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

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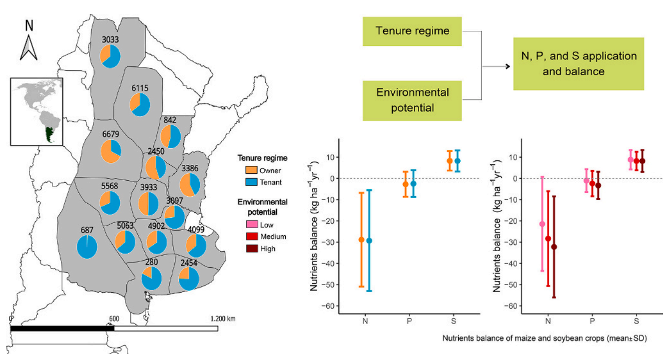
HIGHLIGHTS

- The influence of land tenure and environmental potential on fertilization and nutrient balance was studied.
- Net nutrient exportation prevailed regardless of tenure regime and environmental potential, except for sulfur.
- 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.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Differences in land tenure regimes are one challenge to implementing soil conservation practices in agricultural systems. It is frequently assumed that tenants are less likely 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 on 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 in 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.

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RESULTS AND CONCLUSIONS: Overall, the balance of nitrogen, phosphorus, and sulfur was (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 compared to 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 the net export of nitrogen and phosphorus was 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 were 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.

1. Introduction

Field crops need regular nitrogen (N), phosphorus (P), and sulfur (S), and other nutrients to achieve optimal 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). Certain nutrient-rich soils, such as malisons, 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 over-fertilization 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, 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, so 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 in a field depend on multiple factors, such as the region's climate, expected climatic conditions during the cropping season (e.g., ENSO events), crop species and cultivar, farm-gate fertilizer and agricultural products prices, soil properties, and fertility, all of which can be summarized by 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, particularly when evaluating the amount of fertilizer applied by owners compared to 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, risks of extreme climate events, expected product prices, 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. In the 2020/2021 campaign, 58.4 Mt. of maize and 48.8 Mt. of soybean grains were produced, accounting for 5% and 13% of global maize and soybean production, respectively (FAO, 2023). Furthermore, approximately 28% of the land under extensive agriculture is managed by tenants, with short-term contracts mostly ranging from one to three years (*Instituto Nacional de Estadística y Censos - INDEC,* 2019). Although tenants renewing contracts in 85% of the cases, they often 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 poses challenges to soil conservation, which is a major problem in Argentina. Agricultural production leads to an annual average extraction 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 exhibit 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 loss of soil fertility 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 study was to evaluate the effect of land tenure regimes and environmental potential on agricultural input usage and soil degradation, with a specific focus 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, while any benefits occur in the long term. We expect higher fertilizer additions and less nutrient depletion in owner-managed fields than in tenant-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 spanning from the northern to the central regions of the country (lat 22° S - lat 40° W), this includes the Pampas and Chaco plains (Fig. 1). The climate in this area is characterized as warm temperate, with mean annual precipitation declines from 1200 mm in the central-east to 400 mm in central-west and northern regions. The 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, with Argiudols and Haplustols being the most represented groups (Caviglia and Andrade, 2010). The most widespread cropping systems focus on no-tillage summer crops, mainly glyphosate-resistant soybeans, which represent 40% of the total cropped area, followed by glyphosate-resistant maize (Ministerio de Agricultura, Ganadería y Pesca, 2022). Crop rotation schemes such as maize/soybean or wheat-soybean/maize are widely spread, although soybean monoculture is occasionally observed (de Abelleyra and Verón, 2020). Soybean cropping is mainly inoculated with the symbiont and typically has low fertilizer application rates (Austin et al., 2006) (Fig. 2). It is worth noting that N fertilization can reduce biological nitrogen fixation, although starter N is sometimes applied (Gan et al., 2002).

2.2. Data collection

We analyzed a total of 52,588 fields from the 2017 to 2022 seasons, covering nearly all extensive agriculture areas of Argentina with a total area of 3,791,516 ha (Fig. 1). Among these fields, 27,143 were cropped with soybean and 25,445 were cropped with maize as summer crops. We excluded fields where soybean was preceded by a winter crop, as it 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 of over 1800 farming companies that share farming experiences and knowledge. On average, a CREA farming company manages 737 ha, while the average for Argentine farming companies is 686 ha (*Instituto Nacional de Estadística y Censos - INDEC*, 2019). For each field, we had information 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}). The environmental potential of each field is defined by CREA experts based on soil toposequence and the historic yield. High-potential fields are expected to yield more than medium and low-potential fields (Goldenberg et al., 2022). The environmental potential assessment is intrinsic to each region or to the same climatic regime.

2.3. Nutrients balances

We estimated the nutrient balance as the difference between nutrient inputs and outputs, which are 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 only considered for soybean crops, and we estimated it as 60% of the total N harvested in soybean grains (Collino et al., 2015). We used the estimated atmospheric depositions from a long-term study carried out in a central location in the Rolling Pampa, which reported 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 using the yield per unit of area

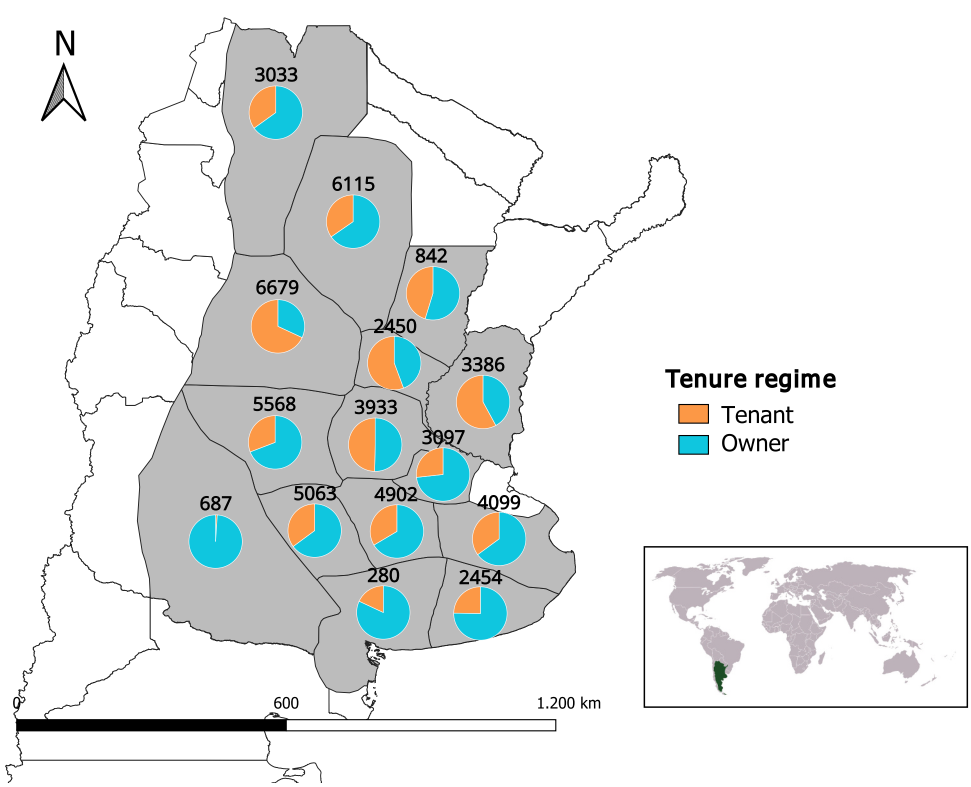

Fig. 1. Study sites with the proportion of tenancy regime and number of observations for each region.

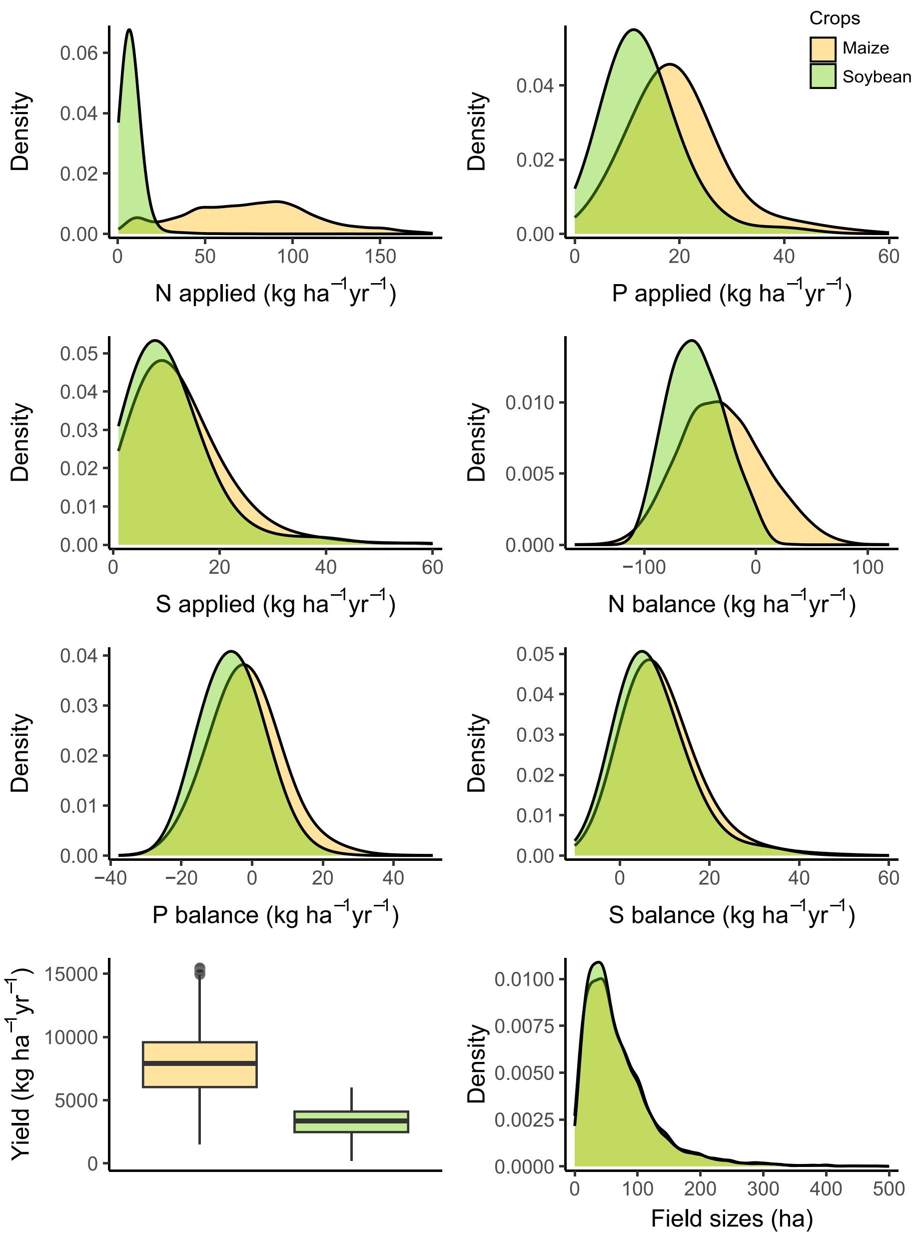

Fig. 2. Density plots show the data distribution of nitrogen, phosphorus and sulfur applied and balance, field sizes, and yield of soybean and maize crops.

(kg ha^{-1}) and the standard values of nutrients required by the crops to produce grain (nutrient content in the grain). The nutritional requirements are as follows: 1 ton of maize requires 13.1 kg of N, 2.64 kg of P, and 1.22 kg of S, while 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 of 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 under a no-tillage system, we assumed that crop residues remain in the soil. We considered that for every 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. Linear mixed-effects models were applied, 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, while tenancy, environmental potential, and their interactions as fixed-effects. We used log transformation in N applied to soybean and S applied in maize and soybean models, while square root transformation was used in P applied to maize and soybean models to address heteroscedasticity of residuals. For each model, we performed a type III two-way ANOVA (package car, Anova function) (Fox and Weisberg, 2019). In cases where the ANOVA evidenced differences between means, a non-orthogonal a priori comparison between environmental potential levels was conducted using the Dunn-Šidák test (multcomp package, cld function) (Šidák, 1967).

3. Results

Of the total fields, 41% (21,718) were managed by tenants, while 59% (30,870) were managed by owners (Fig. 1). High-potential fields were primarily managed by owners, while medium-potential fields were more frequently managed by tenants, and low-potential fields were equally distributed. Soybean was more prevalent 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 for owners and 73.3 ha for tenants (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. For 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 indicating that N fertilization increased with the environmental potential, but no evidence was found suggesting that the tenure regime influenced N fertilization or balance (Fig. 3, Table 1). In contrast, tenants applied less P than owners in high-potential fields, but there were no differences observed in low and medium-potential fields (Fig. 3). Additionally, P fertilization in owners-managed fields increased with the environmental potential, whereas in tenant-managed fields, there was only a difference in P application between low and medium-potential fields (Fig. 3). Regarding S

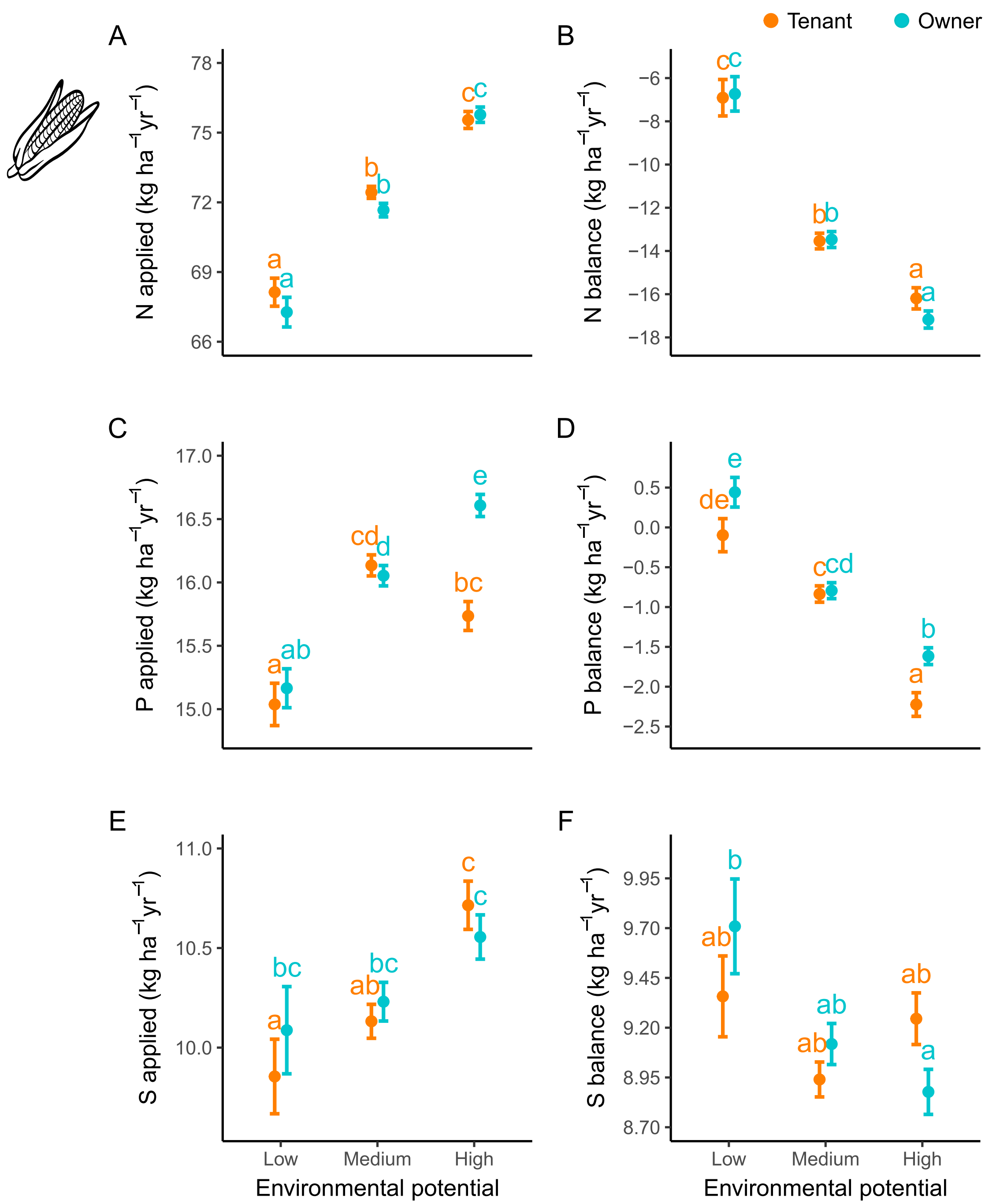

Fig. 3. Mean observed (± SE) of nitrogen applied (A) and balance (B), phosphorus applied (C) and balance (D), and sulfur applied (E) and balance (F) in maize crops managed by tenants and owners in low, medium, and high-potential fields. Means with different lowercase letters differ statistically at α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

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. Degreeś 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 (<0.0001)	1.76 (0.41)	0.67	0.015
	N balance (n = 16,056)	2.85 (0.091)	133.9 (<0.0001)	1.91 (0.38)	0.62	0.013
	P applied (n = 13,937)	8.49 (0.0036)	38.9 (<0.0001)	31.9 (<0.0001)	0.63	0.008
	P balance (n = 13,937)	3.24 (0.071)	140.8 (<0.0001)	13.7 (0.001)	0.55	0.016
	S applied (n = 7523)	12.8 (0.0003)	35.9 (<0.0001)	11.0 (0.0039)	0.71	0.005
	S balance (n = 7523)	0.24 (0.62)	8.68 (0.013)	11.0 (0.004)	0.61	0.002
Soybean	**N applied** (n = 7436)	12.6 (0.0004)	3.51 (0.17)	0.90 (0.63)	0.81	0.004
	N balance (n = 7436)	9.93 (0.001)	194.4 (<0.0001)	16.8 (0.0002)	0.72	0.005
	P applied (n = 11,610)	15.5 (<0.0001)	0.87 (0.64)	4.32 (0.11)	0.71	0.013
	P balance (n = 11,610)	14.1 (0.0001)	150.0 (<0.0001)	6.07 (0.048)	0.68	0.021
	S applied (n = 4222)	6.11 (0.013)	5.48 (0.064)	1.91 (0.38)	0.84	0.003
	S balance (n = 4222)	3.25 (0.071)	12.9 (0.001)	0.90 (0.64)	0.72	0.005

application, tenants applied fewer fertilizers than owners only in low-potential fields (Fig. 3). Differences in S application between environmental potential levels were only observed in tenants-managed fields, where high-potential fields received more fertilizer compared to 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, while no differences were found between tenure regimes (Fig. 3, Table 1, Table 2). P net export moderately increased with the environmental potential, except for low-potential fields managed by owners, where the balance was positive (Fig. 3). Also, tenants net exported more P than owners only 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 lower S net import than low-potential fields (Fig. 3).

3.2. Soybean fields

No evidence was found to suggest 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 compared to owners, although the effect size was weak (Fig. 4, Table 2). Additionally, tenants applied less P than owners across all environmental potential levels (Fig. 4). No evidence of differences between tenure regimes was found for S application (Fig. 3, Table 1).

Similar to the nutrient balance tendency observed in maize crops, 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). Furthermore, 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, although the effect size was smaller than for N (Table 2). Tenants net exported more P than owners for all three environmental potential levels (Fig. 4, Table 2). In contrast, the S balance was positive (Fig. 4). High-potential fields had a lower S net import than low-potential fields (Fig. 4, Table 2). No effect of the tenure regime on S balance was found (Fig. 4, Table 1, Table 2).

4. Discussion

Besides the strong nutrient depletion currently taking place in soybean and maize crops in Argentina, our study shows that environmental potential is the most important factor explaining the dynamics of fertilizer use and resulting nutrient balances at the field scale. We found that high-potential fields received 8% to 12% more fertilizer than low-potential fields (only in maize crops). Contrary to our prediction, high-potential fields exhibited between 25% to 146% higher net nutrient exports than low-potential fields (Fig. 3, Fig. 4). Regarding the tenure regime, the only nutrient affected was P in both maize and soybean crops, although the effect size was small in comparison to the effect of environmental potential. Tenants applied approximately 2% to 3% less P, and had 6.5% to 37% more net P exports compared to owners (Fig. 3, Fig. 4).

4.1. Tenure regime and nutrients dynamic

We found that the tenure regime has a low effect on fertilizer application and soil conservation. The lack of effect of tenure regime on maize N fertilization and balance can be attributed to the low residuality of N in the soil (Glendining et al., 2001), where the majority of applied N is either utilized by the current crop or lost (Cassman et al., 2002). Thus, N fertilization in maize can be considered a short-term practice. Additionally, maize requires adequate N fertilization to achieve economically profitable yields, therefore farmers probably cannot skimp on N fertilizer application (Gregoret et al., 2011). On the opposite, the tenure regime had a weak effect on soybean N fertilization and balance. Should be noted that both tenants and owners applied low rates of N fertilizer in soybean, and the environmental potential did not influence the amount of nutrients applied (Fig. 2, Fig. 4, Table 1). This suggests that soybean crops received a standard amount of N. One possible explanation is that soybean is inoculated with the N-fixing symbiont, and this process is inhibited by N fertilization (Gan et al., 2002). Furthermore, soybean crops are known to achieve high yields despite receiving minimal fertilization (Austin et al., 2006). Finally, soybean fields should have

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 (<0.0001)	−2.55 ± 8.6 (0.77)	3.68 ± 0.11 (<0.0001)	0.28 ± 1.4 (0.85)	1.97 ± 0.088 (<0.0001)	9.65 ± 0.9 (<0.0001)	1.85 ± 0.075 (<0.0001)	−39.8 ± 5.8 (<0.0001)	3.18 ± 0.11 (<0.0001)	−2.22 ± 1.5 (0.18)	1.73 ± 0.14 (<0.0001)	7.86 ± 1.2 (<0.0001)
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 (<0.0001)	1.36 ± 0.36 (0.0001)	0.11 ± 0.047 (0.013)	1.05 ± 0.58 (0.071)
Medium Ep	7.08 ± 1.1 (<0.0001)	−10.5 ± 1.3 (<0.0001)	0.22 ± 0.035 (<0.0001)	−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 (<0.0001)	0.015 ± 0.029 (0.59)	−1.77 ± 0.3 (<0.0001)	0.05 ± 0.036 (0.16)	−0.90 ± 0.45 (0.045)
High Ep	13.6 ± 1.1 (<0.0001)	−15.9 ± 1.4 (<0.0001)	0.16 ± 0.037 (<0.0001)	−3.81 ± 0.40 (<0.0001)	0.17 ± 0.032 (<0.0001)	−0.28 ± 0.40 (0.49)	0.039 ± 0.024 (0.10)	−14.8 ± 1.2 (<0.0001)	0.029 ± 0.031 (0.36)	−3.77 ± 0.32 (<0.0001)	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

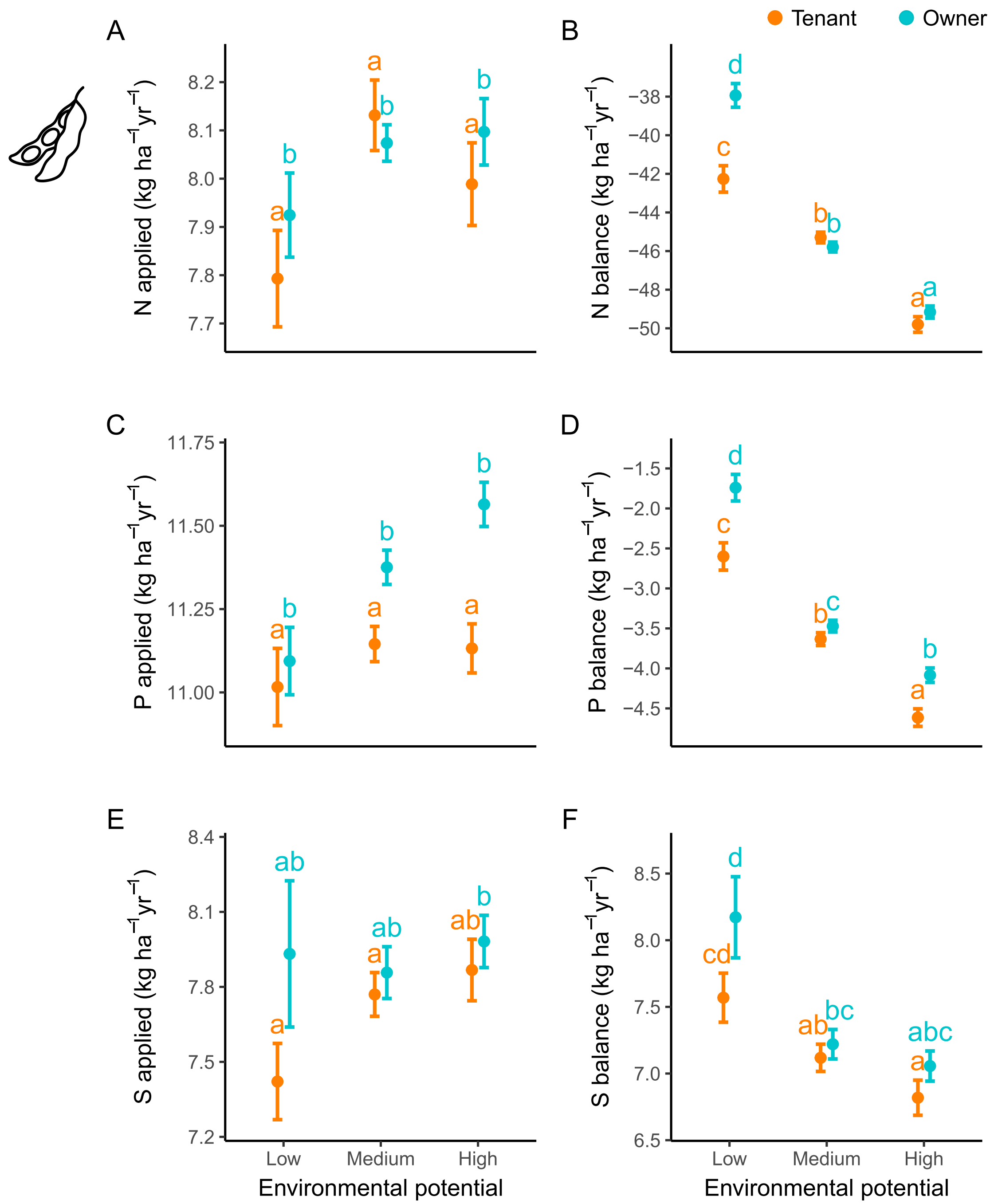

Fig. 4. Mean observed (± SE) of nitrogen applied (A) and balance (B), phosphorus applied (C) and balance (D), and sulfur applied (E) and balance (F) in soybean crops managed by tenants and owners in low, medium, and high-potential fields. Means with different lowercase letters differ statistically at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

other soil conservation practices, such as more diversified crop rotation or overfertilization in winter crops, that compensate for N exportation.

The balance and application of P were affected moderately by the tenure regime. This can be attributed to the fact that a fraction of P applied in fertilization accumulates as residues in the soil. Consequently, tenants may not be willing to apply a high amount of P if they will not benefit from 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 observed in high-potential fields for both crops (Fig. 3, Fig. 4). This suggests that owners have better knowledge of the heterogeneity of their lands or are concerned with preserving the high potential of their fields.

An unexpected result was the positive balance of S, indicating a potential overfertilization of this nutrient. These results differ from a previous study conducted in the same area, which reported a negative S balance (Koritschoner et al., 2023). However, it is important to note that the variation in our findings could be attributed to the differences in S atmospheric deposition data used. In this study, we based on long-term measurements from a single location in the Argentine Pampas (Carnelos et al., 2019), while Koritschoner et al. (2023) relied on a worldwide study that reported lower levels of S atmospheric deposition for the same regions (Vet et al., 2014). It should be emphasized that S atmospheric depositions show significant temporal variability and are influenced by factors such as proximity to the sea or a big city (Carnelos et al., 2019). Local studies and predictive models specific to S atmospheric deposition are necessary to improve S fertilization efficiency. On the other hand, the generally low adoption of S fertilizer application among farmers could explain the lack of effect of tenure regime and environmental potential. Moreover, crops' response to S fertilization remains unclear, both for 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 beneficial 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). However, studies examining the influence of tenure regimes on inorganic fertilization have generally found no difference in the amount of inorganic fertilizer applied between owners and fixed tenants (Akram et al., 2019; Teshome et al., 2016), partially aligning with our results. We found that the tenure regime affects P fertilization, although with a low effect size. Myyrä et al. (2007) show that P fertilization increases with lease contract time. Furthermore, a previous study conducted in the Pampa region established that when tenants have legal lease terms longer than one year, they manage the land similarly to an owner (Arora et al., 2015). In our dataset, the lease term or the period that a field is managed by a single farmer is not specified. If several tenants in our data have long-term leases, this could explain the low effect size on P fertilization.

4.2. Nutrients export and environmental heterogeneity

The most significant finding of our study is 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 research that identifies Argentina as a major exporter of nutrients worldwide (Díaz de Astarloa and Pengue, 2018; Guareschi et al., 2019; Koritschoner et al., 2023), particularly the country with the major P depletion process of the world (Schipanski and Bennett, 2012). Soybean crops, in particular, exported large quantities of N, which aligns with previous studies that identified soybean crops as one of the main contributors to 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 approximately 60% of the N required by soybean crops, with the remaining portion absorbed from the soil (Collino et al., 2015).

We found that nutrient depletion is strongly influenced by the environmental potential of the fields. This may be explained by the fact that high-potential fields yield more than low-potential fields, and respond to fertilization in terms of increased yield. However, this higher yield is not accompanied by a proportional increase in fertilizer application, leading to a higher net export of nutrients from high-potential fields (Fig. 3, Fig. 4). This pattern of increased fertilizer application with higher environmental potential can be attributed to the profitability of achieving high yields in high-potential fields, making farmers more likely to recoup their investment. Alternatively, this trend may also indicate that high-potential fields conserve their favorable characteristics due to receiving more nutrients, while medium or low-potential fields degrade due to inadequate fertilizer supply (Rawal et al., 2022). However, the field's environmental potential assessment is based on soil type and surface topography, which are not strongly influenced by fertilization. Therefore, the latter hypothesis may partially explain the observed trends.

In contrast to Argentina, other grain-exporting countries, such as Brazil, exhibit positive N and P balances (Guareschi et al., 2019). The biological N fixation in Brazil's fields is approximately 80% of the N required by soybean crops, whereas in Argentina, biological N fixation accounts for 60% (Collino et al., 2015). However, Brazilian soils are deficient in P, necessitating fertilizer application, while Argentine farmers can rely on natural reserves and deplete soils for longer periods without significant yield impacts (Jobbágy et al., 2021). It should be noted that the price of synthetic fertilizers has been rising in recent years, with the trend expected to continue (Brunelle et al., 2015). Consequently, relying solely on synthetic fertilizers for positive nutrient balance may become unsustainable in the future. Sustainable strategies rooted in agroecological principles should be adopted to mitigate nutrient loss and land degradation in both Argentine and global agricultural systems (Brunelle et al., 2015). This paper highlights the significance of environmental potential as a crucial factor in farmer management decisions and the importance of considering soil heterogeneity to ensure appropriate fertilization practices and reduce soil degradation.

While the CREA farm data provides an exceptionally rich data set covering 3.8 M ha, it is important to acknowledge that it may be subject to certain biases. One potential bias is that CREA provides management standards to all farmers, which could lead to a leveling out of differences in management practices between owners and tenants, while the differences might be more pronounced in the more diverse Argentinean agriculture situation. Additionally, 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. It would be interesting in future studies to consider the duration of tenancy to gain a better understanding of this complex variable. Furthermore, other sources of nutrient gains and losses can influence the calculated nutrient balances over time. For instance, the incorporation of N into the soil through the use of winter legumes or the over-fertilization of crops preceding summer crops can improve soil fertility (Koritschoner et al., 2023).

5. Conclusions

Agriculture can have a massive impact on the environment and on the long-term sustainability of natural resources. This study focuses on maize and soybean cultivation in Argentina to explorer the influence of environmental potential on farmers' fertilization decisions and nutrient mining processes. Our findings indicate that high-potential maize fields receive higher fertilization rates but also exhibit higher net exportation of N and P than low-potential fields, implying greater soil degradation in these highly productive fields. On the other hand, 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 exported more P than owners, suggesting that owners possess better knowledge of field heterogeneity and prioritize soil conservation practices.

In contrast, soybean fertilization rates responded weakly to both environmental potential and tenure regime, yet exhibited the highest nutrient mining, particularly for N. However, soybean crops' nutrient balance strongly responds to environmental potential, with high-potential fields being the most affected in this study. While extensive agriculture in Argentina may not require S fertilization, it is important to note that this is a global country result and may vary across regions. Our study reveals the importance of understanding the heterogeneity of soil and environmental conditions of fields to develop adequate fertilization plans that prevent soil degradation. Additional soil conservation practices should be implemented in soybean fields, such as recovering soil nitrogen in other crops within the rotation sequence. Further research addressing the S cycle in agroecosystems is needed to optimize S fertilization practices. Both tenants and owners should aim to increase nutrient input, particularly N and P, by an average of 19%, 1% in maize crops, respectively, and by 574% and 32% in soybean crops, to achieve more sustainable agricultural systems in Argentina.

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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