

Concentration and removal of macronutrients by soybean seeds over 45 years in Brazil: a meta-analysis

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ABSTRACT: A good soil fertility management for soybean production must consider the amount of nutrients that are exported by seeds. In recent decades, soybean yield has increased due to better crop management and genetic improvements, which may affect the amount of nutrients removed. Therefore, this study aimed (i) to analyze the relationship between the concentration of macronutrients in soybean seeds in Brazil with soybean yield and genotypes, and (ii) to update nutrient concentration values in soybean seeds for fertilizer recommendation purposes, comparing them with the values described in the main official fertilization recommendation systems used in Brazil. For this purpose, we used 3,017 observations obtained from 67 studies evaluating at least one macronutrient concentration [nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S)] in soybean seeds in the last 45 years in Brazil (from 1974 to 2019). Results indicate that the concentration of macronutrients in soybean seed is affected by both soybean yield and genetic material. Modern genotypes of the Intacta Roundup Ready-2 group remove 15, 21, 18, 17, and 23 % more K, P, Ca, Mg, and S and 4 % less N compared to non-Roundup Ready genotypes. The increase in soybean yield was followed by an increase in the concentration of N and a decrease in the concentration of P and K in soybean seed. Data obtained from studies published between 2015 and 2019 indicates that soybean removes, on average, 57.2, 17.6, 5.5, 2.9, 2.6, and 2.5 kg Mg⁻¹ of N, K, P, S, Ca, and Mg, respectively. These macronutrient concentrations in soybean seeds are in disparity with most reference values described in the official fertilization recommendation systems in Brazil, highlighting an urgent need to review the standard values for replacement fertilization of soybeans. Moreover, future studies should focus on the influence of genetics on soybean seeds composition to ensure high soybean productivity with rational use of fertilizers.

Keywords: *Glycine max* L., seed yield, nutrient exports, nutrient replenishment, nutrient concentration.

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Received: January 04, 2021

Approved: May 17, 2021

How to cite: Filippi D, Denardin LGO, Ambrosini VG, Alves LA, Flores JPM, Martins AP, Pias OHC, Tiecher T. Concentration and removal of macronutrients by soybean seeds over 45 years in Brazil: a meta-analysis. Rev Bras Cienc Solo. 2021;45:e0200186. <https://doi.org/10.36783/18069657rbc20200186>

Editors: José Miguel Reichert , Adelson Paulo de Araújo , and Clístenes Williams Araújo do Nascimento .

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INTRODUCTION

Brazil is the largest soybean producing country worldwide, accounting for 37 % (120 million megagrams) of the global soybean production in 2019/2020 cropping season (USDA, 2020). In the last 15 years, soybean seed yield in Brazil has increased by 20 % (Conab, 2017), reaching an average of 3.3 Mg ha⁻¹ in the last cropping season (2019/2020). This yield increase is a result of changes in environmental conditions, improvements in genetics and management practices, as well as the interactions among these factors (Rowntree et al., 2013; Balboa et al., 2018), which may affect the nutrient concentration in soybean seeds over the years (Juhász et al., 2017; Tamagno et al., 2017; Balboa et al., 2018).

Soybean requires extracting approximately 170 kg of macronutrients to produce one megagram of seeds, but the removal by the grains is approximately half of that (Lantmann and Castro, 2004; Bender et al., 2015). These nutrients are taken up essentially from the soil (except nitrogen that can also be derived from the air), thus requiring a replenishment to prevent soil nutrient depletion and ensure high soybean yields in the following harvests. In production systems where soil fertility is above the critical limit and losses by erosion and/or leaching are minimal, fertilizer management could be based only on the amount of nutrients exported by seeds (CQFS-RS/SC, 2016; Pauletti and Motta, 2019). Therefore, reliable reference values for nutrient concentration in soybean seeds are essential to increase the accuracy of fertilization recommendation systems.

Reference values of nutrient concentration in soybean seeds used by the official recommendation systems in Brazil present a wide variability. For example, the Cerrado fertilization recommendation system (Sousa and Lobato, 2004) indicates an average P removal of 4.4 kg Mg⁻¹, while the official recommendation for the states of Rio Grande do Sul (RS) and Santa Catarina (SC) (CQFS-RS/SC, 2016) indicates an average value of 6.1 kg Mg⁻¹. The same disagreement can be observed for K; the official recommendation for this nutrient in the Paraná State (PR) (Pauletti and Motta, 2019) indicates an average of 14.2 kg Mg⁻¹, while the official recommendation for the São Paulo State (Raij et al., 1997) indicates an average of 19.0 kg Mg⁻¹. Moreover, although some of these official recommendations are periodically updated, other reference values remain the same for decades [P = 6.1 kg Mg⁻¹ and K = 16.7 kg Mg⁻¹ (CQFS-RS/SC, 2004; CQFS-RS/SC, 2016)], which might cause misleading on the amount of nutrients that must be provided to soybeans. Thus, understanding the variability of macronutrients in seeds is critical to improve the management of soybean fertilization. Moreover, the recommendation systems usually do not indicate when and/or how the data were obtained, and some of them do not have any reference values for nutrient removal by soybean seeds, such as those from the states of Minas Gerais (Ribeiro et al., 1999) and Pará (Brasil et al., 2020).

Studies comparing the concentration of nutrients in seeds and the reference values might be helpful to update the fertilization recommendation systems. In this regard, recently, Duarte et al. (2019) analyzed 175 corn (*Zea mays* L.) seed samples in some states of Brazil, and Villamil et al. (2019) evaluated P and K removal by soybean, corn, and wheat (*Triticum aestivum* L.) seeds in the United States. However, this type of research in a continental-sized country such as Brazil might be unfeasible since it requests a large number of samples in a varied environment of different regions, raising the costs and requiring a complex logistic. Another way to obtain a more representative and reliable database of nutrient concentration in soybean seeds is to compile and analyze data available in the literature through a meta-analysis (Rotundo and Westgate, 2009).

This study consisted of a meta-analysis of the concentration and removal of macronutrients by soybean seeds in Brazil in the last 45 years (1974 to 2019) to provide information for future recommendations of replacement fertilization to soybean. Accordingly, the aims were (i) to analyze the relationship between concentration of macronutrients in soybean seeds in Brazil with soybean yield and genotypes, and (ii) to update nutrient

concentration values in soybean seeds for fertilizer recommendation purposes, comparing them with the values described in the main official fertilization recommendation systems used in Brazil.

MATERIALS AND METHODS

Data search criteria

The data were compiled from studies that evaluated or presented the concentration of macronutrients in soybean seeds produced in Brazil. The scientific publications were retrieved from Science Direct, Scielo, and Google Scholar databases, using the following keywords: “concentration of nutrient in soybean”, “soybean seed”, “soybean grains”, “nutrients removal by soybean”, “nutrients in soybean grains”, and “nutrient in soybean seed”. The database was taken from studies in field and greenhouse experiments, and seed lots. For the inclusion of a given data in our meta-analysis, the study must meet the following criteria: (i) to present the concentration of at least one macronutrient in soybean seed, and (ii) when nutrient removal (kg ha^{-1}) was presented, the soybean yield should also be presented. Studies that calculated the removal of nutrients based on average reference values obtained from the literature were not included. Moreover, in our study, we only used the soybean yield available from field experiments.

Most of the data were retrieved from tables, some from equations, and digitized figures. The removal of nutrients by seeds was expressed on dry matter basis. The concentration of P_2O_5 and K_2O presented in some studies were converted to P and K equivalents. Units were standardized to kilograms per megagrams (kg Mg^{-1}) for nutrients concentration in seeds and kilograms per hectare (kg ha^{-1}) for total macronutrient removal.

Data description

Altogether, 46 scientific papers and short communications, five PhD theses, 11 master dissertations, and five technical reports/abstracts were selected. Relevant experimental details were retrieved from the publications, such as the Brazilian state, the year of the study, experimental environment (field, greenhouse, or seed lots), and soybean yield for field studies. Each value that presented the concentration of some macronutrient (N, P, K, Ca, Mg, or S) in soybean seeds was considered as an observation. We have catalogued a total of 3,208 observations (including replications). The observations that lied above or below three standard deviations of the average of each nutrient were considered as outliers and then excluded. In total, 191 observations were excluded (20 for N, 38 for P, 44 for K, 44 for Ca, 24 for Mg, and 21 for S), remaining 3,017 observations that were used in this study.

Relationship between soybean yield and nutrient concentration in seeds

Firstly, we performed a regression analysis relating year and soybean seed yield using 615 field observations to obtain a time trend for soybean yield using the Stat Soft 2004. Then, total nutrient removal per hectare was calculated by multiplying nutrient seed concentration by the seed yield using 90 field observations presenting all six macronutrients evaluated (seed yields ranging from 0.5 to 4.8 Mg ha^{-1}). Moreover, for field studies providing yield information, we analyze the relationship between soybean yield and the concentration of nutrients in soybean seeds, and between soybean yield and the removal of nutrients per hectare (number of observations per nutrient: N = 233; P = 313; K = 468; Ca = 144; Mg = 161; and S = 134).

Comparison of nutrient concentration in seeds of different soybean genotypes

We classified soybean genotypes into four groups of genetic materials: non-Roundup Ready (non-RR) (conventional genotype), Roundup Ready (RR-1), Intacta RR2 PRO

(RR-2), and “Not informed”. This categorization was an indirect way to evaluate the genetic improvement that materials have received over the years since RR-1 and Intacta RR2 PRO technologies have emerged in succession. Moreover, for this comparison, we only used data from studies published between 2005 and 2019, since genetically modified soybean was legalized in Brazil only in 2005. Altogether in this comparison we used 26 non-RR genotypes ($n = 480$ observations), 66 RR-1 genotypes ($n = 1,217$ observations), and 10 RR-2 genotypes ($n = 163$ observations). For each nutrient, the number of observations ranged from 60-124, 165-258, and 26-29 for the non-RR, RR-1, and RR-2 genotypes. The concentration of nutrients between groups of genotypes was compared using the Kruskal-Wallis non-parametric test. Furthermore, we calculate the 95 % confidence interval for each nutrient in each group of soybean genotypes based on 5,000 samples generated using bootstrap iterations.

Update of nutrient concentration values in soybean seeds for fertilizer recommendation purposes

Data from studies recently published between 2015 and 2019 were selected to obtain the updated average values of macronutrient concentration in soybean seeds. For this purpose, we used a total 1,506 observations ($N = 273$, $P = 279$, $K = 277$, $Ca = 232$, $Mg = 234$, and $S = 211$). These updated average values of the macronutrient concentration in soybean seed (2015-2019) were compared with the reference values available in the main fertilization recommendation systems used in Brazil.

The latest available edition of each fertilizer recommendation system was used in this comparison, namely: (i) Raij et al. (1997) for the São Paulo State; (ii) Sousa and Lobato (2004) for the Brazilian Cerrado (tropical savanna); (iii) CQFS-RS/SC (2016) for the states of Rio Grande do Sul and Santa Catarina; and (iv) Pauletti and Motta (2019) for the Paraná State. When a given official fertilization recommendation system did not explicitly present P and K concentration values in soybean seeds, we used the P and K contents indicated in the replacement fertilization doses recommended by them as reference values.

Subsequently, we calculate the difference between the amount of P and K needed for replacement fertilization using the reference values from official fertilization systems in Brazil and the ones found in our study for the period between 2015 and 2019. For this purpose, soybean production per county was obtained from the database of the Brazilian Institute of Geography and Statistics for the year 2019-2020 (IBGE, 2019).

RESULTS

Characterization of studies evaluating macronutrient removal by soybean seeds

A total of 3,017 observations of macronutrient concentrations in soybean seeds in Brazil were collected in 67 studies published from 1974 to 2019. Approximately 6 % of these data were obtained in the 1970's (1971-1980), 1 % in the 1980's (1981-1990), 14 % in the 1990's (1991-2000), 20 % between 2001 and 2010, and 59 % between 2011 and 2020. Splitting these data according to the Brazilian regions, 47 % (1,412 observations) were obtained in the South region (Rio Grande do Sul and Paraná), 27 % (825) in the Midwestern region (Mato Grosso do Sul, Mato Grosso, Goiás, and Federal District), 24 % (724) in the Southeast region (São Paulo and Minas Gerais), 0.2 % (17) in the North region (Roraima and Tocantins), and 1 % (39) were not informed.

About 60 % of the observations came from scientific publications evaluating the primary macronutrients (N, P, and K), while the secondary macronutrients (Ca, Mg, and S) have gained less attention from Brazilian researchers over the last 45 years. The following nutrients were most researched in decreasing order of representativeness: K, P, Mg,

Ca, N, and S, which represent 26, 20, 15, 15, 14, and 10 % of the total observations, respectively (Table 1). The greater concern about the primary macronutrients is related to their large amount removed by soybean seeds, and also because these nutrients are the ones that most often limit agricultural production in tropical and subtropical weathered soils (Stewart et al., 2005; Withers et al., 2018).

Considering the total data set from 1974 to 2019, the average N concentration in soybean seeds was 57.8 kg Mg⁻¹ and ranged from 44.5 to 70.5 kg Mg⁻¹, with interquartile range (IQR; 25–75 percentiles) from 54.4 to 61.0 kg Mg⁻¹ (Table 1). Average P concentration in soybean seeds was 5.4 kg Mg⁻¹, ranging from 3.2 to 7.5 kg Mg⁻¹ (IQR, 4.8 to 5.9 kg Mg⁻¹), while the average K concentration was 16.7 kg Mg⁻¹ and ranged from 9.3 to 23.9 kg Mg⁻¹ (IQR, 14.8 to 18.6 kg Mg⁻¹). Average Ca concentration in soybean seeds was 2.5 kg Mg⁻¹ and ranged from 1.1 to 3.9 kg Mg⁻¹ (IQR, 2.1 to 2.8 kg Mg⁻¹), and the average Mg concentration was 2.4 kg Mg⁻¹ and ranged from 1.6 to 3.4 kg Mg⁻¹ (IQR, 2.2 to 2.7 kg Mg⁻¹). The average S concentration in soybean seeds was 2.8 kg Mg⁻¹, ranging from 1.3 to 4.5 kg Mg⁻¹ (IQR, 2.3 to 3.2 kg Mg⁻¹). Total amount of macronutrients (N + P + K + Ca + Mg + S) concentration in soybean seeds was 87.7 kg Mg⁻¹, in the following order of magnitude (in kg Mg⁻¹): N (57.8) > K (16.7) > P (5.4) > S (2.8) > Ca (2.5) > Mg (2.4).

The observations that evaluated soybean yield for the non-RR genotypes occurred between 1974 to approximately 2010. By contrast, the evaluated studies using RR-1 and RR-2 genotypes started in 2010 and 2015, respectively. Genotype identification was not informed for many observations, although the authors of the studies showed the

Table 1. Descriptive statistics for macronutrient concentration in soybean seeds in Brazil from 1974 to 2019 and from 2015 to 2019

Period	Descriptive statistics	Macronutrient concentration					Seed yield	
		N	P	K	Ca	Mg		S
		kg Mg ⁻¹						
1974-2019	Mean	57.8	5.36	16.75	2.45	2.45	2.82	2.9
	Confidence interval (-95 %)	57.4	5.30	16.56	2.40	2.41	2.75	2.9
	Confidence interval (+95 %)	58.3	5.43	16.94	2.50	2.48	2.89	3.0
	Standard deviation	5.1	0.82	2.68	0.54	0.36	0.62	0.8
	Minimum	44.5	3.19	9.25	1.10	1.57	1.31	0.4
	Interquartile range 25 %	54.4	4.81	14.83	2.07	2.21	2.34	2.3
	Median	57.7	5.30	16.97	2.42	2.48	2.72	3.0
	Interquartile range 75 %	61.0	5.90	18.55	2.80	2.69	3.20	3.5
	Maximum	70.5	7.45	23.90	3.86	3.40	4.50	4.8
	Coefficient of variation (%)	8.8	15.3	16.0	22.2	14.8	22.1	28.4
Number of observations	437	603	772	439	450	316	659	
2015-2019	Mean	57.2	5.46	17.61	2.59	2.47	2.86	3.0
	Confidence interval (-95 %)	56.6	5.37	17.31	2.51	2.42	2.77	2.9
	Confidence interval (+95 %)	57.9	5.55	17.91	2.66	2.53	2.94	3.2
	Standard deviation	5.5	0.77	2.55	0.60	0.39	0.63	0.9
	Minimum	44.5	3.19	9.25	1.25	1.60	1.31	0.5
	Interquartile range 25 %	53.3	5.00	16.09	2.11	2.21	2.40	2.4
	Median	56.9	5.50	17.51	2.60	2.44	2.80	3.3
	Interquartile range 75 %	60.9	5.90	19.10	3.00	2.70	3.24	3.5
	Maximum	70.3	7.30	23.90	3.86	3.40	4.50	4.6
	Coefficient of variation (%)	9.6	14.1	14.5	23.0	15.9	21.9	30.5
Number of observations	273	279	277	232	234	211	157	

The descriptive statistic for the period 1974 to 2019 refers to the total set of observations obtained in this study. The descriptive statistic for the period from 2015 to 2019 refers to the set of observations used to update the macronutrients concentration in soybean seeds.

seed yield (Figure 1). The average seed yield obtained through the set of observations was 2.9 Mg ha^{-1} (Table 1).

Concentration of macronutrients in soybean seeds of different groups of genetic material

Our results showed the genetic evolution of soybean genotypes impacting the macronutrients concentration in seeds (Figure 2). The genotypes non-RR (Figure 2a) presented higher N concentration in seeds (58.4 kg Mg^{-1}) compared to RR-1 and RR-2 genotypes (56.8 and 56.3 kg Mg^{-1} , respectively). However, the genotypes RR-2 (Figures 2c and 2e) had 18 and 17 % more K and Mg in seeds (19.6 and 2.8 kg Mg^{-1} , respectively) than non-RR and RR-1 genotypes (16.6 and 2.4 kg Mg^{-1} , respectively). For the other nutrients, there was no difference between RR-1 and RR-2 genotypes, but they both presented concentration of P, Ca, and S in soybean seeds about 13, 17, and 15 % higher than non-RR genotypes, respectively (Figures 2b, 2d, and 2f).

Concentration and removal of macronutrients in soybean seeds as a function of yield

Figures 3a, 3b, 3c, 3d, 3e, and 3f show the relationship between seed yield and macronutrient concentration in seeds. While the N concentration in seeds increased 1.1 kg per each megagram of seeds produced ($p < 0.05$; Figure 3a), P and K concentration were reduced 276 ($p < 0.001$; Figure 3b), and 553 g ($p < 0.0001$; Figure 3c) per each megagram of seeds produced, respectively. Calcium, Mg, and S concentration were not affected by seed yield increments (Figures 3d, 3e, and 3f).

Moreover, the total removal of macronutrients (N, P, K, Ca, Mg, and S) increased linearly with the seed yield increment, corresponding to 87.6 kg macronutrients per megagram of seeds for the yield range of 0.5 to 4.8 Mg ha^{-1} ($n = 90$) (Figure 4). The same behavior occurred for the removal of each macronutrient, where nutrient removal by seed harvesting depended on the increment in seed yield (Figure 5).

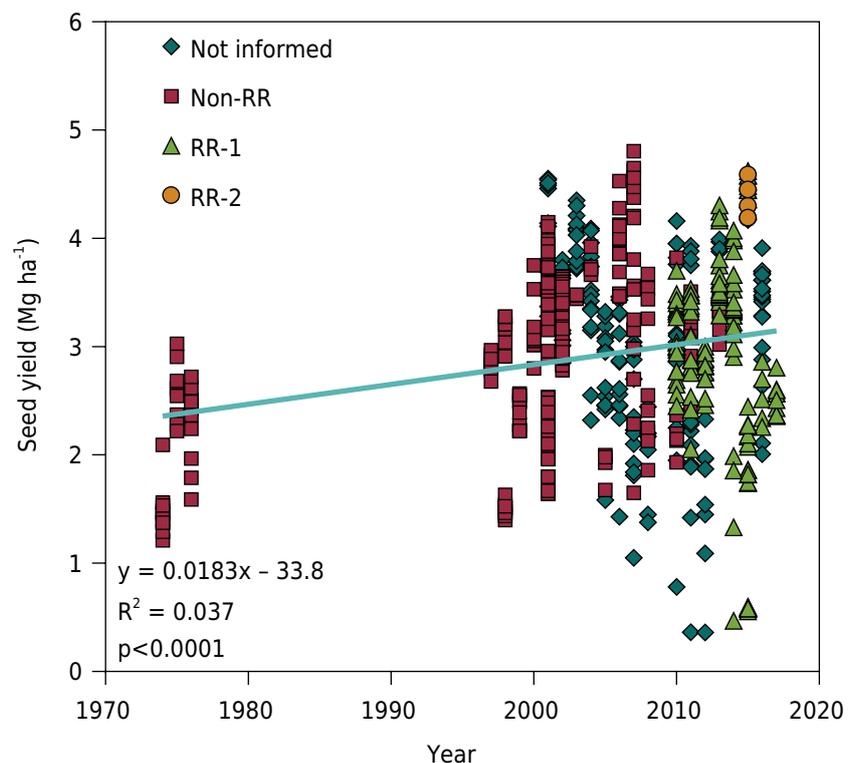


Figure 1. Time trend (1974 to 2019) for soybean seed yield. Number of field observations for seed yield = 615. Solid blue line represents a positive slope.

Update of nutrient concentration in soybean seeds and comparison with reference values of official recommendations

The recent data obtained from studies published between 2015 to 2019 indicates that soybean removes, on average, 57.2, 17.6, 5.5, 2.9, 2.6, and 2.5 kg Mg⁻¹ of N, K, P, S, Ca, and Mg, respectively (Table 1). Among the official recommendations for soybean cultivation available in Brazil, only the Fertilization Recommendation System for Paraná State (Pauletti and Motta, 2019) presents the concentration of all macronutrients in soybean seeds. The Technical Bulletin 100 (Raij et al., 1997) does not show the values for

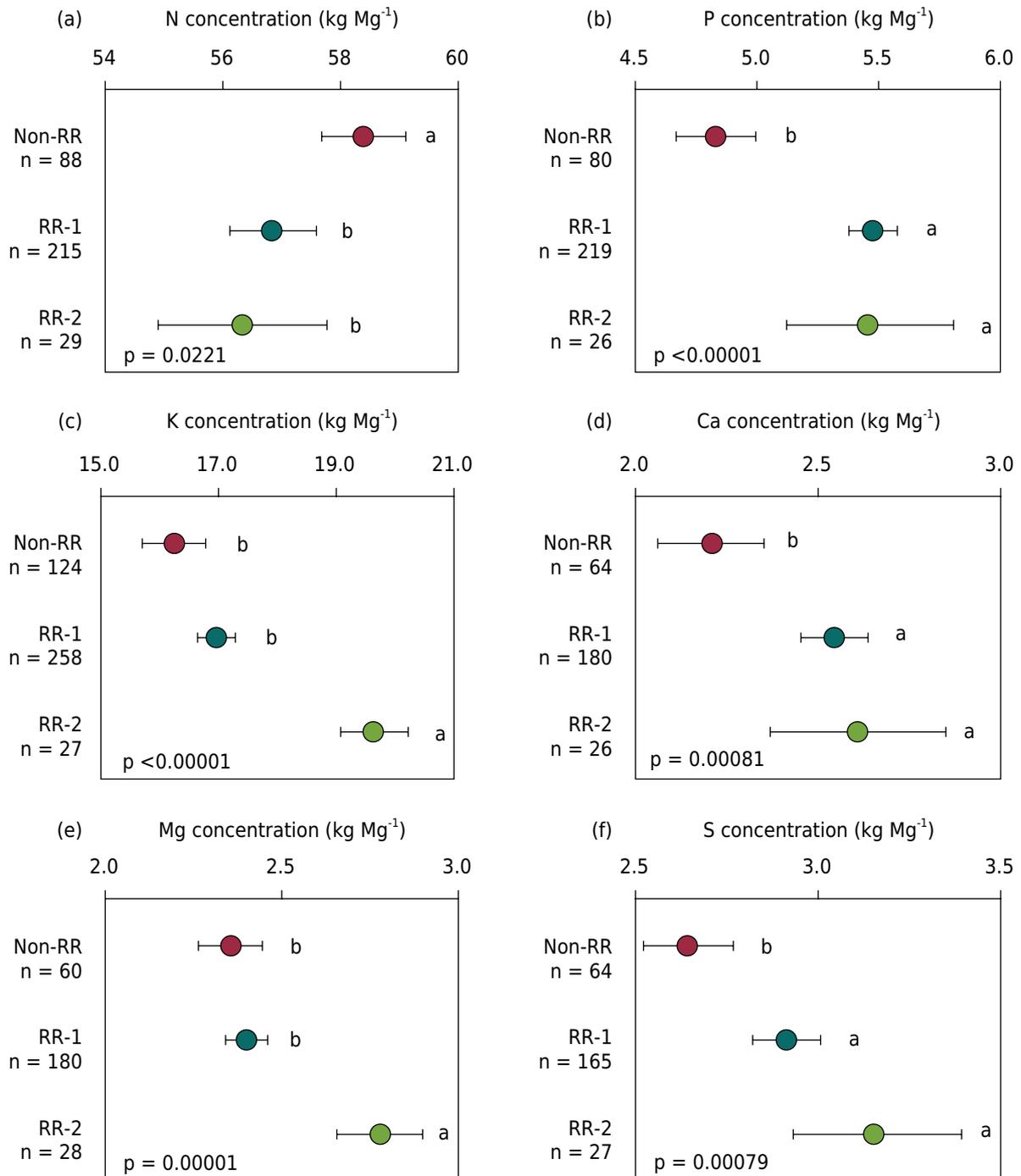


Figure 2. Concentration of N (a), P (b), K (c), Ca (d), Mg (e), and S (f) in soybean seeds of each genetic material group from studies published between 2005 and 2019. Non-RR: conventional material; RR-1: Roundup Ready; RR-2: Intact RR-2. Means followed by the same lowercase letter do not differ statistically by the Kruskal-Wallis H -test ($p < 0.05$). n = number of observations for each genetic material group. The circles indicate the mean values, and the whiskers indicate the 95 % confidence interval calculated with 5,000 samples generated using bootstrap iterations.

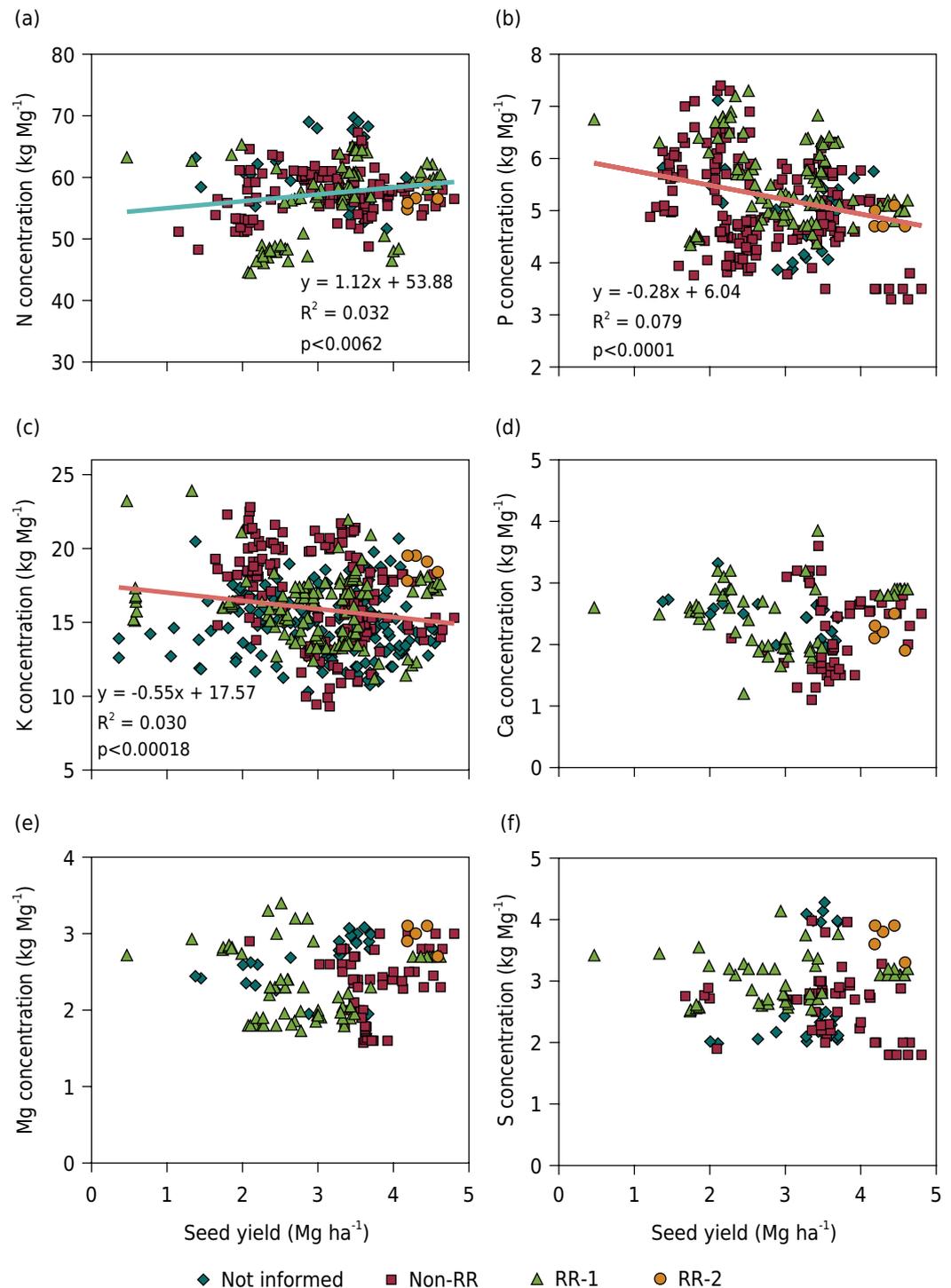


Figure 3. Relationship between soybean yield and seed concentrations of N (a), P (b), K (c), Ca (d), Mg (e), and S (f). Solid blue line represents a positive slope ($p < 0.05$). Solid red line represents a negative slope ($p < 0.05$). Graphs were generated using all available data from field experiments containing nutrient content and soybean yield from 1974 to 2019.

Ca and Mg; the Cerrado Fertilization Recommendation System (Sousa and Lobato, 2004) does not present the values for N, Ca, Mg and S; and the Fertilization Recommendation System for the states of Rio Grande do Sul and Santa Catarina (CQFS-RS/SC, 2016) does not present the values for Ca, Mg, and S.

Reference values for macronutrient concentration in soybean seeds available in Brazil are, in general, quite different from those found in the present meta-analysis for the 2015-2019 period (Figure 6). Only the concentration of K in the soybean seed indicated

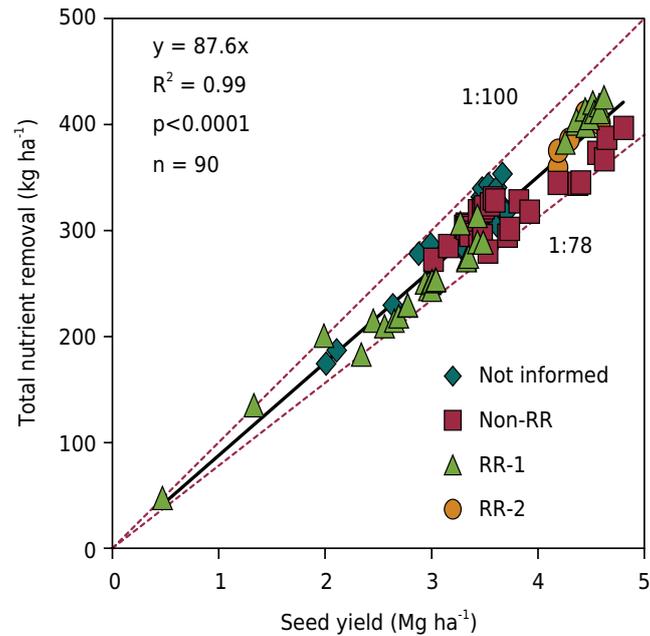


Figure 4. Relationship between soybean yield and the total removal of macronutrients in soybean seeds. Solid black line represents a positive slope ($p < 0.05$). Graphs were generated using all available data from field experiments containing all six nutrients content in soybean seeds and the soybean yield from 1974 to 2019. Dotted lines indicate boundaries for maximum and minimum ratio for each dataset.

by CQFS-RS/SC (2016) and Sousa and Lobato (2004) (Figure 6c) were close to the confidence interval obtained in our study. Considering the interquartile range observed in the present study, the N values indicated by Raji et al. (1997) and CQFS-RS/SC (2016) (Figure 6a), the P values indicated by Raji et al. (1997) (Figure 6b), the K value indicated by Raji et al. (1997), CQFS-RS/SC (2016), and Sousa and Lobato (2004) (Figure 6c), and the Ca values indicated by Pauletti and Motta (2019) (Figure 6d) could be considered adequate. The remaining reference values under or overestimate the concentration of macronutrients in soybean seeds and need to be reconsidered in future updates of these recommendations.

Values of N, P, K, and Mg indicated by Pauletti and Motta (2019) are all below the interquartile observed in the present meta-analysis for studies published between 2015 to 2019 (Figure 6). Furthermore, the N and Mg content indicated by Pauletti and Motta (2019) is closer to the minimum value than the average value recorded in the literature for the same period evaluated. Using these reference values to estimate the need for fertilizers may decrease P, K, and Mg in the soil in the long term. By contrast, the S content indicated by Pauletti and Motta (2019) is even higher than the maximum value found in the literature in studies published between 2015 to 2019 (Figure 6f).

Impact of P and K replacement fertilization on fertilizer demand

Figure 7 shows the difference between the amount of P and K needed for replacement fertilization based on regional fertilization recommendations, the amount of P and K required for replacement fertilization based on updated values of macronutrient concentration in seeds obtained from 2015-2019 in our study.

Considering the soybean production of 20.8 million tons in the states of Rio Grande do Sul and Santa Catarina and using the reference value for P concentration in soybean seeds available in CQFS-RS/SC (2016), we estimate an overestimate of P replacement fertilization of about 13.6 thousand tons in 2019 in these two states combined (Table 2). By contrast, in the other Brazilian fertilizer recommendation systems [Raji et al. (1997); Sousa and Lobato (2004); and Pauletti and Motta (2019)] there is an underestimation

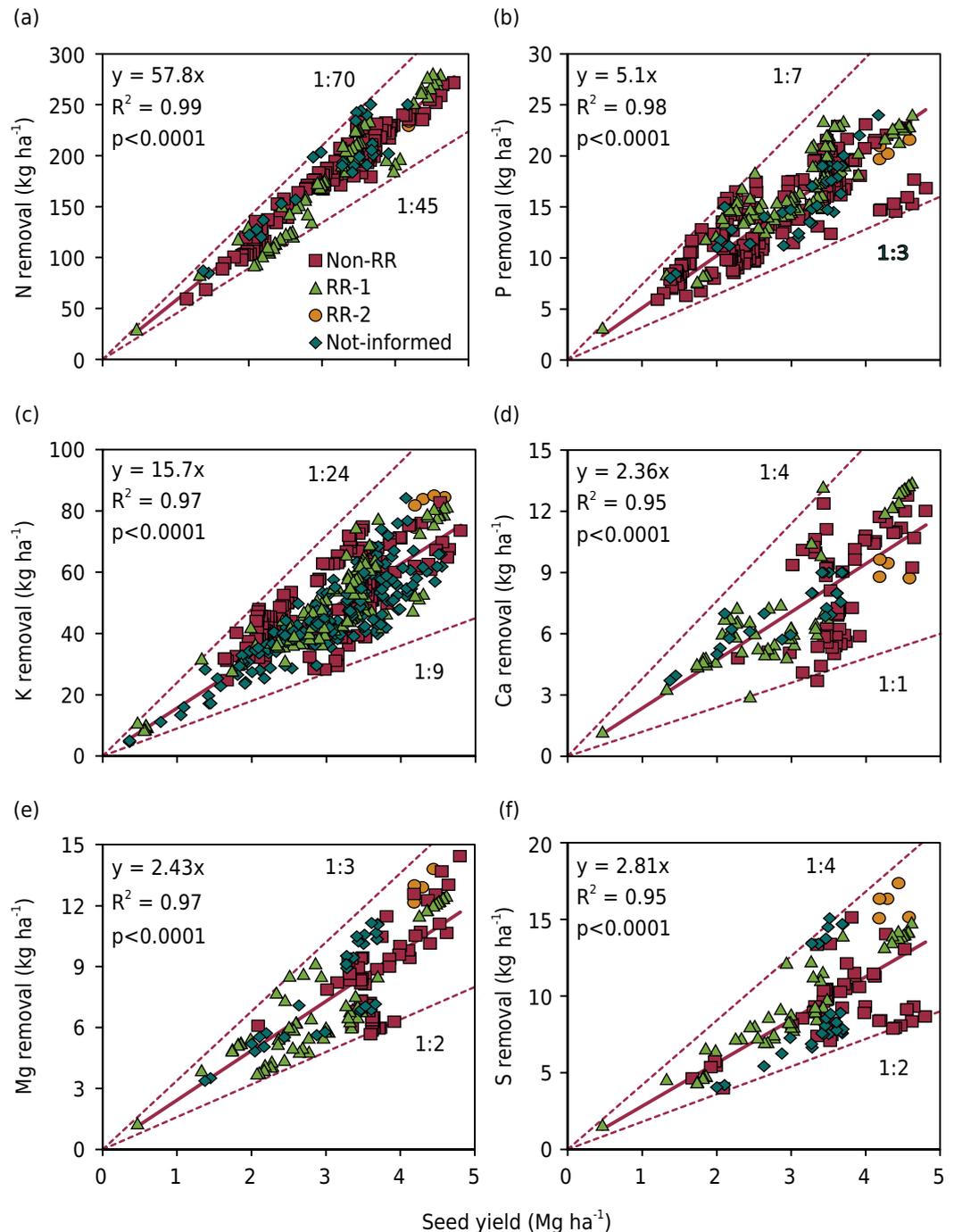


Figure 5. Relationship between soybean yield and the total removal of N (a), P (b), K (c), Ca (d), Mg (e), and S (f) in soybean seeds. Solid black line represents a positive slope ($p < 0.05$). Graphs were generated using all available data from field experiments containing nutrient content and soybean yield from 1974 to 2019. Dotted lines indicate boundaries for maximum and minimum ratio for each dataset.

of P replacement fertilization. When using the reference value for P concentration in soybean seeds available in Sousa and Lobato (2004) and considering the soybean production of 70.6 million tons in the states of Mato Grosso, Mato Grosso do Sul, Goiás, Tocantins, Minas Gerais, Bahia, Piauí, and Maranhão, we estimated an underestimate of P replacement fertilization of about 77.1 thousand tons in 2019 (Table 2). In the same way, considering the soybean production of 16.3 and 3.5 million tons in the states of Paraná and São Paulo, respectively, when using the reference value for P concentration in soybean seeds available in Pauletti and Motta (2019) and Raji et al. (1997), there is an underestimate of P replacement fertilization of about 15.6 and 1.6 thousand tons in 2019 for the states of Paraná and São Paulo, respectively (Table 2).

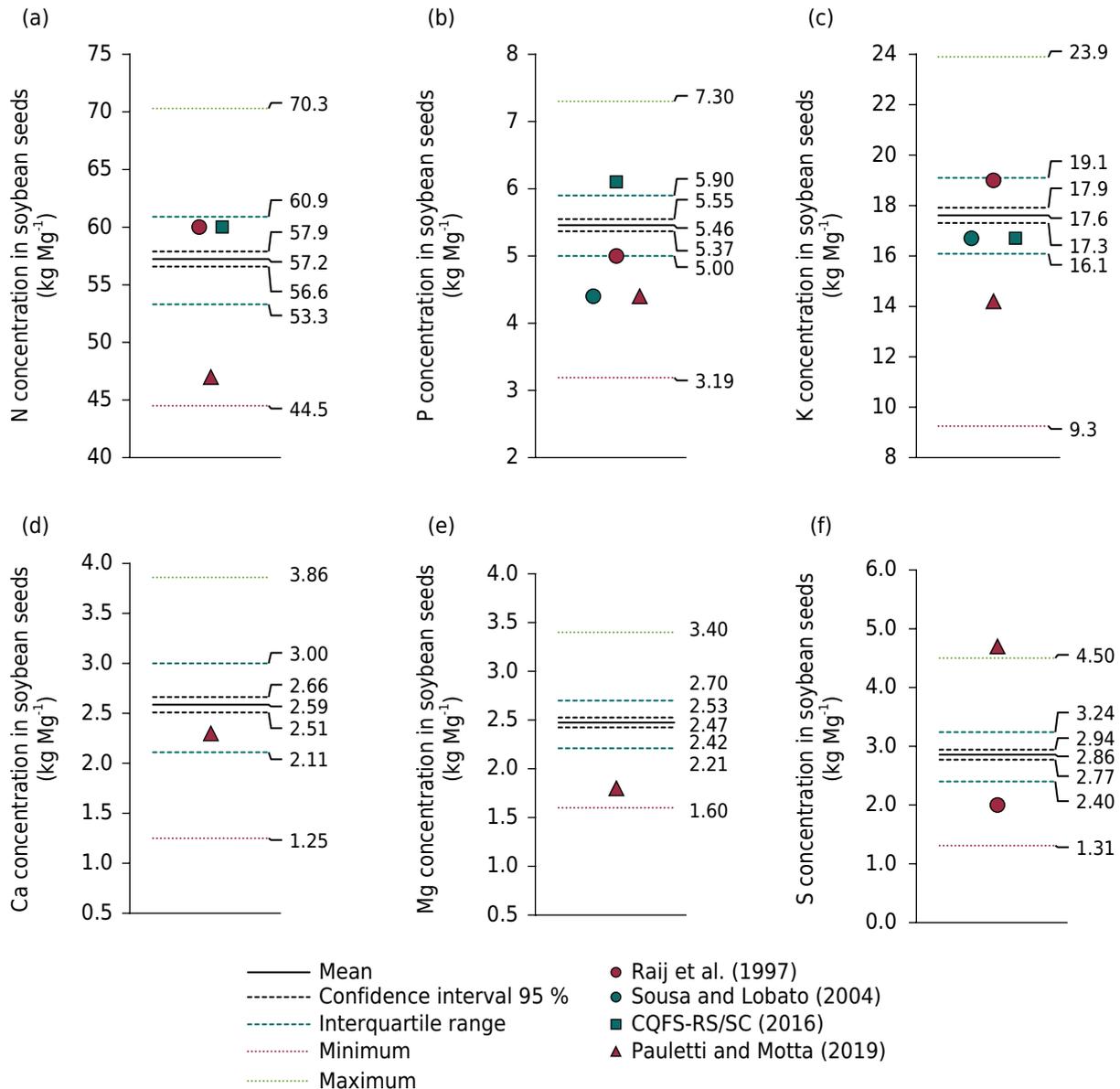


Figure 6. Comparison of updated values for N (a), P (b), K (c), Ca (d), Mg (e), and S (f) concentration in soybean seeds observed in this meta-analysis for studies published between 2015 to 2019 (lines indicating mean, confidence interval, interquartile range, maximum and minimum values) and the reference values used in the main official recommendations in Brazil. Raij et al. (1997) corresponds to the Technical Bulletin 100 for the state of São Paulo; Sousa and Lobato (2004) corresponds to the official fertilization recommendation system for the Brazilian Cerrado; CQFS-RS/SC corresponds to the official fertilization recommendation system for the states of Rio Grande do Sul and Santa Catarina; Pauletti and Motta (2019) corresponds to the official fertilization recommendation system for the state of Paraná.

Recommendations of all Brazilian regions underestimate the K replacement fertilization values, except the recommendations for São Paulo State. For the soybean production in 2019, the recommendations of the Paraná State underestimate the replacement fertilization of K by 56.2 thousand tons, very close to the value referring to the entire Brazilian Cerrado, which is 66.7 thousand tons (Table 2). In addition, the states of Rio Grande do Sul and Santa Catarina together also underestimate the replacement fertilization of K by 19.6 thousand tons (Table 2). On the other hand, the recommendations for the São Paulo State overestimate the replacement fertilization of K by 4.8 thousand tons. In addition, it is possible to verify that the demand for S using the recommendation of the Paraná State results in an overestimation of 30.1 thousand tons of S for that state (Table 2).

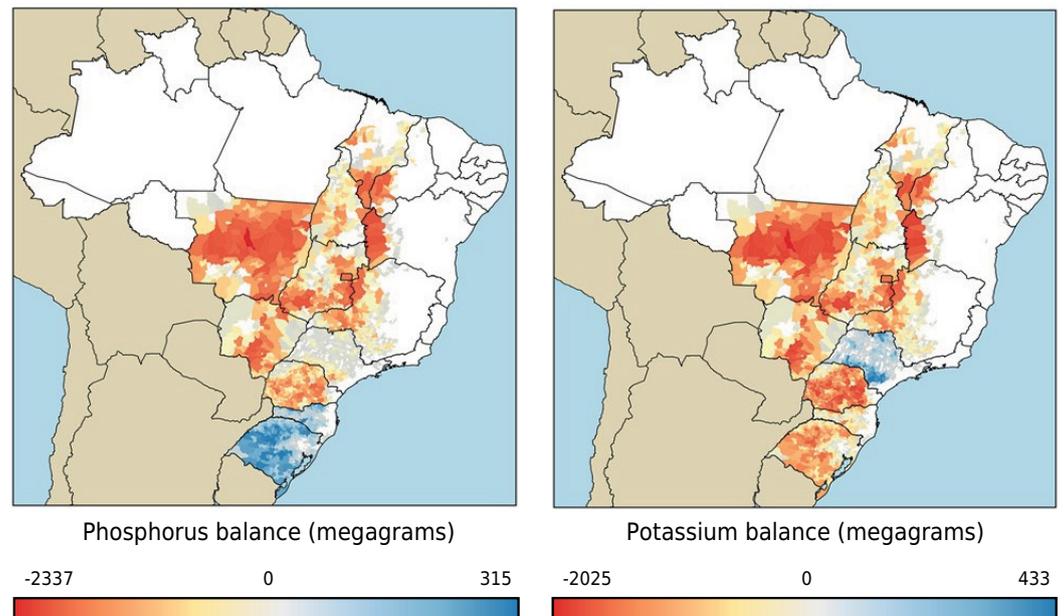


Figure 7. The difference between P and K replacement fertilization calculated by the main official fertilization recommendations in Brazil and the estimative based on the concentration of P and K obtained in the present study for the period 2015-2019. The official fertilization recommendations used were: CQFS-RS/SC (2016) for the states of Rio Grande do Sul and Santa Catarina; Pauletti and Motta (2019) for the state of Paraná; Technical Bulletin 100 (Rajj et al., 1997) for the state of São Paulo; and Sousa and Lobato (2004) for the Brazilian Cerrado (states of Mato Grosso do Sul, Mato Grosso, Goiás, Minas Gerais, Tocantins, Bahia, Piauí, and Maranhão).

DISCUSSION

Over the last 45 years, there was important progress in the development of technology for the production and management of soybean, such as the genetic improvement of varieties more adapted to diverse growing conditions and the approval of cultivation of genetically modified soybean in Brazil (RR-1 and RR-2 genotypes) (Toledo et al., 1990; Santos Silva et al., 2017). From 1961 to 2018 in Brazil, the average seed yield shifted from 1.1 to 3.4 Mg ha⁻¹, corresponding to an increase of 40 kg ha⁻¹ yr⁻¹ (Faostat, 2020). Considering the total amount of macronutrients removed by soybeans (87.7 kg Mg⁻¹ of seeds) obtained in our study, this increase in soybean yield promotes an increase in macronutrient removal by seeds about 3.5 kg ha⁻¹ yr⁻¹ in the last six decades. Although this annual increase seems insignificant, it directly impacts the fertilizer rate demanded to replenish the nutrient removed by harvest.

Our results suggest that modern soybean genotypes are more demanding in macronutrients than older varieties, thus requiring greater amounts of K, P, Ca, Mg, and S to replenish their greater removal by seeds (Figure 2). Two main physiological processes contribute to the increase of nutrient concentration in the soybean seeds: (i) via direct partitioning after the beginning of the seed filling for tissue synthesis or (ii) via remobilization of nutrients from plant tissues (Bender et al., 2013). The increase in K concentration in soybean seeds, especially in the modern RR-2 genotypes, might be related to the increment in oil content (Wijewardana et al., 2019) and/or to high levels of soil available K (Stewart et al., 2005; Moreira et al., 2015; Firmano et al., 2019). This may be associated with decreased protein content in soybeans (Ortez et al., 2018), as observed in our study through the lower N concentration in the seeds of modern cultivars (RR-1 and RR-2) compared to non-RR genotypes. These findings might be helpful to the fertilization programs calibrate the nutrient replacement rates for different groups of genetic materials.

Decrease in the P concentration in soybean seeds with the increase in soybean yield may be related to the reduction of the P partition for the reproductive organs with the increase

Table 2. Difference between the need for replacement fertilization of P, K, Ca, Mg and S in the main soybean producing states of Brazil considering the reference values in official Brazilian guidelines and the suggested recommendation considering the updated values of macronutrient concentration in soybean seeds obtained in the present study for the period between 2015 and 2019

Nutrient	Reference	Brazilian state	Soybean production	Using reference values in official Brazilian guidelines		Using reference values of our study		Difference in the need for nutrients
				Concentration in soybean seeds	Need for nutrient replacement	Concentration in soybean seeds	Need for nutrient replacement	
			10 ⁶ Mg	kg Mg ⁻¹	10 ³ Mg	kg Mg ⁻¹	10 ³ Mg	10 ³ Mg
Phosphorus	CQFS-RS/SC (2016)	RS	18,498	6.1	113.1	5.5	101.0	12.1
	CQFS-RS/SC (2016)	SC	2,270	6.1	13.9	5.5	12.4	1.5
	Pauletti and Motta (2019)	PR	16,323	4.5	73.5	5.5	89.1	-15.6
	Raij et al. (1997)	SP	3,456	5.0	17.3	5.5	18.9	-1.6
	Sousa and Lobato (2004)	MS	8,698	4.4	38.0	5.5	47.5	-9.5
	Sousa and Lobato (2004)	MT	32,242	4.4	140.8	5.5	176.0	-35.2
	Sousa and Lobato (2004)	GO	11,341	4.4	49.5	5.5	61.9	-12.4
	Sousa and Lobato (2004)	TO	2,615	4.4	11.4	5.5	14.3	-2.9
	Sousa and Lobato (2004)	MG	5,206	4.4	22.7	5.5	28.4	-5.7
	Sousa and Lobato (2004)	BA	5,314	4.4	23.2	5.5	29.0	-5.8
	Sousa and Lobato (2004)	PI	2,326	4.4	10.2	5.5	12.7	-2.5
	Sousa and Lobato (2004)	MA	2,850	4.4	12.4	5.5	15.6	-3.1
Potassium	CQFS-RS/SC (2016)	RS	18,498	16.7	308.3	17.6	325.8	-17.5
	CQFS-RS/SC (2016)	SC	2,270	16.7	37.8	17.6	40.0	-2.1
	Pauletti and Motta (2019)	PR	16,323	14.2	231.8	17.6	287.5	-55.7
	Raij et al. (1997)	SP	3,456	19.0	65.7	17.6	60.9	4.8
	Sousa and Lobato (2004)	MS	8,698	16.7	145.0	17.6	153.2	-8.2
	Sousa and Lobato (2004)	MT	32,242	16.7	537.4	17.6	567.9	-30.5
	Sousa and Lobato (2004)	GO	11,341	16.7	189.0	17.6	199.8	-10.7
	Sousa and Lobato (2004)	TO	2,615	16.7	43.6	17.6	46.1	-2.5
	Sousa and Lobato (2004)	MG	5,206	16.7	86.8	17.6	91.7	-4.9
	Sousa and Lobato (2004)	BA	5,314	16.7	88.6	17.6	93.6	-5.0
	Sousa and Lobato (2004)	PI	2,326	16.7	38.8	17.6	41.0	-2.2
	Sousa and Lobato (2004)	MA	2,850	16.7	47.5	17.6	50.2	-2.7
Calcium	Pauletti and Motta (2019)	PR	16,323	2.3	37.5	2.6	42.2	-4.7
Magnesium	Pauletti and Motta (2019)	PR	16,323	1.8	29.4	2.5	40.4	-11.0
Sulfur	Pauletti and Motta (2019)	PR	16,323	4.7	76.7	2.9	46.6	30.1
	Raij et al. (1997)	SP	3,456	2.0	6.9	2.9	9.9	-3.0

RS: Rio Grande do Sul; SC: Santa Catarina; PR: Paraná; SP: São Paulo; MS: Mato Grosso do Sul; MT: Mato Grosso; GO: Goiás; TO: Tocantins; MG: Minas Gerais; BA: Bahia; PI: Piauí; and MA: Maranhão.

of the phosphorus internal efficiency (PIE) (Balboa et al., 2018). This means that there is a higher grain yield but with a lower concentration of P in these organs (Figure 3b). Bender et al. (2015) observed that more than 45 % of P was taken up by soybean during the period of seed filling (growth stage R4). Therefore, the adequate content of soil available P until the final stages of the crop is essential to ensure adequate plant nutrition. By contrast, the decrease in the concentration of K in the soybean seeds may be related to the lower K harvest index (KHI) or K internal efficiency (KIE) (Balboa et al., 2018), despite a higher absorption of K by the plant (Figure 3c). According to Bender et al. (2015), almost $\frac{3}{4}$ of total K uptake occurred before the seed filling stage (growth stage R4); however, only 46 % of the total accumulated in the plant was remobilized for the seeds, with an important contribution of K present in the stem. As for P, adequate available K levels in the soil, especially until the grain filling period, can guarantee better nutrition for the plant.

Concentration of Ca, Mg, and S in the soybean seed was not affected by soybean yield. This may be related to the low harvest index (HI) for Ca and Mg [about 9 and 18 %, respectively (Bender et al., 2015)], showing that even in high yields, only a small part of the total of these nutrients accumulated in the plant tissue is remobilized and removed by the seeds. Despite the increment in the total amount of macronutrients removal by increasing soybean yield, there is a greater distance from the values of total nutrient removal in relation to the 1:100 line plotted as seed yield increases (Figure 4), which suggest a lower concentration of nutrients in seeds when high yields are reached. Since the seed yield and amount of removed nutrients are variables intrinsically auto-correlated, this result is possibly related to nutrient remobilization below the demanded by seeds in high yield condition, thus causing a nutrient dilution in seeds – especially for P and K (Figures 3b and 3c). As seed yield increases, the greater the total amount of nutrients removal by soybeans. Thus, the seed yield estimate for a given site might be useful to predict the amount of nutrient removal by soybean harvest, such as the seed yield maps used in precision agriculture to set nutrient replacement at variable rates (Amado et al., 2016).

Although the concentration of macronutrients in seeds related to seed yield varied among the nutrients, the removal of all of them by seed harvest was dependent on the seed yield increment (Figures 5a, 5b, 5c, 5d, 5e, and 5f). This relationship was expected since the removal was calculated based on seed yield. The dispersion of observations around the tendency line for nutrient removal shows that it is possible to obtain different nutrient removal for very close yields. Such variations might be associated with environmental factors related to genetics (genotypes) and/or soil and crop management (Houx III et al., 2014). Variability in nutrient removal was also observed by Culman et al. (2019) and Villamil et al. (2019) for soybeans in the United States, and Duarte et al. (2019) in a recent study reporting nutrient concentration in corn grains in some states of Brazil.

Considering only the soybean production of 2019 in Brazil and the reference values currently used for P and K replacement fertilization in each state of the federation, it is possible to obtain underestimates and overestimates in the order of hundreds of thousands of tons of fertilizers (Figure 7). Moreover, despite the growing increase in soybean yield over the years in Brazil, the average soybean yield can still increase by 2.5 Mg ha^{-1} (Battisti et al., 2018), impacting the amount of nutrient removal by seeds directly. The increase in soybean yield coupled with unbalanced estimates of the removal of nutrients by the crop's seeds may threaten the sustainability of soybean production in the country, especially due to the high dependence on imports of P and K fertilizers used in Brazilian agriculture (ANDA, 2020). Therefore, seeking to reduce the impacts on the use of finite natural resources such as fertilizers for soybean production, it is essential to adjust the fertilizer rates according to the soil analysis and with the removal via soybean seeds to replace an adequate amount of nutrients in the soil. For this purpose,

future studies must seek to understand better the environmental and genetic factors that affect the concentration of nutrients in soybean seeds, in the different groups of genetic materials and different yield ranges, aiming to improve the estimates of nutrient removal by the seeds.

CONCLUSIONS

Concentration of macronutrients in soybean seed is affected by both soybean yield and genetic material. Modern genotypes of the Intacta Roundup Ready-2 group remove 15, 21, 18, 17, and 23 % more K, P, Ca, Mg, and S and 4 % less N compared to non-Roundup Ready genotypes. The increase in soybean yield was followed by an increase in the concentration of N and a decrease in the concentration of P and K in soybean seed.

Data obtained from studies published between 2015 to 2019 indicates that soybean removes, on average, 57.2, 17.6, 5.5, 2.9, 2.6, and 2.5 kg Mg⁻¹ of N, K, P, S, Ca, and Mg, respectively. These macronutrient concentrations in soybean seeds are in disparity with most reference values described in official fertilization recommendation systems in Brazil. The reference values used for P replacement fertilization in the states of Rio Grande do Sul, and Santa Catarina are overestimated, while the other Brazilian recommendation systems underestimate the need for P replacement fertilization. On the other hand, the reference values used for K replacement fertilization in the state of São Paulo are overestimated, while the other Brazilian recommendation systems underestimate the need for K replacement fertilization.

Our results highlight the need to review the standard values for macronutrient removal by soybean seed from Brazilian fertilization recommendation systems. Current findings can contribute to agronomic recommendations, improving the efficiency of fertilizer use by replenishing the quantities required according to plant demand. Future studies should focus on the influence of genetics on soybean seed composition to ensure high soybean productivity with rational use of fertilizers.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-45-e0200186/1806-9657-rbcs-45-e0200186-suppl01.pdf

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