nitrate and phosphorus concentrations are reported for each scenario. The main indices to report water pollution are mean and median values nitrate and phosphorus on water as well as maximum values and the percentage of time (measured in days) in which the environmental threshold is breached.

In the case of nitrates (NO3), in the rainfed agriculture scenario, the simulated mean value for the 2000-2019 period was of 3.11 mg/l while the simulated median value was of 1.26 mg/l. These results are in line with those reported by the Environment Ministry of Uruguay.[6] For alternative scenarios, results indicate that nitrate concentrations will be higher as agricultural intensification is based on higher quantities of fertilizer application. In the most intensive scenario, where the increase in fertilization quantities is high and irrigation is applied on both rotations, the median value increases up to 3.58 mg/l and the median to 1.40 mg/l. As observed in Table 7, these variations are of 15.38% and 11.11% for nitrate mean and median concentration respectively.

On the other hand, the maximum recorded values for daily nitrate concentrations in the same period are excessively high, with values as high as 242 mg/l in the worst case scenario (9). These values are mainly explained by low simulated flow in the year 2008, when there was a major drought in the region. Nevertheless, those maximum values decay slowly in the most intensive scenarios.

The established environmental threshold for nitrate concentration was suggested by the Environment Ministry, which uses a value of 1 mg/l. This threshold is breached in most of the simulated days. In the rainfed agriculture scenario, the threshold is breached in 53.74% of the days. Conversely, in the most intensive use scenario this value grows up to 57.92%, which implies an increase rate of 7.75 with respect to rainfed production.

For phosphorus, as indicated before in the model data section, the reported values are informative only in relative terms. This is so because the basin SWAT model is still being in its development phase for phosphorus loads. Therefore, we will focus our phosphorus results analysis on relative variations as presented in Table 7. In this table we observe that, in the most intensive land use scenario (1), the mean phosphorus concentration grows 5.81% while the median value grows 13.28%.

Scenario	Mean NO3	Max NO3	Median NO3	NO3 Viol	Meean P	Max P	Median P	P viol
1	3.58	220.63	1.40	57.92 %	0.0072	0.3194	0.0051	0.42 %
2	3.44	218.39	1.36	57.50 %	0.0072	0.3179	0.0050	0.42 %
3	3.32	222.01	1.34	57.50 %	0.0072	0.3171	0.0050	0.42 %
4	3.39	218.26	1.33	55.83 %	0.0071	0.3172	0.0050	0.42 %
5	3.34	223.98	1.33	55.83 %	0.0071	0.3161	0.0049	0.42 %
6	3.24	219.60	1.33	55.83 %	0.0071	0.3159	0.0049	0.42 %
7	3.29	234.44	1.31	56.25 %	0.0070	0.3330	0.0046	0.42 %
8	3.25	236.40	1.30	55.83 %	0.0070	0.3339	0.0046	0.42 %
9	3.22	242.00	1.30	55.83 %	0.0069	0.3342	0.0046	0.42 %
10	3.11	232.50	1.26	53.75 %	0.0068	0.3296	0.0045	0.42 %

Table 6: Nitrates (NO3) and Phosphorus (P) Concentrations at the Basin Outlet.

[6] Measurements reported in the document, for the 2014-2019 period, are of 2.4 mg/l for median values. https://www.gub.uy/ministerio-ambiente/comunicacion/publicaciones/evolucion-calidad-agua-cuenca-del-rio-san-salvador-2014-2019

Scenario	Mean NO3	Max NO3	Median NO3	NO3 Viol	Median P	Max P	Median P	P Viol
1	15.38 %	-5.10 %	11.11 %	7.75 %	5.81 %	-3.10 %	13.24 %	0 %
2	10.86 %	-6.07 %	8.54 %	6.98 %	5.39 %	-3.57 %	13.06 %	0 %
3	7.06 %	-4.51 %	6.91 %	6.98 %	4.84 %	-3.80 %	12.68 %	0 %
4	9.17 %	-6.12 %	6.02 %	3.88 %	4.19 %	-3.78 %	11.10 %	0 %
5	7.41 %	-3.66 %	5.82 %	3.88 %	3.86 %	-4.12 %	10.56 %	0 %
6	4.48 %	-5.55 %	5.66 %	3.88 %	3.58 %	-4.17 %	10.39 %	0 %
7	6.07 %	0.83 %	4.18 %	4.65 %	1.65 %	1.02 %	2.87 %	0 %
8	4.57 %	1.68 %	3.79 %	3.88 %	1.60 %	1.29 %	2.87 %	0 %
9	3.67 %	4.09 %	3.48 %	3.88 %	1.57 %	1.38 %	2.91 %	0 %

Table 7: Nutrient Concentration Variations With Respect to the Rainfed Agriculture Scenario.

Additionally, the cumulative density function for nitrates is displayed on Figure 4. As noted above, mean nitrate concentration values are higher than median values due to the presence of extreme concentrations on dry years. The red vertical line indicates the environmental threshold of 1 mg/l. Comparing cumulative density functions between scenarios, a shift towards higher concentrations is noted as agriculture becomes more intensive.

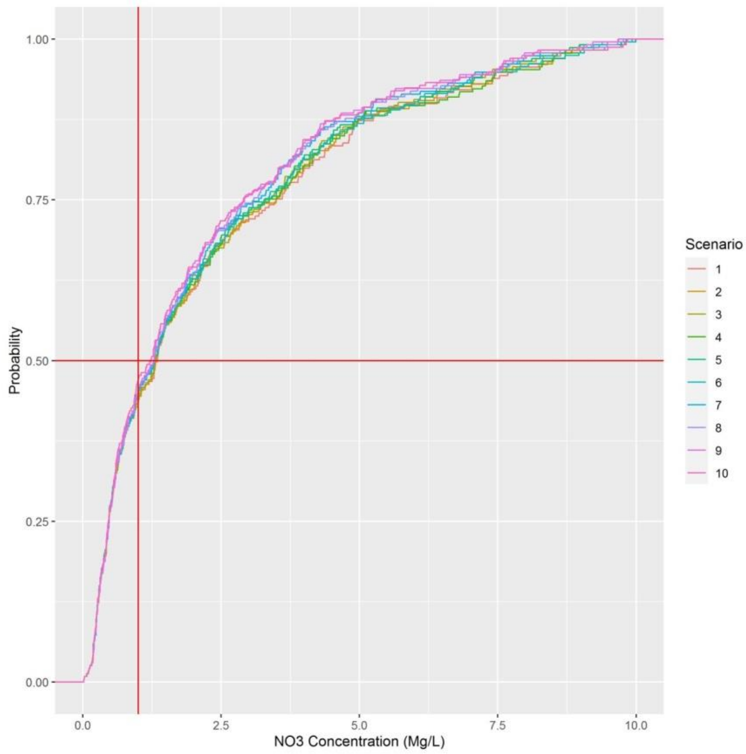

Figure 4: Cumulative Density Function for Nitrates Concentration at the Basin Outlet. The Vertical Line indicates the Environmental Threshold.

For phosphorus concentrations, shown in **¡Error! No se encuentra el origen de la referencia.**, as concentration levels are not informative, we focus our analysis only on the relative variations between the cumulative density functions. In this case, we also note a shift from lower concentration levels, in the rainfed agriculture scenario, towards higher phosphorus concentrations as agriculture intensifies its practices.

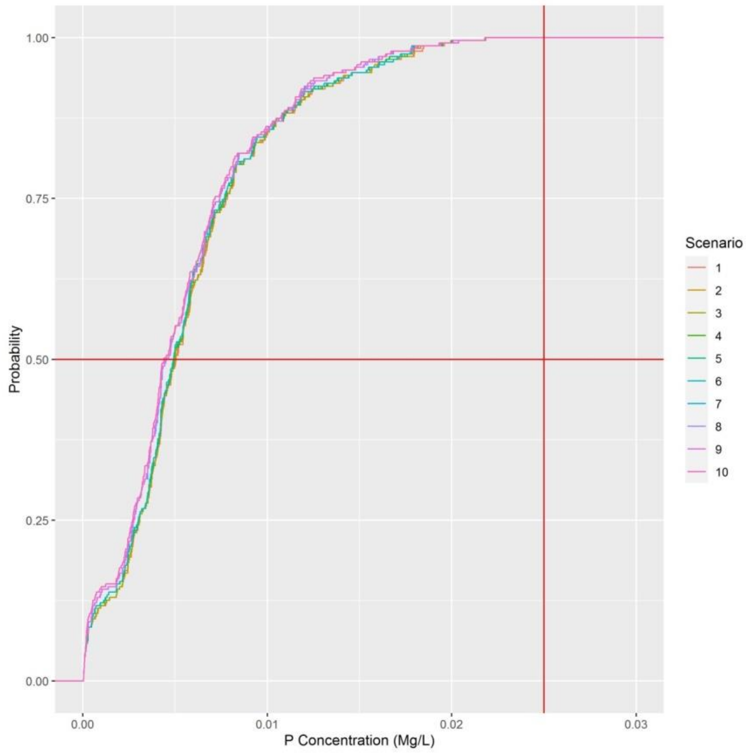

Figure 5: Cumulative Density Function for Phosphorus Concentration at the Basin Outlet. The Vertical Line indicates the Environmental Threshold.

Lastly, Table 8 quantifies the cumulative density function shifts for each scenario with respect to the base rainfed agriculture scenario. In order to compare those shifts we normalize each scenario's mean, computing them intro a unitary range by subtracting the range's minimum value (zero) and dividing by the length of the range (maximum simulated concentration level minus zero). Hence, using the normalized mean ($\mu_{normalized} = \frac{\mu - Min}{Max - Min}$) for each scenario, we measure the shift for each scenario by computing the difference between its mean and the base (rainfed) scenario's mean. As noted in the Table, the shifts between scenarios (excepting scenarios 3 and 6) are greater for nitrates than for phosphorus.

Scenario	Normalized Mean NO3	Variation	Normalized Mean P	Variation
1	0.0148	0.0020	0.0217	0.0012
2	0.0142	0.0014	0.0216	0.0011
3	0.0137	0.0009	0.0215	0.0010
4	0.0140	0.0012	0.0213	0.0009
5	0.0138	0.0010	0.0213	0.0008
6	0.0134	0.0006	0.0212	0.0007
7	0.0136	0.0008	0.0208	0.0003
8	0.0134	0.0006	0.0208	0.0003
9	0.0133	0.0005	0.0208	0.0003
10	0.0128	0.0000	0.0205	0.0000

Table 8: Cumulative Density Function Shift With Respect to the Rainfed Agriculture Scenario.

5.2 Cost-Effectiveness

Results about equations (11) and (12) are presented on Table 9 and Table 10. These tables show the impact of a marginal relaxation of one percentage point of nutrient concentration (median value) on the annual certainty equivalent per hectare. Each table places scenarios on its rows and risk aversion levels on its columns. In this way, the value placed in each cell represents the tradeoff between a marginal relaxation in the nutrient level for a given scenario and risk aversion level.

	Absolute Risk Aversion Coefficient					
Scenario	0	0.007	0.014	0.021	0.028	0.035
1	4.39	8.61	12.69	14.98	16.10	16.69
2	7.38	12.94	17.97	20.61	21.83	22.44
3	10.66	17.12	22.82	25.65	26.90	27.49
4	6.65	10.72	16.52	19.82	21.39	22.18
5	8.59	13.02	18.70	21.75	23.15	23.82
6	10.16	14.48	19.89	22.72	23.97	24.57
7	2.10	7.47	10.00	11.32	12.04	12.48
8	3.44	9.21	11.85	13.11	13.74	14.07
9	4.66	10.50	13.02	14.07	14.51	14.70

Table 9: Tradeoff Ratios Between Economic Benefits and Median Nitrates Pollution.

	Absolute Risk Aversion Coefficient					
Scenario	0	0.007	0.014	0.021	0.028	0.035
1	3.68	7.22	10.65	12.57	13.51	14.01
2	4.83	8.47	11.76	13.49	14.29	14.69
3	5.81	9.33	12.43	13.98	14.66	14.98
4	3.60	5.81	8.95	10.74	11.59	12.02
5	4.74	7.18	10.31	11.99	12.76	13.13
6	5.53	7.88	10.83	12.37	13.05	13.38
7	3.06	10.88	14.56	16.49	17.55	18.18
8	4.55	12.16	15.65	17.32	18.15	18.59
9	5.58	12.55	15.56	16.82	17.34	17.58

Table 10: Tradeoff Ratios Between Economic Benefits and Median Phosphorus Pollution.

As noted in the economic results section, agricultural intensification through irrigation and fertilization practices tend to raise yield and economic benefits for producers. At the same time, this phenomenon could bring higher nutrient (P and NO3) concentration levels as a consequence of numerous factors such as growing fertilizer use and its interaction with other biophysical processes such as surface runoff, leaching, etc.

As presented on Table 9, the tradeoff between median nitrate concentrations and the certainty equivalent is greater for scenarios 6 and 3. Those scenarios imply a low increase of nutrient application. As a consequence of the variation on certainty equivalents (ratio numerator) we observe a monotone increase in the tradeoff ratio as risk aversion grows. Results show that, on the best scenario (3), the relaxation of one percentage point on median nitrate concentration could yield an increase of 10.66 dollars per hectare in the certainty equivalent of a risk neutral planner whereas this amount grows to 27.49 dollars for an extreme risk averse individual (ARA equal to 0.035).

For phosphorus, results show that scenarios 7, 8 and 9 are those with best tradeoff ratios when the planner is risk averse while scenario 3 if preferred if the planner is risk neutral. In the case of an extremely risk averse planner, in the best scenario (8), a resignation of one percentage point in the median value of phosphorus could yield an increase of the certainty equivalent of 18.59 dollars. In the case of a risk neutral planner, in the best scenario (3), a resignation of one percentage point in phosphorus median concentration yield an increase of the certainty equivalent valued on 5.81 dollars. The convenience of scenarios 7, 8 and 9 could be explained by the lower relative variation in their median phosphorus concentrations (lower denominator).

When taking into account the central planner tradeoffs in terms of both nutrients, the optimal decision varies according to its risk aversion preferences as well as the importance placed on each nutrient concentration. In the case of a neutral risk planner, the best tradeoff scenario is scenario 3, which combines low increases in fertilizer application with irrigation on both rotations. Conversely, when the planner is extremely risk averse, there is not a single scenario that comes first for both nutrients. However, assuming that both nutrients are equally important, when comparing the best scenario (3) for nitrate tradeoffs with the best scenario (8) for phosphorus tradeoffs, scenario 3 seems to be better for the joint quantities.

Results also show that high increases of fertilizer application do not seem to have good relative economic or environmental results given that scenarios 1, 4 and 7 are not particularly highlighted in our results. Lastly, although rainfed agriculture achieves better environmental results than the rest of the nine scenarios of agricultural intensification in terms of water pollution, it implies a significant opportunity cost in economic terms. More specifically, this cost will be even higher for an extremely risk averse basin central planner, who might resign economic benefits valued as high as 190 dollars per hectare (Table 4), which is a significant amount for agricultural returns.

6. Conclusions

The present work measured the effects of agricultural intensification through irrigation and fertilization practices, on economic and environmental results for one of the most important Uruguayan agricultural basins, the San Salvador river basin. This work has been carried out through the novel application the first time in the country, of an integrated assessment model (IAM). This modeling approach enabled us to explore in the period 2000-2019, the effects of ten different agricultural management scenarios in terms of irrigated area and fertilizer application. Particularly, the integrated model consisted on the integration of a widely used biophysical model as the SWAT (Neitsch et al., 2011) with an economic model based on the expected value theory. This latter was based on national antecedents such as Rosas et al. (2017) and also international ones (Pandey, 1990; Apland, 1980).

For two of the most typical agricultural rotations in the basin, we estimated the economic benefits and nutrient concentrations in a rainfed agriculture scenario. Moreover, considering the economic potential of irrigation and fertilizer application practices on both of these rotations, the same results were computed for nine alternative scenarios with different levels of irrigation and fertilization application.

The proposed model includes the economic benefits valuation derived from higher expected yield as well as those derived from lower yield volatility. These benefits are measured through the application of the expected utility theory concept of certainty equivalent. This concept allows us to measure, for a given risk aversion preference profile, the economic benefits of agricultural intensification derived from yield increases and yield interannual volatility reductions.

Results show an estimated mean profit per hectare of 257 dollars under rainfed agriculture for the whole period. Notwithstanding, this value could increase up to 330 dollars per hectare when both rotations are irrigated with low increases in fertilizer application. Taking into account different profiles on risk preferences, the difference between economic benefits under irrigation and rainfed agriculture could increase to 189 dollars. This result is explained by a reduction in the basin planner risk premium.

Additionally, when considering the tradeoffs between the economic benefits and water pollution, irrigation scenarios with low increases in fertilizer application (with respect to rainfed agriculture) are the ones with better performance. Most of the considered scenarios show increases in the certainty equivalent in the range of 1-30 dollars when the nutrient median concentration is relaxed in one percentage point.

Finally, it must be noted that our model results depend on the quality of the SWAT biophysical calibration, which is still being developed. Model developments are being held mainly on aspects related to the simulation of phosphorus and nitrates nutrient concentrations. Therefore, results are subject to revisions as SWAT model calibration improvements related to those variables are made.

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7. Annex

7.1 Crop Operations

Crop	Planting Date	Harvest Date
Corn	23-Sep	20-Feb
Oats	2-May	11-Nov
Oats (After Corn or Soybean 2)	22-Apr	22-Sep
Soybean	12-Nov	21-Apr
Soybean 2	10-Dec	1-May
Wheat	14-Jun	25-Nov
Barley	14-Jun	25-Nov
Pasture	22-Apr	11-Nov

Table 11: Dates of Operations

7.2 Economic Data

7.2.1 Prices

Crop	Price per Ton
Soybean	310
Wheat	140
Barley	140
Corn	185
Oats	195

Table 12: Crop Prices.

7.2.2 Costs

Crop	Cost per Hectare by Fertilization Increase Level			
	Base	Low	Medium	High
Soybean (1st)	488	496	504	512
Soybean (2nd)	395	401	406	412
Wheat	476	504	531	559
Barley	539	568	599	628
Corn	694	733	773	813
Oats	393	415	436	458

Table 13: Costs per Crop and Fertilization Level.

7.3 Additional Figures

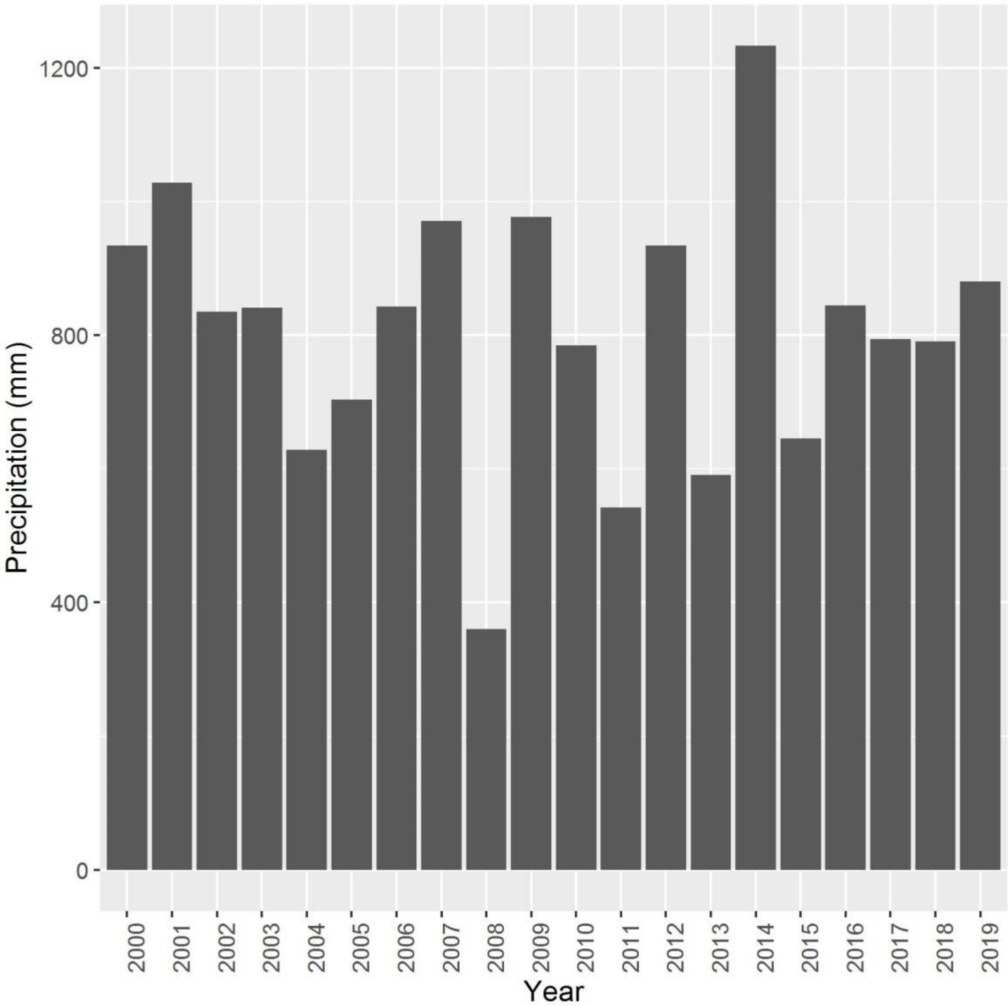

Figure 6: Precipitations per Year.

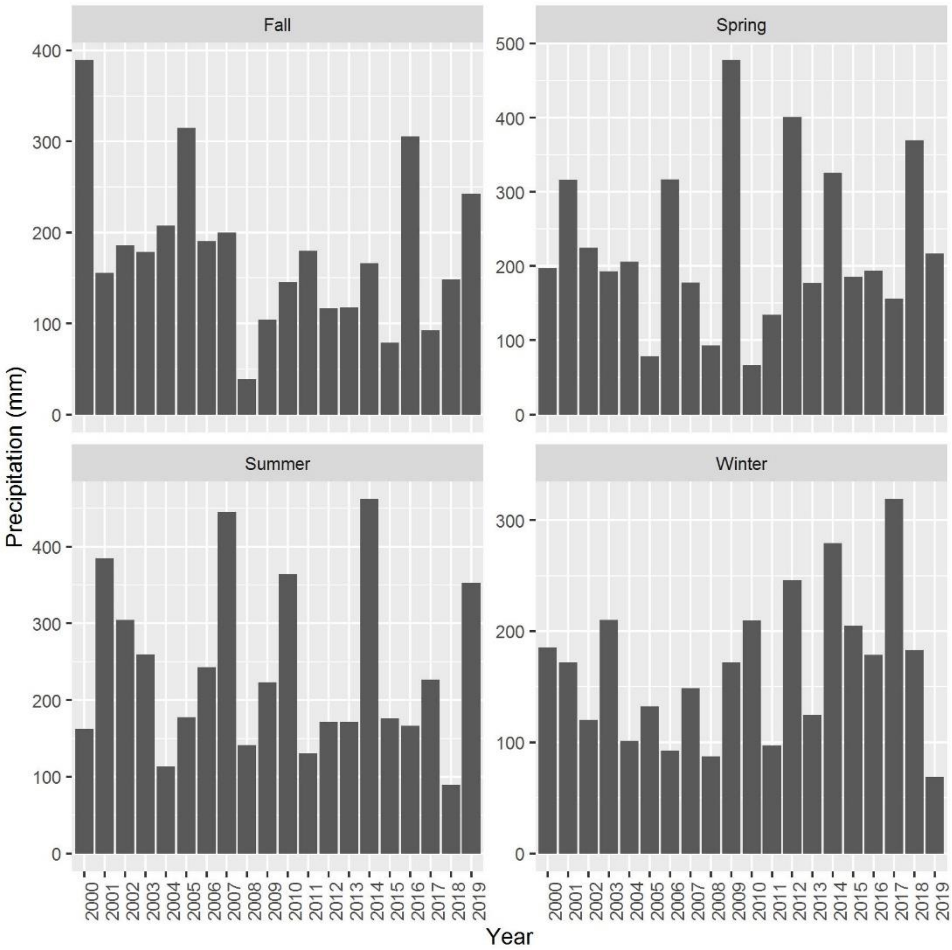

Figure 7: Seasonal Precipitations.

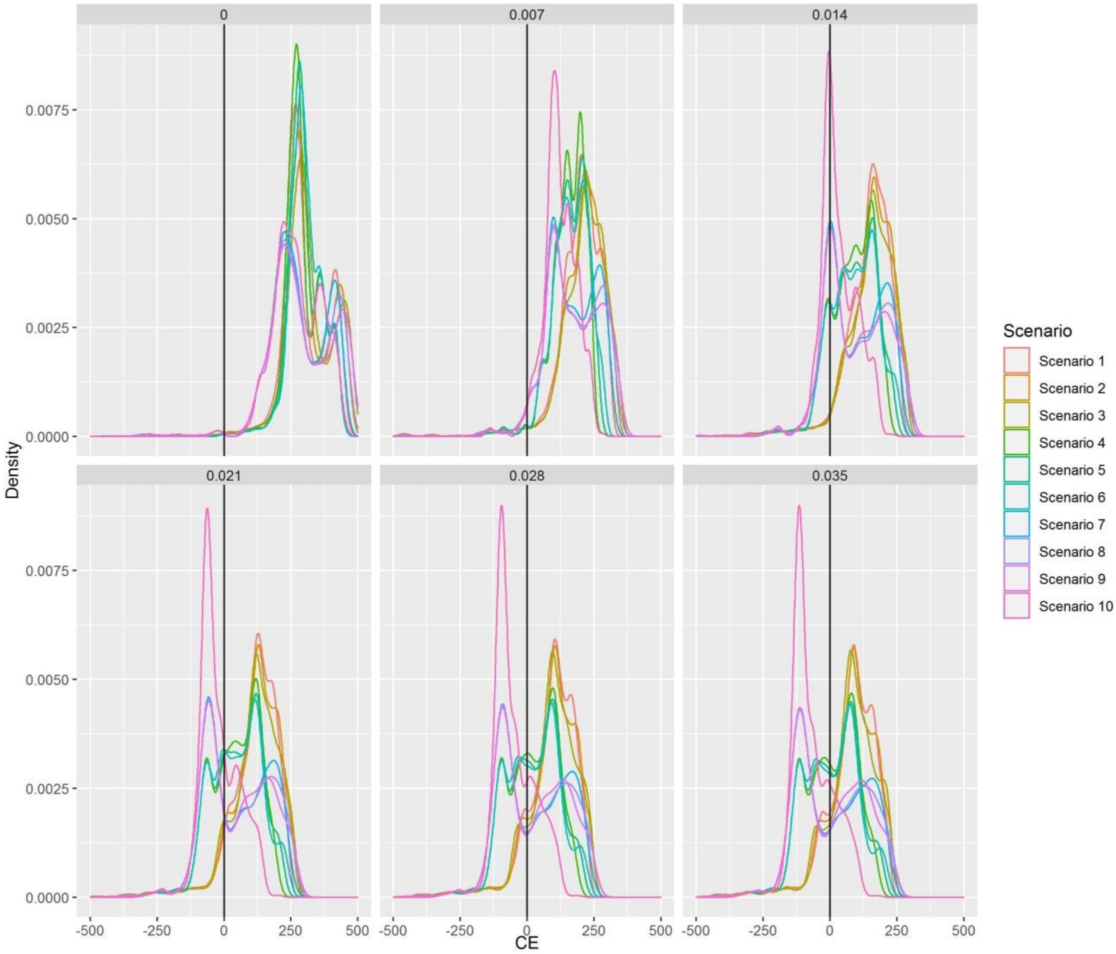

Figure 8: Certainty Equivalent per Scenario and Risk Aversion Level.

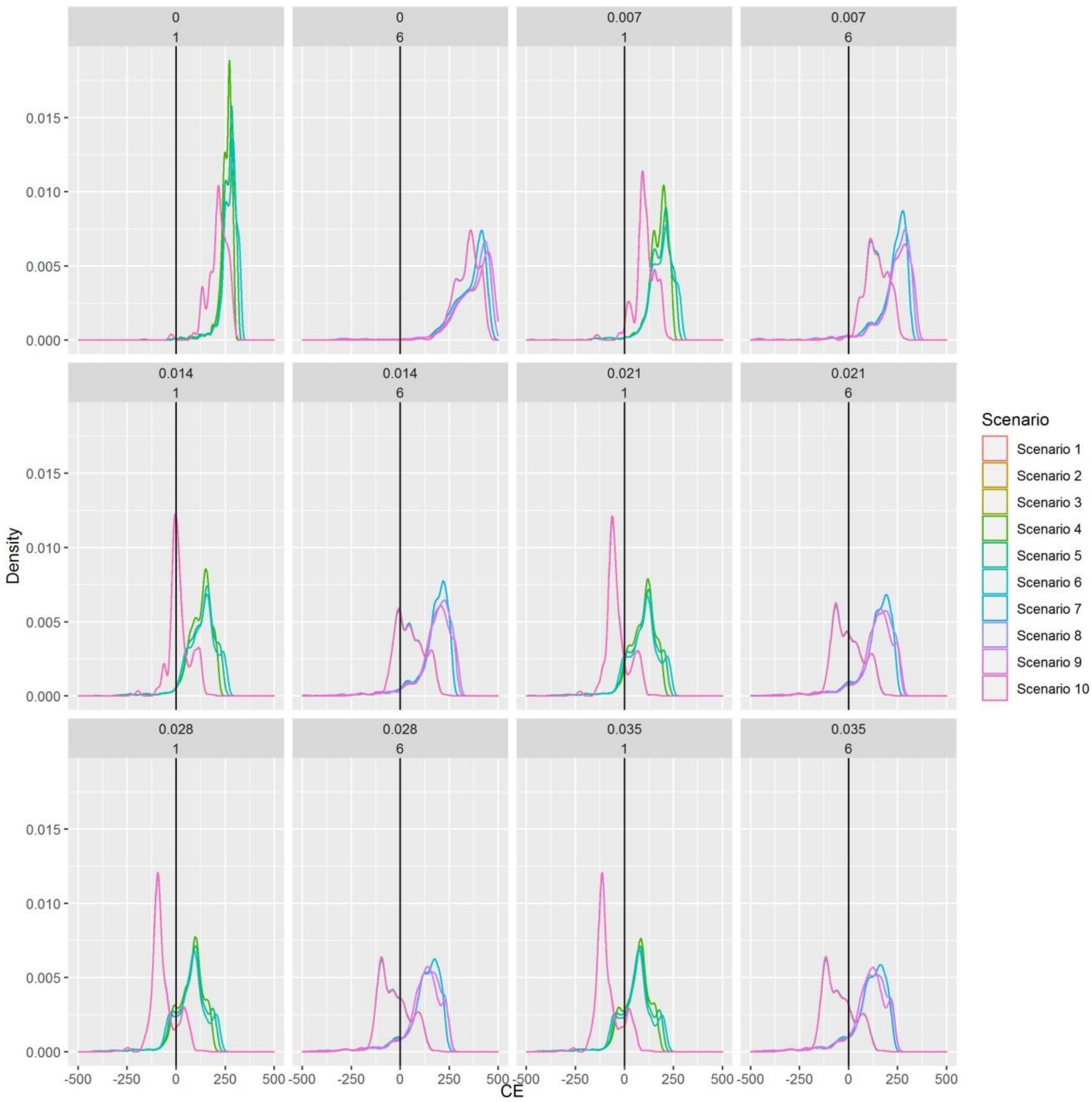

Figure 9: Certainty Equivalent per Scenario, Risk Aversion Level and Rotation.