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Assessing the limits of sustainable intensification for agriculture using a spatial model framework

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Abstract

In a collaborative effort with private agents of the oilseed industry, we carried out a research project to determine the feasibility of framing soybean production in Uruguay into sustainable development pathway. We adopted a spatial model based on land suitability analysis to estimate potential yields and the most suitable area for cultivation. We imposed several restrictions to define the potential cropping land based on risk erosion, current and alternative soil uses, transportation and logistics costs, and crop economic margins. We built different price-yields scenarios to estimate the potential area. With all restrictions imposed, the potential soybean area would be 2.1 million hectares by 2050, on rotation with other crops and pastures with an average yield of 3.3 MT/ha. This ad-hoc approach can be extended to any crop situation or region when the objective is to define how far it is possible to expand and intensify production without compromising the environment.

JEL Codes : O30, Q20, Q55

1. Background

Soybean is the most widely planted oilseed in the world. Worldwide production attained 388 million metric tons in 2022/23 (USDA, 2023). It offers various food and technical uses, highlighting its use in animal feed. A large part of soy production is not consumed where it is produced. While three-quarters of world soybeans are produced in the 'Americas', more than 90% of the soybeans traded in the international market, nearly 40% of total production, find the origin in this region. Brazil and the USA are the main worldwide producers and exporters. As shown in Table 1, the top-6 world exporters of this oilseed in 2021 came from South (Brazil, Paraguay, Argentina, and Uruguay) and North America (USA and Canada).

<TABLE 1>

Uruguay enjoys an important reputation as a sustainable food and fiber producer for the rest of the world. For decades, crop production has been carried out basically in rotation with pastures and other commercial crops. In addition, farmers must accomplish mandatory 'land use and management plans' (Hill and Clérici, 2011). They are expected to choose realistic and sustainable crop rotation sequences to optimize yields and profits while, at the same time, preserving natural resources, maintaining soil structure, avoiding erosion, and maximizing natural control of weeds, pests, and diseases, among other things.

In the last ten years, Uruguay positioned between 9^{th} and 12^{th} in the ranking of largest soybean producers in the world. In 2021, it was the 12^{th} producer and the 6^{th} worldwide exporter. However, the history of the country regarding this crop is relatively recent. Being a very small producer during the last Quarter of the XX century, the area devoted to the oilseed was boosted at the beginning of the new century with the growth of Chinese demand. On the farmer's side, the growth was driven largely by foreign producers coming to Uruguay, especially from Argentina. These farmers commanded the new "soy boom", bringing state-of-the-art technology, particularly no-tillage cultivation, and GM varieties.

The high quotes recorded during the global "commodity boom" pushed soy cultivation to marginal agricultural areas, which were able to receive very high rents. Soon after, in 2013, the area planted in the country was attaining one million hectares annually, peaking at more than 1.3 million hectares in 2014-2015. The subsequent decline in international prices led to a reduction in the following years, to around 900 thousand hectares in 2020 and 2021.

Even when Uruguay only represents something more than 1% of the global market, both in quantity and value, the area devoted to this crop and the level of production is nevertheless of great relevance in economic terms. More than 90% of the national production is exported with a very low degree of processing, mostly to China (85-90%) and the European Union (9%). In 2022, the monetary value of the exports reached roughly 2 billion US dollars, constituting one of the top-three export products, along with beef and cellulose pulp.

Borges *et al*. (2022) estimated that in 2021, from each ton of soybeans exported, the soybean chain transferred US$ 100 to the rest of the Uruguayan economy (28% of the total net benefit of US$ 354). Considering the whole rotation including soybeans (including winter crops), the transfer to the rest of the economy reached US$ 181 out of a total benefit of US$ 408 (44%) per metric ton of soybeans exported to the rest of the world.

In turn, Ferraro *et al*. (2021) valued the GDP of the oilseed complex at US$ 783 million in the 2021 harvest. This represented 1.4% of the total GDP of the economy and a growth of 3.4% compared to the previous year. In 2022, this contribution doubled and reached 2.8% (US$ 1.7 billion), the highest value since records are available (Fernández *et al*., 2022).

In 2014, Uruguay was chosen as a pilot experience to implement an 'agricultural transformation pathway", under the Sustainable Development Solutions Network (SDSN) initiative of the United Nations. The objective was to promote practical problem-solving solutions through sustainable development actions (Kanter *et al*., 2016; Schwoob *et al*., 2016). The Ministry of Livestock, Agriculture, and Fisheries of Uruguay and the National Institute for Agricultural Research (MGAP and INIA, respectively, according to their corresponding Spanish acronyms) included the five most relevant agribusiness sectors for the country: dairy, rice, non-irrigated crops, and forestry (Ferraro *et al*., 2015).

In 2021, INIA started a new research study, as part of a broader collaboration project with the Oilseeds Technological Board (MTO) and the Uruguayan Oilseeds Conglomerate (OUY), the two entities gathering the private agents that make up the oilseed chain in Uruguay. This project aimed to determine the real capacity to frame soybean production in a path of sustainable development and to define how far it is possible to grow and intensify production without compromising natural resources and the environment. The main results of this component of the study are presented in this article.

2. Data and Methods

2.1. General framework

To estimate the area and potential yields of soybean cultivation that ensure the viability and profitability of the production system, as well as the sustainability of resources, this study adopted a six-step spatial model framework (Figure 1).

<FIGURE 1>

Based on a land suitability analysis, potential soybean yields were calculated on land with good aptitude for production. The model imposed several constraints to refine crop potential, based on erosion risk, current and alternative land uses, transportation, and logistics costs, and crop economic margins. The latter was estimated by considering different price scenarios and potential yields due to expected technological improvements.

In practice, each constraint was applied independently, resulting in a set of separate layers, each one corresponding to an independent map. The final composed area, all the restrictions applied, was obtained by over-imposing all the layers simultaneously to subtract the restricted areas from the potential area without restrictions. This calculation was performed through a geographical information system (GIS).

2.2. Land suitable analysis

We conducted a biophysical land suitability analysis (LSA) to determine the appropriateness of soils for a specific end, providing a powerful decision support tool to inform land use planning (FAO, 1976; Faggian *et al*., 2016). It compares crop requirements in terms of water, nutrients, and soil characteristics with observed values for those variables. Where ideal conditions are met, the potential yields can be reached. The farther the actual conditions are from those required, the lower the yield will be. We first evaluated for single-crop soybeans (no preceding winter crop) since it used to be the predominant situation in Uruguay, in the last decade until season 2020/21. We built upon the model developed by Borges (2019), which was revised and adjusted considering valuable contributions and recommendations made by several INIA specialists.

2.3. Model variables

Following research data available from Rizzo (2018), the potential soybean yield was set at 5.5 tons per hectare and defined as the dependent variable. The independent or explanatory variables were split into two categories: ‘water availability’ and ‘soil indicators’, the latter reflecting different soil characteristics and nutrient availability (Figure 2).

<FIGURE 2>

We used a simplified water balance model to estimate water availability (FAO, 2012).

$$WA_t = WA_{t-1} + R_t + I_t - PET_t - L_t \qquad t = 1, 2, \ldots, T \qquad (1)$$

where WA is water availability, R is rainfall, I variable denotes irrigation, PET is potential evapotranspiration, L corresponds to water losses, and subscript *t* denotes time. With WHC standing for water holding capacity,

If WA < 0 → set to 0 | If WA > WHC → set to WHC

As it truncates at zero, equation (1) tells whether there is a water deficit or not. However, it does not say how much is the deficit, in case it occurs. Since soybeans’ water demand is generally greater than available supply, we considered a second equation to measure the magnitude of the deficit. Defining water balance as WB, which allows for negative figures.

$$WB_t = WA_{t-1} + R_t + I_t - PET_t - L_t \qquad \text{If } WB > WHC \Rightarrow \text{set to } WHC \qquad (2)$$

The water balance model was run every month, from October to April, contemplating all phenological stages (emergence, flowering, grain filling, and maturity). After calculating the water balance for each month (see Figure 3), it was estimated for the entire crop cycle, aggregating the information in a weighted manner. The highest weights were assigned to January and February (60%), critical periods for plant growth. Climate information was obtained from INIA's Agroclimate and Information Systems Unit (INIA, 2023a), while soil water holding capacity information was obtained from Molfino (2009). The "soil indicators" variables included soil fertility, erosion, pH, drainage, rockiness, and exchangeable sodium. The data was downloaded from INIA (2023b).

<FIGURE 3>

After determining the variables, we set different ranges of values for each one and assigned a rating to reflect that the closer the actual conditions are to the ideal ones, the higher the yield and vice versa. For instance, soils with a pH higher than 7 are ideal for soybeans and therefore a rating of 1 was assigned, meaning that in those cases a 100% potential yield would be reached. When pH is between 4.5 and 5, only 50% of the potential yield would be achieved, and the rating drops to 0.5. Finally, if pH is lower than 4.5, it would be practically unfeasible to produce soybeans on those soils, and hence, a score of -1 was assigned, signifying that the area is restricted for this crop. The same reasoning also applies to the rest of the factors.

Later, the model verified for each pixel in the map, the rating obtained in each variable, and takes the lowest value as the result of the LSA, reflecting the well-known Liebig's 'Law of the Minimum'. The latter states that crop yield is determined by the nutrient element that is found in the lowest quantity (Liebig, 1855). Finally, the index was re-expressed in terms of yields. As aforementioned, a rating of 1 means that 100% of the potential yield could be achieved (5.5 metric ton/ha). A score of 0.9 means that 90% of potential could be obtained (5 metric ton/ha) and so on.

2.4. Environ mental considerations and current land uses

The model contemplated compliance with environmental regulations related to the Responsible Land Use and Management Plans[1] (PUMS, for its acronym in Spanish). In general terms, the PUMS's establish that a production unit can only carry out rotations that imply a soil loss due to erosion below the tolerance level determined for the type of soil in the unit analyzed. For this reason, the model estimated the potential erosion that would be generated if soybeans were planted throughout the territory, using data from García-Préchac (1992), Clérici and García-Préchac (2001), and Pérez et.al (2017). Then, it compared these values with the corresponding tolerance levels of each type of soil. In those cases where the threshold would be exceeded, the area was restricted or set as not available for soybean production.

Additionally, current land uses (Petraglia *et al*., 2019) were considered to impose restrictions on soybean expansion where it is impossible or highly unfeasible to convert land from one use to another, being consistent with the growth expected for other productive activities. This is the case for urban areas, infrastructure, water bodies, horticulture, dairy, native forest, olives, sugar cane, and rice. Wetlands and protected areas were also excluded.

2.5. Model calibration

Given that there was not enough information to pursue a complete calibration analysis, a simplified evaluation was made instead. First, the LSA index results for the current rainfed agricultural area from 2015/16 to 2018/19 were compared to national average yields (DIEA, 2023). As a result, some model parameters, variable ranges, and ratings (especially those linked to water availability) were subsequently changed until the simulated results were as close as possible to the actual ones.

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[1] https://planesdeuso.mgap.gub.uy/planesdeuso/App/index.aspx

2.6. Logistics, transportation, and economic margins

The economic information was added to the biophysical model. Soybean production costs (seeds, fertilizers, phytosanitary, salaries, etc.) were computed using data provided by the Oilseeds Technological Board (MTO, 2023) and other public sources (DIEA, 2023; MTOP, 2018). The same figures were assumed for all farmers around the country. The only distinction was made regarding transportation costs, which were estimated based on distances from the farms to the storehouses (REOPINAGRA, 2017) and from the storehouses to the closest port (Nueva Palmira or Montevideo). Income was computed by multiplying physical yields by soybean price. Afterward, “margins before rent” were calculated as the difference between incomes and operating costs.

Finally, “margins after rent” were estimated by deducing the previous result the average cost of land lease for rainfed production per department (DIEA, 2023). The land renting cost was considered through a single average number, to present the economic margins before and after land rent). Thus, the proportion of landowners and land tenants (40% and 60% respectively) was considered to calculate a weighted average.

2.7. Scenario analysis and cropping system considerations

To build the scenarios toward 2050, the initial assumptions related to soybean prices and yields were changed by adding the possible effects of technological and climate changes. Different feasible price and productivity combinations (scenarios) were applied to the disposable land up to this moment, only those that allowed positive economic margins were considered to define the final area. Lands for which the margins were negative were discarded by the model. The average yield that would be obtained in that area was used to estimate the expected production for each scenario. This paper only shows the results of 2 of the 4 scenarios developed. Scenarios based on some technological changes (drought tolerance advances) and climate change are still under discussion. Data to run the scenarios was downloaded from INIA (2023c), Worldclim (2023), and UNL (2015) platforms.

Even when the outcome obtained following those steps complied with PUMS requirements and current land uses (see section 2.3), a further restriction was imposed to improve the results. Soybeans are part of a crop or crop-pasture rotation since the latter offers better environmental conditions, disease control, and economic outcomes, thus soybean is not cultivated in the whole rotation area every year. Therefore, a discount rate was applied considering the predominant rotations systems in the country.

According to data from currently approved PUMS, the predominant system is a 3-year rotation including corn/cover crop, soybeans/cover crop, and soybeans/cover crop (2 soybeans crops in 3 years). This would determine that the most accurate estimate of the potential effective soybeans area would be 67% of the total potential area.

In turn, according to sector experts and historical data, the expansion of soybeans in the future would be most probably driven by an increase in single-crop soybean areas. Given current prices and midterm market predictions it is highly unlikely that winter crops (preceding double-crop soybeans in the same year) would reach cropping areas higher than their historical records. Therefore, surpassing 1 million hectares of soybeans crop area, any additional area would be managed under a pasture-crop rotation, with 2 years of single crop soybeans and 3 years of pasture. Thus, the correction factor to apply in this case is 40% of the potential area.

2.8. Other environmental considerations

We made additional efforts to integrate environmental restrictions into the LSA model. We also assessed some environmental impacts of soybean production to fully incorporate them in forthcoming model updates, since they have repercussions on ecosystems and, consequently, on future soil productivity. These indicators were: residues biomass, surface nutrients runoff (nitrogen and phosphorus), nitrous oxide emissions, energy consumption, water use, phytosanitary toxicity, and nitrogen balance. Although not integrated into the model yet, they are being individually assessed to evaluate their potential impact given the projected scenarios. However, we did not consider their potential impact on future ecosystem service delivery as restrictions in the current model

2.9. Logistics, transportation, and economic margins

Some of the main methodological considerations are described below.

- Although we considered technology improvements in some scenarios (genetic growth trend, new management practices) we did not include associated incremental costs in the model. That is, the same costs were assumed for all scenarios.
- The final area estimated by the model, after imposing all the restrictions, considers null and positive economic margins (≥ 0). This implies some overestimation as farmers may require a minimum at least like the foregone benefits from other productive land uses.
- There were some highly productive areas in relatively isolated places, where logistics are scarce or difficult to develop. Although it was easy to visually notice those areas, quantifying the total area involved implied some difficulties given their size and distribution. For that reason, they were not excluded from potential cropping land in this study if crop margins were positive.
- Although the model conceptually follows the steps shown in Figure 1, we obtained the final area by over-imposing the independently estimated restrictions maps.

3. Results and Discussion

3.1. Land suitable analysis and potential yields

In this first step, from the total country area, agronomic restrictions, including: slope, flooding risk, rockiness, height, soil pH, past erosion, drainage, fertility, exchangeable sodium, were simultaneously applied to identify unsuitable areas for cultivation. Excluded areas correspond to low land areas in the east of the country, main rivers basins, hilly areas, and some soils with long agricultural history with low fertility and pH problems (Figure 4).

<FIGURE 4>

At this stage, the expected potential yields were calculated on the remaining area, applying the land suitable index method, which considers yields depending on water and nutrients restrictions and soil characteristics (see Figure 1, Map step 1).

3.2. Erosion and land use restriction

Calculated erosion rates for different soybean production systems were compared to soil loss tolerance rates established by PUMS for the different types of soil units on the total area. Suitable and unsuitable areas for cropping systems with soybeans is shown in Figure 5. Soil erosion potential is calculated using the Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978). We did not consider current soil condition due to past usage.

<FIGURE 5>

Figure 6 shows restricted areas due to current land uses. Besides those areas that are not suitable for agriculture production like urban areas, sandy coastal areas, water surfaces, roads, highways, etc. Also, areas that are currently under agriculture production but where changes are highly improbable are excluded. Some production areas because of their history, and comparative and competitive advantages for certain productions are not expected to change under the scenarios considered (i.e. milk, horticulture, fruits, forestry, and rice traditional production areas).

<FIGURE 6>

The total potential productive area and expected yields before economic margin restriction are shown in Figure 7. The total potential cropping area is 9.69 million ha with an average soybean yield of 2.0 metric ton/ha. This area includes land that is currently used exclusively for livestock production grazing native pastures. Although included as potential cropping land since all restrictions imposed have been sorted out, there are also other factors determining whether changes may happen. Livestock production has a long tradition, is a very competitive industry, and it has always been an important export product.

<FIGURE 7>

Subtracting from this potential cropping land the area with lower yields (equal or less than 1.4 ton/ha), assuming it is marginal productive land, the total potential cropping area is 6.53 million ha. This figure agrees with the 6.57 million hectares of moderately suitable (2.51 million ha) and suitable and most suitable (4.06 million ha) land for non-irrigated crop production calculated by Souto and Tommasino (2011). These authors applied a land use classification scheme based on agronomic and topographic soil properties.

3.3. Economic margins

We calculated total costs by adding location-specific logistic and transportation costs, a national average crop operation cost, and the average land rent cost by department (country's administrative division). Figure 8 shows the result of each cost category.

<FIGURE 8>

Assuming soybean prices at 310 US$/ton and the calculated costs, and yields for the potential cropping area, the economics margins were computed (Figure 9). Margins after rent assume that the total crop area pays rent. Red areas on the maps correspond to negative crop margin at the given price. Positive margin areas represent 27.4% before land rent costs and 5% after considering rent.

<FIGURE 9>

3.4. Scenarios

According to the spatial model, the potential area would range from 0.5 and 2.7 million hectares before and after rent in the less favorable scenario (soybean price = 310 USD/ton with no technological change) to more than 6.5 million hectares in the best scenario (soybean price = 400 USD/metric ton and keeping the estimated trend rate of yield growth), without any other additional restriction (Figure 10).

<FIGURE 10>

However, as explained in the methodological section, being soybean part of a crop or a crop-pasture rotation, the potential area for the crop needs to be adjusted to estimate the effective area. For instance, in the conservative scenario, where soybean price remains at 310 U$S/ton and productivity increases at its historical trend rate (outlined in Figure 9), the potential area would be between 6.5 and 3.4 million hectares before and after rent, respectively (see Figure 10). This potential area would fall to 2.9 and 1.6 by considering the rotations discussed in subsection 2.7 (upper limit: 1 million ha × 67% + 5.53 million ha × 40% = 2.9 million ha; lower limit: 1 million ha × 67% + 2.4 million ha × 40% = 1.6 million ha).

Additionally, considering the proportion of landowners and tenants (40% and 60% respectively), the adjusted potential soybean area on rotation would be 2.1 million hectares by 2050, the national average yield would be 3.3 metric tons/ha.

Similar figures were found by Rava *et al*. (2021) using an alternative model based on soil aptitude for crop production (Souto and Tommasino, 2011), achievable soybean yields limited only by water availability (Rizzo and Ernst, 2018), and imposing similar subsequent economic and infrastructure restrictions (Figure 11). Rava *et al*. (2021) estimated a potential area for 2050 of 1.58 million ha, with a total production of 5.6 million tons, and an average yield of 3.5 metric ton/ha, for the most restricted scenario and using the same cost structure and soybean prices. In this case, some areas of the country (departments) were excluded from the potential area since storage facilities, logistics, and infrastructure are not currently available. This probably accounts for the difference in the estimates.

<FIGURE 11>

4. Conclusions

Oilseeds represent an important industry for Uruguay's economy. In 2022, the GDP of the oilseed complex reached the highest value since records are available. If demand and prices remain at current levels, soybean cultivation will continue to be an attractive option for local farmers. In Uruguay, soybeans are planted in a marginal area, in terms of soil and climate. Yields are lower compared to other regions of South America with better-growing conditions. Thus, from a productive, social, economic, and environmental perspective, the sustainability of this productive system is an essential condition, representing a great opportunity but also a great challenge.

The developed model allowed a first approximation to estimate the potential expansion of the crop considering agronomic, economic, and environmental aspects. The model has fostered discussion among private and public agents related to the development of the industry, its growth strategy at the national level, potential scenarios, and research and development needs.

In the base scenario (without technological changes and with the price of soybeans at 310 USD/ton) there are more than 2.6 million hectares that would reach a positive economic margin, before land rent. However, after paying the rent, this figure would drop sharply, to approximately 0.5 million hectares. Considering that soybean is planted in a crop rotation system and that currently, around 60% of the producers rent the land, the potential effective area of soybeans would be around 1.1 million hectares.

New environmental restrictions are already being tested in the model allowing to address other potential impacts of area expansion and increasing yields, parameterized not just for soybeans but for any single crop or crop rotation and any region or soil system. Additionally, the assessment of a potential affectation of ecosystem services would allow a significant advance in the determination of the net economic return of an agricultural expansion. With these improvements, this ad-hoc approach could be a useful contribution to researchers and decision-makers.

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Table 1. Main worldwide soybeans exporters, year 2021

Country / Region	Quantity		Monetary Value		Position in world export ranking
	Metric Tons	%	USD × 1000	%	
Brazil	86,109,786	53.4	38,638,731	49.7	1st
United States	53,050,523	32.9	27,522,855	35.4	2nd
Paraguay	6,329,541	3.9	2,975,124	3.8	3rd
Canada	4,504,523	2.8	2,449,989	3.2	4th
Argentina	4,284,453	2.7	2,232,371	2.9	5th
Uruguay	1,768,288	1.1	896,993	1.2	6th
Americas	156,141,835	96.9	74,775,979	96.2	---
World	161,212.557	100.0	77,703,371	100.0	---

Source: FAOSTAT (2023)

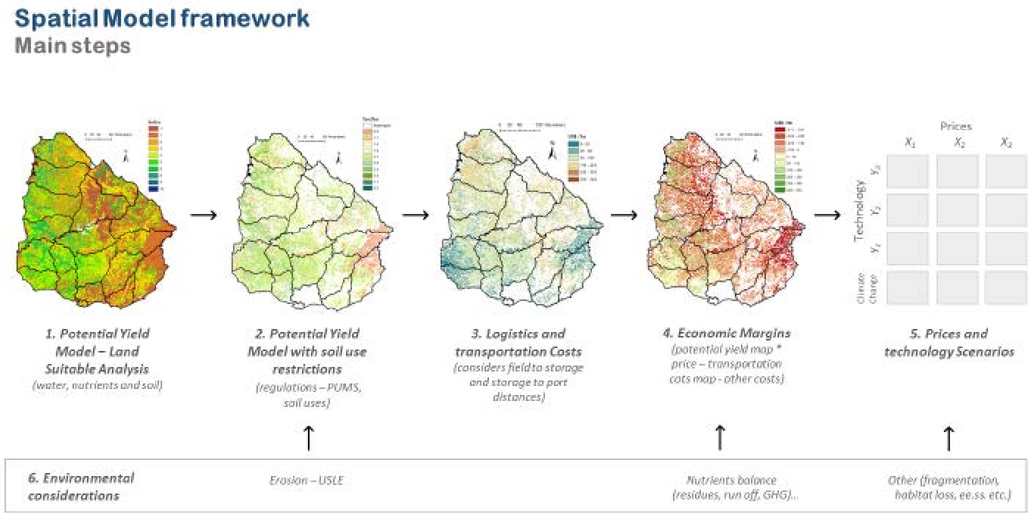


Figure 1. Main steps of the spatial model framework

Land Suitable Analysis Model

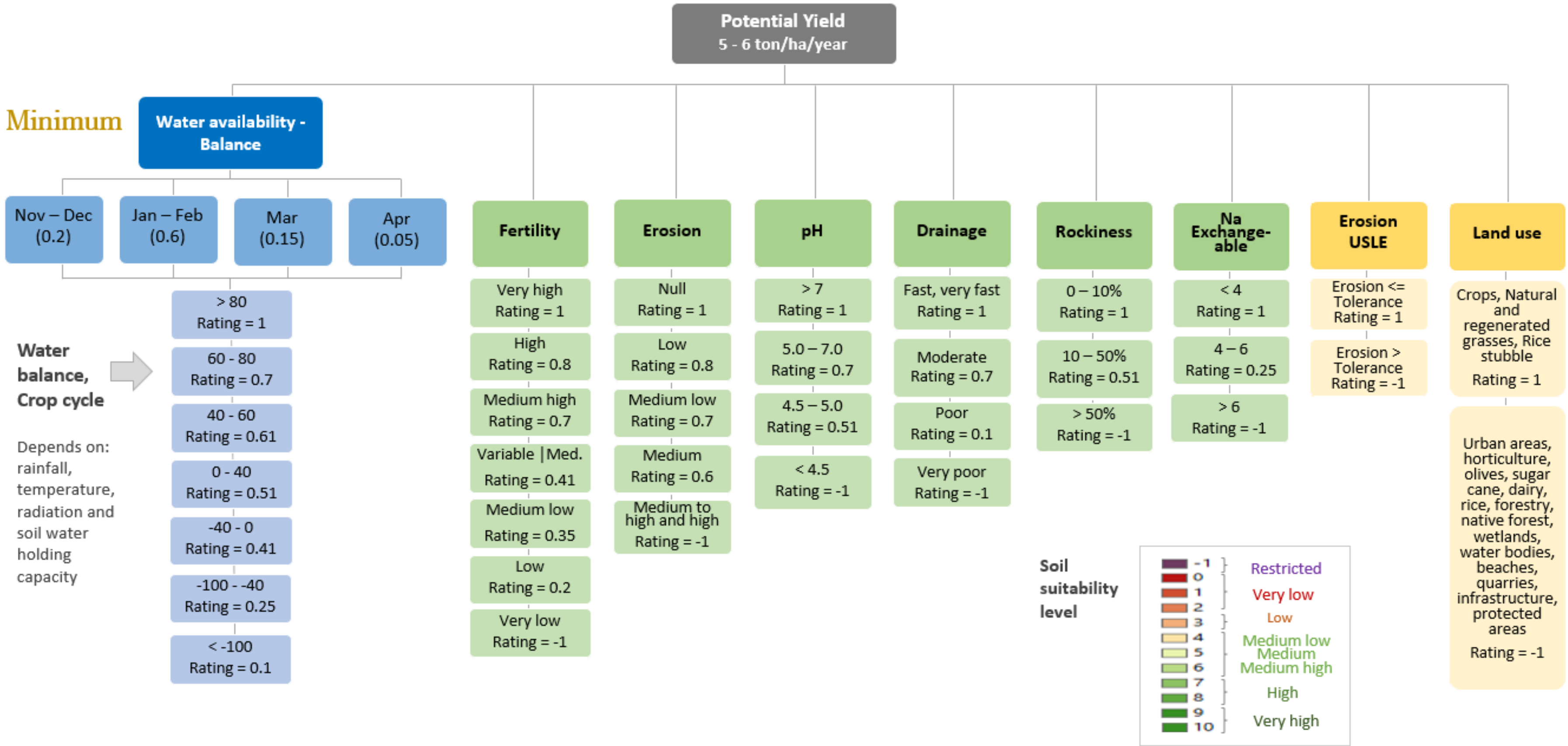


Figure 2. LSA model, with water availability balance and soil suitability level

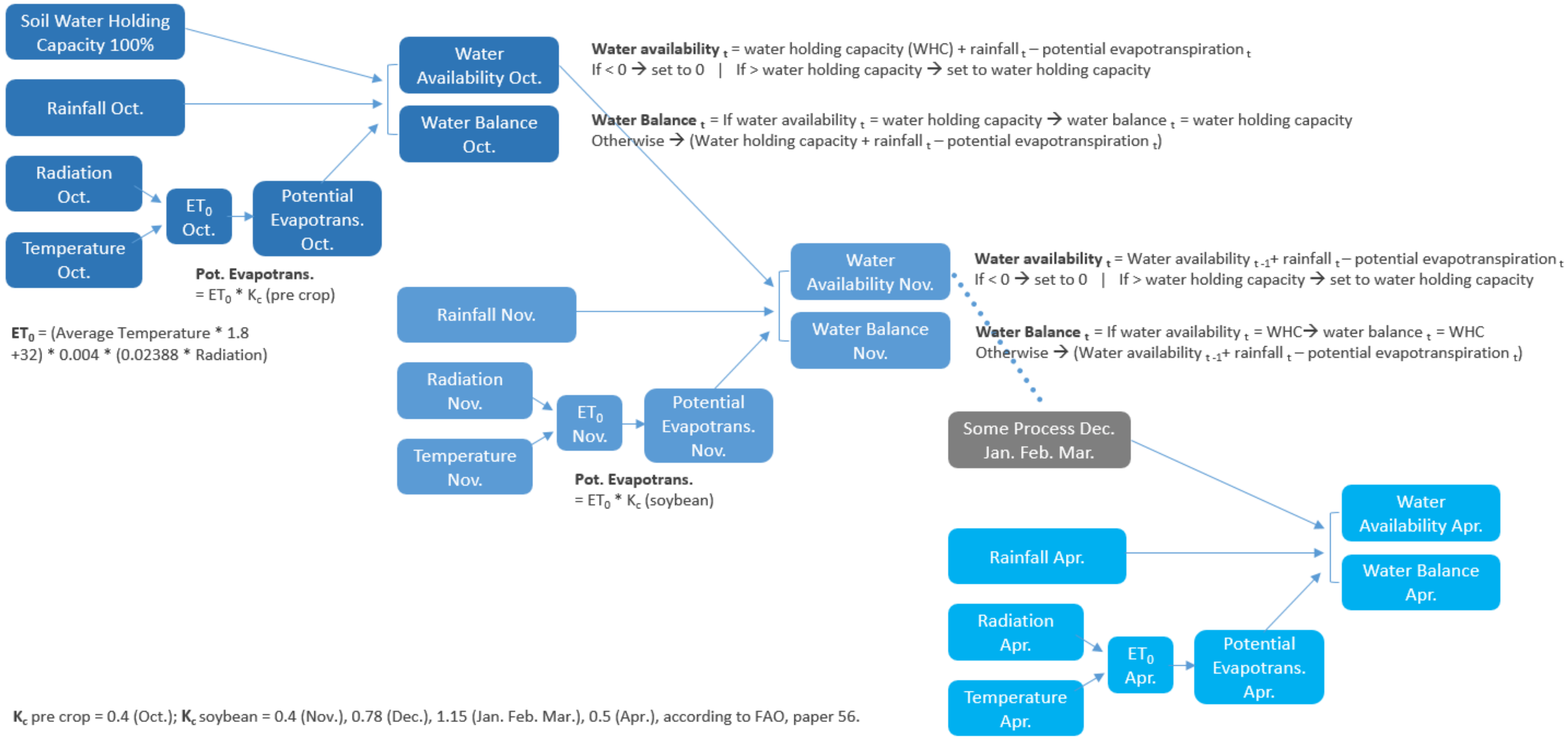


Figure 3. LSA model - water balance component

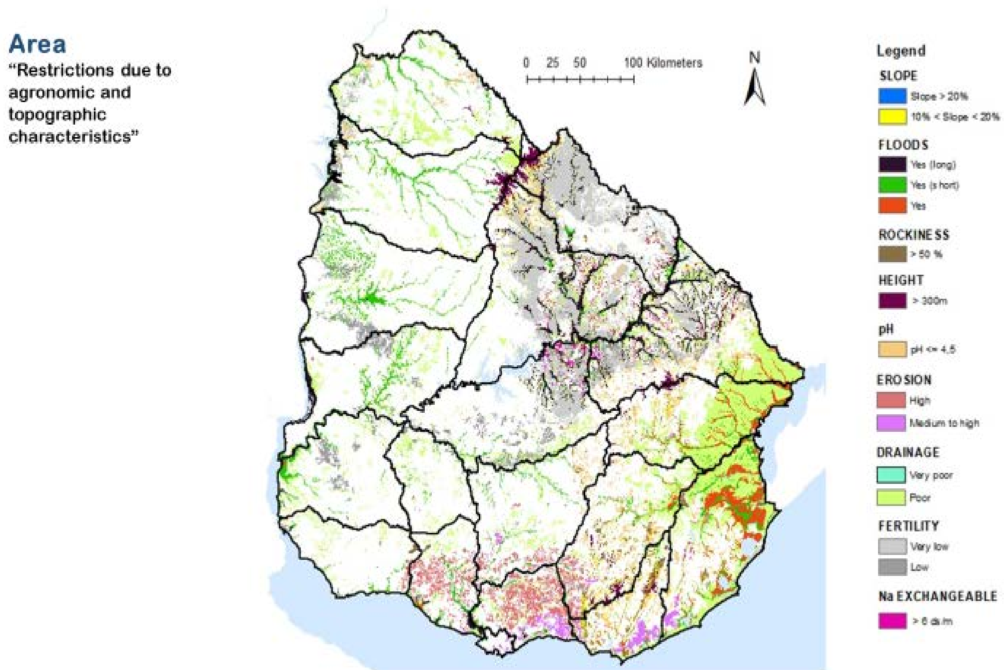


Figure 4. Land discarded due to unsuitable agronomic and topographic characteristics

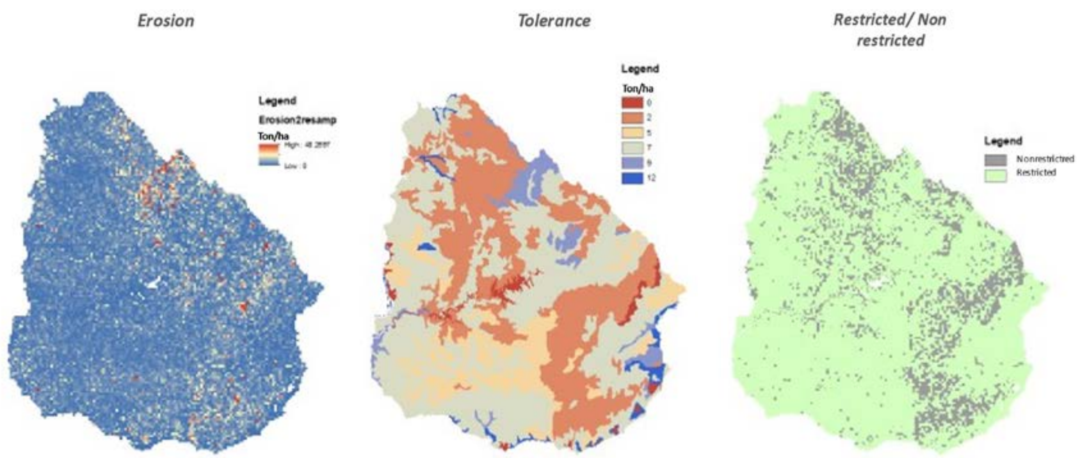


Figure 5. Calculated erosion risk, erosion rates tolerance and erosion restricted area.

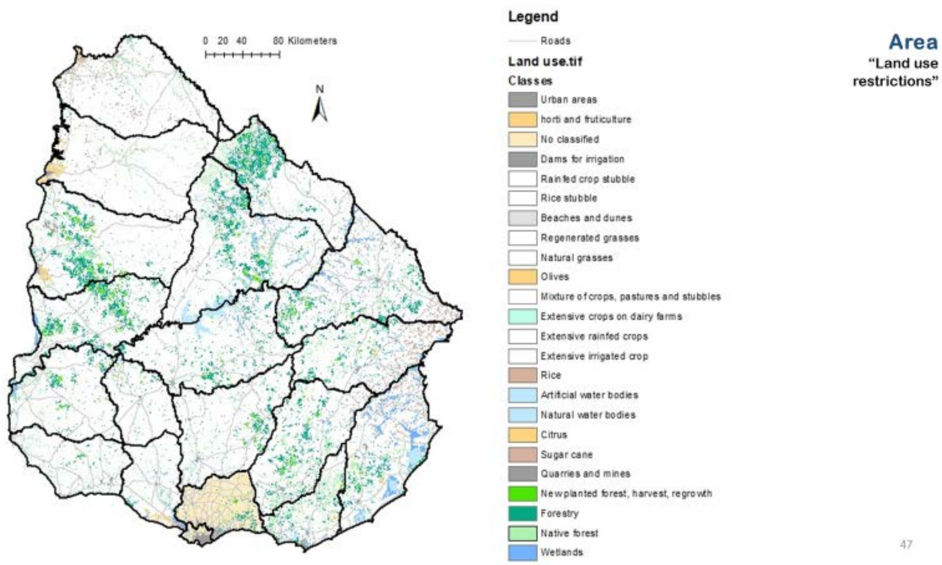
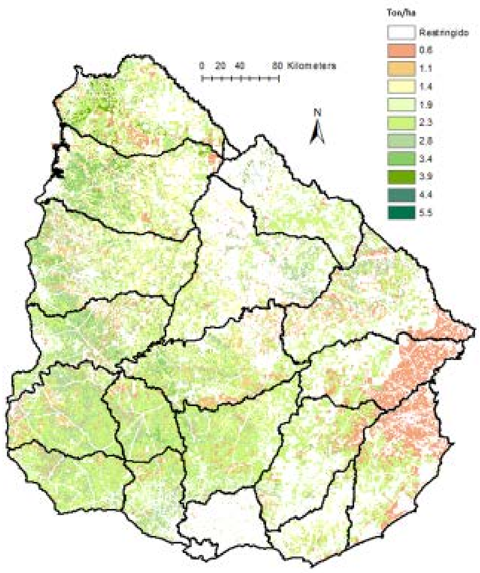


Figure 6. Land use restricted area



Yield (ton)	Total area (Thousand ha)	% area
Rest.	7,906	-
0.6	1,382	14%
1.1	195	2%
1.4	1,581	16%
1.9	135	1%
2.3	4,474	46%
2.8	1,483	15%
3.4	354	4%
3.9	86	1%
4.4	0,5	0%
5.5	0,3	0%
	17,597	100%

National weighted
average Yield
Soybean : 2.01 ton/ha

Figure 7. Total potential productive area and expected yields.

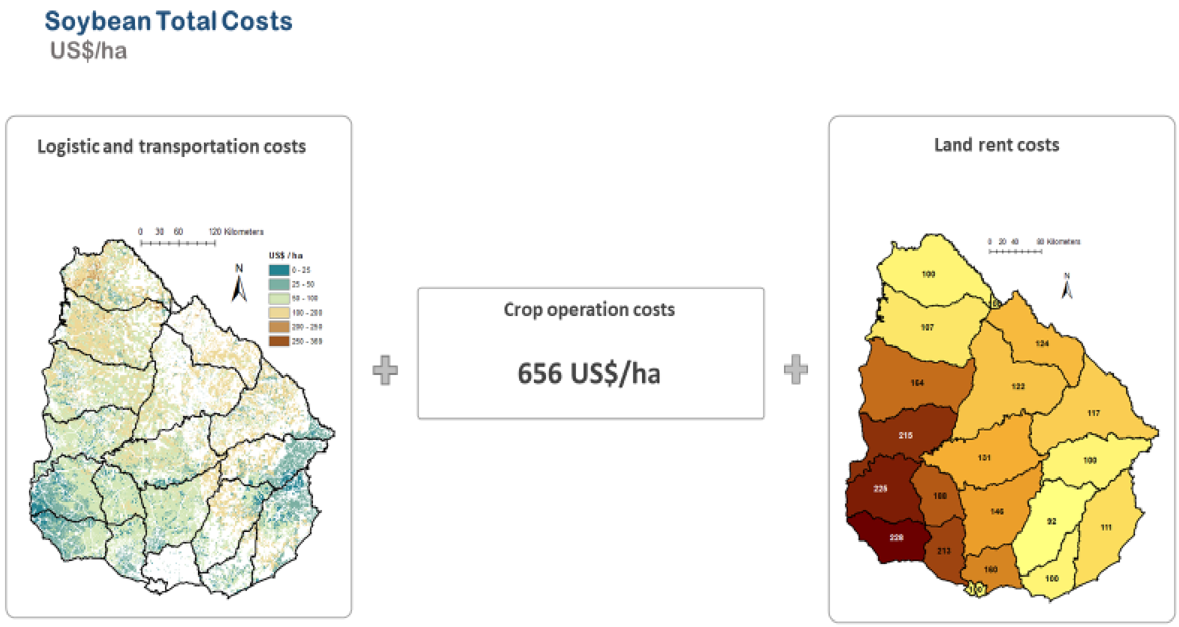


Figure 8. Soybean production costs by category

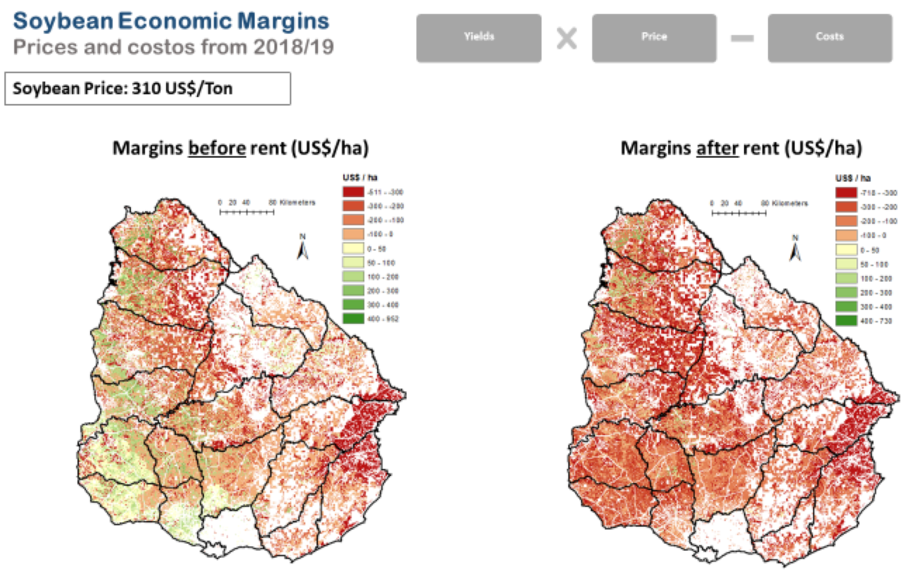


Figure 9. Soybean economic margins

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SCENARIOS

Area – million ha
Yields - ton/ha
Production - million tons

PRICES (US$/ton)

TECHNOLOGIES		310 No rent	310 Rent	350 No rent	350 Rent	400 No rent	400 Rent
No technological changes	Area:	2.65	0.49	6.37	1.89	6.53	5.26
	Yield:	2.78	3.43	2.50	2.96	2.49	2.54
	Prod.:	7.4	1.7	15.9	5.6	16.2	13.4
Trend maintenance (0.78% genetic and managment yield increase rate)	Area:	6.46	3.41	6.53	6.39	6.59	6.53
	Yield:	3.17	3.39	3.16	3.17	3.14	3.16
	Prod.:	20.4	11.6	20.6	20.3	20.7	20.6

Figure 10. Potential soybean area, average yield, and total production under different scenarios

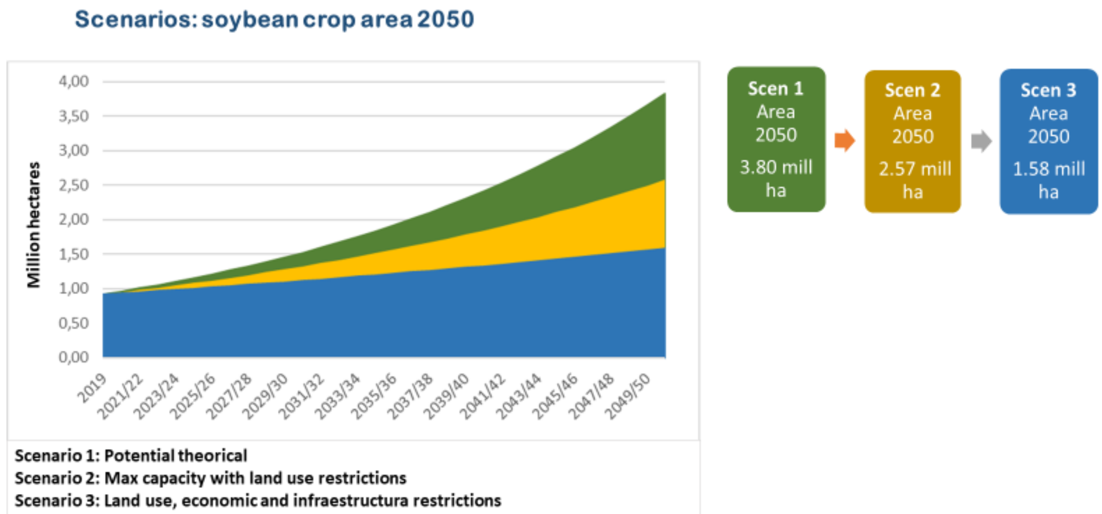

Figure 11. Soybean crop area by 2050 estimated by Rava *et al*. (2021) for three scenarios