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Is mineral nutrient concentration of soybean, maize, and wheat grain affected by cropping sequence and agronomic management?

D. E. Becheran^{1,2} | F. H. Miguez³ | F. E. Miguez⁴ | A. Peper⁵ | B. Benedit⁵

¹Cátedra de Cerealicultura, Departamento de Producción Vegetal, Universidad de Buenos Aires, Ciudad de Buenos Aires, Argentina

²Cátedra de Cultivos Industriales, Departamento de Producción Vegetal, Universidad de Buenos Aires, Ciudad de Buenos Aires, Argentina

³Facultad de Ciencias Agrarias, Universidad Católica Argentina, Buenos Aires, Argentina

⁴Department of Agronomy, Iowa State University, Ames, Iowa, USA

⁵Bayer Crop Science, Pergamino, Argentina

Correspondence

D. E. Becheran, Cátedra de Cerealicultura, Departamento de Producción Vegetal, Universidad de Buenos Aires, Av. San Martín 4453 (C 1417 DSE), Ciudad de Buenos Aires, Argentina.

Email: dbechera@agro.uba.ar

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Abstract

Producers in the Argentine Pampas often fail to fully replenish the nutrients extracted by crops, leading to unsustainable soil fertility management. The objectives of this study were to (i) evaluate grain yield, mineral nutrient concentration, and extraction for maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.) under contrasting agronomic management systems and (ii) compare mineral nutrient concentration with nutrient removal values commonly used as reference in Argentina when assessing crop nutrient soil uptake. The study was conducted over 8 years in a field experiment located in the central Rolling Pampas, under three crop sequences: continuous soybean (Sy), a 2-year rotation alternating maize and soybean (Mz–Sy), and a 3-year rotation including wheat/soybean double crop, maize, and soybean (Wt/SyDC–Mz–Sy). In addition, these were evaluated with either fallow or winter cover crops (CCs) present under two agronomic systems: conventional management (CM) and intensified management (IM). The IM system included different genotypes, plant densities, fertilizer types, and rates. The IM increased yield for Mz by 1.25 Mg ha^{−1} ($p < 0.01$), Wt by 0.82 Mg ha^{−1} ($p < 0.05$), Sy1 (soybean full season crop) by 0.28 Mg ha^{−1} ($p < 0.05$), and SyDC by 0.39 Mg ha^{−1} ($p < 0.05$). The inclusion of a CC decreased yield for Mz by 1.20 Mg ha^{−1} ($p < 0.01$) and Sy1 by 0.34 Mg ha^{−1} ($p < 0.05$), only within CM and in the drier years. The IM increased nitrogen (N) and sulfur (S) concentrations for Sy but had no consistent effects on nutrient concentrations in other crops. Observed grain nutrient concentration values, despite their variability, could be used to estimate nutrient exports by these crops.

Plain Language Summary

Farmers in the Argentine Pampas often do not replace the nutrients removed by their crops, which can harm long-term soil health. This study looked at how different crop

Abbreviations: CC, cover crop; CCF, complex compound fertilizer; CM, conventional management; CSy, continuous soybean; GG, granular gypsum; IM, intensified management; SSP, single superphosphate; Sy1, soybean full season crop; SyDC, soybean second crop; TSP, triple superphosphate.

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rotations and management practices affect grain yield and nutrient removal in maize, wheat, and soybean. We compared traditional farming with more intensive practices that use improved varieties, increased plant densities, and better fertilization. Intensive management increased yields in all crops, while winter cover crops sometimes reduced yields in dry years. We also measured the nutrients taken up by each crop and found that the observed nutrient concentrations can reliably estimate how much nitrogen, sulfur, and other nutrients are removed from the field. These results help farmers make better decisions about fertilization to protect soil fertility over time.

1 | INTRODUCTION

Improved agricultural productivity is essential to meet the increasing demand for agricultural products while minimizing further environmental impacts (Andrade, 2020; García et al., 2007; Tilman et al., 2011). Sustainable intensification aims to enhance crop yields by optimizing input efficiency and resource productivity while prioritizing soil and water conservation (Cassman, 1999; Hisse et al., 2022; Pretty & Bharucha, 2014). One effective practice for promoting sustainability is no tillage farming, where the crop stubble left on the surface protects the soil from rain and sun, enhances water use efficiency, and increases topsoil organic matter content (Teasdale et al., 2007; Thomas et al., 2007; Triplett & Dick, 2008). Remarkably, over 90% of the total farmland in the Argentine Pampas already adopts a no-tillage system (AAPRESID, 2020).

To further intensify cropping systems and promote sustainability, sowing winter cover crops (CCs) between two summer cash crops, instead of maintaining a long fallow, can be beneficial (Clark et al., 1995; Doré et al., 2011; Huang et al., 2020; Pinto et al., 2017). These CC, composed of grasses, for example, cereal rye (*Secale cereale* L.), oats (*Avena sativa* L.), triticale (*Triticosecale* Wittm. ex A. Camus), and ryegrass (*Lolium multiflorum* Lam.), and legumes, for example, hairy vetch (*Vicia villosa* Roth.) and field peas (*Pisum sativum* L.), or a combination of them may have positive effects on the summer cash crop productivity. CCs can improve soil aeration, control erosion, increase soil organic matter, promote N fixation from the atmosphere, capture nutrients, and suppress weeds (Chen et al., 2014; Ding et al., 2006; Duval et al., 2016; Hermawan & Bomke, 1997; Miguez & Bollero, 2005, 2006; Nichols et al., 2020; Osipitan et al., 2018). However, it is important to consider water consumption by winter CCs, as it can limit water availability for the subsequent summer cash crop (Alvarez et al., 2017; Duval et al., 2021). Although CC use has been increasing during the last decade, only about 20% of producers usually seed these CCs in rainfed cropping systems in the Argentinean Pampas (Bolsa de Cereales, 2021).

Maize (Mz), soybean (Sy), and wheat (Wt) are among the highest valued grain commodities in the world (FAO, 2022) and are the primary cash crops in the Argentinean Pampas region. Over the past 5 years, an average of 16.78 million ha of soybean, 9.62 million ha of maize, and 6.53 million ha of wheat were cultivated, resulting in a combined production above 124 million Mg. This accounts for more than 85% of the total farmland in the region (INDEC, 2022). However, probably due to the heavy taxes imposed on agricultural products in Argentina (FADA, 2022), farmers refrain from fully replenishing the nutrients exported by these crops. The average nutrient replacement through fertilizers in recent years has been very low. Only 31% of N, 39% of P, 31% of S, 3% of K, and 46% of Ca were replaced through fertilizers (Cruzate & Casas, 2017). This is leading to an unsustainable pathway, resulting in a decline in soil fertility.

The grain mineral concentration is the relative amount of that nutrient present in grain to total grain weight. Soil type and texture can play a role in influencing the mineral concentration of plants and seeds, with clay soils generally associated with more mineral-enriched grains compared to sandy soils. Additionally, soil pH strongly affects nutrient solubility and availability for plants (Jordan-Meille et al., 2021). However, mineral composition of plants and seeds is not a direct result of the soil solution mineral concentration. Soil mineral deficiencies, excesses, or imbalances can trigger specific plant reactions that may modify nutrient absorption (Maathuis & Diatloff, 2013; Singh et al., 2020). Moreover, the specific chemistry of the rhizosphere may facilitate microbial or chemical solubilization and enhance nutrient absorption (Díaz Franco et al., 2013; Elhaissoufi et al., 2022; Pii et al., 2015; Zablotowicz et al., 1991). Once absorbed, minerals may accumulate differently in grain or vegetative tissues (Bruulsema et al., 2013). The genotype can also play a role in determining grain mineral concentration. For example, flint maize varieties generally exhibit higher protein content than dented maize varieties (García-Lara et al., 2018). Maize hybrids bred for higher starch content typically have lower protein and fiber content, while those bred for higher protein tend

to have lower starch content (Jaradat & Goldstein, 2013). Modern high-yielding maize hybrids tend to have a lower mineral concentration than old varieties (Guo et al., 2020). Likewise, there are considerable differences in grain mineral concentration among soybean varieties, including Ca, Fe, Mg, Mn, and Zn (Bellaloui et al., 2011; Kim et al., 2021). High-protein and ultra-high-protein soybean varieties have a higher N concentration than conventional ones. Even among conventional varieties, there are variations in N concentrations, with late maturity varieties typically exhibiting higher protein concentration than early maturing ones (Dardanelli et al., 2006). Furthermore, wheat varieties show significant differences in both mineral concentration and yield potential (Hao et al., 2022; Pandey et al., 2016). In Argentina, wheat varieties are grouped based on their milling quality and protein contents (INASE, 2022). Overall, understanding the factors influencing grain mineral concentration is essential for optimizing crop production and ensuring adequate nutrient levels in agricultural products. Ongoing research in this field will undoubtedly contribute to improved agricultural practices and enhanced food quality.

The mineral concentration of grain can be modified through various methods, including fertilization, soil amendments, and nutrient management practices. Environmental factors such as rainfall, temperature, and radiation also affect grain mineral concentration. These effects have been extensively studied and documented. For instance, in the case of wheat, numerous studies have reported on the impact of these factors on its mineral concentration (Abdel-Aziz et al., 2018; Jordan-Meille et al., 2021; Miguez et al., 2013; Szostak et al., 2020). There are also studies for soybean (Assefa et al., 2019; Batal et al., 2010; Caviglia et al., 2011; Ciampitti et al., 2012; Davèrède et al., 2019; Kumar & Goh, 2000; Rotundo & Westgate, 2010; Salvagiotti et al., 2008) and for maize (Cheřan et al., 2021; Ciampitti et al., 2013; Guo et al., 2020; Sahrawat et al., 2008).

Sustainable intensification of cropping systems has been mostly studied at the crop level, with fewer studies investigating the impact of different agronomic management systems on diverse crop sequences (Hisse et al., 2022; Monzon et al., 2018). To our knowledge, there are no references regarding the effects of intensified systems, which encompass various crop sequences, genotypes, fertilizer inputs, plant density, and CCs, on the mineral concentration of maize, soybean, and wheat grains. An increased mineral concentration in grains could indicate a higher nutritional value for these grain crops (Bellaloui et al., 2010; Bruulsema et al., 2013) and a greater export of mineral nutrients from the cropping system, potentially leading to increased fertilizer replacement needs.

The goals of this work were first, to characterize the average mineral concentration and its variability of maize, soybean, and wheat grains and compare them with reference values commonly used in Argentina; and second, to assess the impact

of different intensification levels of cropping sequences and agronomic practices on their grain yield (GY) and mineral concentration. To achieve these objectives, three different crop sequences were evaluated: (i) continuous soybean (CSy), (ii) a 2-year rotation of maize and soybean, and (iii) a 3-year rotation of wheat/soybean, maize, and soybean. Each crop sequence was studied under two agronomic practices: conventional management (CM) and intensified management (IM). Additionally, during the cool season, winter CCs were included to evaluate their effects on the overall system.

2 | MATERIALS AND METHODS

2.1 | Field experiment

The experiment was carried out in a rainfed field during eight consecutive growing seasons (2014–2015 to 2021–2022). It was conducted in a commercial farm located near Pergamino, in the province of Buenos Aires, Argentina (33°51' S; 60°40' W). The soil is classified as a Mollisol, specifically a deep Typic Argiudol, Pergamino series (Table S1). The soil was characterized at the start of the experiment to assess the effect of management systems on soil chemical composition and fertility (Table S2, Semmartin et al., 2023), and all mineral nutrients analyzed showed concentrations ranging from moderate to good values (Grasso & Diaz Zorita, 2020). The average annual temperature and precipitation for the last 30 years were 17°C and 964 mm, respectively. Throughout this study, the lowest annual cumulative precipitation (460 mm) occurred during the 2021–2022 growing season, while the highest (1282 mm) occurred in the 2015–2016 growing season. The average annual distribution of precipitation was lowest in the months of June and July (24–27 mm) and highest in December and January (133–140 mm) (Figure 1).

The main crops in the Rolling Pampas are soybean, maize, and wheat. These crops are commonly used by producers in the area in regular sequences, including CSy, a 2-year rotation of maize and soybean, and a 3-year sequence that includes double cropping of wheat and soybean, as well as maize and soybean (Table 1). No-tillage was used both in CM and IM systems since it is the most common practice in the region. Crop sequences were grown under the presence (CC) and absence (F: fallow) of winter CCs. Triticale and hairy vetch were used as CCs and sown mixed after the summer crops were harvested. Chemical weed management for the different crops and growing seasons is detailed in Table S3.

2.2 | Experimental design

The experiment was a split-plot design with three blocks. The primary plots were assigned to two different conditions: CC

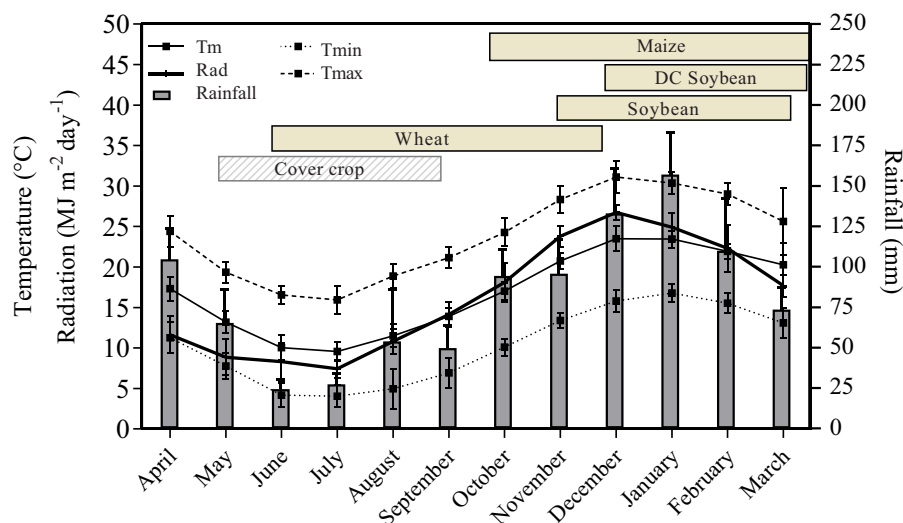


FIGURE 1 Average monthly records of daily mean temperature, mean incident solar radiation, and rainfall from April to March for the average of eight experimental years (2014–2015, 2015–2016, 2016–2017, 2017–2018, 2018–2019, 2019–2020, 2020–2021, and 2021–2022) recorded at the Pergamino Experimental Station of INTA. The horizontal bars represent the crop rotation cycle in which the various crops are located (Soybean, soybean full season crop; DC Soybean, soybean second crop).

TABLE 1 Crop, crop sequences, agronomic system, and cover crop.

Crop	Crop sequences	Agronomic system		Cover crop	
Maize	Mz–Sy	CM	IM	F	CC
	Wt/Sy–Mz–Sy	CM	IM	F	CC
Soybean	Mz–Sy	CM	IM	F	CC
	Wt/Sy–Mz–Sy	CM	IM	F	CC
	Sy–Sy	CM	–	F	CC
Wheat	Wt/Sy–Mz–Sy	CM	IM	F	CC

Abbreviations: CC, winter cover crops; CM, conventional management; F, fallow; IM, intensified management; Mz, maize; Sy, soybean; Wt, wheat.

and fallow (F) and an incomplete factorial combination of three crop sequences: Sy, Mz–Sy, and Wt/Sy–Mz–Sy. Additionally, two management systems, CM and IM, organized as strips were assigned to the subplots. A total of 66 plots were set up for the experiment, and each plot covered an area of 7.3 m in width and 100 m in length, thus occupying 730 m² (730 m²) per plot. Overall, the experiment encompassed an area of 6 ha.

Continuous Sy cultivation is considered to be unsustainable since it has a low organic input and a negative C balance (Salvagiotti et al., 2024; Semmartin et al., 2023), and it was grown only under CM. In all other crop sequences, two agronomic systems were implemented: (i) a CM system, comprising the prevailing agricultural practices used by farmers in the region; and (ii) an IM system, based on prior knowledge, aimed at enhancing GY through increased resource productivity. These two systems were aimed at creating distinct and contrasting scenarios. Several cultivation techniques were used to achieve this objective, including the selection of different genotypes,

adjusting sowing density in specific cases, and varying the timing and fertilization rate. Genotype selection for the IM system was based on their performance in comparative trials conducted in the area. Moreover, some of these genotypes possess genetic technology that confers greater resistance to diseases and pests, thus enabling higher productivity and improved quality (Dekalb, 2022; Don Mario, 2022).

Plant densities were selected to optimize the use of available resources and differed between the agricultural systems for maize and wheat, with the highest density observed in maize and wheat under the IM system. On average, in the CM, enough seeds were sown to obtain 7 plants per square meter (plt m⁻²) of maize and 380 plt m⁻² of wheat. In contrast, in the IM system, the populations were 9 plt m⁻² for maize and 420 plt m⁻² for wheat, representing an increase of 29% and 11%, respectively. Planting densities in soybean were similar in both agronomic systems. For the soybean full season crop (Sy1), the stand count was 33 plt m⁻², and 40 plt m⁻² for the double-cropped soybean, a 21% increase in den-

TABLE 2 Growing seasons are used for grain mineral concentration analysis in crops.

Crop	Nutrient analysis					
	N	P	S	Mg	Ca	K
Maize	Seven growing seasons (2014/2015 to 2016/2017 and 2018/2019 to 2021/2022)			Seven growing seasons (2014/2015 to 2016/2017 and 2018/2019 to 2021/2022)		
Soybean and soybean DC	Six growing seasons (2014/2015 to 2019/2020)			Five growing seasons (2014/2015 to 2016/2017 and 2018/2019 to 2019/2020)		
Wheat	Five growing seasons (2015/2016 to 2018/2019 and 2021/2022)			Four growing seasons (2015/2016, 2016/2017, 2018/2019 and 2021/2022)		

sity. Planting dates were the same for both systems within the same growing season. Wheat was planted between late May and mid-June. The summer crop planting began with maize in mid-September and October, while Sy1 and soybean second crop (SyDC) were sown in November and December, respectively.

Fertilizer management differed between the intensification systems for maize and wheat cultivation. For both crops, P fertilization rate in the CM was calculated as to not limit yield and was usually below the amount extracted by the crops. In the IM system, in contrast, the rate was calculated not only to replace the extracted P but also to build up soil available P by about $1 \text{ g Mg}^{-1} \text{ year}^{-1}$ (Bray 1) (Bray & Kurtz, 1945). N fertilization rate for maize and wheat was calculated using local fertilization models to cover the target yield needs. In the CM system for wheat, a N fertilization rate of 69 kg N ha^{-1} was applied in the form of urea (46-0-0) during the early tillering stage (Z2.2) (Zadoks et al., 1974). On the other hand, in the IM system applications varied for different growing seasons, in most cases, 21 kg N ha^{-1} was applied at sowing, followed by an additional $67.5 \text{ kg N ha}^{-1}$ at the early tillering stage.

For maize in the CM system, N fertilization was conducted using urea, with application rates ranging from 48 to 69 kg N ha^{-1} at sowing, followed by an additional $36.8 \text{ kg N ha}^{-1}$ at the V6 growth stage (six-ligulated leaf stage) (Abendroth et al., 2011). For the IM system, a broader range of N applications was used, with rates from 61.5 to 115 kg N ha^{-1} at sowing and an additional 36.8 – $86.4 \text{ kg N ha}^{-1}$ at the V6 stage. This approach resulted in total N applications ranging from 110 to 165 kg N ha^{-1} , adjusted according to the specific seasonal requirements. On average, N application rates in the IM system were 42% higher for maize and 35% higher for wheat compared to the CM system.

Regarding P fertilization, in the CM system for wheat, 16 kg P ha^{-1} was applied as triple superphosphate (TSP; 0-20-0) at sowing. In contrast, in the IM system two types of applications were used depending on the season and type of fertilizer: (i) 34 kg P ha^{-1} as TSP or (ii) $19.6 \text{ kg P ha}^{-1}$ as complex compound fertilizer (CCF) at sowing. For maize in the CM system, 16 kg P ha^{-1} was applied as TSP at sowing, while in the IM, two types of applications were used: (i) 16 kg P ha^{-1} as sin-

gle superphosphate (SSP 0:20:0; S12) at sowing or (ii) 28 kg P ha^{-1} as CCF prior to sowing. Soybean crop fertilization followed a similar pattern, with 16 kg P ha^{-1} as TSP applied at sowing in CM and either 34 kg P ha^{-1} as TSP or $19.6 \text{ kg P ha}^{-1}$ as CCF applied in the IM; also, 8.3 kg P ha^{-1} as CCF was applied at sowing in Sy2. Phosphorus fertilization levels were significantly higher in the IM system, with increases of 46% for wheat, 42% for maize, and 58% for soybean compared to the CM system.

Sulfur was applied exclusively in the IM, along with P fertilization in some cases, and the fertilizer used was CCF or SSP. For wheat, two different rates were applied depending on the season: (i) $17.1 \text{ kg S ha}^{-1}$ was applied as granular gypsum (GG; S 18,6) or (ii) 12 kg S ha^{-1} as CCF at sowing. For maize, $15.2 \text{ kg S ha}^{-1}$ was applied as GG in some seasons, and in others, 16 kg S ha^{-1} as CCF prior to sowing. Similar rates of CCF were applied to soybean and to maize at sowing, with 12 kg S ha^{-1} as CCF; also, 4.8 kg S ha^{-1} as CCF at sowing was applied in SyDC (Table S4). No K fertilizer was used in any of the systems, since soil K concentration is high and above the yield response threshold for these crops.

2.3 | Grain mineral nutrient concentration

The analysis of grain mineral concentration in maize, soybean, and wheat was conducted across multiple growing seasons (Table 2). The data include concentrations of N, P, S, Mg, Ca, and K. For maize, nutrient analyses were performed over seven growing seasons. For soybean, data are available for six seasons for N, P, and S, and for five seasons for Mg, Ca, and K. Wheat analysis was carried out over five seasons for N, P, and S and over four seasons for Mg, Ca, and K.

All grain samples were dried to room temperature and analyzed in the same laboratory. Nitrogen concentration was determined by the Kjeldahl method, which involved digestion with sulfuric acid and catalyst salts, followed by distillation and titration with HCl (McKean, 1993). Potassium, Mg, and Ca concentrations were determined by atomic absorption spectrophotometry after nitric and perchloric acids digestion. Phosphorus concentration was measured colori-

metrically using the molybdenum blue method (Murphy & Riley, 1962) and sulfur concentration by turbidimetry using barium chloride as the reagent, both measured with a spectrophotometer (Dewis & Freitas, 1970). Grain weight was measured with a precision scale, and grain number per unit area was calculated by dividing GY (g m^{-2}) by the average grain weight (g grain^{-1}).

2.4 | Statistical analysis

Statistical analyses were performed using R 4.4.2 (R Core Team, 2024). Linear mixed-effects models were fitted using the *lmer* function from the *lme4* package to evaluate the effects of agronomic systems (CM and IM) and CC on each crop. In these models, CC and agronomic system were treated as fixed effects, while year and block were included as random effects to account for experimental variability.

To examine the relationship between GY and grain nutrient concentrations (N, P, S, Mg, Ca, and K), both linear and bilinear models were considered and fitted with the *nlraa* R package (Miguez, 2024). Initially, linear models were fitted for all variables, and model performance was assessed using the coefficient of determination (R^2), root mean square error (RMSE), and normalized root mean square error (nRMSE). For K, or cases where the R^2 of the linear model was below 0.5, bilinear models were used. RMSE and nRMSE values were also computed for bilinear models, and the model with the best fit was selected for interpretation. Scatter plots were generated for each nutrient, displaying observed data points, the fitted trend line (linear or bilinear), and annotations with model performance metrics (R^2 , RMSE, and nRMSE). Pearson correlation analyses were conducted to explore relationships among the variables. Correlation coefficients were computed and statistical significance evaluated at an α -level of 0.05. The significance of the correlations was represented as $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$.

3 | RESULTS AND DISCUSSION

3.1 | Grain yield

3.1.1 | Maize

The IM system consistently increased yield for maize by $\sim 16\%$ (1.2 Mg ha^{-1} $p < 0.01$) as an average of the eight growing seasons and crop sequences (Table 3). The inclusion of a CC had a negative impact on Mz yield, reducing it by 1.2 Mg ha^{-1} ($p < 0.01$) on average for both systems, with a more pronounced penalty in years characterized by drier conditions during the critical period for grain set (VT [tasseling] to R3 [milk stage]) (Abendroth et al., 2011; Ritchie

& Hanway, 1982), as observed in the growing seasons 2015–2016; 2020–2021 and 2021–2022 (Table S5). Within the IM system, the yield penalty was only significant in the drier growing seasons (2.6 Mg ha^{-1} , $p < 0.05$), suggesting that CC could be included without a yield penalty, if an intensified cropping system is used, and rainfall is close to the historical average. It is likely that CC transpiration during winter reduced the water availability for the summer crop, as reported by others (Alvarez et al., 2017; Coombs et al., 2017; Deines et al., 2023). For example, Alvarez et al. (2017) found that, in general, maize yields tend to decrease with nonleguminous CCs and increase with leguminous CCs. The yield penalty could also be related to the composition of the CCs used in our study, a combination of grasses and legumes.

The economic effect of CC should be evaluated together with the beneficial effects on the soil and environment, including the potential reduction in N fertilizers and herbicide needs. However, weed control was efficient and the same in both systems. To assess this, specific experiments across a range of environmental conditions and crop sequences throughout several years are needed.

Comparing all 10 treatments, an additive effect of IM and CC on Mz yield was observed (Table 3). The crop sequence did not affect Mz yield, and it was similar if the previous crop was Sy or Wt/SyDC for both management systems.

Planting maize early in the spring, as we did in our experiment, allows it to develop under optimal weather conditions during the vegetative stages characterized by low atmospheric demand, moderate temperature, and high solar radiation (Figure 1). Also, the reproductive stages occur with the longest days of the year, so the crop GY potential is higher than planting maize late in the spring (Bert & Satorre, 2012). However, this early sowing date presents a risk since the grain set period occurs in December, a month with potential for water deficits. Water stress around anthesis reduces stigma receptivity to pollen and pollen availability, subsequently reducing grain set (Otegui et al., 1995). Maize yield was highly explained by an increase in grain number ($R^2 = 0.94$), while grain weight was not related with yield.

Maize yield was correlated with rainfall around anthesis ($r = 0.90$, $p < 0.01$), suggesting that water availability could have been the most limiting factor for yield. Temperature and radiation during the grain set period were not related to yield. Average temperature during the whole growing season was negatively related with yield ($r = -0.81$, $p < 0.05$).

3.1.2 | Soybean

Yield was significantly greater in the IM system by $\sim 8\%$ for Sy1 (0.28 Mg ha^{-1} $p < 0.05$) and by $\sim 15\%$ for SyDC (0.37 Mg ha^{-1} $p < 0.05$), as an average of the eight growing seasons

TABLE 3 Grain yield of maize, soybean, and wheat in conventional agronomic systems (CM) and intensified agronomic systems (IM) with cover crops (CC) and without cover crops (F), as an average of the eight growing seasons.

Source of variation		Grain yield (Mg ha ⁻¹)			
		Maize	Soybean (Sy)	Soybean (Sy DC)	Wheat
Agronomic system	CM	7.92b	3.35b	2.46b	3.61b
	IM	9.16a	3.64a	2.82a	4.54a
Cover crop	F	9.14a	3.59a	2.63	4.02
	CC	7.94b	3.40b	2.66	4.13
Agronomic system x Cover crop	CM × F	8.52	3.52a	2.49	3.60
	CM × CC	7.31	3.19b	2.43	3.61
	IM × F	9.75	3.66a	2.77	4.45
	IM × CC	8.57	3.61a	2.88	4.64
Agronomic system (AS)		***	***	*	***
Cover crop (C)		***	***	0.7377	0.1507
AS × C		0.9336	*	0.2954	0.2997

Note: Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Reported *p*-values correspond to the main effects (agronomic system and cover crop) and their interaction (AS × C). Sy1, soybean full season crop; SyDC, soybean second crop.

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

and crop sequences. The CC decreased Sy1 yield by 0.33 Mg ha⁻¹ ($p < 0.01$) only for the CM system. There was no yield penalty for the IM system. This suggests that a CC could be included before Sy1 without a yield penalty if improved agronomic practices are applied to the crop. The CC did not affect SyDC yield. The prior crop was always wheat, and no CC was sown immediately before this crop sequence. Within CM, CSy showed a lower yield (0.44 Mg ha⁻¹ $p < 0.05$) compared to when maize was the previous crop. The CSy cropping sequence was not included when comparing management systems because it was only grown under CM. Similar results were reported in other long-term experiments in the region (Basanta & Alvarez, 2015). Sy1 showed a higher yield than soybean double-cropped (0.78 Mg ha⁻¹ $p < 0.05$) as an average of all treatments and growing seasons. This agrees with other experiments in the region (Martin, 2021), regional variety trials (INASE, 2022), and reports from commercial plots (Bolsa de Comercio de Rosario, 2022). Comparing all 10 treatments, an additive effect of crop sequence, IM, and F on Sy1 yield was observed (Table 3). GY, both for Sy1 and SyDC, averaged across all treatments, was not related with rainfall, radiation, or temperature throughout the entire growing season or during the critical period for yield development (R3 to R6) (Fehr & Caviness, 1977) (Table S5).

3.1.3 | Wheat

The IM consistently increased Wt yield by ~27% (0.94 Mg ha⁻¹, $p < 0.05$) over CM as an average of all treatments. The CC or crop sequence did not affect Wt yield, and this is partially explained by the fact that the prior crop for Wt

was always Sy1 and no CC was sown immediately before Wt.

Wheat yield, as an average of all treatments, was not related with rainfall, radiation, or temperature during the entire growing season or during the grain set and filling period Z5 to Z9 (Zadok et al., 1974) (Table S5). It has been reported (Natali et al., 2004; Zilio et al., 2014) that lower temperatures, not reaching the freezing point, and higher radiation during spring, are usually associated with higher wheat yield. Within limits, wheat yield is usually higher in drier years since disease incidence is lower (Brendel et al., 2017; Scian, 2002). Fillat et al. (unpublished data), working with this same dataset, concluded that these yield increases covered the extra cost of fertilizer and seed, thereby increasing profitability and rate of return on investment for all crop sequences. Thus, the IM system, which includes higher fertilizer rates, increased plant density, and better genotypes, resulted in higher profitability.

3.2 | Mineral concentration

3.2.1 | Maize

Mineral concentration for maize grain was not consistently modified by the intensification level, so its nutritional value was not improved. The IM only slightly increased Mg concentration when no CC was included, without affecting other nutrients (Table 4).

There were differences among growing seasons ($p < 0.05$) for all nutrient concentrations, as an average of all treatments (Table S6). These differences were not associated with GY,

TABLE 4 Mineral concentration (g kg^{-1}) for maize as affected by intensification system: Conventional management (CM), intensified management (IM), and cover crop (CC), as an average over the seven growing seasons analyzed.

Maize							
Source of variation		N (g kg^{-1})	P (g kg^{-1})	S (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})	K (g kg^{-1})
Agronomic system	CM	12.83	2.85	0.80	1.21b	0.39	3.97
	IM	12.93	2.87	0.84	1.25a	0.35	3.90
Cover crop	F	12.89	2.85	0.83	1.24	0.40	3.91
	CC	12.86	2.87	0.81	1.22	0.33	3.96
Agronomic system x Cover crop	CM $\times$ F	12.68	2.81	0.82	1.20	0.41	3.93
	CM $\times$ CC	12.97	2.89	0.77	1.21	0.36	4.10
	IM $\times$ F	13.10	2.89	0.83	1.28	0.39	3.90
	IM $\times$ CC	12.76	2.85	0.84	1.22	0.30	3.91
Agronomic system (AS)		0.5710	0.7033	0.1515	*	0.3460	0.5217
Cover crop (C)		0.8670	0.7034	0.4589	0.2572	0.0827	0.6560
AS $\times$ C		0.0906	0.1432	0.3604	0.0760	0.7101	0.7692

Note: Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Reported p -values correspond to the main effects (agronomic system and cover crop) and their interaction (AS $\times$ C).

* $p < 0.05$.

temperature, radiation, or rainfall during the entire growing season or around crop anthesis. Heckman et al. (2003) and Ferreira et al. (2012) also reported a large variability in nutrient concentrations in maize grains, which raises concerns about the use of fixed values when assessing nutrient exports by these crops.

GY was not strongly associated with any of the mineral nutrient concentrations analyzed (Figure 2g). Calcium and K concentrations showed positive correlations with GY, with Ca having a higher correlation coefficient ($r = 0.49$). In contrast, the correlations between GY and the concentrations of N, S, and Mg were negative and very weak. There was no correlation with P concentration (Figure 2g). Previous studies have also reported a weak and inconsistent relationship between N and P concentrations (Bélanger et al., 2012).

The use of different management systems can increase variability and prevent attribution of results to a single factor, but it is more representative of variability in nutrient extraction for the different systems and inference to other fields. Since the concentrations of nutrients in grain were unaffected, nutrients extraction per area was proportional to GY. Maize yield ranged from 1.69 to 18.62 Mg ha^{-1} considering all treatments and years. The relationship between maize yield and nutrient export was high for N ($R^2 = 0.81$), P ($R^2 = 0.85$), Mg ($R^2 = 0.79$), and K ($R^2 = 0.72$), while it was lower for S ($R^2 = 0.49$) and Ca ($R^2 = 0.54$). Here, R^2 represents the coefficient of determination derived from regression analysis reflecting the variability in the observed concentration values (Figure 2a–f). Duarte et al. (2019) reported that N, S, and Cu concentrations were lower in high-yielding maize crops in Brazil, considering early and late-season crops, but yield was associated with an increase in grain

number and its weight. This could explain the difference with our results, where GY was not associated with grain weight.

3.2.2 | Soybean

On average, for the six growing seasons analyzed, the IM system increased concentration of N and S, and decreased concentration of P, Mg, and Ca for Sy. Other authors, such as Davêrêde et al. (2019) and Martinez and Cordone (2015) concluded that a high rate of P and S fertilization increased protein concentration in soybean. This suggests a potential to improve soybean grain quality with appropriate management. For SyDC, the IM system increased average concentrations of S and P for the six growing seasons (Table 5), but other nutrients were not affected.

For Sy1, the IM increased concentrations of N in three growing seasons (2014–2015, 2016–2017, and 2021–2022), of P in 1 year (2016–17), of S in 3 years (2018–19, 2019–2020, and 2021–2022), and of K in 1 year (2015–2016). Other nutrients had a reverse trend, with decreased concentration of Mg in 1 year (2021–2022) and Ca in 2 years (2018–2019 and 2021–2022). The inclusion of CC did not have a significant effect. For SyDC, the IM resulted in a decreased concentration of N in 1 year (2016–2017) and increased concentration of S in 3 years (2018–2019, 2019–2020, and 2021–2022), but did not affect the other mineral concentrations (Tables S7 and S8). Within the CM system, CSy showed a lower S concentration than when maize was the previous crop. Averaged over all treatments, nutrient concentration values were similar for both Sy1 and SyDC.

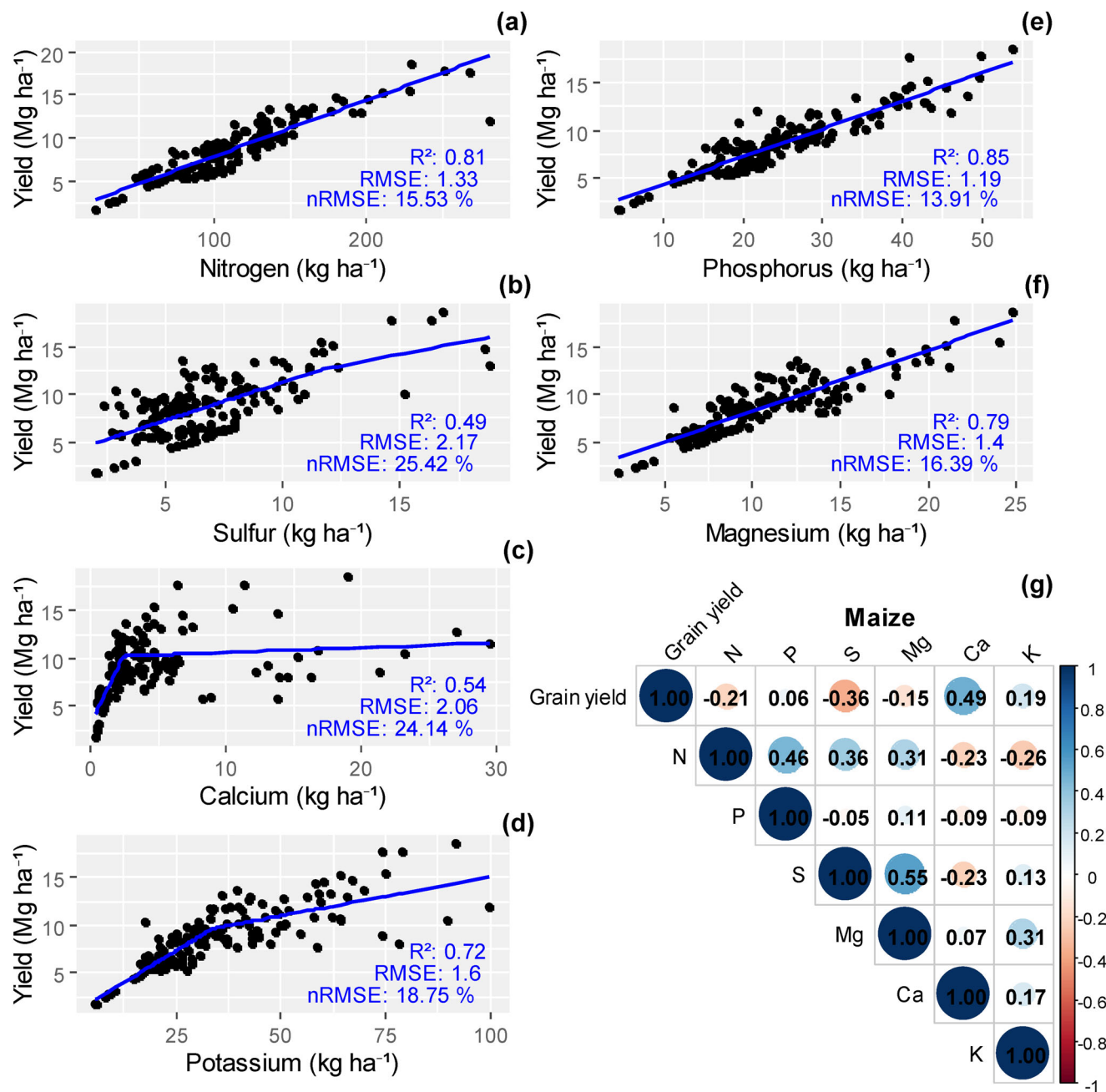


FIGURE 2 Regression analysis of grain yield and nutrients in maize. (a), (b), (c), (d), (e), and (f) Relationship between grain yield (Mg ha⁻¹) and nutrient extraction (kg ha⁻¹); the root mean square error (RMSE), the RMSE expressed as a percentage of the observed mean (nRMSE), and the coefficient of determination (R^2) are shown for each. (g) Spearman correlation matrix between grain yield (Mg ha⁻¹) and nutrient concentration (g kg⁻¹); N: nitrogen; P: phosphorus; S: sulfur; Mg: magnesium; Ca: calcium; K: potassium) in wheat. The circles represent both the strength of the relationship between the variables and the statistical significance ($p < 0.05$). The numbers inside the circles indicate the magnitude of the correlation. The color of the numbers reflects the type of correlation: blue for positive correlations and red for negative correlations. A value close to 1 indicates a strong positive correlation, while a value close to -1 indicates a strong negative correlation. * p values are significant at 0.05.

There were differences in mineral concentrations among growing seasons both for Sy1 and SyDC (Tables S7 and S8). Nutrient concentrations were not associated with temperature, radiation, or rainfall during the growing season or the grain set and filling period. For Sy1, GY was positively associated with N ($r = 0.21$, $p < 0.05$) concentration and negatively with P ($r = -0.29$, $p < 0.05$), Mg ($r = -0.24$,

$p < 0.05$), Ca ($r = -0.32$, $p < 0.05$), and K ($r = -0.22$, $p < 0.05$) concentrations. For SyDC, GY was positively associated with N ($r = 0.28$, $p < 0.05$), S ($r = 0.34$, $p < 0.05$), and Mg ($r = 0.24$, $p < 0.05$) and negatively with P ($r = -0.40$, $p < 0.05$) concentration. Phosphorus concentration was negatively associated with Ca concentration ($r = -0.47$, $p < 0.05$) in SyDC. Other correlation values among nutrient concentra-

TABLE 5 Mineral concentration (g kg^{-1}) in soybean according to intensification system: Conventional management (CM), intensified management (IM), and cover crop (CC), averaged over all growing seasons.

Soybean (Sy)							
Source of variation		N (g kg^{-1})	P (g kg^{-1})	S (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})	K (g kg^{-1})
Agronomic system	CM	51.84b	5.41a	2.22b	2.73a	3.65a	17.43
	IM	53.35a	5.15b	2.56a	2.64b	3.42b	17.62
Cover crop	F	52.61	5.24	2.46a	2.69	3.45	17.69
	CC	52.57	5.31	2.33b	2.68	3.62	17.36
Agronomic system $\times$ cover crop	CM $\times$ F	51.77	5.07	2.34	2.73	3.54	17.3
	CM $\times$ CC	51.91	5.23	2.1	2.73	3.76	17.56
	IM $\times$ F	53.45	5.51	2.57	2.65	3.37	18.08
	IM $\times$ CC	53.24	5.40	2.55	2.63	3.48	17.15
Agronomic system (AS)		**	*	***	*	*	0.6645
Cover crop (C)		0.9956	0.4268	*	0.8115	0.0975	0.6020
AS $\times$ C		0.7220	0.4549	0.0866	0.8967	0.5966	0.1623
DC soybean (SyDC)							
Agronomic system	CM	53.13	5.43b	2.24b	2.6	3.40	15.80
	IM	53.23	5.86a	2.59a	2.56	3.29	16.98
Cover crop	F	52.91	5.78	2.44	2.58	3.35	16.88
	CC	53.45	5.51	2.39	2.57	3.33	15.91
Agronomic system $\times$ cover crop	CM $\times$ F	52.55	5.46	2.25	2.59	3.5	16.75
	CM $\times$ CC	52.98	5.4	2.23	2.61	3.29	14.85
	IM $\times$ F	52.55	6.1	2.61	2.58	3.21	17.01
	IM $\times$ CC	53.92	5.61	2.55	2.53	3.37	16.96
Agronomic system (AS)		0.9007	**	**	0.2358	0.4818	0.1727
Cover crop (C)		0.5067	0.0660	0.6405	0.9175	0.8636	0.2731
AS $\times$ C		0.3070	0.1693	0.8357	0.2661	0.2587	0.2982

Note: Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Reported p -values correspond to the main effects (agronomic system and cover crop) and their interaction (AS $\times$ C).

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

tions, both for Sy1 and SyDC, were not significant (Figure 3). Gibson and Mullen (2001), Samarah et al. (2004), Bellaloui et al. (2015), and Vargas et al. (2018) also reported a large variability in nutrient concentration in soybean grains. As for maize, this variability might lead to incorrect estimates of nutrient exports when using a single value.

Considering both Sy1 and SyDC, yield ranged from 1.46 to 5.84 Mg ha^{-1} , for all treatments and years. Nutrient extractions were related to yield since their concentrations were not consistently affected (Figure 3). A low RMSE, expressed as a percentage of the observed mean (nRMSE), indicates low variability in mineral nutrient concentrations for N (nRMSE = 8.76% Sy and 9.49% SyDC) and Mg (nRMSE = 9.59% Sy and 7.28% SyDC) (Figures 3 and 4).

3.2.3 | Wheat

There was no consistent effect of the intensification management on Wt grain mineral concentration; therefore, its

nutritional value was not affected. Averaged over all growing seasons, the IM system increased Ca concentration and did not affect other nutrients (Table 6). The combination of different genotypes, plant populations, and fertilizer inputs throughout the growing seasons increased variability and had little effect on the grain mineral concentrations.

There were differences in nutrient concentrations among years (Table S9), but they were not related to GY, temperature, radiation, or rainfall during the growing seasons or grain set and filling period. Other authors also reported a large variability in grain nutrient concentration in wheat (Oury et al., 2006; Rodehutsord et al., 2016; Volke, 1968), which can lead to a substantial over- or under-estimation of nutrient exports by the crop. GY was associated with the concentration of N ($r = 0.56$, $p < 0.05$), P ($r = 0.52$, $p < 0.05$), and K ($r = 0.62$, $p < 0.05$). The concentrations of S, Mg, and Ca were not associated with yield (Figure 5).

Since nutrient concentrations were not affected, nutrient extraction per area was proportional to yield. Wheat yield

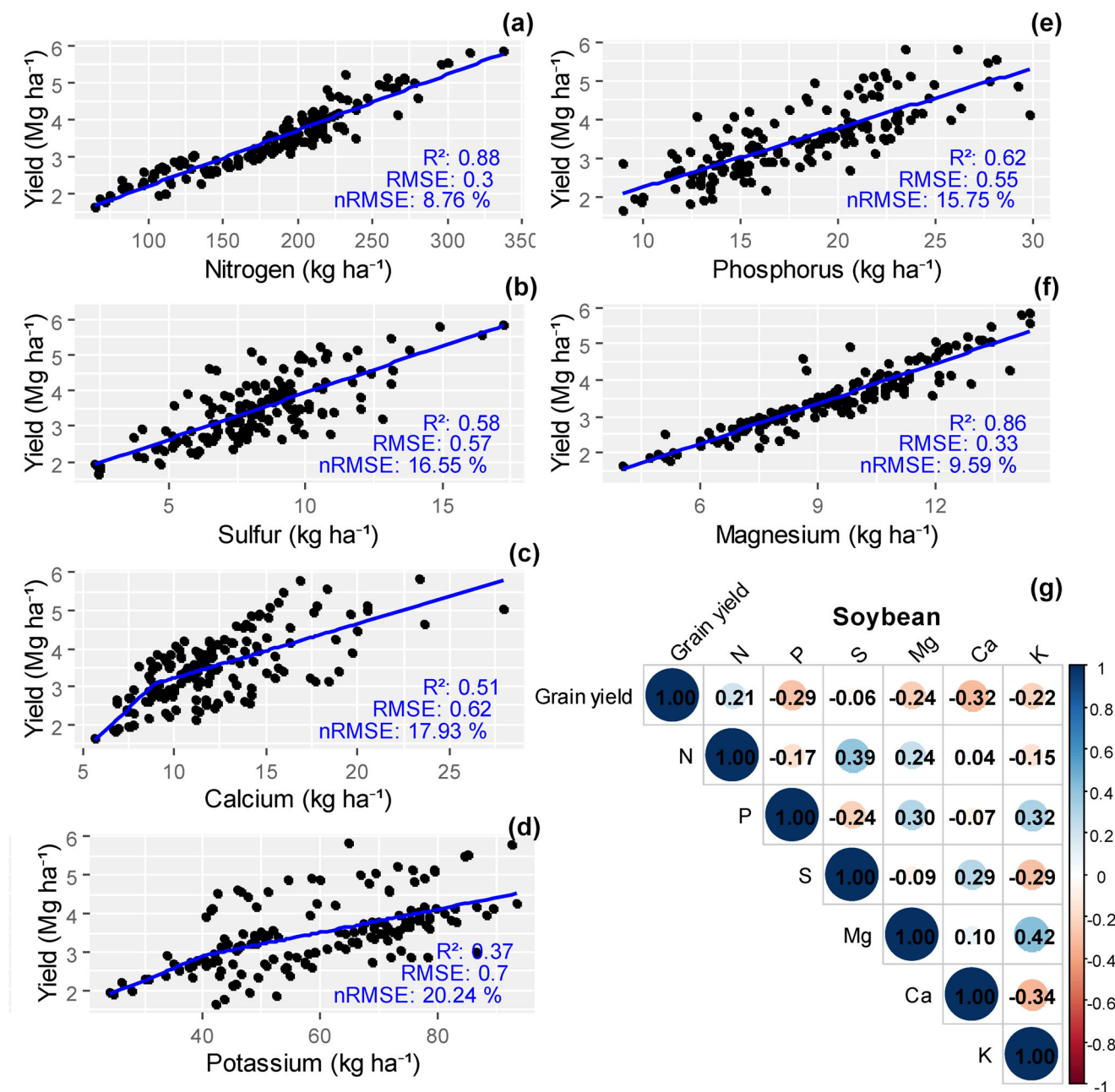


FIGURE 3 Regression analysis of grain yield and nutrients in soybean. (a), (b), (c), (d), (e), and (f) Relationship between grain yield (Mg ha⁻¹) and nutrient extraction (kg ha⁻¹); the root mean square error (RMSE), the RMSE expressed as a percentage of the observed mean (nRMSE), and the coefficient of determination (R^2) are shown for each. (g) Spearman correlation matrix between grain yield (Mg ha⁻¹) and nutrient concentration (g kg⁻¹); N: nitrogen; P: phosphorus; S: sulfur; Mg: magnesium; Ca: calcium; K: potassium) in wheat. The circles represent both the strength of the relationship between the variables and the statistical significance ($p < 0.05$). The numbers inside the circles indicate the magnitude of the correlation. The color of the numbers reflects the type of correlation: blue for positive correlations and red for negative correlations. A value close to 1 indicates a strong positive correlation, while a value close to -1 indicates a strong negative correlation. * p values are significant at 0.05.

ranged from 2.22 to 6.10 Mg ha⁻¹ considering all treatments and years. The relationship between GY and mineral nutrient extraction was high for N ($R^2 = 0.71$), P ($R^2 = 0.74$), and K ($R^2 = 0.81$); medium for Mg ($R^2 = 0.62$); and very weak for

Ca ($R^2 = 0.09$) and S ($R^2 = 0.13$) reflecting the variability in mineral concentrations observed (Figure 5). Separate analyses, exploring the effect of technology or CC, did not affect fit.

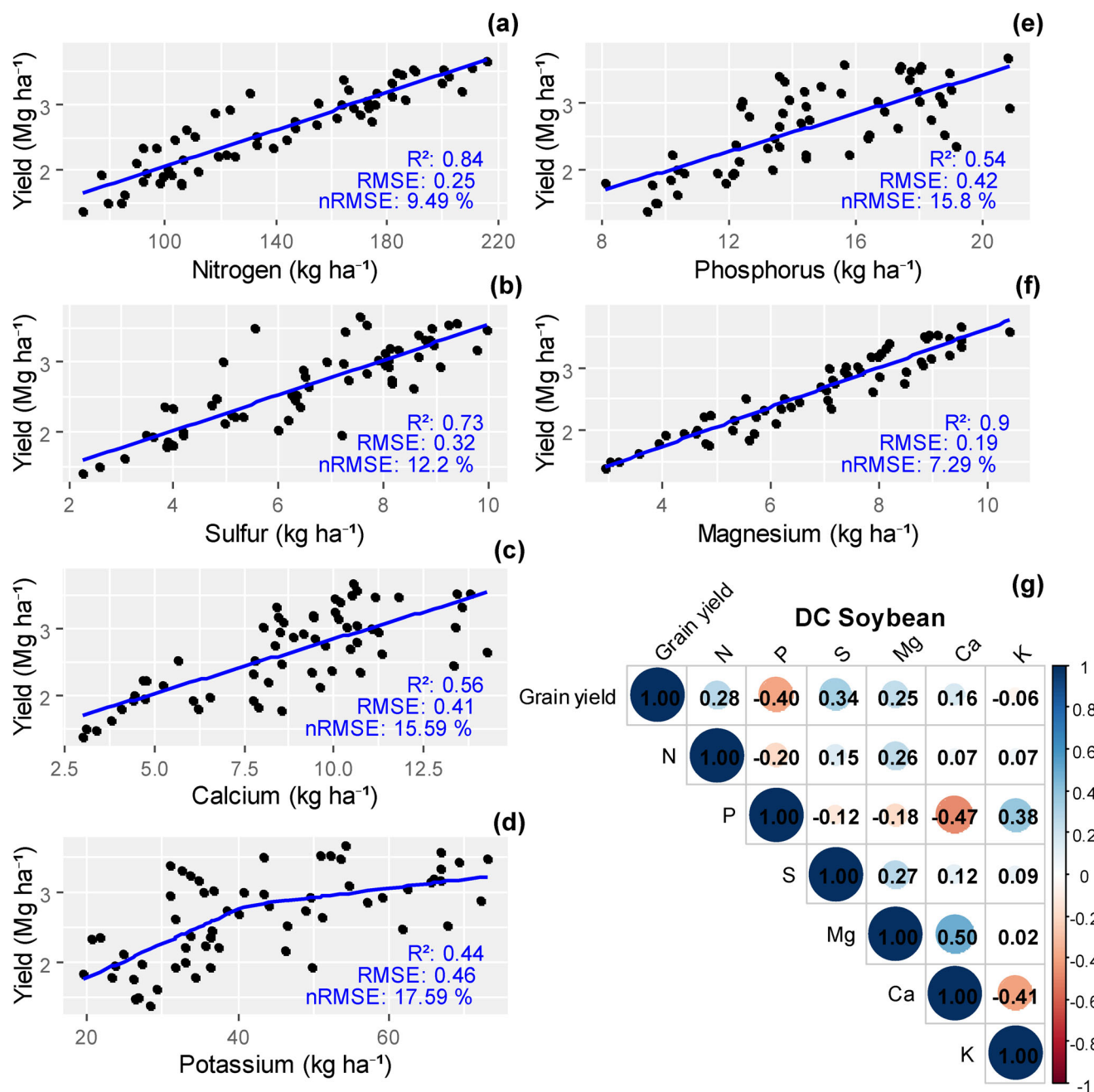


FIGURE 4 Regression analysis of grain yield and nutrients in soybean second crop (DC Soybean). (a), (b);(c);(d);(e);(f) Relationship between grain yield (kg ha⁻¹) and nutrient extraction (kg ha⁻¹); the root mean square error (RMSE), the RMSE expressed as a percentage of the observed mean (nRMSE) and the coefficient of determination (R^2) are shown for each. (g) Spearman correlation matrix between grain yield (kg ha⁻¹) and nutrient concentration (g kg⁻¹); N: nitrogen; P: phosphorus; S: sulfur; Mg: magnesium; Ca: calcium; K: potassium) in wheat. The circles represent both the strength of the relationship between the variables and the statistical significance ($p < 0.05$). The numbers inside the circles indicate the magnitude of the correlation. The color of the numbers reflects the type of correlation: blue for positive correlations and red for negative correlations. A value close to 1 indicates a strong positive correlation, while a value close to -1 indicates a strong negative correlation. * p values are significant at 0.05.

3.2.4 | Mineral concentration comparison with reference values

Table 7 shows the average mineral concentration of Mz, Sy1, Sy2, and Wt found in our experiment, compared to the refer-

ence values commonly used in Argentina (Ciampitti & García, 2008). For maize, the average mineral concentration in our experiment were slightly lower for N, lower for Mg, similar for P, S, and K, and higher for Ca, than the reference values. Average extraction values found in our experiments did

TABLE 6 Mineral concentration (g kg^{-1}) in wheat according to intensification system conventional management (CM), intensified management (IM), and cover crop (CC), as an average over the analyzed growing seasons.

Wheat							
Source of variation		N (g kg^{-1})	P (g kg^{-1})	S (g kg^{-1})	Mg (g kg^{-1})	Ca (g kg^{-1})	K (g kg^{-1})
Agronomic system	CM	18.36	3.33	0.97	1.40b	0.44b	4.54
	IM	19.15	3.40	1.02	1.57a	0.63a	4.78
Cover crop	F	18.46	3.37	1.00	1.51	0.51	4.73
	CC	19.05	3.36	0.98	1.45	0.56	4.59
Agronomic system $\times$ cover crop	CM $\times$ F	18.20	3.32	0.99	1.40	0.44	4.58
	CM $\times$ CC	18.52	3.35	0.91	1.39	0.44	4.5
	IM $\times$ F	18.73	3.42	0.99	1.62	0.58	4.88
	IM $\times$ CC	19.57	3.38	1.04	1.52	0.67	4.68
Agronomic system (AS)		0.0928	0.3521	0.3629	**	*	0.2243
Cover crop (C)		0.2028	0.8432	0.8924	0.3667	0.5441	0.4771
AS $\times$ C		0.6701	0.6448	0.1096	0.4584	0.5588	0.7677

Note: Different letters within a column indicate significant differences according to Tukey's test ($\alpha = 0.05$). Reported p -values correspond to the main effects (agronomic system and cover crop) and their interaction (AS $\times$ C).

* $p < 0.05$; ** $p < 0.01$.

TABLE 7 Mineral concentration (g kg^{-1}) and standard deviation averaged over all treatments and growing seasons for Mz, Sy1, SyDC, and Wt, compared to the reference values commonly used in Argentina (Ciampitti & Garcia., 2008).

Nutrient	Maize (g kg^{-1})		Soybean (g kg^{-1})	DC soybean (g kg^{-1})	Soybean (g kg^{-1})	Wheat (g kg^{-1})	
	Experiment	Reference	Experiment		Reference	Experiment	Reference
N	12.88 $\pm$ 1.98	15.0	52.74 $\pm$ 5.78	53.65 $\pm$ 5.53	55.0	18.75 $\pm$ 3.31	21.0
P	2.86 $\pm$ 0.42	3.0	4.66 $\pm$ 1.49	5.04 $\pm$ 1.44	6.0	3.37 $\pm$ 0.64	4.0
S	0.82 $\pm$ 0.28	1.0	2.81 $\pm$ 1.40	2.86 $\pm$ 1.41	3.0	0.99 $\pm$ 0.32	2.0
Mg	1.23 $\pm$ 0.20	2.0	2.22 $\pm$ 0.97	2.16 $\pm$ 0.92	4.0	1.48 $\pm$ 0.70	3.0
Ca	0.42 $\pm$ 0.48	0.2	2.88 $\pm$ 1.43	2.66 $\pm$ 1.41	3.0	0.53 $\pm$ 0.76	0.4
K	3.96 $\pm$ 1.13	4.0	14.54 $\pm$ 7.24	14.64 $\pm$ 7.25	19.0	3.73 $\pm$ 2.09	4.0

not differ between Sy1 and SyDC and were similar for N, S, and Ca and slightly lower for P and K and lower for Mg than the reference values. Averaged over all treatments and years, Wt concentration values were lower for Mg and S, slightly lower for N and P, similar for K, and higher for Ca. In many cases, the average values observed were within one standard deviation from the reference values. Since these concentration measurements come from a local experiment with contrasting management systems and for several growing seasons, they could be representative of nutrient extraction by these crops in other areas. When estimating nutrient exports by crops, average values are the best point estimates we have. However, the variability reported in this study, for all mineral concentrations in the three crops, suggests that a range of values should be considered when performing regional assessments of nutrient extraction.

4 | CONCLUSIONS

The IM consistently increased yields of maize, wheat, and soybean for all cropping sequences, averaged over several growing seasons, compared to the CM. CCs decreased maize yield for all years in the CM. Within the IM, there was a yield penalty only in the drier years. The inclusion of CC decreased soybean yield only in the CM. CCs did not affect yield of wheat and soybean as second crop since they were not sown immediately before this crop sequence. Grain mineral composition was not consistently affected by the IM for maize, wheat, and soybean as a second crop; therefore, its nutritional value was not affected. N and S concentrations were increased for soybean as full-season crop, suggesting that IM could improve their nutritional value. Some extraction values found in our experiment differ from the values commonly

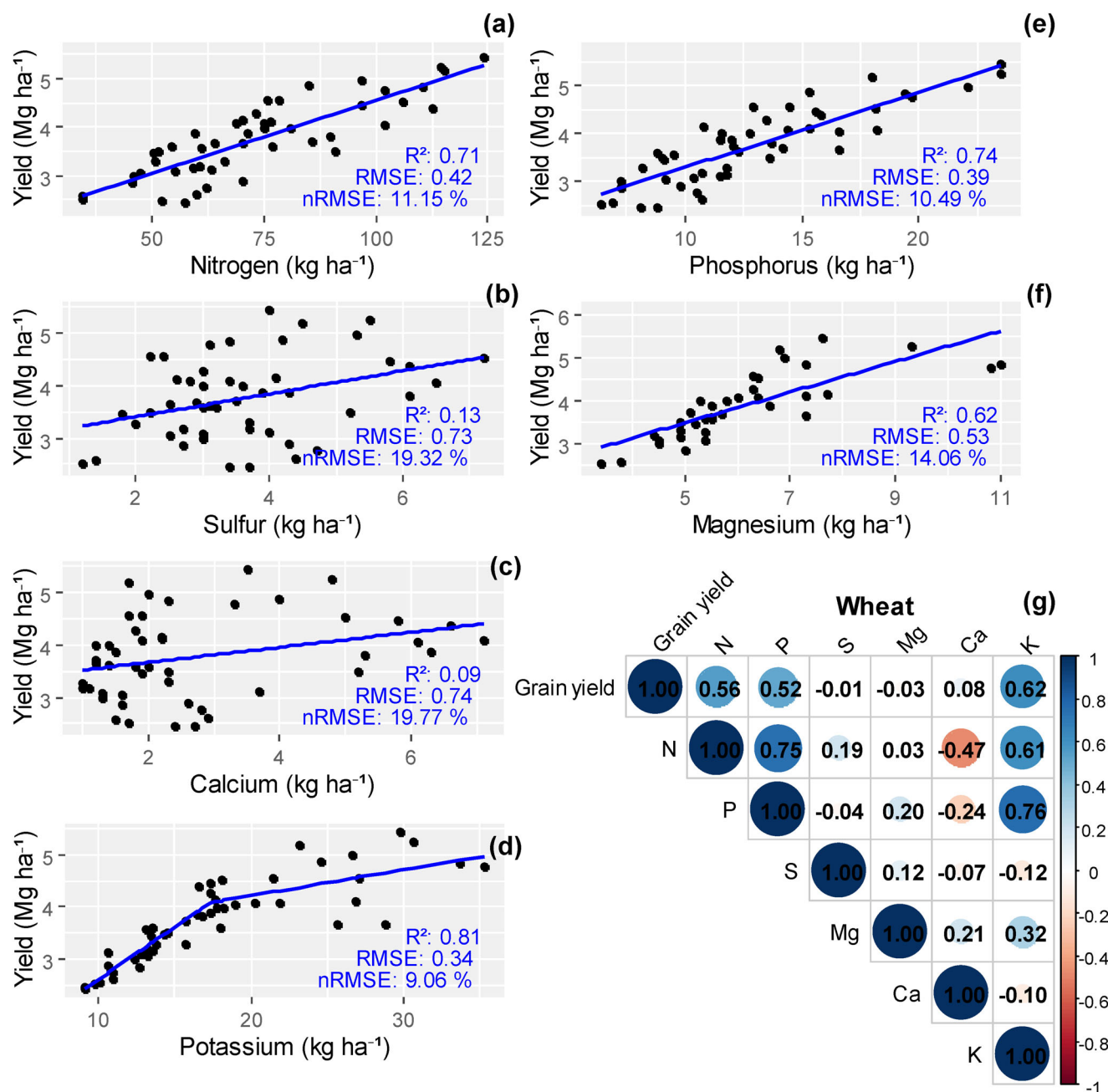


FIGURE 5 Regression analysis of grain yield and nutrients in wheat. (a), (b), (c), (d), (e), and (f) Relationship between grain yield (Mg ha⁻¹) and nutrient extraction (kg ha⁻¹); the root mean square error (RMSE), the RMSE expressed as a percentage of the observed mean (nRMSE), and the coefficient of determination (R^2) are shown for each. (g) Spearman correlation matrix between grain yield (Mg ha⁻¹) and nutrient concentration (g kg⁻¹); N: nitrogen; P: phosphorus; S: sulfur; Mg: magnesium; Ca: calcium; K: potassium in wheat. The circles represent both the strength of the relationship between the variables and the statistical significance ($p < 0.05$). The numbers inside the circles indicate the magnitude of the correlation. The color of the numbers reflects the type of correlation: blue for positive correlations and red for negative correlations. A value close to 1 indicates a strong positive correlation, while a value close to -1 indicates a strong negative correlation. * p values are significant at 0.05.

used as reference in Argentina. Since these concentrations come from a local experiment, with contrasting management systems, through several growing seasons, they could be considered when assessing nutrients extraction by the crops, but since variability was high, a range of values should be used instead of a single fixed value in future estimates.

AUTHOR CONTRIBUTIONS

D. E. Becheran: Conceptualization; data curation; data curation; formal analysis; formal analysis; investigation; investigation; methodology; methodology; software; software; validation; validation; visualization; visualization; writing—original draft; writing—original draft; writing—review and

editing; writing—review and editing. **F.H. Miguez:** Conceptualization; data curation; formal analysis; investigation; methodology; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **F.E. Miguez:** Conceptualization; formal analysis; investigation; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **A. Peper:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization. **B. Bénédict:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; visualization.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ORCID

D. E. Becheran  <https://orcid.org/0000-0001-8212-1479>

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