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Effects of natural habitat composition and configuration, environment and agricultural input on soybean and maize yields in Argentina

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ABSTRACT

A fundamental challenge of land use management is to sustain the production of food, energy and fiber whilst preserving biodiversity and ecosystem functions. Some promising solutions to current resource-use conflicts are rooted in (agro) ecological intensification, which proposes that ecosystem functions provided by natural habitat can largely replace agrochemical inputs. Here, we evaluate how natural habitat is distributed in relation to agricultural input and the environmental potential for crop production, and whether natural habitat can explain the variations in yield not explained by management and environmental factors. In our analysis, we relied on environmental and management variables from 2858 soybean and 1548 individual maize fields provided by a farming organization in Argentina, and assessed landscape metrics of natural habitat composition (percentage of natural habitat) and configuration (edge density) for each one. We found that fields with higher fertilizer and seed input had lower percentages of natural habitat. Spatial variation in yield was well explained by environmental and management variables for both soybean and maize fields, and landscape metrics showed no relationship to the residuals of the models. However, fields recently transformed from natural habitat had higher yields than those with a long history of agricultural use. We conclude that compensatory management may mask the beneficial effects of natural habitat to some extent, especially in fields with intensive agrochemical use.

1. Introduction

Agricultural expansion and conventional land-use intensification have led to landscape homogenization and global biodiversity loss (Diaz et al., 2019, Martin et al., 2019, Seppelt et al., 2014). Decreases of biodiversity in agricultural landscapes have also resulted in a decline in ecosystem services supporting sustainable crop production (Tscharntke et al., 2005). Such decreases are not surprising, since conventional intensification has largely ignored the positive role of biodiversity in crop production systems (Seppelt et al., 2020).

Over the last few years, the establishment and conservation of natural habitat in agricultural landscapes have been promoted under the paradigm of ecological intensification (Garibaldi et al., 2019). The presence of natural areas in agroecosystems is expected to create win-win situations for biodiversity and agriculture through the ecosystem functions these areas provide for crops (Garibaldi et al., 2020). Some of the most important ecosystem functions in this context are generated by mobile species and their interactions with crops (Kremen et al., 2007). The importance of migration between natural and agricultural habitats has been shown for multiple crop types and ecosystem functions such as pollination (Ricketts et al., 2008) and biological pest control (Karp et al., 2018; Tscharntke et al., 2016). However,

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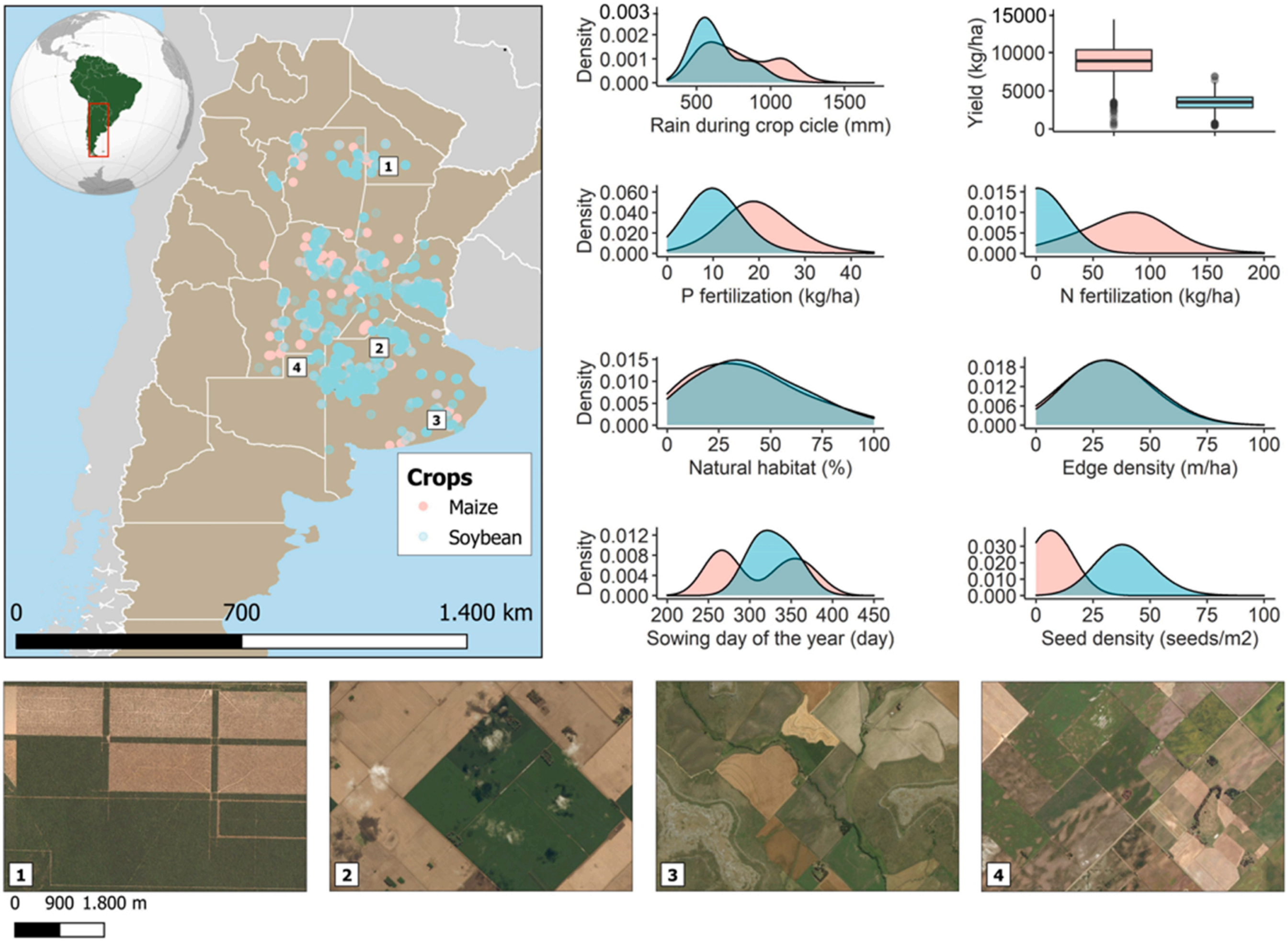

Fig. 1. Soybean and maize field distribution across Argentina, covering more than 324,000 ha of farmland. The images below show contrasting landscapes from different regions. The density plots on the right show the data distribution of some continuous variables of 2858 soybean fields and 1548 maize fields for 2018–2019.

the effect of the composition and configuration of natural habitat on field crop yield is still little understood.

Farmers are responsible for managing most of the worlds populated land (Ramankutty et al., 2008). Improved knowledge of on-farm benefits of changes in the composition and configuration of natural habitat on a landscape scale could have worldwide environmental implications. For example, previous studies showed that both soybean and maize, two of the most widely grown crops, benefit from natural habitat as it promotes the natural enemies of pests (Gonzalez et al., 2020, Santana Sousa et al., 2012). Additionally, soybean yields are also increased through more effective pollination (Garibaldi et al., 2021; Monasterolo et al., 2015).

Our main objective was to assess the relationships between the environment, land management, landscape structure and yields of soybean and maize in Argentina. We targeted soybean and maize crops because, globally, 120.5 and 197.2 million ha were harvested of these crops, respectively, during 2019 (Anon, 2019). Argentina accounted for 14% of the global soybean and 4% of the global maize production area in that year (Anon, 2019). To understand the relationships between landscape, environmental and management variables, we first evaluated how the landscape metrics (percentage of natural habitat and edge density) were distributed with regard to agricultural input and environmental potential for crop production. We then assessed the main drivers of crop yield and evaluated whether landscape metrics could account for the spatial variation in yield that was not explained by management and environmental factors. This information would indicate whether the ecosystem services provided by natural habitat substantially impact yields. In total, we gathered data from 2858 soybean and 1548 maize fields.

2. Methods

2.1. Data collection

Data was collected using an extensive, standardized protocol co-developed with the Regional Consortiums for Agricultural Experimentation (CREA) through the DAT CREA project. Regional Consortiums for Agricultural Experimentation is a non-profit civil association integrated and directed by agricultural entrepreneurs (>1800 farms) who meet in groups to share experiences and knowledge (https://www.crea.org.ar/). In total, the assessed area covered more than 324,000 ha of agricultural land distributed across almost all the extensive grain-producing regions of Argentina (Fig. 1). Specifically, we used data from individual fields of CREA farms for the 2018–2019 growing season. For each soybean and maize field, we gathered data on environmental and management variables (Table 1). In addition, we used Argentina's national Crop Data Layer 1 (Anon, 2019) to quantify the landscape composition and configuration around each field in our database. We established a radius of 1500 m as landscape size since this distance covers some of the most important ecosystem functions provided by natural habitat (Greenleaf & Kremen 2006) and is within the range of similar previous studies (Martin et al., 2019). This crop data layer was divided into two categories:

Table 1
Environmental, crop management and landscape variables considered in this study. Quantitative variables data is summarized in Table A.1.

Variable class	Variable	Type	Units/categories
Environment	Latitude	Quantitative	degrees
	Longitude	Quantitative	degrees
	Region	Qualitative	11 categories
	Environmental potential	Quantitative	1–3
Management	Nitrogen fertilization	Quantitative	kg ha^{-1}
	Phosphorus fertilization	Quantitative	kg ha^{-1}
	Sowing date	Quantitative	days
	Seed density	Quantitative	seeds ha^{-1}
	Seed treatment	Qualitative	no treatment, field treatment, professional seed treatment
	Previous crop	Qualitative	double crop, service crop, same crop, different crop, and natural area (i.e., recently converted into agricultural land)
	Fungicide application	Qualitative	yes/no
	Irrigation	Qualitative	yes/no
	Farm	Qualitative	farm ID
	Crop cultivar	Qualitative	cultivar ID
Landscape	Natural habitat	Quantitative	%
	Edge density	Quantitative	m ha^{-1}

*Environmental potential is a variable that summarizes the environmental (climatic and soil) conditions and yield potential of each field. This is established by experienced agronomists directly involved in crop management decisions related to the fields. For simplification, this variable was converted to a quantitative value ranging from 1 to 3.

Table 2
Spearman correlation coefficients between the main environmental and input quantitative variables and the landscape variables for soybean and maize. Numbers in bold indicate statistically significant coefficients (p-value *< 0.05, **<0.01, ***<0.001).

Crop	Intensification variables	Landscape variables	
		Natural habitat (%)	Edge density (m ha^{-1})
Soybean	Environmental potential	**-0.163** * **	0.020
	Phosphorus fertilization	**-0.212** * **	-0.053
	Seed density	0.035	-0.019
	Sowing date	-0.031	**0.083** *
Maize	Environmental potential	-0.065	-0.046
	Nitrogen fertilization	**-0.147** * **	-0.075
	Phosphorus fertilization	**-0.101** * *	-0.073
	Seed density	**-0.222** * **	**-0.097** *
	Sowing date	**-0.182** * **	**-0.198** * **

cropped and non-cropped areas. Non-cropped areas included natural forests, grasslands and wetlands corresponding to semi-natural and natural habitats (hereafter natural habitat for simplification). Land classification was carried out through the Google Earth Engine platform (https://earthengine.google.com). For each field we then calculated the percentage of natural habitat and edge density (Table 1); i.e., the sum of the lengths of all crop edge segments that bordered natural habitat in the landscape, divided by the total area. This analysis was implemented using the “landscapemetrics” package in R (R Core Team, 2020).

2.2. *Data analysis*

2.2.1. *Correlations between environmental, management and landscape variables*

We computed Spearman’s correlation to investigate associations between landscape variables (percentage of natural habitat and edge density), the environmental potential and crop management variables presented in Table 1 (i.e., nitrogen fertilization, phosphorus fertilization, seed density and sowing date). The environmental potential is a variable that summarizes the environmental (climatic and soil) conditions that influence the yield potential of fields. Nitrogen fertilization was not considered for soybeans since it is a natural nitrogen fixer, and this crop is also inoculated to promote the biological nitrogen fixation capacity of this species (Leggett et al., 2017). Fertilization and seed density are direct measures of intensification as they reflect the level of input that a field crop receives. Sowing date is related to different strategies for crop development, to take advantage of the best climatic conditions and thus maximize yields or reduce losses.

2.2.2. *Prediction of soybean and maize yields*

We estimated mixed-effects models to evaluate the main drivers of crop yield, with separate models being established for soybean and maize yields. Due to the complex correlation between landscape structure and management variables (Table 2), we first implemented yield models without considering landscape metrics. We identified all the potentially relevant variables for yield prediction, which included all the environmental and management variables shown in Table 1. Three non-nested random intercepts were included to account for the potential confounding effects of region, crop cultivar (to account for genetic variation among cultivars) and farm (the same farm may manage multiple fields). We visually determined which predictors needed transformation to achieve linearity and confirmed transformation choices by comparing the Akaike information criterion (AIC) values of the models with and without transformation (Burnham et al., 2011). Phosphorus fertilization was log-transformed for soybean. To position variables on a common scale all quantitative variables were normalized. This normalization involved rescaling the values of each variable so that they ranged between 0 and 1 (min-max scaling). We also calculated pairwise correlations of continuous predictors and calculated the variance inflation factor for all predictors to rule out multicollinearity.

For the model selection, we followed the Zuur et al. (2009) protocol for fitting mixed-effects models, first establishing the random structure and then the fixed effects. We compared models of different complexity using the AIC. Our most complex model included all fixed and random effects and the following two-way interaction effects among fixed effects: previous crop x fertilization (nitrogen and phosphorus), nitrogen fertilization x phosphorus fertilization, environmental potential x phosphorus fertilization, and environmental potential x nitrogen fertilization. Mixed-effects models were fitted using the *lmer*() function from “lme4” package in R (Bates et al., 2015). To select the fixed effects, the parameters of the global model were re-estimated using maximum likelihood. Based on AIC, we then eliminated each interaction following a stepwise procedure, using delta AIC > 2 as a guideline (Oddi et al., 2019; Burnham and Anderson, 2002). Therefore, an interaction was considered important if it reduced the AIC value of the model by at least 2 units from the value without the interaction (Oddi et al., 2019). The same procedure was then carried out for non-interaction fixed-effect terms following a parsimonious criterion (Garibaldi et al., 2014). The final model parameter values were estimated using restricted maximum likelihood estimation. Model assumptions were checked by visual evaluation of the residual scatter plots (residual vs. predicted values). The conditional r^2 was used as a goodness-of-fit metric and is hereafter referred to as r^2.

2.2.3. *The effects of the percentage of natural habitat and edge density on models’ residuals*

We extracted the standardized Pearson’s residuals from the final models of soybean and maize and built regression models to evaluate whether they responded to the percentage of natural habitat and edge density. This was done to determine whether there was still yield variability that could be explained by these landscape metrics after

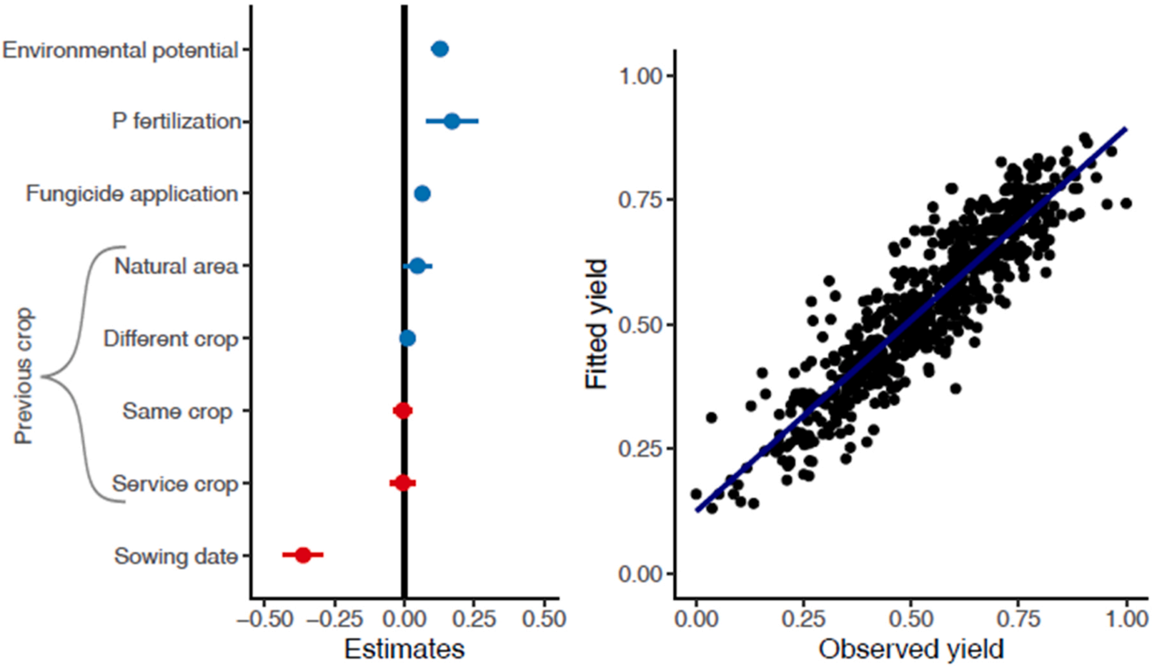

Fig. 2. The left panel shows normalized parameter estimates and confidence intervals for the fixed part of the soybean yield model (Intercept = 0.480). Random effects had a standard deviation of 0.080 for region, 0.027 for cultivar and 0.074 for farm. The right panel shows the observed versus fitted values from the model (r^2 = 0.82).

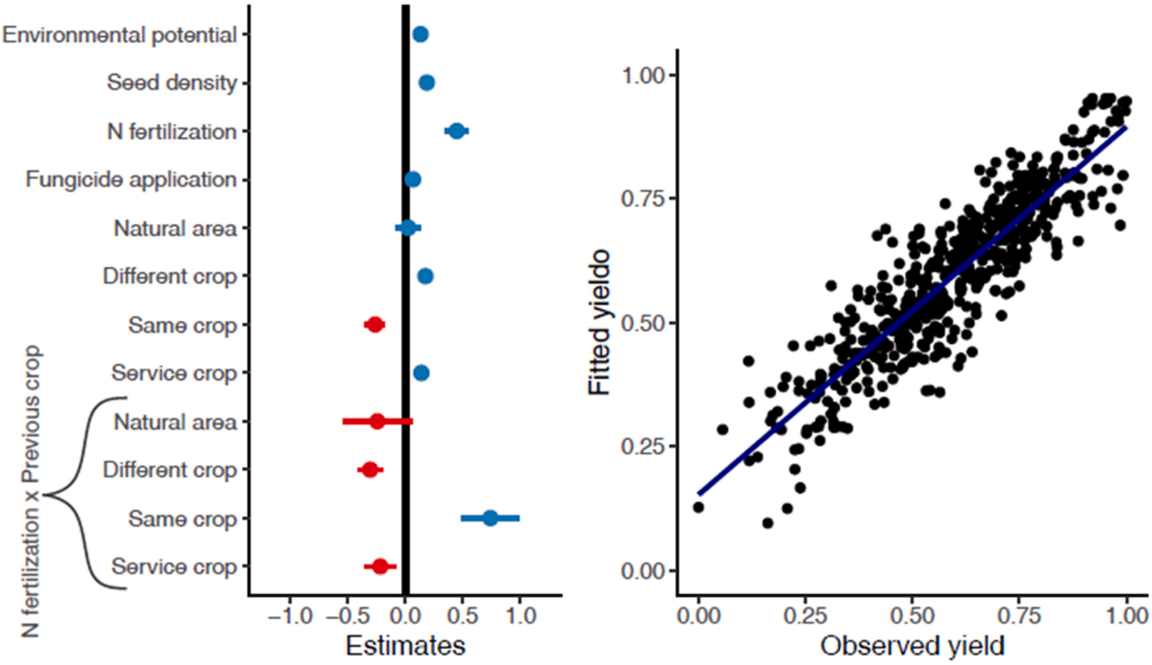

Fig. 3. The left panel shows normalized parameter estimates and confidence intervals for the fixed part of the maize yield model (Intercept = 0.179). Random effects had a standard deviation of 0.060 for region, 0.060 for cultivar and 0.098 for farm. The right panel shows the observed values versus model prediction (r^2 = 0.81).

accounting for environmental and management variables through the yield model. Models (one for each crop's residuals as a response variable) were fitted using the *lm*() functions of the base package in R. Using AIC, we then evaluated whether the percentage of natural habitat and edge density were important predictors of the residuals of soybean and maize models. To address possible variations in the effect of the percentage of natural habitat due to landscape complexity (Tscharntke et al., 2012), the interaction between the percentage of natural habitat and edge density (as a proxy for landscape complexity) was also evaluated. As before, we used AIC values to identify the most parsimonious models and checked model assumptions by visual evaluation of the residual scatter plots (residual vs. predicted values).

3. Results

During the 2018–2019 growing season, we collected data from 2858 soybean and 1548 maize fields across almost all extensive crop regions of Argentina (Fig. 1). Average single field size was 70.83 ha for soybean

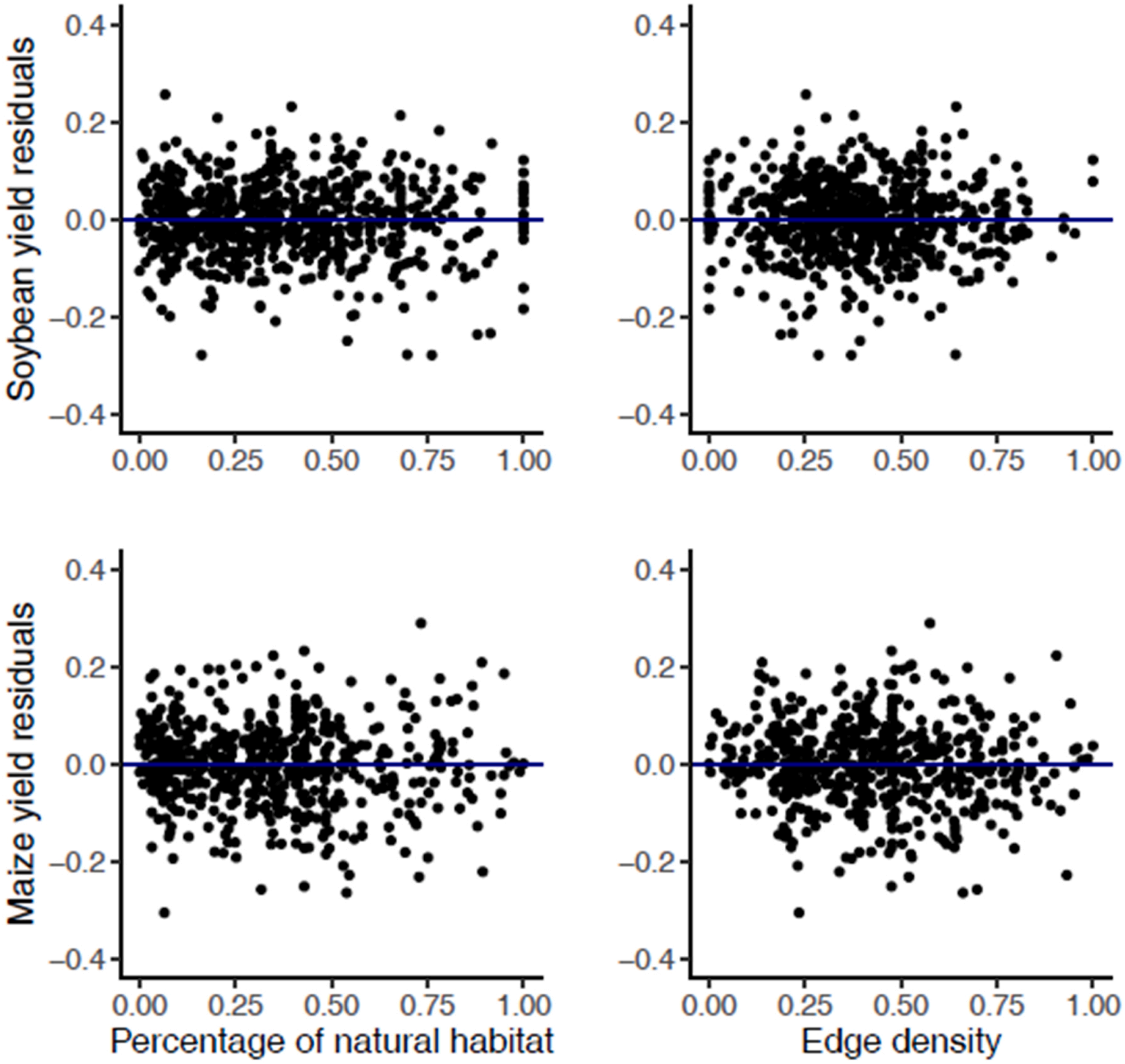

Fig. 4. Effect of the percentage of natural habitat and edge density on the standardized residuals of the soybean and maize models (Figs. 2 and 3 respectively).

and 63.90 ha for maize; maximum field sizes were 500 and 360 ha, respectively. Landscapes with soybean fields were characterized by an average of 36.9% natural habitat and an edge density of 33.6 m ha^{-1}. Maize field landscapes had an average of 35.3% natural habitat and 31.3 m ha^{-1} edge density. The soybean yield ranged between 982 kg ha^{-1} and 5984 kg ha^{-1}, whilst the maize yield varied between 3200 kg ha^{-1} and 14,300 kg ha^{-1} (Fig. 1).

Table A1
Data summary for quantitative variables of Table 1.

Variable class	Variable	Crop	Min value	Max value	Mean value
Environment	Latitude	Soybean	-38.59	-26.36	-33.95
		Maize	-38.03	-26.50	-33.80
	Longitude	Soybean	-65.59	-57.80	-61.52
		Maize	-65.55	-58.92	-62.36
	Environmental potential	Soybean	1	3	2.35
		Maize	1	3	2.36
Management	Nitrogen fertilization	Maize	5.50	227.66	83.09
	Phosphorus fertilization	Soybean	1.63	50.24	11.13
		Maize	2.97	73.50	20.84
	Sowing date	Soybean	10/10/18	01/21/19	11/15/18
		Maize	08/05/18	01/21/19	10/20/18
	Seed density	Soybean	22	75	40.01
		Maize	3.80	9.80	6.82
Landscape	Natural habitat	Soybean	0.06	≈ 100	36.90
		Maize	0.03	≈ 100	35.31
	Edge density	Soybean	0.00	84.93	33.55
		Maize	0.00	72.78	31.32

3.1. Correlations between environmental, management and landscape variables

We consistently found negative correlations between conventional intensification and natural habitats for each of the two crop types (Table 2). For soybean, phosphorus fertilization had the highest negative correlation with the percentage of natural habitat. Environmental potential showed a significant but weaker negative correlation. A significant positive correlation between edge density and sowing date was detected, although the correlation coefficient was low.

In maize fields, seed density had the highest negative correlation with the percentage of natural habitat, and sowing date also had a negative correlation with this variable. Although fertilization use had a significant negative correlation with the percentage of natural habitat, the correlation coefficient was rather low (Table 2). A strong negative correlation for maize was detected between edge density and sowing date. The negative correlation between seed density and edge density was also significant, but much lower in magnitude.

3.2. Prediction of soybean and maize yields

Environmental potential, phosphorus fertilization, fungicide application, previous crop, and sowing date were the predictors of the fixed part of the model that best explained soybean yield variability (Fig. 2). The most important predictor of yield was the sowing date, which had a strong negative impact. Yield decreased on average by 147 kg ha^{-1} for each week of later sowing. Between the beginning and the end of the sowing period studied (103 days), yield predictions decreased by 2169 kg ha^{-1}. Field history also affected soybean yield. Fields recently converted from natural vegetation (i.e., natural area, natural habitat) had the highest yields (e.g., 260 kg ha^{-1} more than fields that had previously been used for soybean production). When phosphorus fertilization increased by 20 kg ha^{-1}, the predicted yields increased by 350 kg ha^{-1}. Moreover, the predicted yield increased by 640 kg ha^{-1} when environmental potential went from 0 to 1 on the scale, and by 320 kg ha^{-1} due to fungicide application. Of the random effects, the region was the one that most explained yield variability (Fig. 2). The model including the random effects described the overall spatial variation in soybean yield with an r^2 value of 0.82 and a delta AIC of 671.20 when compared with the null model.

The fixed part of the final model that explained yield variability in maize included environmental potential, seed density, phosphorus and nitrogen fertilization, fungicide application, previous crop type, and the interaction between previous crop type and nitrogen fertilization (Fig. 3). Nitrogen fertilization was the predictor that most explained yield, the response of yield to nitrogen being much higher in fields previously sown with maize. For example, increasing nitrogen fertilization by 20 kg ha^{-1} led to a yield increase of 1186 kg ha^{-1} in fields where maize had previously been sown, but the increase was only 205 kg ha^{-1} in fields that had recently been converted from natural areas. This stronger response to fertilization was accompanied by lower expected yields when no fertilizer was applied (decrease of model intercept by 744 kg ha^{-1} in fields when maize was followed by maize). In contrast, a previous plantation of a different grain or service crop had a positive effect on yield. Furthermore, yield increased by 1466 kg ha^{-1} when environmental potential changed from 0 to 1 on the scale. Increasing seed density from 3.8 seeds m^{-2} to 9.8 seeds m^{-2} raised yields from 7929 to 10,015 kg ha^{-1}, and fungicide application increased yields by 744 kg ha^{-1}. The random effect of the farm was the one that most explained yield variability in maize (Fig. 3). This model (including the random effects) described the spatial variation in maize yield with an r^2 value of 0.81 and a delta AIC value of 424.97 when compared with the null model.

3.3. The effects of the percentage of natural habitat and edge density on models' residuals

The standardized residuals of neither the soybean model nor the maize model were significantly related to the percentage of natural habitat or edge density (Fig. 4). For soybean, the model that included natural habitat, edge density and their interaction had 4.75 more AIC units than the null model. In the case of maize, the model that included natural habitat, edge density and their interaction had an AIC that was 2.32 units higher than the null model.

4. Discussion

In this study, we gathered data from hundreds of fields in Argentina to assess the relationships between the environment, land management, landscape structure and yields. Due to the complex correlation structure between environmental, management and landscape variables, we implemented a three-step approach. We found that fields with greater agricultural input negatively correlated with the percentage of natural habitat. Land with higher environmental potential for grain production (i.e., field productivity) correlated negatively with the percentage of natural habitat in soybean. Spatial variation in yield was well explained by environmental and management variables for both soybean and maize fields. Neither percentage of natural habitat nor edge density could explain the variation in crop yield that was not described by environmental and management variables in the datasets analyzed in this study.

4.1. Correlations between environmental, management and landscape variables

We found that fields with greater agricultural input negatively correlated with the percentage of natural habitat. Our results agree with previous findings which show that conventional agricultural intensification associated with higher levels of agricultural input and intensified crop sequences are currently co-occurring in landscapes with few areas of natural habitat in Argentina (Satorre and Andrade, 2021). In our study, this process is especially evident in the negative correlations between the percentage of natural habitat and phosphorus fertilization in soybean and seed density in maize fields.

Across soybean fields, land with higher environmental potential for grain production correlated negatively with the percentage of natural habitat. This pattern is expected because agriculture has been expanding in Argentina since the late 1980 s, due to modern technology (no-tillage techniques and genetically modified crops), climate change (increase in warm-period rainfalls), and market conditions (global increase in soybean demand) (Baldi and Paruelo, 2008; Satorre, 2005). Mixed cattle grazing-cropping systems were replaced by continuous cropping, and an increase in field sizes led to landscape homogenization and fewer natural habitats in most new productive agricultural areas (Medan et al., 2011).

In some regions, a high percentage of the natural habitat measured in this study was possibly related to lowlands where cropping has lower yields due to soil and weather limitations. Therefore, cattle raising is still the main activity in these areas (Cid et al., 2011) since agriculture is risky and limited to scattered productive areas. On the other hand, in the north of the country, natural habitat was represented by forested land that was often only recently cleared for agriculture (Volante et al., 2016). In this case, due to the few environmental limitations (i.e., soil and weather) for crop production, large areas of natural habitat are more likely to be converted for agricultural use despite the limitations imposed by the forest regulatory framework, which has proven to be insufficient for protecting these areas (Vallejos et al., 2021).

These different regions are important drivers of the negative correlations between the sowing date and landscape metrics of maize. This crop is now being sown late in new, less productive areas, where fields tend to be large (Satorre and Andrade 2020), since late sowing avoids summer drought and prevents yield variability at these northern latitudes (Satorre et al., 2021).

4.2. Prediction of soybean and maize yields

In the soybean yield model, the sowing date was the predictor with the highest impact on yield. Our results confirm the results of other studies performed in different regions of Argentina, which found that the sowing date is a key variable in explaining yield variability (Madias et al., 2021; Vitantonio-Mazzini et al., 2021; Di Mauro et al., 2018). In fact, we found that late sowing led to an average decrease of 21 kg ha^{-1} d^{-1}, which lies within the range of yield losses found for different regions of Argentina (Madias et al., 2021; Vitantonio-Mazzini et al., 2021) and other parts of the world (Rattaliano et al., 2017). This negative effect of late sowing is related to the environmental conditions, which the crop experiences during critical periods of its cycle (Satorre, 2003).

Soybean development is regulated by temperature and photoperiod, and their interactions (Constable and Rose, 1988). In consequence, the shorter days experienced by later-sown soybean crops cause the plants to flower more rapidly (Lawn and Byth, 1973), shortening the vegetative period and positioning shifting the most important yield determination periods in less favorable, less productive conditions (Satorre, 2003).

Our paper demonstrates that phosphorus fertilization, fungicide application and previous crop are also key management variables that explain soybean yields, in agreement with previous findings in Argentina (Di Mauro et al., 2018). Environmental variables were also addressed, with the field environmental potential variable in the fixed part of the model and the region as a random effect. Removing region as a random effect from the model reduced the AIC value by 80.49 units, indicating the importance of environmental and management conditions at a regional level on crop yield.

In the maize model, nitrogen fertilization was the predictor with the highest impact on yield; furthermore, the response to nitrogen addition was around 5 times higher in fields where maize had previously been grown than in those that had previously been natural areas. Varvel and Peterson (1990) also found this enhanced response of yield to nitrogen in maize-maize rotation compared with other rotations. This effect arises due to differences in nutrient immobilization as a response to different previous crops (Kramberger et al., 2009). Maize as a previous crop has high immobilization rates which means that added nitrogen, contributes a larger part of the total available nitrogen to the crop. Although maize-maize rotations show strong yield responses to nitrogen fertilization, yields are the lowest under low levels of fertilization (Fig. 3). The previous crop can also increase soil nitrogen availability by symbiotically incorporating nitrogen into the soil, or by mineralization of the soil nitrogen, depending on the previous species (Kramberger et al., 2009).

Seed density also had an important impact on maize yield. Seed density has a direct association with stand density, which is known to be another important management decision that affects maize yield (Satorre et al., 2021, Gambini et al., 2016, Hernandez et al., 2014). Although yield response to stand density usually follows a non-linear response (Sarlangue et al., 2007), we found a linear response, which suggests that our field data included only the linear part of the yield response to this variable. Environmental potential and fungicide application had a similar positive effect on maize as it did on soybean yield, in accordance with previous studies (Vitantonio-Mazzini et al., 2020).

4.3. *The effect of the percentage of natural habitat and edge density on models' residuals*

Ecological intensification proposes that the conservation of natural habitats which provide ecosystem functions in agricultural landscapes will diminish external inputs and favor more environmentally friendly agriculture (Garibaldi et al., 2019). We analyzed whether landscape variables could explain the yield variability not explained by environmental and crop management variables. In this study, we did not find evidence for a substantial impact of landscape structure on yields, contrasting with earlier findings of positive relationships in maize (Yang et al., 2019; Santana Sousa et al., 2011) and soybean yields (Gonzalez et al., 2020; Monasterolo et al., 2015).

The positive effects of natural habitats on crop yield mainly arise from natural pest control and pollination as key ecosystem services (Alexandridis et al., 2021; Garibaldi et al., 2021). In our study, we investigated commercial farms, which depend on the intensive use of pesticides and transgenic Bt maize hybrids with resistance to Lepidoptera. This high, consistent input is reflected in transgenic Bt maize covering ~98% of total maize sown area (argenbio.com.ar) and the preventive use of insecticides (Butinof et al., 2014). Such high investments in pest control are likely to mask the ecosystem service pest control provided by natural habitats in these field crops (Costamagna et al., 2008).

Pollination is another important ecosystem service provided by natural habitat which is relevant for soybean (Garibaldi et al., 2021), but does not affect the wind-pollinated maize plants. Soybean has an intermediate dependency on pollinators: reductions of 10% to slightly less than 40% have been found when comparing experiments with and without animal pollinators (Klein et al., 2007; Chacoff et al., 2010). A previous study found a mean increase of 21% in soybean yield when comparing open versus exclosure treatments (Garibaldi et al., 2021). Although there is increasing scientific evidence to support soybean entomophile pollination, this has traditionally been neglected by farmers in the study area (e.g., soybean farmers do not usually place hives in or near their fields). In our study, we found that natural habitat, which provides important nesting grounds and food sources during non-crop flowering periods for pollinators, did not increase soybean yields. A possible explanation for this could be that the general level of pollinator densities could have been sufficiently high, since in our study 70% of soybean fields were surrounded by at least 20% of natural habitat. A proportion of 20% of natural habitat is often suggested as an important threshold to saturate the requirements of most crops for the provision of pollination and other supporting ecosystem services (Garibaldi et al., 2020).

We would like to point out that our classification of natural habitat did not consider differences in the quality (i.e., plant diversity) of natural habitat, and that for simplicity we assessed only a single landscape size (i.e., the radius around fields). Both landscape scale (Le Provost et al., 2021) and habitat quality could be very important for pollination and ecosystem services provision in general (Kremen et al., 2007, Liere et al., 2015).

It should also be noted that yield responses to natural habitat are complex and may have not only positive but also negative effects. For example, natural habitat can compete for resources, which can have substantial negative effects on crop yields (Zhang et al., 2007) and outbalance the positive impacts, such as the decrease in numbers of herbicide-resistant weeds in the presence of natural habitats, which was observed in our study area (Alexandridis et al., 2022; Garibaldi et al., 2022). Resulting net neutral responses might be a common result, especially when some key ecosystem services are masked, as expected in our study.

Conservation of natural habitat in private agricultural landscapes is considered for several different reasons. Legal frameworks can impose natural habitat conservation in productive land (Garibaldi et al., 2020), but the recognition of its effects on crop yield could provide a strong additional motivation for farmers to contribute to natural habitat conservation. Through this study, we propose that in high-input dependent cropping systems such as soybean and maize in Argentina, farm gross income (USD ha^{-1}) response to landscape composition and configuration should be studied in depth. Direct costs are sensitive to ecosystem functions since much of the cost responds to dynamics between natural habitat and crop performance (e.g., plagues/natural enemies, pesticide use). The high agricultural input (e.g., intense use of pesticide) could mask the benefits provided by natural habitat. However, the economic cost of these agricultural practices could lead to lower farm gross income once production costs are considered (Zou et al., 2020). For example, if the frequency and amount of pesticide used diminishes with greater quantities of natural habitat and/or edge density, the increase of natural habitat may help to substantially reduce farming costs while maintain yields resulting in more environmentally friendly production systems.

5. Conclusions

In this paper, we covered almost all major field-crop regions of Argentina, where soybean and maize production represents one of the country's main sources of income. Agricultural input was negatively correlated with natural habitat. Environmental and management variables explained yield variability in both crops, and yield models considering these effects satisfactorily described the large spatial variation of yield in the study regions. Neither percentage of natural habitat nor edge density could account for the variation in crop yield that was not explained by environmental and management variables in our datasets. As compensatory management probably masks to some extent the beneficial effects of natural habitat in terms of yields, we recommend that future studies focus on agricultural costs (USD ha^{-1}). This could help to determine whether the interaction between crop performance and the ecosystem functions provided by natural habitat could have a beneficial influence on them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

See Appendix Table A1.

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