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Landscape configuration is an important predictor of sunflower yield in the Argentinean Pampas Region

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Abstract. Conventional agriculture is frequently associated with large-scale environmental degradation and landscape homogenization. In contrast, ecological intensification incorporates natural habitat conservation and landscape complexity to improve important ecosystem services such as pollination and crop yields. In an observational study of 105 fields in the Argentinean Pampas Region, we explored whether sunflower yields were related to landscape composition (percentage of natural habitat) and configuration (field size and edge density), and covariates of agricultural management practices such as nitrogen fertilizer addition, seed density, sowing date and crop cultivar. Our mixed-effects models revealed that field size and edge densities between crop and natural habitat are important predictors of yield. For example, a doubling of edge density from 40 m/ha to 80 m/ha predicted an 11.3% (269 kg/ha) yield increase, while a doubling in the field size from 40 ha to 80 ha predicted a 6.1% (149 kg/ha) yield decrease. We suggest that pollination is an important driver of both effects as higher edge densities and smaller field sizes reduce wild pollinator flight distances to crop flowers and thus increases the chances for effective crop pollination. This study provides key information for sustainable management of sunflower agroecosystems.

[Keywords: oleaginous crop, agroecology, natural habitats, landscape]

Resumen. La agricultura convencional suele estar asociada a la degradación ambiental a gran escala y a la homogenización del paisaje. En contraste, la intensificación ecológica incorpora la conservación y la complejidad del paisaje como aspectos relevantes para incrementar la provisión de servicios ecosistémicos como la polinización y los rendimientos. En un experimento observacional de 105 lotes en la Región Pampeana argentina, exploramos si los rendimientos de girasol estaban relacionados con la composición del paisaje (porcentaje de hábitat natural) y con su configuración (reducción en el tamaño de lotes e incrementos en la densidad de borde), además de covariables de manejo del cultivo como fertilización nitrogenada, densidad de semillas, fecha de siembra y cultivar. Nuestros modelos de efectos mixtos muestran que el tamaño del lote y la densidad de borde son predictores importantes del rendimiento. Por ejemplo, duplicar la densidad de borde de 40 m/ha a 80 m/ha predijo un aumento promedio de 11.3% (269 kg/ha), mientras que duplicar el tamaño del lote de 40 ha a 80 ha predijo una reducción promedio del rendimiento de 6.1% (149 kg/ha). Sugerimos que la polinización es uno de los mecanismos importantes que explica este efecto, ya que mayor densidad de borde y lotes más pequeños reducen la distancia de vuelo de los polinizadores silvestres a las flores del cultivo y, por lo tanto, aumenta la probabilidad de una polinización eficiente. Este estudio provee información clave para la producción sostenible en agroecosistemas de girasol.

[Palabras clave: cultivo oleaginoso, agroecología, hábitat natural, paisaje]

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Introduction

The decline in ecosystem services provided by natural habitats in agricultural landscapes has been a widespread problem in the last decades (Foley et al. 2005). This trend is mainly driven by land use intensification and expansion of croplands, leading to landscape homogenization. These processes increase grain production, but lead to natural habitat and biodiversity loss (Aizen et al. 2019; Beckmann et al. 2019; Fahrig 2003). Moreover, for pollination dependent crops, landscape homogenization may exacerbate ecosystem degradation if production losses resulting from pollinator declines are compensated by adding more land to production (Dainese et al. 2019; Garibaldi et al. 2013; Potts et al. 2016; Seppelt et al. 2020; Tscharntke et al. 2005).

In response to this degradation, alternative agricultural approaches that promote natural habitat in agricultural landscapes may enhance ecosystem services provided to crops, such as pollination (Garibaldi et al. 2019; Garibaldi et al. 2017; Garibaldi et al. 2016), biological pest control (Schulte et al. 2017; Tscharntke et al. 2012) and reduce herbicide resistance in weeds (Garibaldi et al. 2022; Vila-Aiub 2019). Moreover, the presence of natural habitat and the diversification of agricultural systems is expected to stabilize crop yields (Egli et al. 2020; Egli et al. 2021a,b; Garibaldi et al. 2011).

Landscape configuration and composition are the two main attributes that characterize landscape structure. Regarding landscape configuration, previous studies suggest that enhancing edge density (and therefore landscape complexity) in agroecosystems can promote functional biodiversity and other yield-enhancing ecosystem services (Martin et al. 2019). Regarding landscape composition, proportion of natural habitat may enhance yields through different ecosystem services also (Raderschall et al. 2021). Although both landscape configuration and composition have been reported as important drivers of yield for different crops, we lack knowledge of the consequences of these landscape attributes on yield in Argentinean field crops.

The objective of our study was to evaluate the importance of landscape structure on the yield of a pollinator-dependent field crop in Argentina: sunflower (*Helianthus annuus*). To this end, we examined 105 sunflower fields in the southern and central part of the Pampas Region in Argentina, one of the most important agricultural areas in South America. We focus on the percentage of natural habitat as a measure of landscape composition. We used the density of edges between fields and natural habitat and the size of agricultural fields as measures of landscape configuration, so that higher edge density and smaller field size indicate higher landscape complexity (Nelson and Burchfield 2021). We predicted that small field sizes and the increase in availability of natural habitat would positively affect sunflower yields, due to yield-enhancing ecosystem services provided by these areas.

Materials and Methods

Study area

The Pampas region (Cabrera and Willink 1973) constitutes one of the most important agricultural landscapes in South America. It is a vast, flat region of Argentina that comprises more than 50 million ha of arable lands used for crop and cattle production (Hall et al. 1992; Viglizzo et al. 2003). In Argentina, an area of almost 1.9 million was cultivated with sunflower during 2019, with a total production of 3.8 million tons (FAO 2019). The central and southern Pampas represent the southern sunflower distribution, which includes center and south region of Buenos Aires province and east region of La Pampa province (Castaño 2017).

Sunflower crops benefit from insect pollination (Perrot et al. 2018). The presence of wild pollinators can have positive direct effects in this species (Garibaldi et al. 2013). Also, indirect effects through behavioral interactions between wild bees and honey bees that lead to a higher pollination efficiency have been reported (Greenleaf and Kremen 2006). However, in this region, pollination is managed trough honey bees alone and the role of pollinators diversity has traditional been largely disregarded among sunflower farmers.

Data collection

We examined 105 sunflower fields distributed in the Pampas Region (Figure 1). The data were gathered from the 2018-2019 growth period in collaboration with CREA (Regional Consortiums for Agricultural Experimentation; crea.org.ar). CREA is a non-profit civil association integrated and directed

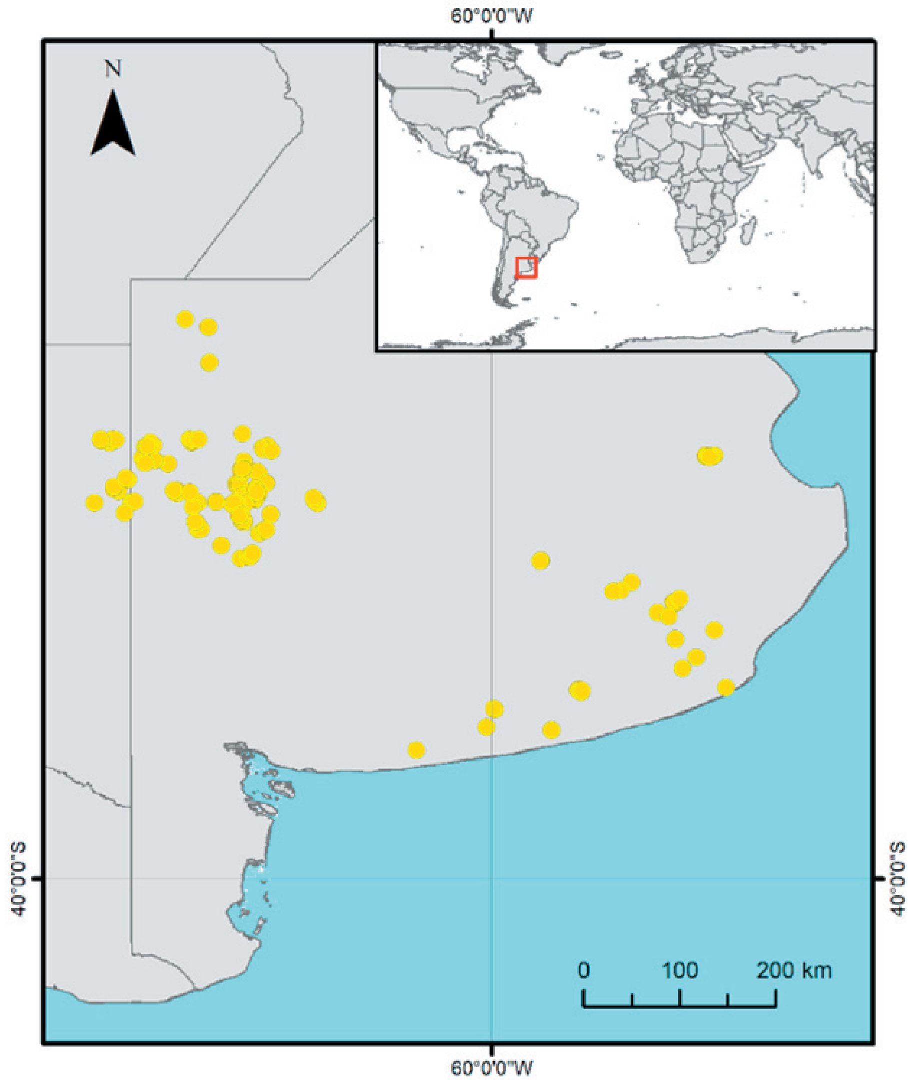

Figure 1. Geographic distribution of the examined sunflower fields in the Pampas Region, Argentine.
Figura 1. Distribución geográfica de los lotes evaluados en la Región Pampeana, Argentina.

by over 1800 farmers with the aim to generate and share experiences and knowledge on farming practices. For each field, we gathered data on crop yield, as well as on many potential predictors of yield, including field size, latitude and longitude, agronomic production region (three categories: oeste y oeste arenoso; mar y sierras and sudeste), identity of crop cultivar, nitrogen fertilizer addition (kg/ha), sowing date and seed density (seeds/ha). Regarding crop cultivars, more than the 70% of the fields sowed SY 3970 CL, SY 4070 CL from Syngenta, CF 202 CL from Advanta or 65A25 from Pioneer. Only fields that suffered extreme weather events were excluded from our analysis to reduce variability resulting from stochastic events (e.g., waterlogging, hail, frost, etc.).

To quantify the landscape composition and configuration, we used Argentina's national Crop Data Layer 1 (de Abelleyra et al. 2019) in a 1 km radius zone surrounding each field, as this distance may cover some of the most important ecosystem services provided by natural habitat (Ricketts et al. 2008). The crop data layer was divided into two categories: cultivated and non-cultivated areas in the Google Earth Engine platform (earthengine.google.com). Non-cultivated areas corresponding to semi-natural and natural habitats included natural forests, grasslands and wetlands (hereafter, natural habitat). For each field, we then calculated two landscape parameters, edge density and the quantity of natural habitat within the 1 km buffer. The quantity of natural habitat was computed as the percentage of natural habitat and edge density as the sum of the lengths of all crop edge segments that bordered natural habitat in the landscape divided by the total landscape area. We used the landscapemetrics package (Hesselbarth et al. 2019) in R (R Core Team 2020) for this analysis.

Data analysis

We analyzed the response of crop yield to landscape and other predictor variables in a mixed effects model using the lme4 package in R (Bates et al. 2015). Predictors included percentage of natural habitat, edge density, and field size along with the covariates: nitrogen fertilizer addition, sowing date and seed density. We also included region and crop cultivar as random effects (random intercepts) in our model. We explored, both visually and formally based on the Akaike information criterion (AIC) (Burnham et al. 2011), which predictors needed transformation to achieve linearity. Nitrogen fertilizer addition was log transformed. All quantitative variables were normalized (range standardization) to facilitate comparisons of effect sizes. We also calculated pairwise correlations of continuous predictors to rule out multicollinearity. No multicollinearity was detected.

Model selection was based on multi-model inference relying on AIC. The minimum adequate model was selected after evaluating the models resulting from all possible combinations of the predicting variables (dredge function in the MuMIn package [Bartoń 2020]). To select the fixed effects, the parameters of the global model were re-estimated using maximum likelihood. Relative importance values were calculated for each predictor by summing the Akaike weights over all models that included the predictor (importance function in the MuMIn package). The final parameter values were established using restricted maximum likelihood estimation.

Results

Sunflower yield ranged between 1400 kg/ha and 3650 kg/ha (mean=2432 kg/ha). This variation in crop yields was best explained by nitrogen fertilizer addition, edge density, field size and seed density. These variables were selected as most parsimonious set of fixed effect predictors (Table 1). Nitrogen fertilizer addition had a positive effect on yield. Predicted yields increased 6 kg/ha for each kg of nitrogen applied. Also, edge density had an important effect on crop yields. When edge density increased from 6.55 m/ha to 102.24 m/ha the predicted yield increased 29.8% (641 kg/ha) (Figure 2). Field size negatively affected sunflower yields with a predicted decrease of 14.5% (378 kg) when field size went from 3.5 ha to 105 ha (Figure 2). Seed density had a positive effect on yields and the predicted yield increased by 565 kg/ha when seed density changed across

Table 1. Results of mixed-effects models evaluating the impact of management and landscapes variables on sunflower yields. The parameters included in the best model and their standard errors, between brackets, are printed in bold. The best model was determined by comparing Akaike information criterion (AIC) values of all possible combinations of predictors. The relative importance score is the sum of the AIC weights of all the models with each predictor.

Tabla 1. Resultados de los modelos de efectos mixtos evaluando el impacto de las variables de manejo y paisaje sobre los rendimientos de girasol. En negrita figuran los parámetros incluidos en el mejor modelo y sus errores estándar, entre paréntesis. El mejor modelo se seleccionó comparando los valores del criterio de información de Akaike (AIC) de todas las combinaciones posibles de predictores. La importancia relativa es la suma de los pesos de AIC de todos los modelos con cada predictor.

Fixed effects (mean)	Relative importance	Normalized parameters estimates
Intercept	-	**0.175 (0.122)**
Edge density	0.93	**0.285 (0.097)**
Field size	0.68	**-0.168 (0.089)**
Seed density	0.84	**0.251 (0.106)**
Nitrogen fertilizer addition	0.95	**0.213 (0.073)**
Sowing date	0.28	-
Percentage of natural habitat	0.27	-
Random effects (sd)		
Region		0.11
Cultivar		0.09
Delta AIC with null model		15.20

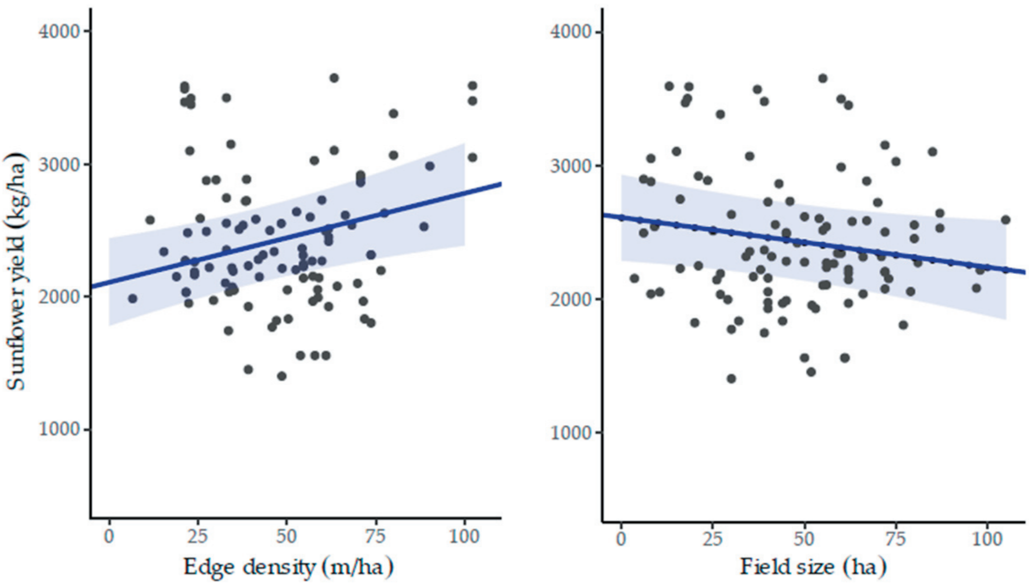

Figure 2. Edge density and field size effects on sunflower yield. Black points represent the recorded data, and the blue lines, the predictions of the best model with the 95% confidence interval bands (Table 1).

Figura 2. Efectos de la densidad de borde y tamaño de lote sobre los rendimientos de girasol. Los puntos representan los datos, y la línea azul, las predicciones del mejor modelo con las bandas de intervalos de confianza del 95% (Tabla 1).

it ranges from 3.1 to 6.7 seed/m. The random effect of region was narrowly more important than crop cultivar to explain yield variability (Table 1).

Discussion

In this study, we found strong effects of landscape configuration variables on sunflower yield. We found a positive effect of edge density on yield, which may be explained by the fact that natural habitats may support pollinators in this region (Sáez et al. 2014; Sáez et al. 2012; Torretta and Poggio 2013) so spillover of pollination services from edges to sunflower fields can be expected. Increasing edges may promote other yield-enhancing ecosystem services such as biological pest control (Martin et al. 2019) and resistant weed control (Garibaldi et al. 2022; Vila-Aiub 2019).

Field size negatively affected sunflower yields in our model. In the frequent rectangular fields of the pampas, increasing field size increases the proportion of sunflower plants far from edges. Previous findings demonstrate that wild bee abundance, fruit set, and sunflower yields decrease with increasing distance to field edge (Hevia et al. 2016). In another study, an increasing distance of the sunflower heads from the field edge determined a lower number of flower-visiting wild bees and honey bees (Lajos et al. 2021). In fact, since wild bees have been determined as important drivers of sunflower yield (Blitzer et al. 2012; Greenleaf and Kremen 2006; Sardinas and Kremen 2015), the positive role of edges and the negative effect of field size in the context of pollination appears to be the one of the dominant mechanisms behind our results.

Contrary to landscape configuration variables, we found no effects of landscape composition on sunflower yield when landscape composition was measured as the percentage of natural habitat. Interestingly, while land sparing (i.e., separating land for natural habitat conservation from agricultural land) is often preferable in terms of maximizing biodiversity and yield (Ekroos et al. 2016), we found no response in yield at the field-scale analysis for sunflower. Our results suggest that at least some degree of land sharing (i.e., agricultural fields mixed within natural habitat) is required not only to maximize crops stability and resistance (Redhead et al. 2020), but also to achieve high yields in mass flowering crops for a specific growing season. A potential limitation of our analyses concerns landscape metrics which we calculated with a spatial resolution of 30 m, limiting our ability to detect some non-cultivated areas such as road verges, which represent important habitats for pollinators (Monasterolo et al. 2020). Future studies should consider higher resolution images or other techniques to incorporate these areas as natural habitat.

Nitrogen fertilizer addition and seed density were also important determinants of sunflower yield. It should be noticed that a yield saturating (i.e., nonlinear) response to nitrogen addition is expected in this crop (Ruffo et al. 2003). However, we explored only the linear part of the curve, as the maximum nitrogen application of all data set in this study was 83.4 kg/ha, which is considerably lower than the amount needed to maximize sunflower yield in the southern Pampas Region (Ruffo et al. 2003). We also found a positive effect of seed density on yield under the explored range of seed density. Seed density is related with plants density (plants/ha), which increases biomass production and translates into higher yield in the range we evaluated (Pereira and Hall 2019). Therefore, our results agree with previous reports indicating that nitrogen and plant density are key determinants of sunflower yield. Region as a random effect explained narrowly more of the spatial variability in yield than cultivar probably due to the extensive area this study covered.

Conclusions

This study shows that landscape configuration is an important predictor of sunflower yield. Specifically, our results suggest that increasing landscape complexity, represented as higher edge density and smaller field size, favors sunflower crop yield probably due to enhancement of ecosystem services such as crop pollination among other yield-enhancing ecosystem services. Thus, to promote high sunflower yields, landscape complexity should be considered.

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