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Abstract

CONTEXT

Differences in land tenure regimes are one challenge to implement soil conservation practices in agricultural systems. It is frequently assumed that tenants are less prone to adopt soil conservation strategies than owners, given a shorter-term engagement with the field. Also, the field's environmental potential (i.e., potential for agricultural production) may influence farmers' investment decisions, since high-potential fields increase the chances of achieving a return of the investment.

OBJECTIVE

Understand the effect of land tenure regimes and environmental potential on fertilization rates and balance of nitrogen, phosphorus, and sulfur in soybean and maize crops of Argentina.

METHODS

We applied mixed-effects models on a database of 52,588 fields of soybean and maize farms, covering a total area of 3.8 M ha in Argentina during the period of 2017-2022.

RESULTS AND CONCLUSIONS

In general, the balance of nitrogen, phosphorus, and sulfur were (mean ± SE) -29.11 ± 0.15, -2.58 ± 0.38, and 8.26 ± 0.044 kg $ha^{-1}yr^{-1}$, respectively. Despite 8.04 and 0.63 kg $ha^{-1}yr^{-1}$ more nitrogen and phosphorus were applied in high-potential than in low-potential maize fields, nutrient outputs were still higher, therefore, net nutrient exports of the most productive fields increased by 9.99 and 2.06 kg $ha^{-1}yr^{-1}$ for nitrogen and phosphorus, respectively. In soybean fields, environmental potential had no effect on nutrient application, but nitrogen and phosphorus net nutrient exports were 9.85 and 2.14 kg $ha^{-1}yr^{-1}$ higher in high-potential fields compared to low-potential fields. Tenure regime had a weak effect, mainly on phosphorus. On average, owners applied 0.37 kg $ha^{-1}yr^{-1}$ more and exported 0.28 kg $ha^{-1}yr^{-1}$ less phosphorus than tenants in both crops. Sulfur application and balance was weakly affected by the studied variables, and the positive balance suggests overfertilization under the assumptions of this paper. We conclude that the Argentine farming system depletes some of the main nutrients, regardless of the field's environmental potential or the land tenure system. The effect of the tenure regime is overwhelmed by the impact of environmental potential on

farmers’ fertilization management, with high-potential fields degrading due to soil mining at a faster pace than low-potential fields, putting future yields at risk.

SIGNIFICANCE

By exploring a farming system based on nutrient depletion, our results contribute to the general understanding of tenure regime consequences on soil degradation. Argentinean farmers should consider increasing N and P application and contemplate environmental heterogeneity to avoid nutrient mining and degradation of one of the most productive areas of the world.

Title page

Environmental potential for crop production and tenure regime influence fertilizer application and soil nutrient mining in soybean and maize crops

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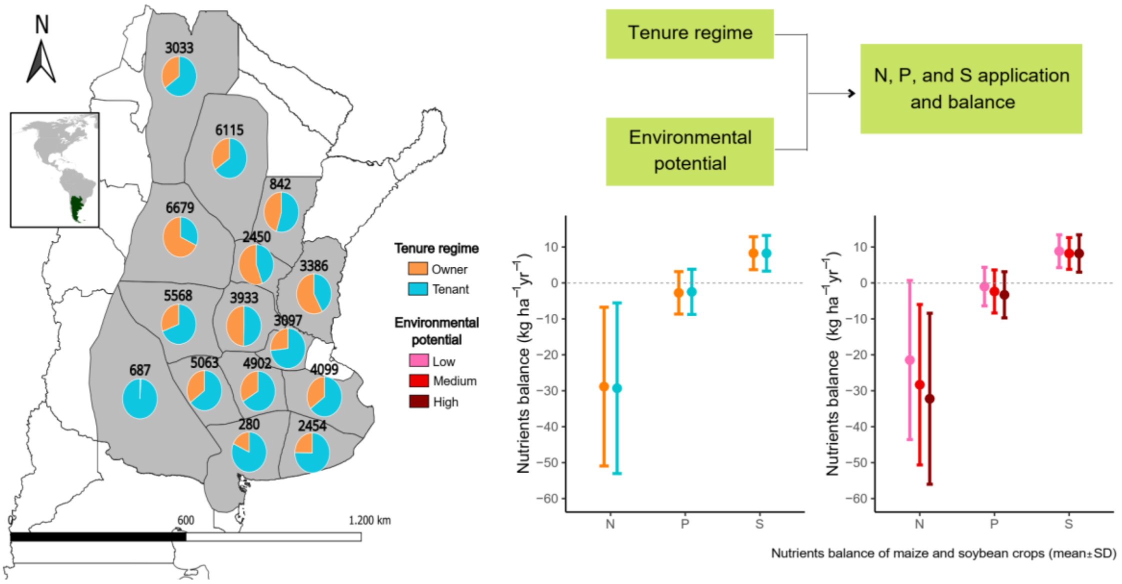
Graphical abstract



Keywords: field crops, crop nutrition, decision making, soil conservation, nutrient mining, tenure regime

Highlights

- The influence of land tenure and environmental potential for crop production on fertilization and nutrient balance was studied.
- Net nutrient exportation prevailed regardless of tenure regime and environmental potential, except for S.
- Land tenure had a low effect on fertilization and nutrient balance.
- In fields of high environmental potential, more nutrients were depleted than in fields of low environmental potential.
- Environmental heterogeneity should be considered when fertilizing.

1. Introduction

Field crops need regular nitrogen (N), phosphorus (P), and sulfur (S), among other nutrients, to achieve yields. When the quantity of fertilizer additions used for crop production does not compensate for the nutrient exported when harvesting, soil nutrient content declines, leading to soil degradation and yields decrease over time (Nawara et al., 2018; Rawal et al., 2022). Nutrient-rich soils, such as mollisols, can withstand negative nutrient balances for a longer time without a significant impact on yield, while for other soils type, fertilization is essential for long-term farming (Jobbágy et al., 2021). Whereas overfertilization is a major concern in several countries, in Latin-American the current trend is soil nutrient mining (i.e., soil nutrient depletion) (FAO, 2019; Vitousek et al., 2009), favored by the capability of soils to produce with low fertilizer addition. Therefore, the implication of this nutrient deficit can have negative consequences for the environment. For example, insufficient fertilizer addition reduces soil organic matter, which is essential for CO^2 atmosphere sequestration, soil quality, and sustainability (Lal, 2009; Liu et al., 2006).

One of the main obstacles to the implementation of soil conservation practices, such as fertilization, is assumed to be land leasing. If tenants cultivate fields in the short term, they may not be interested or financially capable in investing in soil conservation, as its benefits may only materialize in the medium and long-term (Arora et al., 2015; Eder et al., 2021). Furthermore, tenants have to pay rent, which limits their investment capacity when sowing, besides they are at greater risk of losing the investment, profitability, and business viability (Bert et al., 2011). Several studies have documented the negative consequences of land tenancy on soil conservation, such as erosion events (Sklenicka et al., 2022), overexploitation of soils (Eder et al., 2021), more soil compaction, and less soil organic matter content (Walmsley et al., 2020). However, most studies were carried on high fertilization context, it is important to understand the dynamics of farming systems based on nutrient depletion to achieve a more general knowledge of tenure regime implications on land degradation.

Decisions on the fertilization regime applied at a field depend on multiple factors, such as the regions climate, expected climatic conditions during the cropping season (for example ENSO events), crop species and cultivar, farm-gate fertilizer and agricultural products prices, soil properties and fertility, all of which can be resumed in the expected yield of a given field (Zhou et al., 2010). The economic aspect, such as fertilization costs, is a key component of the decision-making process (Brunelle et al., 2015). These two decision dimensions are expected to interact, for example, when evaluating the amount of fertilizer applied by owners versus tenants. For example, differences could be expected when analyzing the field's environmental potential (i.e., potential of the field for agricultural production), where owners and tenants would take different decisions based on their priorities (economic return, extreme climate events risks, expected product price, etc.). Although the impact of land tenure regime on soil conservation investment has been previously studied (Higgins et al., 2018), few works have evaluated the interaction between a field's environmental potential and tenure regimes over the amount of fertilizer applied.

Argentina is mainly an agricultural country in which maize (*Zea mays L.*) and soybean (*Glycine max L.*) are the two dominant field crops. During the 2020/2021 campaign 58.4 Mt of maize and 48.8 Mt of soybean grain were produced. This represents the 5% and 13% of global maize and soybean production (FAOSTAT, 2023). Furthermore, approximately 28% of the land under extensive agriculture is managed by tenants, in which contracts are mostly short-term (one to three years) (INDEC, 2019). Although tenants renew contracts in 85% of the cases, they manage fields as if they were not, focusing on maximizing short-term economic gains at the expense of field conservation (Arora et al., 2015). As a result, the tenure regime makes soil conservation difficult, which is a major problem in Argentina. Agricultural production net extracts an annual average of 26 kg ha^{-1} of N and 5 kg ha^{-1} of P per year (Díaz de Astarloa and Pengue, 2018), and particularly, summer crops have a negative nutrient balance of −31.7 kg N ha^{-1} yr^{-1}, −7.6 kg P ha^{-1} yr^{-1}, and −4.69 kg S ha^{-1} yr^{-1} (Koritschoner et al., 2023). This soil fertility loss is expected to have negative effects on crop yield (Eltun et al., 2002). Therefore, understanding which variables limit adequate fertilizer application in Argentina is essential in terms of conservation and production.

The main objective of this work was to evaluate the effect of land tenure regimes and environmental potential on the amount of agricultural input used and soil degradation. Specifically, we focused on fertilization and balance of three elements: N, P, and S in soybean and maize fields. We hypothesize that tenants' investment in soil conservation practices differs from owners since tenants have to pay rent and possess the lands for a short period of time, while any benefits occur in the long term. We expect higher fertilizer additions and less nutrient depletion on owner-managed fields. Secondly, we hypothesize that high-potential fields (i.e., capacity to obtain high yield) have a better response in yields to fertilizer addition than low-potential fields guaranteeing the recouping of the investment. Therefore, we expect an increase in fertilizer addition and a decrease in nutrient mining as environmental potential increases.

2. Material and methods

2.1 Description of the *study area*

Argentina's extensive agriculture is widely distributed going from the northern to the central part of the country (lat 22° S - lat 40° W), this includes the Pampas and Chaco plains (Fig. 1). This area has a warm temperate climate, mean annual precipitation declines from 1200 mm in the central-east to 400 mm in central-west and to the north, and annual mean temperature declines uniformly from 23 °C in the north to 13 °C in the central part (Cravero et al., 2017). Soils are mainly Mollisols, being Argiudols and Haplustols the most represented groups (Caviglia and Andrade, 2010). The most widespread cropping systems focus on no-tillage summer crops, mainly in glyphosate-resistant soybeans, which actually represent 40% of the total cropped area, and secondly glyphosate-resistant maize (MAGyP, 2022). Some crop rotation schemes, like maize/soybean, or wheat-soybean/maize are widely spread, and soybean monoculture is occasionally used (de Abelleyra and Verón, 2020). Soybean cropping is mainly inoculated with the symbiont and has a very low fertilization rate (Austin et al., 2006) (Fig. 2). Biological nitrogen fixation is reduced by N fertilization; however, sometimes a starter N is applied (Gan et al., 2002).

2.2. Data collection

We analyzed a total of 52,588 fields from seasons 2017 to 2022 from almost all extensive agriculture areas of Argentina, covering a total area of 3,791,516 ha (Fig. 1). Of the total fields, 27,143 were cropping with soybean as the summer crop and 25,445 fields were cropping with maize as the summer crop. Fields cropping with soybean preceded by a winter crop were excluded, because this soybean has a lower yield and different management than soybean preceded by fallow. The data were gathered and systematized by CREA (https://www.crea.org.ar/), a non-profit civil association integrated by more than 1,800 farming companies that share farming experiences and knowledge. On average, a CREA farming company manages 737 ha, while Argentine farming companies manage an average of 686 ha (INDEC, 2019). For each field, we had data on the tenure regime (owned or rented), field location, region (15 regions as defined by CREA), season, farm company identity, crop variety, environmental potential (low, medium, and high), previous crop, N, P, and S fertilization (kg ha^{-1}), and crop yield (kg ha^{-1}). Environmental potential of the field is defined by CREA experts based on soil toposequence and the historic yield. High-potential fields are more prone to yield more than medium and low-potential fields (Goldenberg et al., 2022). The environmental potential assessment is intrinsic to each region, or so the same climatic regime.

2.3. Nutrients balances

We estimated the nutrient balance as the difference between nutrient inputs and outputs, detailed below:

2.3.1. Nutrient Input: These included fertilizer applied per unit of area (kg ha^{-1}), biological N fixation, and atmospheric deposition. Biological N fixation was considered just for soybean crops, and we estimated it as 60% of the total N harvests in soybean grains (Collino et al., 2015). We used the atmospheric depositions estimated in a long-term study carried out on a central location in the Rolling Pampa that measured an average annual atmospheric deposition of 7.2 kg S ha^{-1} and 9 kg N ha^{-1} (Carnelos et al., 2019).

2.3.2. Nutrients output: These included nutrients withdrawn through crop harvests and direct and indirect N emissions. N losses through leaching are insignificant because of the low fertilization rate and the flatness of the landscape in the study area (Portela et al., 2006). Nutrients withdrawn through crop harvests were estimated with the yield per unit of area (kg ha^{-1}) and the standard values of nutrients that the crop requires to produce grain (nutrient content in the grain). The nutritional requirements are: 1 ton of maize requires 13.1 kg N, 2.64 kg of P, and 1.22 kg of S, 1 ton of soybean requires 48.5 kg of N, 5.4 kg of P, and 2.8 kg of S (Cruzate and Casas, 2009). We used the N_2O emissions factors calculated by Koritschoner et al., 2023 based on IPCC guidelines (2019) for the Chaco-Pampean plain. The direct emission factor of N_2O considered was 0.01 kg N_2O-N per kg N applied, and the indirect emission factor of N_2O from volatilization considered was 0.1 kg NH_3-N and NO_x-N per kg of N applied or deposited via crop residues. Since most of the fields are based on a no-tillage system, we assumed that crop residues remain in the soil. We considered that for 1 ton of maize and soybean produced, 7 kg and 20 kg of N, respectively, remain in crop residues (Ciampitti and García, 2007).

2.4. Data analysis

We established separate models for N, P and S addition and balance for maize and soybean. We applied linear mixed-effects models, assuming a Gaussian error distribution (R version 4.1.3, lme4 package, lmer function) (Bates et al., 2015, R Core Team, 2022). All models considered region, farm company identity, year, previous crop, and crop variety as non-nested random effects, and tenancy, environmental potential, and their interactions as fixed-effects. We used log transformation in N applied to soybean and S applied to maize and soybean models, and root-square transformation in P applied to maize and soybean models to reduce the heteroscedasticity of residuals. We performed a type III two-way ANOVA for each model (package car, Anova function) (Fox & Weisberg, 2019), and a no orthogonal a priori comparison between environmental potential levels with Dunn-Šidák test (multcomp package, cld function) (Šidák, 1967) only for the models that evidence differences between means in the ANOVA.

3. Results

Of the total fields, 41% (21,718) were managed by tenants and 59% (30,870) were managed by owners (Fig. 1). High-potential fields were managed mainly by owners, while medium-potential fields were more frequently managed by tenants, and low-potential fields were equally distributed. Soybean was more frequent than maize and had a similar proportion for both tenure regimes. Weak differences in field size were detected with an average size of 72.1 ha and 73.3 ha for owners and tenants, respectively (p-value = 0.0753). Nutrient balance was negative for N and P, and positive for S in both crops. In maize fields, the mean ± standard error (SE) balances of N, P, and S were -14.1 ± 0.19 kg ha^{-1} yr^{-1}, -1.1± 0.052 kg ha^{-1} yr^{-1}, and 9.1 ± 0.051 kg ha^{-1} yr^{-1}, respectively, while in soybean fields the mean ± SE balances of N, P, and S were -46.3 ± 0.01, -3.64 ± 0.041 kg ha^{-1} yr^{-1}, and 7.14 ± 0.054 kg ha^{-1} yr^{-1}, respectively.

3.1. Maize fields

We found strong evidence that N fertilization increased with the environmental potential but there was no evidence that the tenure regime affected N fertilization or balance (Fig. 3, table 1). In contrast, tenants applied less P than owners in high-potential fields, but there was no difference in low and medium-potential fields (Fig. 3). Also, P fertilization in owners-managed fields increased with the environmental potential, but in tenant-managed fields, there was a difference in P application only between low and medium-potential fields (Fig. 3). Regarding S application, tenants fertilized less than owners just in low-potential fields (Fig. 3). Differences in application of S between environmental potential levels were found just for tenants-managed fields, where high-potential fields were fertilizer more than low and medium-potential fields (Fig. 3).

Since productivity increased more than fertilization with the environmental potential, nutrient exports increased as well, except for S. N net export increased strongly with the environmental potential, however, no differences were found between tenure regimes (Fig. 3, table 1, table 2). P net export increased moderately with the environmental potential, except for low-potential fields managed for owners where the balance was positive (Fig. 3). Also, tenants net exported more P than owners just in high-potential fields (Fig. 3). S balance was positive and no differences were found between tenure regimes (Fig. 3, table 1). High-potential fields managed by owners had less S net import than low-potential fields (Fig. 3).

3.2. Soybean fields

No evidence was found that the environmental potential had an effect on fertilizer application, whereas the tenure regime had a moderate influence (Fig. 4, table 1). Tenants applied less N in low and high-potential fields, and more N in medium-potential fields than owners, but the effect size was weak (Fig. 4, table 2). Also, tenants applied less P than owners in all environmental potential levels (Fig. 4). For S application, no evidence of differences between tenure regimes was found (Fig. 3, table 1).

Similar to maize nutrient balance tendency, in soybean crops nutrient outputs exceed inputs, except for S (Fig. 4). Particularly, N net export increased strongly with the environmental potential (Fig. 4, table 2). Further, tenants net exported more N than owners in low-potential fields, whereas no differences were found in medium and high-potential fields (Fig. 4, table 2). P net export also increased with the environmental potential, but the magnitude of the effect was smaller than N (Table 2). Tenants net exported more P than owners for the three environmental potential levels (Fig. 4, table 2). In contrast, S balance was positive (Fig. 4). High-potential fields had less S net import than low-potential fields (Fig. 4, table 2). No effect of tenure regime in S balance was found (Fig. 4, table 1, table 2).

4. Discussion

Besides the strong nutrient depletion currently taking place in soybean and maize crop in Argentina, our study shows that environmental potential is the most important variable explaining the dynamics of fertilizer use and the resulting nutrients balances at the field scale. We found a strong general effect size of between 8% to 12% more fertilizer addition in high-potential fields than in low-potential fields (just in maize crops), and, opposite to our prediction, between 25% to 146% more nutrient net exported in high-potential fields compared to low-potential fields (Fig. 3, Fig. 4). Regarding tenure regime, the only nutrient affected was P in maize and soybean crops, tenants applied less and net exported more P than owners in both crops, however, the effect size was weak (between 2% to 3% more fertilization and 6.5% to 37% more nutrient net exported) compared with environmental potential effect (Fig. 3, Fig. 4).

4.1. Tenure regime and nutrients dynamic

We found that the tenure regime has a low effect on fertilization application and soil conservation. The lack of effect of tenure regime on maize N fertilization and balance can be explained by the fact that N has low residuality in soil (Glendining et al., 2001), so the majority N applied is used by the current crop or is lost (Cassman et al., 2002), thus N fertilization could be considered as a short-term practice. Further, maize has to be fertilized with N to obtain economically profitable yields (Gregoret et al., 2011), therefore farmers probably cannot skimp on N fertilizer application. In the opposite, the tenure regime had a weak effect on soybean N fertilization and balance. Should be noted that both tenures had low N fertilization rates in soybean and the environmental potential had no effect on the amount of nutrients applied (Fig. 2, Fig. 4, Table 1). These results suggest that soybean crops received a standard amount of N. This may be explained by the fact that soybean is inoculated with the N-fixing symbiont, and this process is inhibited by N fertilization (Gan et al., 2002). Furthermore, soybeans show high yields despite receiving very little fertilization (Austin et al. 2006). Finally, soybean fields should have other soil conservation practices, such as more diversified crop rotation or overfertilization in winter crops, that compensate N exportation.

The balance and application of P was affected moderately by the tenure regime. This could be explained by the fact that a fraction of P applied in fertilization accumulates as residues in soil, thus tenants could not be willing to apply a high amount of P if they will not take benefit of it (Eghball et al., 1990; Syers et al., 2008). Hence, adequate P fertilization could be considered a long-term practice. Furthermore, the largest P fertilization gap between owners and tenants was in high-potential fields in both crops (Fig. 3, Fig. 4). This suggests that owners have better knowledge of the heterogeneity of their lands, or they are concerned to conserve the high-potential of their fields.

An unexpected result was the positive balance of S, or rather S overfertilization. Our results contrast with a previous study that found a negative nutrient balance of S in the same studied area (Koritschoner et al., 2023). However, the S atmospheric deposition that we used comes from a long-term measurement from a single location in the Pampa Argentina (Carnelos et al., 2019), while Koritschoner et al. (2023) used a worldwide study that established a low amount of S atmospheric deposition (Vet et al., 2014). This difference between S atmospheric deposition estimation may explain the contrasting results. It should be considered that S atmospheric depositions show a great variability with time and the distance to sea or a big city (Carnelos et al., 2019). Local studies and models to predict S atmospheric deposition are needed to improve S fertilization efficiency. On the other hand, the generally low adoption of S fertilizer application could explain the absence of the effect of the tenure regime and the environmental potential. Also, crop response to S fertilization is still unclear for both farmers and the scientific community (Torres Duggan et al., 2012).

Several studies found that owners are more willing to invest in soil conservation and long-term benefit practices, such as crop rotation with perennials and forage legumes, bunds, and compost investment (Eder et al., 2021; Fraser, 2004; Sklenicka et al., 2015; Teshome et al., 2016). On the contrary, the studies that examined whether inorganic fertilization depends on the tenure regime, show that there was no difference between the amount of inorganic fertilizer applied by owners and fixed tenants (Akram et al., 2019; Teshome et al., 2016), partially in concordance with our results. We found that the tenure regime affects P fertilization, but this effect is low. Myyrä et al. (2007) show that P fertilization increases with lease contract time. Further, a previous study in the Pampa region established that when tenants have legal lease terms of a field for a longer time period than one year, they manage that land similarly to an owned land (Arora et al., 2015). In our data is not established the lease term or the period of time that the field is managed by a unique farmer, if several tenants of our data have a long-term lease, this could explain the low effect size on P fertilization.

4.2. Nutrients export and environmental heterogeneity

The most significant finding of our study are the high rates of N and P exportation in Argentinean soybean and maize crops (Fig. 3, Fig. 4). This general pattern is consistent with previous findings that identify Argentina as one of the major nutrient exporter worldwide (Díaz de Astarloa and Pengue, 2018; Guareschi et al., 2019; Koritschoner et al., 2023), and, particularly, the country with the major P depletion process of the world (Schipanski and Bennett, 2012). Soybean crops exported large quantities of N, and as shown in previous studies, is one of the major N soil mining in Argentina (Austin et al., 2006; Koritschoner et al., 2023). This may be explained by the fact that biological N fixation supplies 60% of that required by soybean crops, and the rest is absorbed from the soil (Collino et al., 2015). We found that nutrient depletion is highly dependent on environmental potential, this may be explained by the fact that high-potential fields yield more than low-potential fields. Also, high-potential fields respond to fertilization with a higher yield than low-potential fields, which is not compensated by higher fertilizer application in high-potential fields, in consequence, the nutrient net export is higher (Fig. 3, Fig. 4). Furthermore, this pattern of increased fertilizer application with the increase of the environmental potential may be explained by the fact that high-potential fields secure high yield profitability, hence farmers will recoup their investment in fertilization. An alternative explanation to the trend of fertilization increased with the environmental potential is that high-potential fields conserve their good features due to receiving more nutrients, while medium or low-potential fields degrade because they were not supplied with enough fertilizer (Rawal et al., 2022). However, the field's environmental potential assessment is based on the soil type and surface topography, which strongly determine fields' yield (and partially, the nutrient balance), so this last hypothesis could be partially correct.

In contrast to Argentina, other grain exporting countries, such as Brazil, have positive N and P balances (Guareschi et al., 2019). N-fixing bacteria in Brazil's fields fix 80% of the N needed by soybean crops, while in Argentina the N-fixation is 60% (Collino et al., 2015). However, Brazil's soils are poor in P, so fertilization is indispensable for farming, whereas Argentine farmers may save fertilize and deplete soils for the longest period without a significant effect on yield (Jobbágy et al., 2021). It should be noted that the synthetic fertilizer's price has risen in the last few years, and the tendency is to continue increasing (Brunelle et al., 2015), so positive nutrient balance based on synthetic fertilizers could be non-viable in the future. To avoid nutrient loss and land degradation sustainable strategies, such as agroecological principles, need to be implemented in Argentine and world agricultural systems (Brunelle et al., 2015). This paper highlights that environmental potential is a key variable in farmer management and considers soil heterogeneity to ensure appropriate fertilization practices and reduce soil degradation is essential.

While the CREA farm data provides an exceptionally rich data set covering 3.8 M ha, the CREA farm data can be prone to some biases. CREA provides management standards to all farmers, which could level out differences in management between owners and tenants, which might be more pronounced in the more diverse Argentinean agriculture situation. Further, this study did not differentiate between short-term and long-term field tenancy. It could be plausibly assumed that long-term tenant management does not differ from owner management. In future studies, it would be interesting to consider the tenancy time period to better understand this complex variable. Further, other sources of nutrient gains and losses are expected to modify the calculated nutrient balances over time. For example, winter legumes or other crops preceding summer crops can incorporate nitrogen into the soil or be over-fertilized to improve soil fertility (Koritschoner et al., 2023).

5. Conclusions

Agriculture can have a massive impact on the environment and on the long-term capacity of the natural capital to produce goods and services. In this study, using maize and soybean in Argentina as an example, we show how environmental potential can have important effects on farmers' fertilization decisions and the nutrient mining process. High-potential maize fields were more fertilized but net exported more N and P than low-potential fields, implying greater soil degradation in the most productive fields. The tenure regime had a weak effect on nutrient application and balance. The highest differences were for P in high-potential fields, where tenants applied and net exported more P than owners, suggesting that owners have a better knowledge of fields heterogeneity and are more concerned with soil conservation. However, soybean fertilization rates responded weakly to the environmental potential and the tenure regime, and presented the highest nutrient mining, principally N, with high-potential fields being the most affected in this study. S fertilization may not be needed in extensive agriculture in Argentina; however, this is a global result and may vary between regions. This work reveals the necessity of a better knowledge of soil and environmental heterogeneity of fields to achieve an adequate fertilization plan that avoids soil degradation. Soybean fields should implement extra soil conservation practices, such recover soil nutrient fertilizing in another crop of the rotation sequence. Also, more studies addressing the S cycle in agroecosystems are needed to optimize S fertilization. Both tenants and owners should increase nutrient input on average of N and P by 19%, 1% in maize crops, and 574% and 32% of N and P in soybean crop to achieve more sustainable agricultural systems in Argentina.

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Table 1: ANOVA table of each model, N, P, and S applied and balance in maize and soybean crops. Table shows chis-q values and p-value in brackets for each fixed variable, number of observations (n=), and R^2 conditional and marginal for each model. Degrees´ freedom were 1 for tenancy, and 2 for environmental potential (EP) and tenancy:EP.

Crop	Response variable	Predictors			R^2	
		Tenancy	EP	Tenancy: EP	Conditional	Marginal
Maize	**N applied** (n= 16,056)	0.12 (0.73)	166.9 (<.0001)	1.76 (0.41)	0.67	0.015
	N balance (n= 16,056)	2.85 (0.091)	133.9 (<.0001)	1.91 (0.38)	0.62	0.013
	P applied (n= 13,937)	8.49 (0.0036)	38.9 (<.0001)	31.9 (<.0001)	0.63	0.008
	P balance (n= 13,937)	3.24 (0.071)	140.8 (<.0001)	13.7 (0.001)	0.55	0.016
	S applied (n= 7,523)	12.8 (0.0003)	35.9 (<.0001)	11.0 (0.0039)	0.71	0.005
	S balance (n= 7,523)	0.24 (0.62)	8.68 (0.013)	11.0 (0.004)	0.61	0.002
Soybean	**N applied** (n= 7,436)	12.6 (0.0004)	3.51 (0.17)	0.90 (0.63)	0.81	0.004
	N balance (n= 7,436)	9.93 (0.001)	194.4 (<.0001)	16.8 (0.0002)	0.72	0.005
	P applied (n=11,610)	15.5 (<.0001)	0.87 (0.64)	4.32 (0.11)	0.71	0.013
	P balance (n=11,610)	14.1 (0.0001)	150.0 (<.0001)	6.07 (0.048)	0.68	0.021
	S applied (n=4,222)	6.11 (0.013)	5.48 (0.064)	1.91 (0.38)	0.84	0.003
	S balance (n=4,222)	3.25 (0.071)	12.9 (0.001)	0.90 (0.64)	0.72	0.005

Table 2: Summary table showing fixed effects estimates, standard error, and P-value in brackets of each parameter of the models explaining nutrients applied and balance as responses to land tenure regime and environmental potential (EP). Standard deviations of random effects are also included.

	Maize						Soybean					
Fixed effects	**N applied**	**N balance**	**P applied**	**P balance**	**S applied**	**S balance**	**N applied**	**N balance**	**P applied**	**P balance**	**S applied**	**S balance**
Intercept	65.1±5.8 (<.0001)	-2.55±8.6 (0.77)	3.68±0.11 (<.0001)	0.28±1.4 (0.85)	1.97±0.088 (<.0001)	9.65±0.9 (<.0001)	1.85±0.075 (<.0001)	-39.8±5.8 (<.0001)	3.18±0.11 (<.0001)	-2.22±1.5 (0.18)	1.73±0.14 (<.0001)	7.86±1.2 (<.0001)
Owner	0.44±1.3 (0.73)	-2.72±1.6 (0.091)	0.12±0.042 (0.0035)	0.81±0.45 (0.071)	0.13±0.038 (0.0003)	0.24±0.48 (0.62)	0.093±0.026 (0.0004)	4.21±1.3 (0.001)	0.14±0.035 (<.0001)	1.36±0.36 (0.0001)	0.11±0.047 (0.013)	1.05±0.58 (0.071)
Medium Ep	7.08±1.1 (<.0001)	-10.5±1.3 (<.0001)	0.22±0.035 (<.0001)	-1.14±0.38 (0.002)	0.08±0.03 (0.008)	-0.9±0.38 (0.018)	0.040±0.021 (0.066)	-5.12±1.1 (<.0001)	0.015±0.029 (0.59)	-1.77±0.3 (<.0001)	0.05±0.036 (0.16)	-0.90±0.45 (0.045)
High Ep	13.6±1.1 (<.0001)	-15.9±1.4 (<.0001)	0.16±0.037 (<.0001)	-3.81±0.40 (<.0001)	0.17±0.032 (<.0001)	-0.28±0.40 (0.49)	0.039±0.024 (0.10)	-14.8±1.2 (<.0001)	0.029±0.031 (0.36)	-3.77±0.32 (<.0001)	0.08±0.037 (0.022)	-1.61±0.46 (0.0005)
Owner: medium	-1.51±1.3 (0.25)	1.84±1.6 (0.26)	-0.08±0.04 (0.045)	-0.47±0.47 (0.31)	-0.08±0.039 (0.037)	0.08±0.5 (0.86)	-0.024±0.025 (0.34)	-5.22±1.3 (0.0001)	0.03±0.035 (0.40)	-0.50±0.37 (0.18)	-0.05±0.05 (0.29)	-0.54±0.60 (0.36)
Owner: high	-0.64±1.4 (0.64)	0.63±1.7 (0.71)	0.07±0.04 (0.080)	0.70±0.49 (0.15)	-0.13±0.039 (0.001)	-1.0±0.50 (0.047)	-0.020±0.027 (0.46)	-2.92±1.4 (0.044)	0.072±0.038 (0.059)	0.13±0.4 (0.72)	-0.07±0.05 (0.16)	-0.32±0.61 (0.60)
Random effects			**Standard deviation**									
Farm	18.2	18.5	0.64	5.70	0.49	5.25	0.40	11.8	0.56	4.64	0.49	5.17
Crop variety	4.92	7.41	0.15	1.04	0.13	1.60	0.10	5.55	0.15	1.47	0.15	1.28
Previous crop	3.16	5.86	0.09	0.64	0.07	0.60	0.065	3.86	0.20	0.50	0.20	0.26
Region	20.2	18.7	0.37	3.42	0.25	2.66	0.22	13.0	0.30	3.87	0.43	3.19
Year	4.64	15.3	0.08	2.31	0.08	0.60	0.06	9.5	0.057	2.42	0.08	1.34

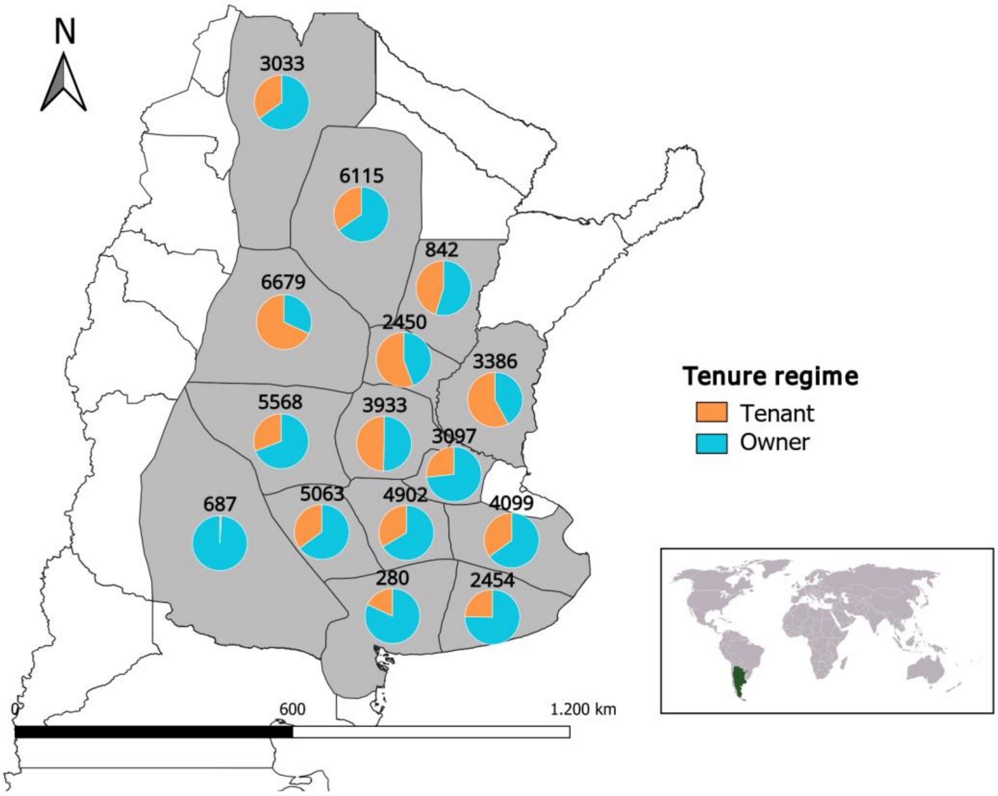
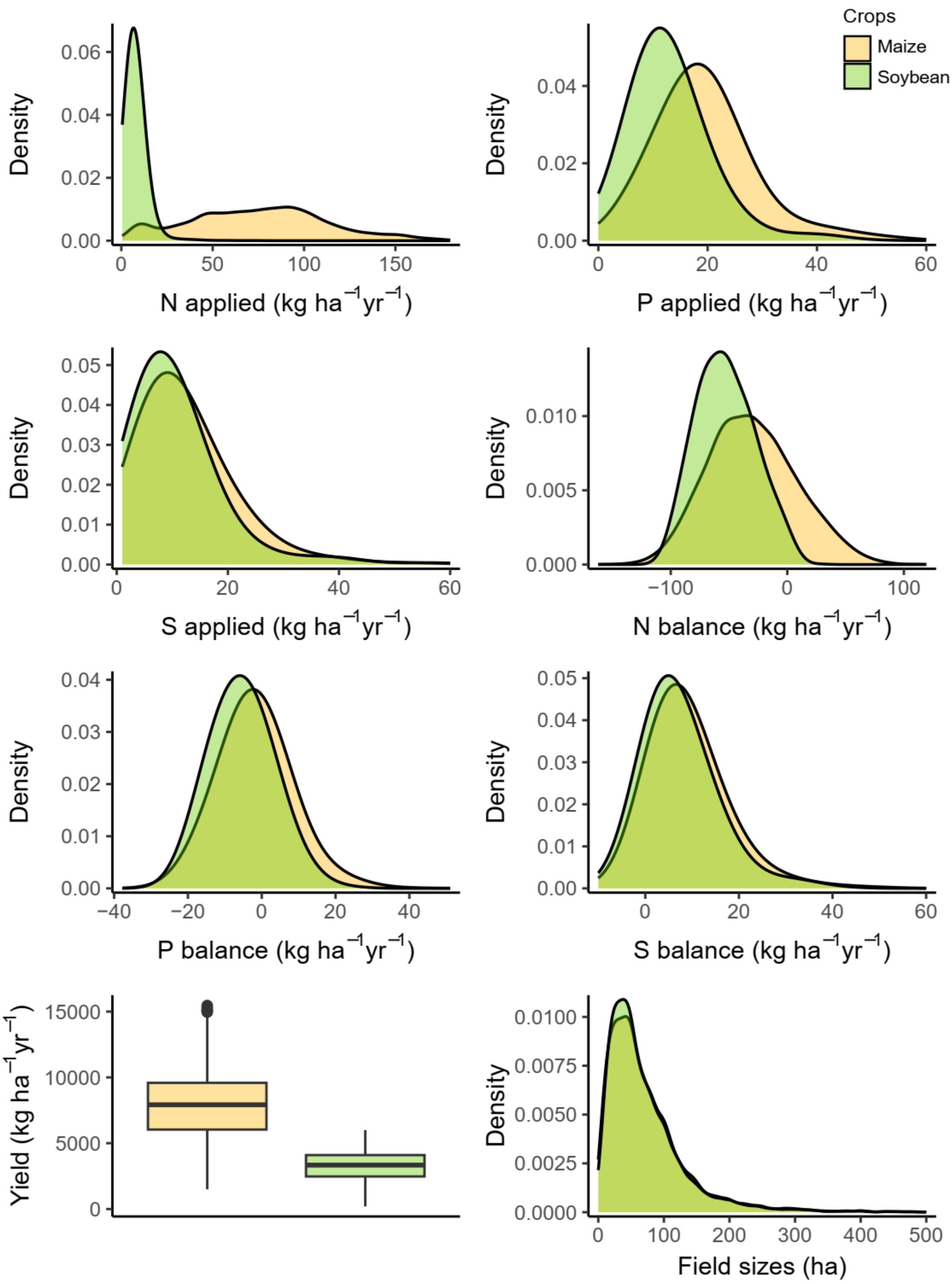


Figure 1: Study sites with the proportion of tenancy regime and number of observations for each region.



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558 **Figure 2**: Density plots show the data distribution of nitrogen, phosphorus and sulfur applied
559 and balance, field sizes, and yield of soybean (green) and maize crops (yellow).

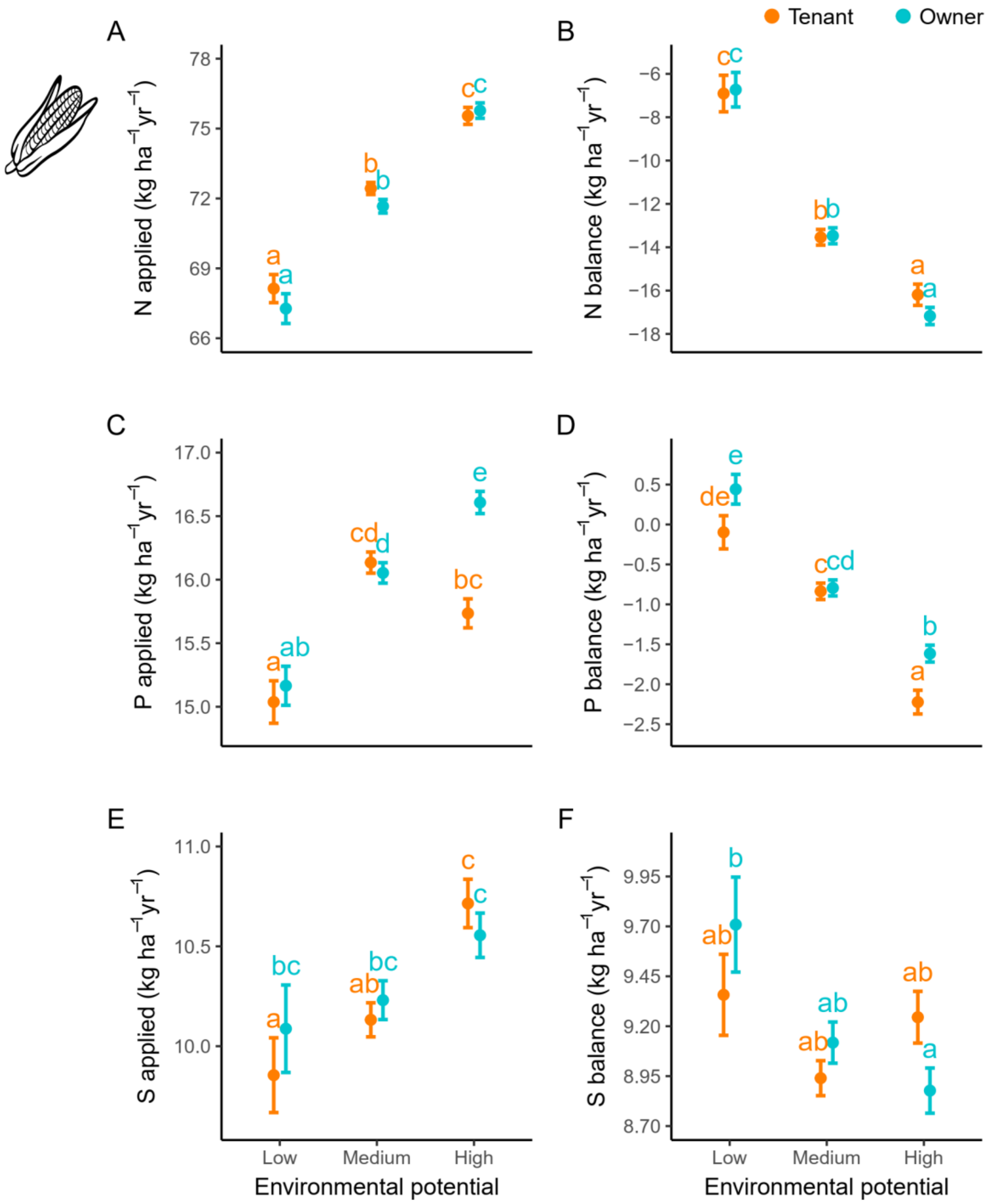

Figure 3: Mean observed (± SE) of nitrogen applied (A) and balance (B), phosphorus applied (C) and balance (D), and sulfur applied (E) and balance (F) in maize crops managed by tenants (orange) and owners (cyan) in low, medium, and high-potential fields. Means with different lowercase letters differ statistically at α = 0.05 according to a pairwise post hoc Dunn-Šidák test.

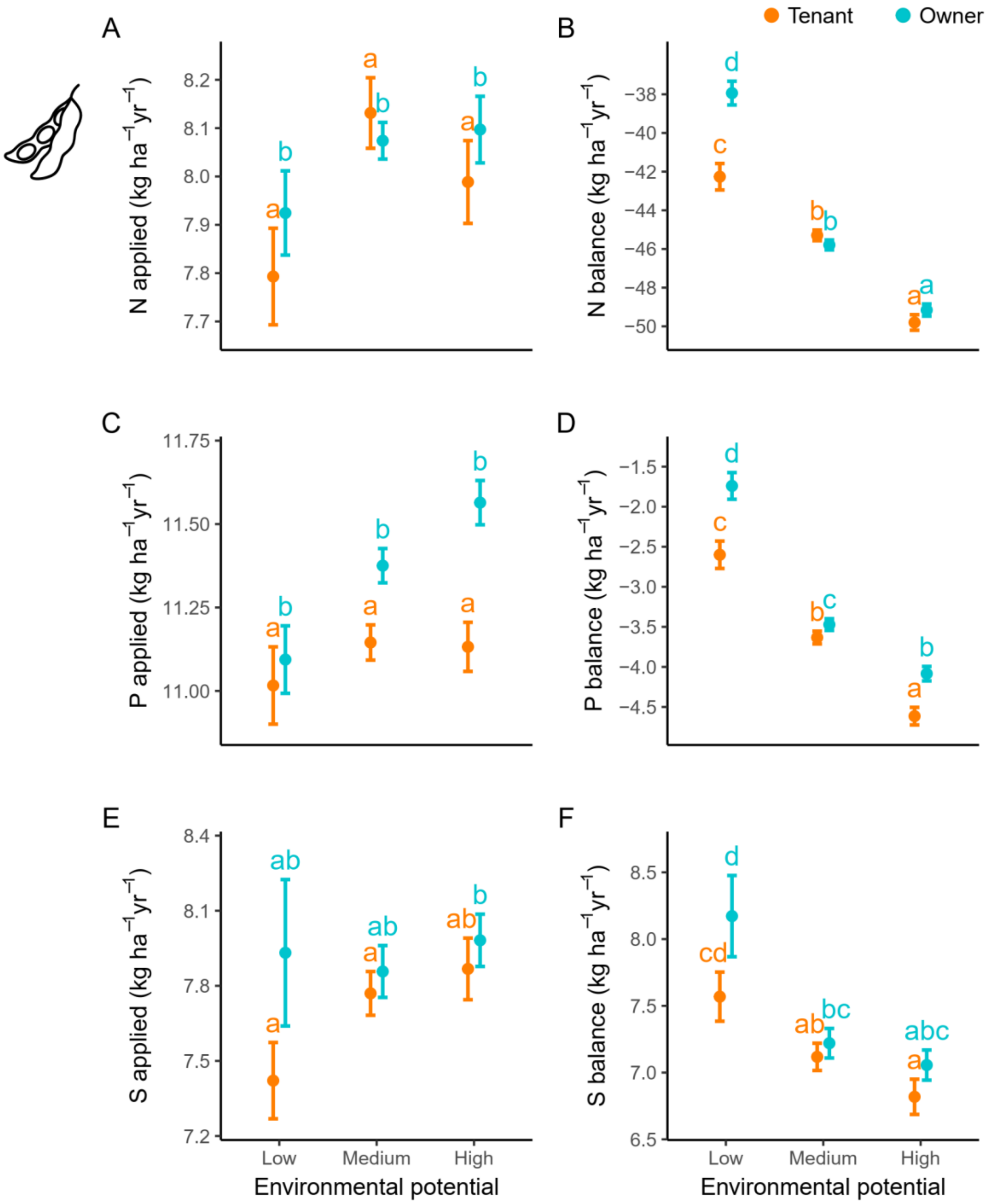

Figure 4: Mean observed (± SE) of nitrogen applied (A) and balance (B), phosphorus applied (C) and balance (D), and sulfur applied (E) and balance (F) in soybean crops managed by tenants (orange) and owners (cyan) in low, medium, and high-potential fields. Means with different lowercase letters differ statistically at α = 0.05 according to a pairwise post hoc Dunn-Šidák test.