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# On-farm assessment of phosphorus fertilization influence on yield and soil P balance of full-season soybean in the Argentinean Pampas

Mariana Antonietta [a,*], José Micheloud [b,c], María Paolini [b], Gustavo Martini [b], Juan J. Guiamet [a], Emilio Satorre [b,c,d]

[a] Instituto de Fisiología Vegetal (INFIVE), Universidad Nacional de La Plata, CONICET. cc 327, La Plata, Provincia de Buenos Aires CP 1900, Argentina
[b] Asociación Argentina de Consorcios Regionales de Experimentación Agrícola (AACREA), Sarmiento 1236, Ciudad Autónoma de Buenos Aires C1041AAZ, Argentina
[c] Cátedra de Cerealicultura, Departamento de Producción Vegetal, Facultad de Agronomía, Universidad de Buenos Aires, Av. San Martín 4453, Ciudad Autónoma de Buenos Aires C1417DSE, Argentina
[d] Instituto de Investigaciones Fisiológicas y Ecológicas Vinculadas a la Agricultura (IFEVA), Universidad de Buenos Aires, CONICET, Av. San Martín 4453, Ciudad Autónoma de Buenos Aires C1417DSE, Argentina

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ABSTRACT

*Context:* The Argentinean Pampas face high soil nutrient mining rates that threaten soil quality and future crop production. Phosphorus (P) depletion is closely associated to soybean, which has increased the interest on soybean P management.
*Objective:* To assess the influence of on-farm P fertilization on yield and soil P balance of full-season soybean.
*Methods:* We used a database gathered by the Argentinean Association of Regional Consortiums for Agricultural Experimentation that included four agro-ecological regions within the Argentinean Pampas (Centre, Sandy West, West and Southeast) and six seasons (2017–2023) with a total of 15753 cases. Cases were divided according to P fertilization in: low P (LP, 7972 cases) and high P fields (HP, 7781 cases), receiving less than or at least 7 kg P ha$^{-1}$, respectively. Differential distribution of yield data between LP and HP fields was analyzed considering environmental yield ranges, seasonal rainfall and soil P Bray1 values.
*Results:* Across regions, significantly higher yields (7–27 %) were obtained in HP fields compared to LP fields, with largest relative differences at low-yielding percentiles. Seasonal rainfall had a varying influence suggesting a role of the organic-P fraction during rainy years. Relative HP yields were larger than expected from soil P Bray1 values. Mean soil P balance was negative but improved with P fertilization.
*Conclusion:* Our results suggest widespread P limitations for soybean yields in the Pampas under a scenario of progressive P depletion with increasing pressure over the organic-P pool, highlighting the need for novel approaches towards closing nutrient cycles.

## 1. Introduction

Rainfed grain production is the most relevant agricultural activity in the Pampas region of Argentina (Satorre, 2005; Satorre and Andrade, 2021). In the last decades, full-season soybean has expanded, currently reaching almost 50 % of the sown area (Viglizzo et al., 2011; de Abelleyra and Verón, 2020; MAGyP, 2023). The expansion of soybean is supported by the adaptability of the crop to the various climate and soil conditions of the Pampas, effective technologies and crop management and its relative high price and low production costs compared to other crops (Satorre and Andrade, 2021). These agro-ecological, technological and economical attributes have led Argentina to be the 3rd top-most soybean producing country after Brazil and USA in 2022 (Ritchie et al., 2023). However, frequent and even continuous soybean cropping results not only in a decreasing crop yield but also in the loss of several chemical and physical soil properties (Novelli et al., 2011; Nosetto et al., 2015; Crespo et al., 2021; Andrade et al., 2023). Therefore, the evaluation of agriculture sustainability has reached the agenda of Pampean farmers.

Among the various factors that may affect agriculture sustainability, soil nutrient depletion is, in extensive grain production, one of the most important and highly under farmers control through management

* Corresponding author.
*E-mail address:* antoniettamariana@gmail.com (M. Antonietta).

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decisions. Long-term agricultural production relies on maintaining the soil mineral stock, which can be met either through closing the nutrient cycles or, more usually, through fertilizer addition. However, crops in low income countries usually face low rates of fertilization that result in soil nutrient depletion (Vitousek et al., 2009) as occurs in the Argentinean Pampas (Cruzate and Casas, 2009). The addition of nitrogen (N) and phosphorous (P), two main widely limiting nutrients in The Pampas, is mostly concentrated in cereal crops (IFA, 2022). By contrast, soybean is inoculated with N fixing bacteria and poorly fertilized with P (Koritschoner et al., 2023), average P rates being 4.4 kg P $ha^{-1}$ compared to 11.4 kg $ha^{-1}$ in USA and 40.2 kg $ha^{-1}$ in Brazil (IFA, 2022). Therefore a substantial gap between nutrient export and fertilizer supply may be causing soil fertility losses.

As a result of sustained P depletion, during the period from 1980 to 1999 soil P Bray1 (a commonly used index of P availability; García et al., 2007) fell below 10 mg $kg^{-1}$ in many regions within the Argentinean Pampas (Sainz Rozas et al., 2012). Roughly, this is below P Bray1 critical values for most crops in the region, including soybean (i.e. 12–13 mg $kg^{-1}$, Echeverría et al., 2002), meaning that yield responses to P fertilizer could be expected. These responses will also be modulated by environmental factors such as soil texture (Correndo et al., 2018) and water availability (e.g., Calviño and Sadras, 1999). While this has been usually analyzed at the experimental scale, extensive on-farm analysis studies are scarce. Approaches based on on-farm management provide a representative background of cost-effective and logistically viable conditions (Andrade et al., 2022) while including a large variation within regional environments, hard to address through traditional experiments.

In Argentina, AACREA (Argentinean Association of Regional Consortiums for Agricultural Experimentation, www.crea.org.ar) has become one of the main sources of information gathering management and yield data from on-farm real fields. AACREA is a non-profit civil organization made up of and run by over 2400 farmers with the aim to generate and share experiences and knowledge on farming practices. Six years ago AACREA started to systematically collect on-field data of the crops grown by its members and register them in a database (DAT-CREA, see below). Based on this, a dataset gathering 15753 on-farm yields across four sub-regions in The Pampas and six cropping seasons was explored to analyze regional variation in: (i) yield data distribution comparing low-P and high-P fertilized fields; (ii) the influence of seasonal rainfall and (iii) of initial soil P Bray1 values on yield data distribution according to P fertilization; and finally, (iv) the overall impact of P management on the estimated soil P balance.

## 2. Materials and Methods

### 2.1. Description of the regions under study

We used the AACREA database (www.crea.org.ar) based on the Agricultural Traced Data Project (DAT-Project). The DAT-Project is a collaborative digitization project that compiles crop management information from the fields of AACREA members in a homogeneous and standardized database. The study was focused on four regions previously defined by AACREA experts based on their agro-ecological characteristics: Sandy West, West, Centre and Southeast, and included six cropping seasons from 2017-18 to 2022–23 (Fig. 1). Traditionally, these regions have been identified with extensive mixed crop-cattle farms. Their productions systems markedly changed to predominantly cropping farms in the past 30 years (Satorre, 2001) making them an interesting case to study the influence of extensive agriculture expansion on a critical soil nutrient. Few soil P data were available at on-farm scale from other sub-regions such as the Rolling or Mesopotamian Pampas, which prevented including these in the present work.

Mollisols are the prevalent type of soil in this area, although there is also disperse occurrence of alfisols, vertisols (towards the Southeast) and entisols (towards the east of the Centre region) (Cruzate et al., 2023). Across the region, there is a varying presence of factors promoting or constraining yields such as access to the water table, insufficient or excessive drainage and presence of a thapto layer below 60 cm depth (Cruzate et al., 2023). In the dataset analyzed here, the influence of the water table was relatively less frequent in the fields of the Southeast (19 %) and Centre (26 %) whereas an increasing proportion of the fields reported influence of the water table in the Sandy West (40 %) and West (60 %) (Table 1).

Regarding weather conditions, mean summer temperatures tend to decrease from the Centre (20–24°C) towards the Southeast (20–22°C), with a similar pattern for summer rainfall, also decreasing from the Centre (300–400 mm) towards the Southeast and West (250–300 mm) (https://www.smn.gob.ar/clima/atlasclimatico). Moreover, the region is influenced by the El Niño Southern Oscillation phenomenon (ENSO). For summer crops in this region, this implies drier and warmer seasons mainly in the spring during La Niña periods and larger rainfalls expected throughout the season during El Niño periods (https://www.smn.gob.

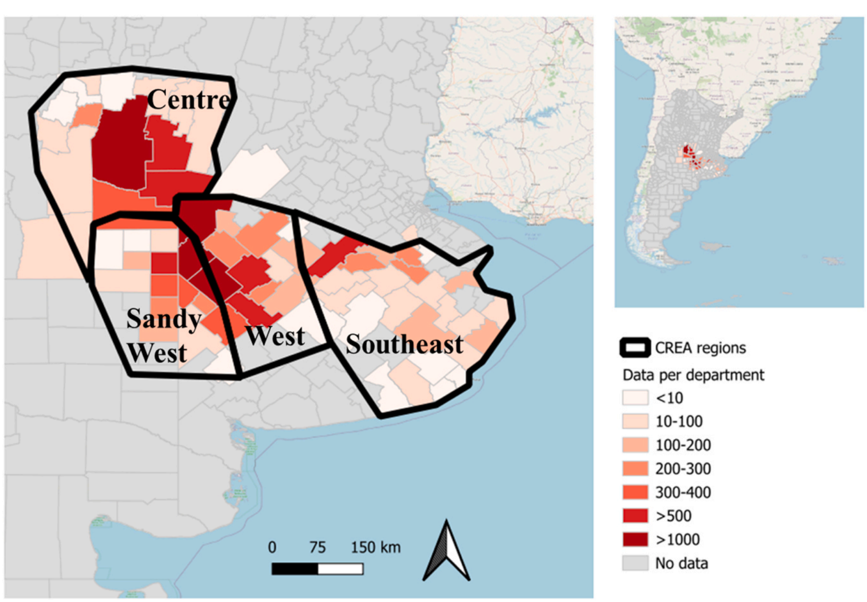


**Fig. 1.** Number of cases per department (red colour scale) in each of the four regions analysed based on CREA classification of main agroecological zones; i.e. Centre, Sandy West, West and Southeast. Total number in the complete dataset is 15753.

**Table 1**
Total number of yield data explored across seasons, land tenancy regime, mean field area sown each year (ha), mean soil P Bray1 values at 0–20 cm soil depth (mg kg$^{-1}$), proportion of fields reporting influence of water table, and most frequent previous crops in each region.

| *Total yield data* | Centre 3463 | Sandy West 3700 | West 5719 | Southeast 2871 |
|---|---|---|---|---|
| *Land tenancy (%)* | | | | |
| *Owner* | 65 | 59 | 65 | 62 |
| *Tenant* | 30 | 35 | 35 | 33 |
| *Sharecropping* | 5 | 6 | 0 | 5 |
| *n* | 3460 | 3698 | 4411 | 2870 |
| *Mean field area (ha)* | 89.7 | 60.4 | 49.8 | 45.1 |
| *n* | 3463 | 3653 | 5719 | 2870 |
| *Mean soil P Bray1 (mg kg$^{-1}$)* | 19.7 | 11.9 | 12.3 | 9.3 |
| *n* | 520 | 1262 | 3694 | 884 |
| *Influence of water table (%)* | | | | |
| *No* | 74 | 60 | 40 | 81 |
| *Yes* | 26 | 40 | 60 | 19 |
| *n* | 3304 | 3567 | 3398 | 1118 |
| *Previous crop (%)* | | | | |
| *Maize* | 78 | 60 | 59 | 50 |
| *Soybean* | 11 | 26 | 28 | 31 |
| *Cover crop* | 9 | 7 | 5 | 6 |
| *Sunflower* | < 1 | 4 | 2 | 7 |
| *Others* | 2 | 3 | 6 | 6 |
| *n* | 3463 | 3700 | 5719 | 2871 |

ar/como_nos_afecta). A more detailed description of rainfall patterns for the seasons under study will be provided as part of the results using data reported at the field scale.

### 2.2. Characteristics of the dataset and pre-processing of data

The variables considered for the entire analyses included: season, region, province, department, crop, season length (first or second sowing), yield, previous crop, water management (rainfed vs. irrigated), fertilizer rate (nitrogen, phosphorus, sulfur, potassium), and occurrence of adversities (hail, drought, fire, flood, frost, weeds, pests). Here, season length refers to whether soybean was preceded by a winter crop in the same year (second sowing) or by winter fallow (first sowing or full season). Other variables also considered in the analysis but having missing cases included tenancy regime (n = 14439), area sown (n = 15705), influence of water table (n = 11388), environmental potential (n = 15046), seasonal rainfall (n = 8761), soil P Bray1 (n = 4915) and soil organic matter at 0–20 cm (n = 3624). A specific procedure for completing missing cases for seasonal rainfall and soil P Bray1 is described in the following section.

Only full-season rainfed soybean data were used. Even though soybean sowings after a winter crop are common, full season soybean accounts for the major area occupied with the crop in the region (e.g., 75 % of the area sown with soybean in our original dataset). In some cases, farmers reported a high influence of yield reducing factors (hail, drought, fire, flood, frost, weeds or pests). When the occurrence of these adversities represented a total yield reduction greater than 35 %, the field was also excluded from the analysis. Moreover, cases with extremely low yields (<500 kg ha$^{-1}$) were excluded. The complete database comprised 15753 soybean farms distributed in four regions and grown along six seasons. However, total number of data varied across regions, being higher for the West (5719 data), intermediate for the Sandy West (3700) and Centre (3463) and lower for the Southeast (2871) (Table 1). Across regions, individual field mean area ranged from 45 to 90 ha, mostly managed by farm owners (59–65 %, Table 1). Previous crop was usually maize (from 50 % in the Southeast up to 78 % in the Centre) with an increased proportion of soybean (either first or second sowing) reported as previous crop in the West (28 %) and Southeast (31 %) (Table 1). Prevalent management included no till system (99 %), GMO seeds (99 %) and control of weeds and pests as required.

### 2.3. Procedure followed for retrieving missing cases for rainfall and soil P Bray1 data

Cumulative seasonal rainfall was calculated for a six-month period starting in October and ending in March. Even though harvest dates can occur later than this, we assume that the crop is almost completely senescent after March and thus, April rainfalls do not contribute substantially to yield. Seasonal rainfall was calculated on the basis of monthly data registered at field scale (<10 km from the plot) and reported in the original database (n = 8761). Missing cases were completed, if possible, using the average seasonal rainfall reported in the original database for the same department (5975 cases). When this was not possible, the monthly data provided by the Meteorological Information Centre (CIM) of the National Meteorological Service of Argentina (SMN) was used considering the closest meteorological station (<50 km from each departmental boundary, 1017 cases). Thus, seasonal rainfall data was gathered for the complete dataset (N = 15753).

Soil P availability was determined using P Bray1 values obtained from soil samples taken at 0–20 cm soil depth. P Bray1 is widely used in Argentina and is considered a reliable index of available P in the slightly acidic soils of the Pampas (García et al., 2007; Alvarez and Steinbach, 2017; Alvarez et al., 2019). From the entire dataset comprising 15753 data, 4915 fields reported P Bray1 values from soil tests performed just before sowing soybean. However, since P Bray1 values are not supposed to change significantly between consecutive seasons (e.g., Sucunza et al., 2018), when available, the total number of cases was increased to n = 6360 by using the P Bray1 value reported for the same plot in the immediately preceding or subsequent summer crop (either soybean, sunflower or maize).

### 2.4. Definition of categories for further analysis: P fertilization, seasonal rainfall and soil P Bray1

In order to analyze the variation in yield data distribution according to P fertilization, the complete dataset (N = 15753) was divided into two categories. Those fields supplied with 0–6.9 kg ha$^{-1}$ of P during the soybean season were considered to have a low P rate (hereafter, LP) whereas those fields with 7 or more kg of P applied ha$^{-1}$ were considered to have a high P rate (hereafter, HP). The 7 kg ha$^{-1}$ threshold was defined on the basis of expert knowledge from technical advisors working in these regions who considered that below this threshold the P applied was likely to be a low addition from other fertilizer formulations (i.e., farmers not specifically aiming to apply P). After dividing the data into these categories, the median P rate in the LP fields ranged from 0.6 to 2.4 kg P ha$^{-1}$ whereas for the HP fields it ranged from 11.3 to 16.3 kg P ha$^{-1}$ (Table 2). By contrast, differences between LP and HP fields in the amount of nitrogen (N), sulfur (S) or potassium (K) applied were much lower (Table 2).

In order to explore the influence of seasonal rainfall on yield data distribution in the complete dataset (N = 15753), a conglomerate analysis was run using seasonal rainfall as the independent variable and season as the classification variable. Seasons aggregated in two main groups: the warm dry season group, including 2017–18, 2020–21 and 2022–23 and the warm rainy season group, including 2018–19, 2019–20 and 2021–22 (Supp. Fig. 1 A). Average seasonal rainfall was 404 mm for the warm dry season group and 642 mm for the warm rainy season group, with rather consistent trends across regions (Supp. Fig. 1B). Roughly, this classification was coincident with national forecasts related to the ENSO phases (https://www.smn.gob.ar/enos), with usually high monthly La Niña indexes for the dry group and high El Niño indexes for the rainy group.

The partial subset of data reporting soil P Bray1 values (n = 6360) was explored to assess the influence of the soil P Bray1 level on the

**Table 2**
Distribution of yield data, environmental potential (%), and fertilizer rates (median values of phosphorus, P, nitrogen, N, sulfur, S, and potassium, K, as kg ha$^{-1}$) across regions and P fertilizer categories: LP fields, receiving less than 7 kg P ha$^{-1}$ and HP fields, receiving at least 7 kg P ha$^{-1}$ during the soybean season. Environmental potential is based on the criteria of who defines the management strategy.

| | | Fertilizer category | **Centre** | Sandy West | **West** | **Southeast** |
|---|---|---|---|---|---|---|
| *Yield data per category* | | LP | 2123 | 1733 | 3103 | 1013 |
| | | HP | 1340 | 1967 | 2616 | 1858 |
| *Environmental potential (%)* | *High* | LP | 29 | 35 | 56 | 30 |
| | | HP | 34 | 40 | 64 | 35 |
| | *Intermediate* | LP | 60 | 49 | 25 | 58 |
| | | HP | 58 | 46 | 18 | 50 |
| | *Low* | LP | 11 | 16 | 19 | 12 |
| | | HP | 8 | 14 | 18 | 15 |
| | *n* | | 3460 | 3580 | 5137 | 2869 |
| *Fertilizer applications (kg ha$^{-1}$)* | *P* | LP | 0.61 | 1.09 | 2.37 | 0.93 |
| | | HP | 16.33 | 11.32 | 11.67 | 14.11 |
| | *N* | LP | 0.00 | 0.00 | 0.00 | 0.00 |
| | | HP | 0.00 | 4.40 | 0.00 | 6.60 |
| | *S* | LP | 0.00 | 0.00 | 0.00 | 0.00 |
| | | HP | 0.00 | 0.00 | 0.00 | 0.00 |
| | *K* | LP | 0.00 | 0.00 | 0.00 | 0.00 |
| | | HP | 0.00 | 0.00 | 0.00 | 0.00 |
| | *n* | | 3463 | 3700 | 5719 | 2871 |

distribution of yield data between fertilizer categories. Previous works have reported P Bray1 critical values for soybean in mollisols spanning from 10 mg kg$^{-1}$ (Correndo et al., 2018), 12–13 mg kg$^{-1}$ (Echeverría et al., 2002) up to 14.3 mg kg$^{-1}$ (Sucunza et al., 2018). In the present work, soil data was divided into two categories using a single threshold of 12 mg kg$^{-1}$ of P Bray1 representing an intermediate critical value for soybean. Even though this value may change according to soil texture (Correndo et al., 2018) lack of data reported at the field-scale prevented us from including this factor in the analysis.

### 2.5. Soil P balance in the soybean crop in the complete dataset

The apparent soil P balance in the soybean crop was calculated as:

$$\Delta \text{ soil P} = \text{P fertilizer input} - (\text{Yield x seed P concentration})$$

The seed P concentration was considered to be 0.6 % according to reference values for soybean (García and Correndo, 2016). Given the flatness of the cultivation area and the dominance of no-tillage systems, P losses related to soil erosion, leaching and runoff were considered negligible (Viglizzo et al., 2011; Koritschoner et al., 2023). Minimal atmospheric P deposition rates of 0.0275 kg P ha$^{-1}$ year$^{-1}$ have been reported for this region (Vet et al., 2014) but were not considered here. Since only full season soybean is analyzed in this paper, the calculated soil P balance for soybean represents roughly a yearly one.

### 2.6. Statistical analysis

The InfoStat program v.2020 (Di Rienzo et al., 2020) was used for processing data and statistical analysis. Descriptive statistics were used to compare regions and management conditions. Multivariate analysis based on Euclidean distances was used to aggregate data as a function of seasonal rainfall. Normal distribution of the residuals was analyzed using a modified Shapiro-Wilks test (Mahibbur and Govindarajulu, 1997). If the distribution was not normal, the Kruskal-Wallis test was applied to find differences between variables (Kruskal and Wallis, 1952) and comparisons between factors were made as in Conover (1999). Linear regression models were fitted when possible and the Pearson test was used to assess the significance. Maps were created using the software QGIS v.3.36. (QGIS Geographic Information System, http://www.qgis.org).

## 3. Results

### 3.1. Distribution of soybean yields across regions and P fertilizer categories

Soybean yields were significantly different ($p < 0.05$) among regions. Lowest yields were obtained in the Southeast (2914 kg ha$^{-1}$), with intermediate values in the Sandy West (3329 kg ha$^{-1}$) and highest values in the West and Centre (3397 and 3419 kg ha$^{-1}$, respectively) (Supp. Fig. 2 A). Moreover, there were significant differences among seasons, with lowest yields in 2022–23 (2311 kg ha$^{-1}$) coinciding with a harsh La Niña season and highest yields achieved in 2018–19 and 2021–22 (3878 kg ha$^{-1}$) (Supp. Fig. 2B). Soybean yields in HP fields (fertilized with at least 7 kg of P ha$^{-1}$) were significantly higher than in LP fields, with larger differences in the Southeast (27.0 %) and Sandy West (21.3 %) than in the West (13.7 %) and Centre (7.7 %) (Fig. 2). Roughly, this trend related to regional variation in soil P Bray1, which decreased from the Centre (19.7 mg kg$^{-1}$), towards the West and Sandy West (12.3–11.9 mg kg$^{-1}$) reaching lowest values in the Southeast

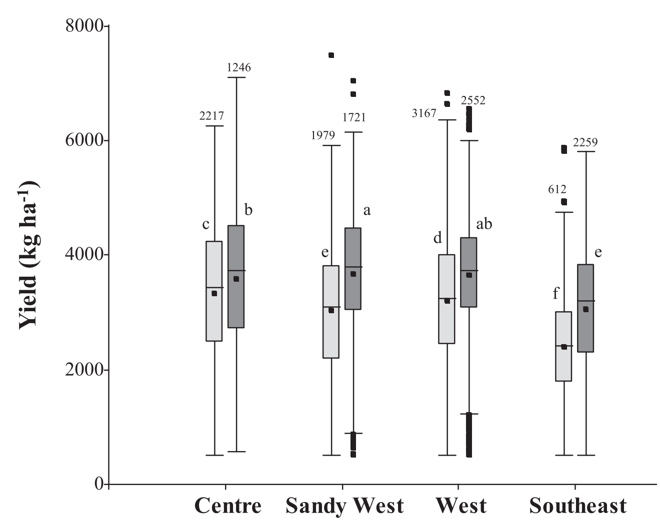


**Fig. 2.** Average yield across the six seasons analysed in each region in LP plots (receiving an average of 1.45 kg P ha$^{-1}$, light grey) and HP plots (receiving an average of 13.05 kg P ha$^{-1}$, dark grey). Different letters above each box denote different groups according to the Conover test ($P < 0.05$) whereas the numbers above the error bars indicate the total observations (n) per category.

(9.3 mg kg$^{-1}$) (Table 1).

The relative difference between HP and LP fields decreased at higher environmental yields (Fig. 3). In the West and Sandy West the relative difference obtained at HP fields decreased sharply at increasing yield percentiles, with ca. 10 % reductions per every t ha$^{-1}$ of yield increase. Absolute yield gains were also larger at lower percentiles, being highest at percentile 25 for both the West (+644 kg ha$^{-1}$) and Sandy West (+844 kg ha$^{-1}$). By contrast, the relative difference was less variable across yield percentiles in the Centre (slight) and Southeast (large) suggesting rather low (Centre) or high (Southeast) P limitations for soybean yields. Largest absolute differences were obtained at percentiles 55 in the Centre (+360 kg ha$^{-1}$) and 65 in the Southeast (+880 kg ha$^{-1}$). Therefore, these data suggest that larger advantages from P fertilizer supply may be obtained at lower-yielding environments, particularly in the West and Sandy West. At the same time, these results may imply that widespread P limitations in these regions are the main factor involved in yield variation across percentiles. Based on this and since water availability is a main limiting factor in Pampean dryland cropping, we further analyzed whether seasonal rainfall influenced the performance of HP and LP fields.

### 3.2. Seasonal rainfall modified the distribution of yield data between fertilizer categories

Seasonal rainfall affected the distribution of yield data in HP and LP fields with a region-specific pattern (Fig. 4 and Supp. Fig. 3). In the Centre, yield data distribution did not vary between LP and HP fertilizer categories in dry seasons, whereas in rainy seasons, yields per percentile were higher in the HP group (Fig. 4, Centre). By contrast, for the rest of the regions explored, HP yields compared to LP ones at same percentiles of data distribution were higher in both group of seasons (Fig. 4 and Supp. Fig. 3). Relative differences between HP and LP fertilizer categories did not vary with seasonal rainfall in the Southeast; yields being 27.9 and 28.6 % higher in the HP than in LP group for dry and rainy seasons, respectively (Fig. 4, Southeast). By contrast, in the Sandy West and West regions, relative differences between LP and HP categories were higher in dry seasons compared to rainy seasons (21.5 vs. 16.2 % for Sandy West and 16.9 vs. 6.7 % for West region; Fig. 4). To assess whether this could be related to an increased soil organic-P supply in rainy seasons, we further explored a subset of data for the West region, reporting organic matter concentration (0–20 cm, n = 2709) (insufficient data precluded analysis in the rest of the regions). Consistent with this speculation, in fields with low organic matter concentration (mean 1.77 %) relative yields in HP fields were 18.6 and 9.6 % higher than in LP fields in dry and rainy seasons, respectively, but these values dropped to 10.8 and 2.7 % in fields with higher organic matter concentration (mean 2.6 %) (Supp. Fig. 4). Thus, yield data distribution suggests that relative advantages of P fertilization can be lower (Centre), similar (Southeast) or even greater (West and Sandy West) in dry seasons compared with rainy ones with soil organic matter dynamics likely explaining part of this variation.

### 3.3. Initial soil P Bray1 values modified the distribution of yield data between fertilizer categories

Across the complete dataset (n = 6360), yields obtained at LP fields were significantly related to soil P Bray1 values spanning from 5 up to 17 mg kg$^{-1}$ ($r^2$=0.83 ***) whereas no significant relationship was obtained for yields at HP fields (Fig. 5). Well beyond soil P Bray1 values considered critical for soybean, at 17 mg kg$^{-1}$, the relative yield difference between LP and HP fields was 11 %. Further, yield data was analyzed separately for each region and P Bray1 category. At the low soil

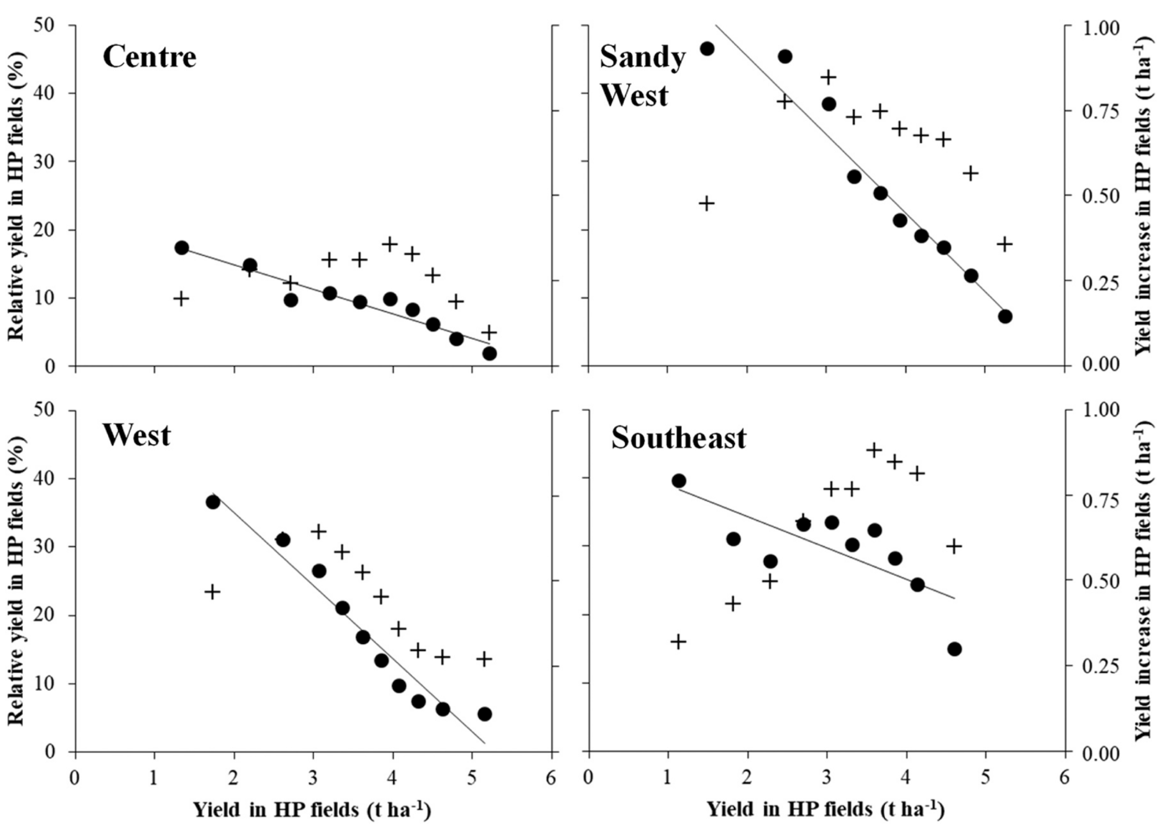


**Fig. 3.** Linear regressions fitted per region between the relative yield in HP fields (receiving an average of 13.05 kg P ha$^{-1}$) compared to LP fields (receiving an average of 1.45 kg P ha$^{-1}$) and yields obtained in HP fields. Each symbol denotes the mean difference (relative, black circles; absolute, crosses) at different percentiles (from 5 to 95, n = 10) calculated separately for each region and P fertilizer category. The regression parameters obtained per region are: Centre: Y = -3.6x + 22.1; $r^2$= 0.91 * ** ; Sandy West: Y = -11.5x + 68.5; $r^2$= 0.95 * ** ; West: Y = -10.7x + 56.4; $r^2$= 0.95 * ** ; Southeast: Y = -4.6x + 43.5; $r^2$= 0.58 * .

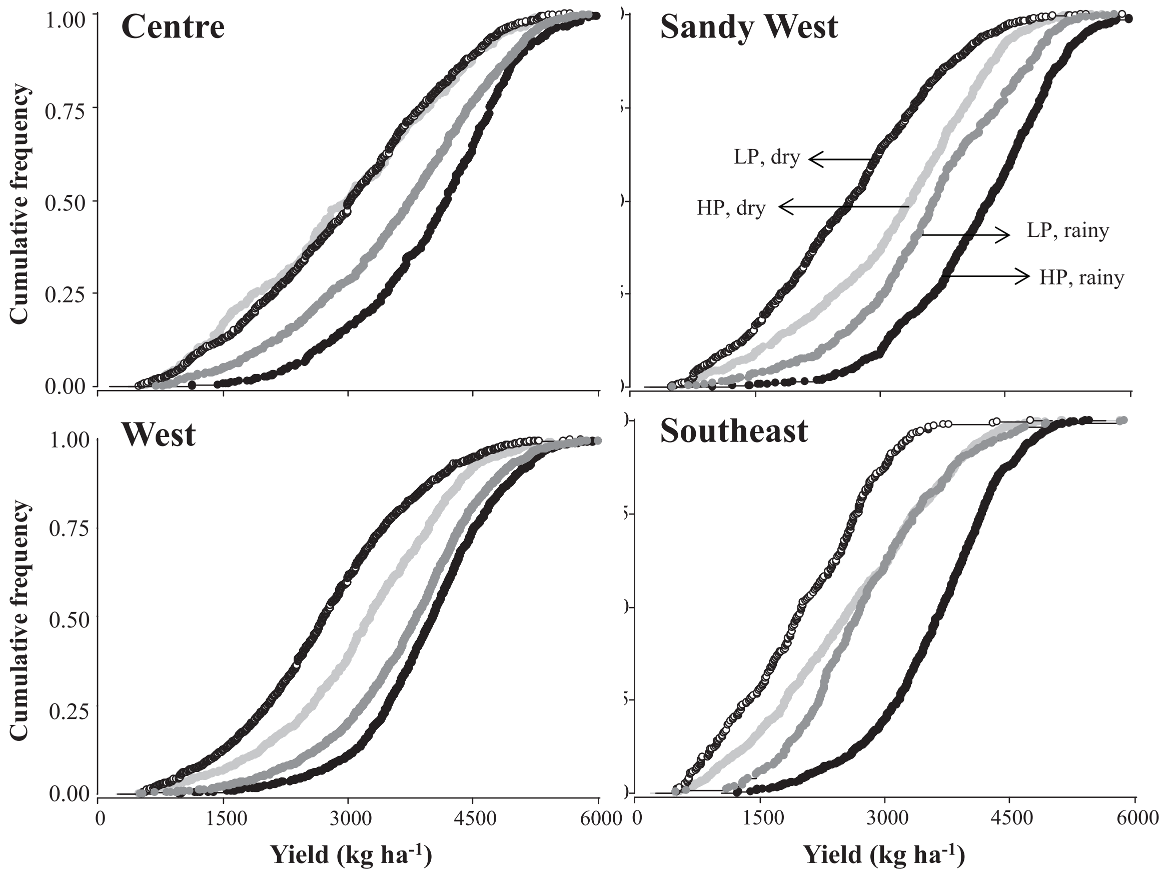


**Fig. 4.** Cumulative frequency of yields per region according to seasonal rainfall and P fertilizer category. Seasons were classified as warm dry (mean seasonal rainfall of 404 mm), or warm rainy (mean seasonal rainfall of 642 mm). Fields were classified as LP (receiving an average of 1.45 kg P $ha^{-1}$) and HP (receiving an average of 13.05 kg P $ha^{-1}$). Each symbol represents a single case. Empty symbols, LP fields in warm dry seasons; light grey symbols, HP fields in warm dry seasons; dark grey symbols, LP fields in warm rainy seasons; black symbols, HP fields in warm rainy seasons.

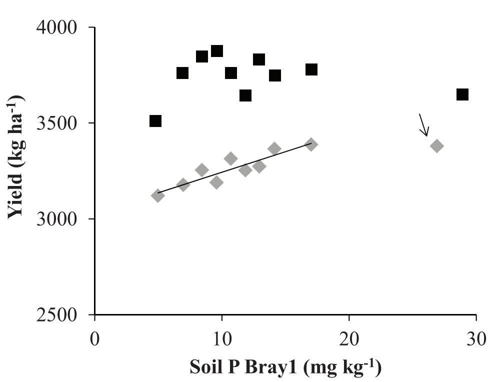


**Fig. 5.** Relationship between mean yields and soil P Bray1 values obtained across regions and seasons for LP fields (in light grey, receiving a mean rate of 2.2 kg P $ha^{-1}$) and HP fields (in black, receiving a mean rate of 12.9 kg P $ha^{-1}$) in the partial dataset used for P Bray1 analyses (n = 6360). Each symbol represents a percentile of soil P Bray1 obtained independently for each P fertilizer category across the entire dataset, thus many regions can be represented within the same percentile. Parameters of the linear regression are: Y= 21.5 x + 3028, $r^2$= 0.83; $P < 0.05$ * ** , n = 9 (the highest percentile of P Bray1 at LP pointed with an arrow was not included in the regression).

P Bray1 category, all the regions achieved similar mean P Bray1 values (8.9–9.5 mg $kg^{-1}$) except for the Southeast (6.8 mg $kg^{-1}$), whereas at the high soil P Bray1 category, mean P Bray1 was lower in the West and Sandy West (16.7–16.1 mg $kg^{-1}$) and increased in the Southeast (19.8 mg $kg^{-1}$) and Centre (22.6 mg $kg^{-1}$) (Supp. Fig. 5 A). Within each region P rates applied were statistically similar between soil P Bray1 categories except for slightly higher P rates within LP fields at the lower soil P Bray1 category in the West (Supp. Fig. 5B).

Soybean yields remained higher in the HP group of fields compared to the LP group, even in the highest soil P Bray1 category (those fields above 12 mg $kg^{-1}$ of P Bray1 0–20 cm), except for the Centre fields with more than 12 mg $kg^{-1}$ of initial soil P Bray1 (Fig. 6). Relative yield gains with P fertilization tend to be reduced in soils with high soil P Bray1 values at sowing. This trend was evidenced in the Centre and Sandy West regions, where relative yield differences between LP and HP fields decreased from 22.8 % to 5.5 % (Centre) and from 21.6 % to 16.1 % (Sandy West), in low vs. high soil P Bray1 fields, respectively. In the West region, relative yield differences between fertilizer categories remained similar regardless of initial soil P Bray1 values (16.4–14.3 %), while in the Southeast region, unexpectedly, relative yield increases in the HP group were larger in the high (>12 mg $kg^{-1}$) soil P Bray1 category (52.2 %) compared to fields reporting less than 12 mg $kg^{-1}$ at sowing (23.6 %). Overall, relative yield differences between HP and LP fields were negatively related to mean soil P Bray1 across regions ($r^2$=0.30, $P < 0.05$; Fig. 7) but with still a large proportion of variation not explained by the model and extending far beyond values considered critical for soybean.

### *3.4. Estimated soil P balances across regions between fertilizer categories*

Soil P balances, estimated on the basis of yield, standard P concentrations in soybean seeds and applied P fertilizer, varied among regions and fertilizer categories (Fig. 8). In LP fields, receiving none or a very

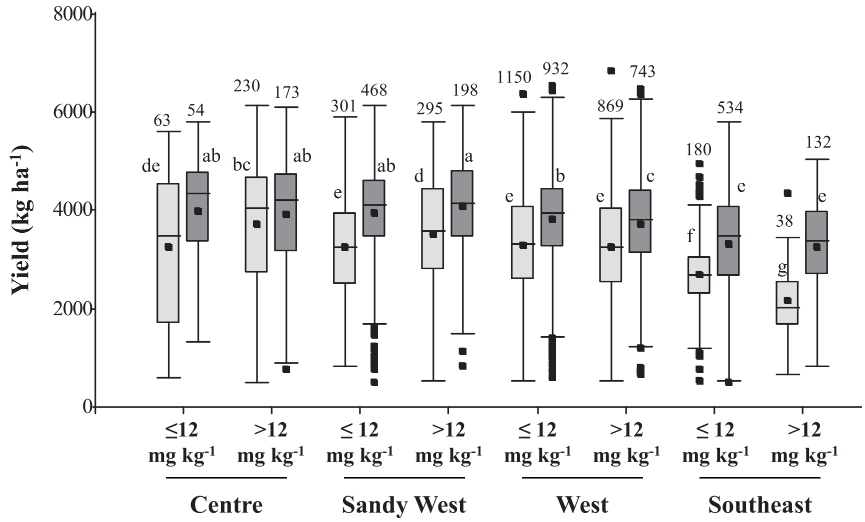


**Fig. 6.** Average yields obtained per region, soil P Bray1 category and P fertilizer category (LP fields receiving an average of 2.2 kg P ha$^{-1}$, light grey; HP fields receiving an average of 12.9 kg P ha$^{-1}$, dark grey) in the partial dataset reporting P Bray1 values (n = 6360). Same letters above each box denote homogenous groups according to Conover test (P < 0.05) whereas the numbers above the error bars indicate the total observations (n) per category.

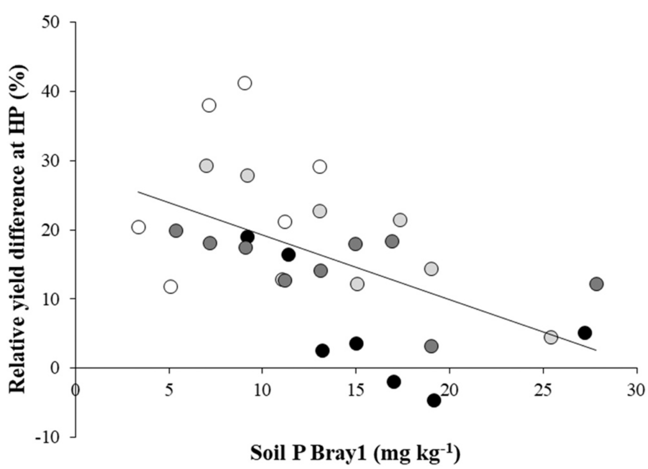


**Fig. 7.** Relationship between relative yield difference (HP minus LP expressed as a percentage of yields at LP) and P Bray1 value obtained for different soil P Bray1 ranges within regions, denoted by symbols (empty, Southeast; light grey, Sandy West; dark grey, West; black, Centre). Within a region, only P Bray1 ranges obtained from at least 10 fields were considered, reaching 30 HP-LP pairs and a mean of 100 fields in each pair. Overall linear regression obtained between relative yield differences at HP fields and mean soil P Bray1 of each range was Y= 28.6 + (-0.93) x ($r^2$=0.30, p > 0.05, n = 30).

low amount of P fertilizer, the most negative P balances were achieved in the Centre region (-19 kg P ha$^{-1}$), with intermediate values in the West and Sandy West (-17 kg P ha$^{-1}$) and least negative in the Southeast (-13 kg P ha$^{-1}$), thus, negatively relating with mean regional P Bray1 values. Fertilization with P significantly increased the soil P balance towards more neutral values but still it was not enough to avoid soil P reductions in most of the cases. Least negative P balances were obtained in HP fields of the Southeast and Centre (-5 and −6 kg P ha$^{-1}$, respectively) whereas for the West and Sandy West, mean P balances remained below −12 kg P ha$^{-1}$.

Overall, across regions, P rates were lower than those which would maintain neutral or positive P balances except for very few cases located at the right of the dashed diagonal relating P extraction with P fertilization rates (Fig. 9A). Remarkably, P rates maximizing yields tended to be larger than those most frequently utilized by farmers, with increasing yields at P rates beyond 15 kg P ha$^{-1}$ in most cases. Moreover, yield variability represented by the coefficient of variation, tended to decrease towards higher P rates (Fig. 9B). Taken together, these results highlight the potential advantages of increasing P fertilization rates in soybean sown in these Pampean regions by reducing P mining, increasing yields and improving yield stability.

## 4. Discussion

### 4.1. Differences between fertilizer categories suggest widespread P limitations

Across regions, the differences observed for yield between fertilizer categories (high and low P rates) suggest widespread P limitations for soybean in the region under study (Fig. 2; Fig. 5). Even though we cannot disregard the influence of other factors also changing between P fertilizer categories, further exploration of the dataset reinforced the role of P on soybean yield data distribution. Relative yield differences between fertilizer categories increased with lower soil P Bray1 values, being largest in the Southeast (average soil P Bray1 = 9.6 mg kg$^{-1}$), intermediate in the Sandy West and West (soil P Bray1 = 11.9–12.3 mg kg$^{-1}$) and lowest in the Centre (soil P Bray1 = 19.7 mg kg$^{-1}$). While environmental yield potential can be an additional criteria for soybean P management (Leguizamón et al., 2023), our results suggest that low-yielding environments may show even larger yield responses to P fertilization (Fig. 3, absolute values for the West and Sandy West). In order to assess whether this yield variability could be related to seasonal rainfall or soil P Bray1, we further explored the influence of these factors on yield distribution between P fertilizer categories.

### 4.2. Seasonal rainfall modified yield data distribution with a region-specific pattern

Cumulative seasonal rainfall can be used as a rough estimator of water availability to crops, even though it does not account for stored soil water, run-off, evapotranspiration and within-season rainfall distribution (Calviño and Sadras, 1999). Grouping the seasons according to seasonal rainfall resulted in different patterns of yield distribution (Fig. 4). In the Centre region, where P Bray1 values are still high (19.7 mg kg$^{-1}$), differences between LP and HP yields were only seen in rainy seasons, consistent with water being the main yield limiting factor in dry seasons. By contrast, in the Southeast region, with the lowest P

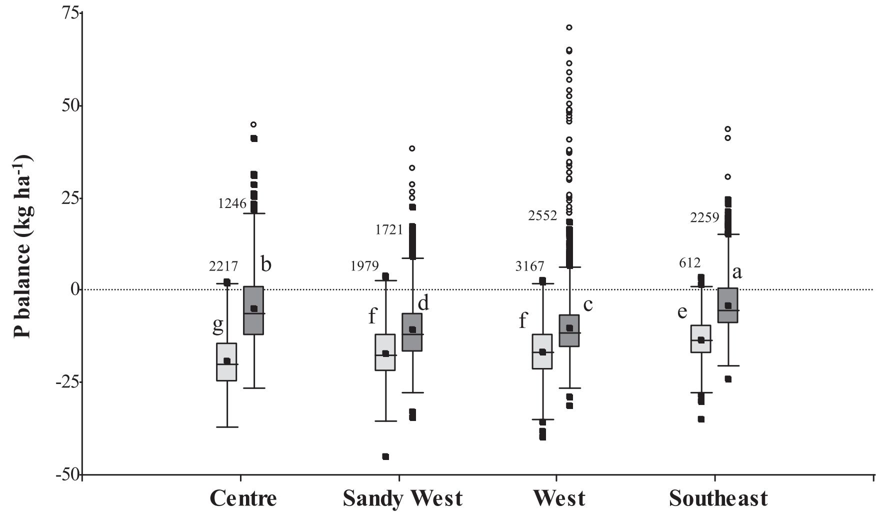


**Fig. 8.** Mean P balance across regions and fertilizer categories identified by the box colour: LP fields (light grey, receiving an average of 1.45 kg P ha$^{-1}$) and HP fields (dark grey, receiving an average of 13.05 kg P ha$^{-1}$). Same letters above each box denote homogenous groups according to Conover test ($P < 0.05$) whereas the numbers above the error bars indicate the total observations (n) per category.

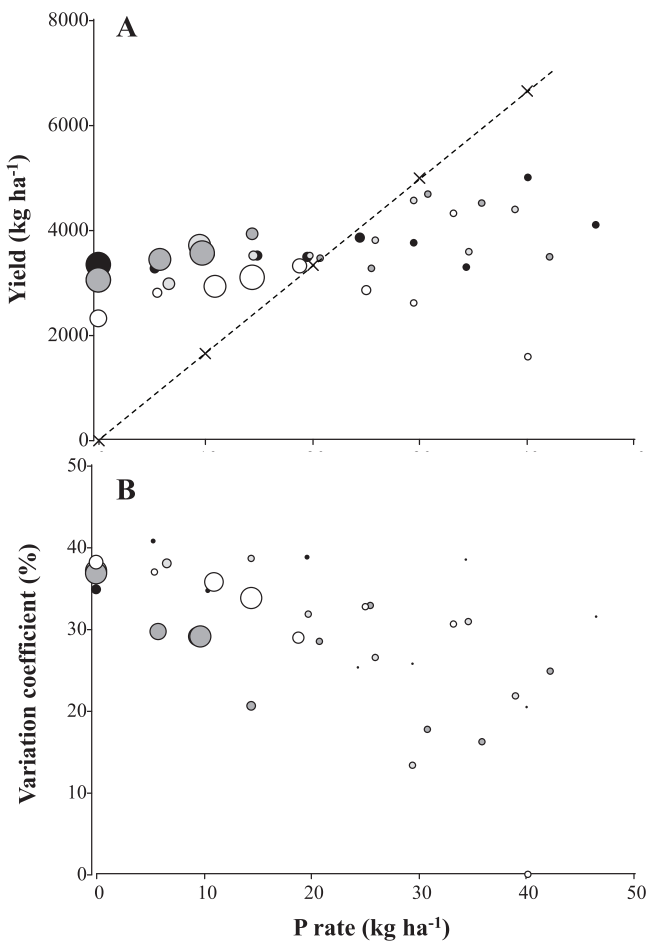


**Fig. 9.** Yields (A) and coefficient of variation of yields (B) as a function of P rates supplied across seasons and regions. Different colours denote the region (empty, Southeast; light grey, Sandy West; dark grey, West; black, Centre) whereas symbol size represents the amount of data in each case. In A, the dashed line indicates the threshold yield above which negative P balances occur.

Bray1 values (9.3 mg kg$^{-1}$) the much lower P availability maintained the relative difference between LP and HP fields. Soils of the Southern Pampas tend to have large P sorption rates related to the parental material (Cabello et al., 2016), which may also reduce seasonal variation in alternative soil P sources other than P fertilizer.

A different trend was observed for both the Sandy West and West regions, where differences between LP and HP fields increased in dry seasons. Several factors may be involved in this variation. On one hand, this might relate to water availability promoting root exploration at greater soil depths (e.g., at 60 cm, Benjamin and Nielsen, 2006), and thus, allowing access to better preserved P sources, since agricultural soils do not differ from pristine soils for organic-P below 25 cm depth, or inorganic-P below 50 cm depth (Alvarez et al., 2019). On the other hand, water availability may promote solubilisation of specific P fractions such as Ca-P (e.g., Ippolito et al., 2010; Feng et al., 2016) as well as mineralization of organic-P (Leirós et al., 1999) increasing overall P availability in rainy seasons and reducing yield response to fertilizer P.

Further, the analysis of a subset of data for the West (n = 2709) evidenced the importance of soil organic matter in reducing yield differences between LP and HP fields in rainy seasons (Supp. Fig. 4). In fields with low organic matter (≤2 %, mean 1.7 %), yield differences between LP and HP fields were larger and relatively maintained in rainy seasons. By contrast, in fields with high organic matter (>2 %, mean 2.6 %), yield differences between P fertilizer categories were overall lower and almost disappeared in rainy seasons even though soil P Bray1 was similar between these two group of fields (12.67 and 11.64 mg kg$^{-1}$ in low and high organic matter fields, respectively).Thus, we speculate that organic-P may have played an important role in rainy seasons almost suppressing any difference resulting from P fertilizer applications, as it occurs in maize (Appelhans et al., 2021). Organic-P has been less affected by agricultural activity in this region (Alvarez et al., 2019), and can account for the largest proportion of total P absorbed by the crop in P-mined soils (Sun et al., 2022) showing closer relationships with soybean yields than P Bray1 in the Pampas (Appelhans et al., 2016). As the inorganic-P pool decreases, biological P solubilisation is promoted (e.g., Bünemann, 2015) and crops such as soybean play an active role in this process (Chen et al., 2024). Taken together, the question arises on how P mining may be increasing the pressure over the organic-P pool and how this might be threatening the conservation of soil organic matter.

### 4.3. Differences in yield distribution between P fertilizer categories were higher than expected on the basis of soil P Bray1 values

In the present dataset, yields obtained in LP fields linearly related to soil P Bray1 with relative yield differences between LP and HP fields above 10 % at 17 mg kg$^{-1}$ (Fig. 5) which spans beyond soybean critical values based on experimental approaches (e.g., 14.3 mg kg$^{-1}$ in Sucunza et al., 2018). Still, we used the 12 mg kg$^{-1}$ threshold to define groups according to P availability, representing usual criteria to define soybean fertilization management in the region. Except for the Centre (with a mean of 22.3 mg kg$^{-1}$ at the high soil P Bray1 category), for the rest of the regions, yield differences between P fertilizer categories were still evident at soil P Bray1 values above 12 mg kg$^{-1}$ (Fig. 6). An apparently conflicting trend was found in the Southeast, where LP fields attained lower yields at the high P Bray1 category than at the low P Bray1 category. Native soil P Bray1 levels in this region have been reported to be below 10 mg kg$^{-1}$ and have increased as a consequence of agricultural use (Sainz Rozas et al., 2012). Thus, in the Southeast, the high soil P Bray1 category likely represents soils with a longer agricultural history and associated soil degradation that reduces yields under LP management, highlighting the risk of simplifying the complex soil dynamics by just fertilizer addition.

Overall, relative yield differences between LP and HP plots tended to decrease with higher soil P Bray1 values as expected (Fig. 7) but with a considerable proportion of variation not explained by the model. Relative differences tended to be larger than the mean trend in the Sandy West and Southeast, but lower than expected in the Centre. Together with seasonal influence, these results suggest that other soil processes (including mineralization of organic-P when present) may modulate the expected relationship between relative yield gains in P-fertilized fields and soil P Bray1. By contrast, in regions with reduced organic matter level or mineralization rates as the Sandy West and Southeast, the dependency on inorganic P may enhance relative yield gains obtained from P fertilization. Overall, our results support the idea that P fertilizer management based on experimentally obtained soil P critical values for soybean may underestimate the probable yield benefit obtained from P fertilizer supply since factors such as agricultural history are not taken into account under on-farm P management decisions.

### 4.4. Estimated soil P balances across regions in fertilized and unfertilized plots

Simplified estimations of apparent soil P balances as the one carried out here do not account for other P losses related to leaching or runoff. In any case, P leaching is usually low in these types of soils, reaching as low as 0.4 kg ha$^{-1}$ year$^{-1}$ in maize-soybean rotations in typical argiudolls and even lower values in hapludolls (Portela et al., 2024) whereas runoff is considered negligible given the flatness of the region (Viglizzo et al., 2011). By contrast, using a standard value of seed P concentration may bias P balances, since soybean seed P concentration varies as a result of P fertilization as well as in soils with high P Bray1 values, increasing from 0.4 up to 0.8 in soils varying from 10 to 20 mg kg$^{-1}$ of P Bray1 (Anthony et al., 2013). More precise measurements are needed to avoid overestimating the effect of P fertilization on soil P balances or underestimating P depletion in P-rich soils as the one of the Centre here.

Overall, the soil P balance across seasons and P fertilizer categories was worse than reported in previous works, being around −13.8 to −14.2 kg P ha$^{-1}$ yr$^{-1}$ in all the regions except for the Southeast where it reached −6.2 kg P ha$^{-1}$ yr$^{-1}$ (Supp. Fig. 6). Leguizamón et al. (2023), covering a larger region, reported P balances for soybean spanning from −2- to −4.5 kg P ha$^{-1}$ yr$^{-1}$ but also much higher P fertilization rates than here (11–12 kg P ha$^{-1}$). In our work, mean P rates (without distinguishing P fertilizer categories) ranged from 5.8 to 6.5 kg P ha$^{-1}$, slightly higher than the IFA estimation of 4.36 kg P ha$^{-1}$ for P supply on soybean in Argentina (IFA, 2022), except for the Southeast, with 11.3 kg P ha$^{-1}$. In any case, farming practices of CREA members may not exactly resemble those outside CREA and thus, national statistics. In line with this, land tenancy regime influences crop management (Leguizamón et al., 2023), with land owner proportion being higher in the present dataset (59–65 %, Table 1) than reports for Argentinean Pampas (around 50 %, Choumert and Phélinas, 2015). Thus, the P balances estimated here may not be completely representative of those outside CREA farms, but are still valid to assess the relative effects of P management on soybean P balances.

Our results contribute to quantify the relative effect of P fertilization management on improving soil P balances across regions (Fig. 8). In LP fields, soil P balances were inversely related to soil P Bray1 values, being most negative in the Centre, with highest soil P availability (and yield), and least negative in the Southeast. Similarly, other reports show more negative P balances in soils with initially higher P Bray1 values (Alvarez et al., 2019), which are also prone to faster rates of P Bray1 decline for similar P extraction rates (Sucunza et al., 2018). Thus, the projected impact of negative P balances on soil P Bray1 in the medium-term may be larger in the Centre compared with the rest of the regions of this study.

In the West and Sandy West, similar P Bray1 values (Table 1) and soil P balances (Fig. 8, LP fields) occurred despite its different soil textures. Given the higher organic matter content in soils of the West (Sainz Rozas et al., 2011), the larger organic-P fraction in fine than in coarse soils (Siebers et al., 2017), and the more similar yield distribution between P fertilizer categories in rainy seasons in the West we hypothesize a larger contribution of the organic-P fraction in the West compared to the Sandy West. In the medium term, this could lead to a larger impact of soil P depletion in the Sandy West, given the lower ability to restore the labile P fraction in soils with low organic matter and coarse texture (Tiessen et al., 1984; Sainz Rozas et al., 2012). In the Southeast, the low values of soil P Bray1 limited yields in LP fields, thus also limiting the magnitude of the negative balance.

By contrast, a different trend was found in HP fields, with P balances being most negative in the Sandy West and West, and least in the Centre and Southeast. Here, regional differences in P rates (higher in the Centre and Southeast, Table 2) but also in yields, explain differences in P balances. In the West and Sandy West, larger yield differences between LP and HP fields (Fig. 2) reduced the impact of P fertilization on the P balance (Fig. 8). This highlights the need for a proper estimation of yield response to P fertilizer addition for further assessment of the effects of P fertilization on P balances. Overall, most of the cases explored in the dataset used P fertilizer rates that were lower than those maximizing yields and much lower than those required to attain neutral P balances (Fig. 9A). Moreover, yield variability decreased with increasing P rates (Fig. 9B) in line with fertilizer supply reducing reliance on P fractions that vary according to seasonal rainfall (Fig. 4). Taken together, these results suggest that there is room to increase P fertilization rates in the Pampas with projected returns in terms of improved P balances, yields and yield stability.

### 4.5. Conclusions and future prospects

Our data indicates that even in fields applying P fertilization, current P rates are not enough to avoid soil P depletion. Soil P mining could imply an increasing pressure over the organic-P fraction, suggested here by seasonal differences in the West and Sandy West (Fig. 4) which are influenced by soil organic matter (Supp. Fig. 4) and evidenced in previous works (Appelhans et al., 2016; Sun et al., 2022; Chen et al., 2024). In the same line, the exponential function that represents the decay rate of P Bray1 as a result of cumulative negative P balances (Sucunza et al., 2018) may imply a progressively exhausted labile P-fraction in P-poor soils. Future work could explore the relative contribution of different P-fractions in P-mined soils of the Pampas and whether P-mining is aggravating soil organic matter loss in soybean cropping systems.

Usually proposed solutions to cope with P mining come hand in hand with larger P rates applied, even though P fertilizers are obtained from finite and geographically concentrated sources (de Boer et al., 2019) and prices are already experiencing non-linear trends related to scarcity (Elser et al., 2014) with uncertain projections of world P demand coming from other P-depleted regions (e.g., Sanyal et al., 2014). Ecophysiological approaches to the problem could include reducing seed P concentration, which spans from 0.3 % to 0.9 % regardless of dilution effects (Anthony et al., 2013). By contrast, efforts aimed to increase soybean ability for soil P solubilisation and extraction (e.g., Bello, 2021) may not be helpful in the Argentinean context.

However, the problem also requires political and economic approaches. Asymmetrical nutrient fluxes will continue to generate nutrient surplus and contamination issues in grain importers (e.g., Vandermoere et al., 2021). Substantial reduction of P mining could be obtained with commercial agreements promoting replacement of animal feed exports by meat exports (Abbona, 2017). This should also be complemented with nutrient recovery from animal manure to be reutilized in agricultural fields and the enrichment of top soil layers from deep soil mineral P by roots from perennial forage plants. A global agreement towards more sustainable nutrient fluxes is needed to avoid seriously compromising future crop yields in important world breadbaskets as the Argentinean Pampas.

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**CRediT authorship contribution statement**

**Satorre Emilio:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Paolini María:** Writing – review & editing, Supervision, Data curation. **Micheloud José:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Guiamet Juan:** Writing – review & editing, Supervision, Conceptualization. **Martini Gustavo:** Writing – review & editing, Project administration, Conceptualization. **Antonietta Mariana:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

**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.

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**Appendix A. Supporting information**

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109986.

**Data Availability**

The authors do not have permission to share data.

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