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Yield and Nutrient Uptake of Soybean Cultivars Under Intensive Cropping Systems

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Abstract

Sustainable agricultural systems are necessary to improve soybean [*Glycine max* (L.) Merr.] seed yield and to increase nutrient use efficiency. Intensification of agricultural systems is an important tool to increase farmers' profitability in the Cerrado region (Brazil), where soybean is rotated with corn in the same growing season. However, this intensification requires soybean cultivar with short growing periods which is achieved by indeterminate soybean cultivars. There is a lack of information regarding the nutrient uptake by soybean cultivars under intensive agricultural systems in the Cerrado. We sought to investigate soybean biomass production and soybean seed yield of determinate and indeterminate soybean cultivars. We also aimed to quantify the amounts of nutrients taken up by soybean biomass and seeds. Field research was conducted to evaluate 17 soybean cultivars commonly grown by farmers, and we considered the determinate and indeterminate soybean growth habit. Nutrient uptake and aboveground soybean biomass were higher under shorter soybean growth and development cycles. Nitrogen, phosphorus and potassium extraction in modern cultivars was higher than in cultivars used in past decades. Nutrient use efficiency was higher in determinate soybean cultivars than in indeterminate soybean cultivars.

Keywords: nutrient recommendation, sustainable intensification, no-till

1. Introduction

Soybean is considered a major crop because it is an important source of protein for animal feed and oil for human consumption. Therefore, increasing its production is important for the food supply (Batisti & Sentelhas 2017). The increasing world population and growing food demand have led to a need to increase soybean production, and Brazil is one of the countries with the highest potential for agricultural land expansion to meet this demand (Alves et al., 2017).

The Cerrado is the region responsible for the increase in agricultural production in Brazil. This region includes the MATOPIBA (states of Maranhão, Tocantins, Piauí, and Bahia), which is considered Brazil's newest agricultural frontier. This region is responsible for 10% of the country's grain production, with a predicted tripling in this production over the next few years (Horvat et al., 2015). Within MATOPIBA, the state of Tocantins stands out for the fast expansion of its soybean-cultivated area, which increased by 75% between 2013 and 2017 (CONAB, 2017) and has the potential to increase even more with the recovery and intensification of its wide areas of degraded pastures (Bortolon et al., 2016). Land use intensification, especially of degraded pastures, is a method to increase the efficiency of production systems (Vilela et al., 2011) while generating environmental services, such as reduction of greenhouse gas emissions, and improvement of water and soil quality (Franzluebbers et al., 2014; Lemaire et al., 2015). In addition, at the Copenhagen climate change conference in

2009, Brazil committed to implementing actions to mitigate greenhouse gas emissions from 36 to 39% by 2020, and the main methods to achieve this goal adopted in agriculture are the recovery of degraded pastures, no tillage, and integrated crop-livestock systems (ICLs) (Gurgel & Paltsev, 2014).

Intensifying soybean cultivation by intercropping with pasture in ICLs results in increased soybean seed yields of crops planted following pasture and higher weight gain or milk production of cows grazing on pastures grown off-season (Alves et al., 2017; Liebig et al., 2017). To intensify soybean production using ICLs or succession with an interim harvest, soybean cultivars are needed that can adapt to intensive land use. Therefore, the use of cultivars with indeterminate growth habits has increased with the aim of shortening the soybean crop cycle and decreasing the incidence of Asian soybean rust (Machado et al., 2017). Soybean cultivars with indeterminate growth habits usually present more erect shoots than cultivars with determinate growth, which increases the chances of fungicides reaching the lower third of the plant and enables intercropping with forage grasses by overseeding (Machado et al., 2017; Andrade et al., 2017). Interspecies genetic variability results in variations in development and productivity between different cultivars under the same cultivation conditions (Fageria & Nascente, 2014). Because different cultivars have different nutrient demands, different yields are observed frequently for the same soil fertility conditions (Fageria & Nascente, 2014).

The studies of Bataglia et al. (1976), Osaki (1991), and Tanaka et al. (1993) investigated nutrient uptake by soybeans in Brazil and were used as references for several fertilization and liming recommendation guidelines in Brazil. However, soybean cultivars have improved since their publications and now soybean cultivars have increased yields, shortened crop cycles and growth habits to allow cropping systems with corn as second harvest. These changes have led to changes in nutrient demands. Bender et al. (2015) observed that modern soybean cultivars exhibited doubled daily biomass production and nutrient uptake compared to cultivars planted in the American Midwest in the 1950s.

Corn, rice and soybean are the major crops grown in the state of Tocantins. Nitrogen (N), phosphorus (P), and potassium (K) fertilizers are applied at 38.2 kg t^{-1} of grains produced. This application is lower than reports in states such as Mato Grosso (47.8 kg t^{-1}) and Goiás (53.3 kg t^{-1}), where fertilizers are applied at higher doses and present higher corn, rice and soybean yields. In the case of soybean, where nitrogen is supplied via symbiotic association with Bradyrhizobium, the discrepancy among states may indicate that fertilizer application does not meet soybean nutrient demands in the state of Tocantins (Cunha et al., 2010). Although there is information on soybean nutrient requirements in boundary states, a regional study of soybean nutrient requirements is needed that considers regional agricultural systems and soil and climatic conditions. Furthermore, the results can be used as a tool for forming nutrient recommendations and increasing nutrient use efficiency. In addition, studies are needed to quantify nutrient uptake by soybean aboveground biomass and subsequent nutrient translocation to the soybean seeds using cultivars currently adopted in intensive agricultural systems, with yield potential in accordance with observations at the regional scale and considering the soybean growth habit.

Data on nutrient removal by modern soybean cultivars under intensive agricultural systems are scarce, but this information is important for adequate nutrient management, especially considering that fertilization represents approximately 50% of soybean production costs in Brazil (Cunha et al., 2010). In addition, we hypothesizes that the nutrient uptake and removal from previous studies must be updated considering both modern and growth habit of soybean cultivars. The aim of the present study was to evaluate aboveground biomass accumulation, seeds yield, and nutrient uptake and removal by different soybean cultivars with two different growth habits grown in intensive agricultural systems.

2. Materials and Methods

An on-farm experiment was performed during the 2014/2015 growing season at the Brejinho Farm located in the municipality of Pedro Afonso, state of Tocantins (08º58′ S, 48º10′ W, and 201-m altitude). The experimental area has been cropped with soybean since 1988 and has been under no-tillage since 1995. The agricultural system consisted of soybean as the main crop (rainy season from October to April) and millet/sorghum as the successional crop for soil cover or grain production (dry season from May to September). In 2006, ICLs was adopted, with cattle grazing for 18 months, followed by 36-months of soybean-corn rotation; after soybean harvest, pasture is planted and grazed for another 18-month cycle. The region’s climate is predominantly Aw according to the Köppen climate classification (*i.e.*, tropical humid with dry winters and rainy summers), and the average annual temperature is 26.1 °C (Souza et al., 2016). The average rainfall and air temperatures during the experiment are presented in Table 1.

Table 1. Monthly rainfall and air temperature near Pedro Afonso (TO) in 2014 and 2015. Thirty-year means were computed between 1985 and 2015†

Month	Rainfall			Air temperature		
	30-yr	2014	2015	30-yr	2014	2015
	---------------------- mm ----------------------			------------------------- °C -------------------------		
January	284	182	256	31.5	32.3	26.1
February	237	247	198	31.4	31.3	26.1
March	272	280	214	31.4	32.1	26.3
April	179	138	211	32.2	32.9	26.6
May	64	129	95	32.9	33.3	27.0
June	4.7	0.0	0	33.7	34.3	26.3
July	3.6	0.0	0	34.7	35.4	26.5
August	8.0	0.2	0	36.1	37.1	27.2
September	41	134	28	36.1	36.2	29.4
October	147	133	100	33.8	34.8	29.8
November	228	295	228	32.5	33.3	27.9
December	247	277	106	31.7	32.2	27.5

Note. † INMET.

The soil in the experimental area was classified as clayey Oxisol with the following chemical characteristics in the topsoil layer (0-20 cm) (Embrapa, 1997): pH in water (1:1) = 5.6; Ca (ammonium acetate) = 2.5 cmolc Kg^{-1}; Mg (ammonium acetate) = 1.1 cmol$_c$ Kg^{-1}; Al (ammonium acetate) = 0.0 cmol$_c$ Kg^{-1}; P (Mehlich-1) = 12.3 mg Kg^{-1}; K (Mehlich-1) = 155 mg Kg^{-1}; Cu (Mehlich-1) = 1.0 mg Kg^{-1}; Mn (Mehlich-1) = 17 mg Kg^{-1}; Zn (Mehlich-1) = 4.0 mg Kg^{-1}; V = 45.5%; and organic matter (OM) (Walkley Black) = 44 g kg^{-1}. Before the experiment was implemented, the experimental area was cultivated with soybean-corn rotation. Fertilizer was applied by surface broadcasting before planting in September 2014 with the application of 90 kg ha^{-1} of P_2O_5 and 80 kg ha^{-1} of K_2O. Phosphorus and K fertilizers were applied by broadcasting because soil P and K concentrations were classified as adequate, and in this case, fertilization did not affect crop yield. The weeds were killed with 0.7 kg a.i. ha^{-1} glyphosate [N-(phosphonomethyl)glycine] at the beginning of October and 30 days after soybean emergence. Sowing was performed on November 5, 2014. The soybean seeds were inoculated with Bradyrhizobium japonicum at the recommended dose. Planting was performed using a no-tillage pneumatic vacuum 11-row planter (Jumil JM 7080 PD) with 0.5-m spacing. Pest, disease, and weed control strategies were performed as needed.

A randomized complete block experimental design was used with four replicates. The treatments consisted of 17 soybean cultivars (Table 2). The cultivars were chosen considering the following factors: representative area cropped with the cultivar in the region; farmer demand; seeds companies and cultivar recommendations for the region; growth habit; and crop cycle. The maximum soybean cycle was defined as 120-days to reach reproductive stage of R8 (Litch, 2014) to allow corn to be planted after soybean without coinciding with the period of water stress during the corn critical stage. Each experimental unit was 11-m wide and 22.4-m long. The experiment was implemented in the second year after grazing period was finished.

Soybean aboveground biomass samples were collected at stage R5 (Litch, 2014) to determine the biomass. Stage R5 was chosen because the soybean nutrient uptake, growth, light interception, and water use peaked at this stage (Litch, 2104). Ten soybean plants were collected from the central plot area (8 central rows, 4-m wide and 22.4-m long). The plants were placed in paper bags, dried in a forced-air circulation oven at 65 °C for 72 h, ground, and digested by nitric-perchloric acid digestion (P, K, Ca, Mg, S, Cu, Zn, Fe, Mn, and B) and sulfuric digestion (N) (Embrapa, 1997). The nutrient concentrations were determined in the nitric-perchloric extracts by inductively coupled plasma optical emission spectrometry (ICP-OES) (Perkin Elmer, Optima 8300 DV), and N was determined by titration (Embrapa, 1997).

When the soybeans reached physiological maturity (stage R8), the final plant density (central plot area) was determined in each plot by counting the plants in 3 linear meters in the central rows in three random replicates. Then, the plot was harvested using a plot combine (Wintersteiger Classic). Following harvest, the total seeds weight was determined using a digital scale. A subsample was used to determine the moisture content, the total seeds weight was corrected to 130 g kg^{-1} moisture, and the final seeds yield was calculated by converting the values to kg ha^{-1}. A seed subsample was placed in paper bags, dried in a forced-air oven at 65 °C for 72 h, ground, and digested by nitric-perchloric acid digestion (P, K, Ca, Mg, S, Cu, Zn, Fe, Mn, and B) and sulfuric digestion (N) (Embrapa, 1997). The nutrient concentrations were determined in the nitric-perchloric extracts by ICP-OES (Perkin Elmer, optima 8300 DV), and N was determined by titration.

Table 2. Soybean cultivars, maturity group, growth habits and growth period in the 2014-2015 growing season in Pedro Afonso, TO

Cultivar	Brand	Maturity group	Growth habit	Growth period (days)
P 98Y30	Pionner	8.3	Determinate	118
P 98Y12	Pionner	8.1	Determinate	114
BRS 8180	Embrapa	8.1	Determinate	112
M 8766	Monsoy	8.7	Determinate	120
W 799	Wermann	7.7	Indeterminate	114
SYN 1279	Syngenta	7.9	Indeterminate	112
P 99R03	Pionner	9.0	Determinate	120
TMG 132	TMG	8.5	Determinate	114
BRS 8280	Embrapa	8.2	Determinate	118
CD 2737	Coodetec	7.3	Indeterminate	99
CD 251	Coodetec	8.6	Determinate	120
TMG 1180	TMG	8.8	Semideterminate	118
W 791	Wermann	7.6	Indeterminate	114
P 97R73	Pionner	7.7	Indeterminate	113
SYN 1183	Syngenta	8.3	Indeterminate	113
ST 820	Monsoy	8.2	Determinate	118
P 97R21	Pionner	7.2	Indeterminate	99

The calculations of nutrient uptake, nutrient removal and nutrient translocation were the same approach used by Rotundo et al. (2014). The nutrient uptake by soybeans in stage R5 was calculated based on the shoot biomass production (kg ha^{-1}) and nutrient concentrations (g kg^{-1}). The nutrient removal by soybean seeds was calculated based on the soybean yield (kg ha^{-1}) and nutrient concentrations in soybean seeds (g kg^{-1}). The total nutrient removal needed to produce one ton of seed was calculated combining the nutrient uptake in R5 (kg ha^{-1}) plus the nutrient removal by soybean seeds (kg ha^{-1}). The amounts of nutrient uptake in R5 that was translocated to the soybean seeds was calculated and results expressed in percentage (%).

The data were subjected to analysis of variance (One-Way ANOVA). Normality test was carried out with Shapiro-Wilk, and the averages were compared using the Scott-Knott test ($p < 0.05$) with the ASSISTAT 7.7 software (ASSIS, 2015). The aboveground biomass, seed yield, and nutrient uptake in soybean cultivars with determinate and indeterminate growth habits were compared using the Mann-Whitney U test ($p < 0.05$).

3. Results and Discussion

Significant differences in the dry aboveground biomass at the R5 stage were observed between soybean cultivars (Table 3). The aboveground soybean biomass varied from 3560 to 8934 kg ha^{-1}, with an overall average of 6189 kg ha^{-1}. Cultivars CD-2737, SYN-1279, and P 97R21 presented the highest aboveground biomasses (8661, 8927, and 8934 kg ha^{-1}, respectively), whereas CD-251, BRS 8280, and M 8766 presented the lowest (3560, 3639, and 4200 kg ha^{-1}, respectively). Differences in aboveground biomass production between cultivars are due to several factors, including different recommended plant densities (the number of plants per area is directly proportional to the biomass produced), growth habits, and crop cycles (Litch, 2014). Cultivars with longer cycles tend to present taller plants, thereby increasing the number of pods and seeds and resulting in higher biomass production (Bender et al. 2015). However, plant density plays an essential role in soybean biomass production, and higher yields are often obtained with a higher plant density. Soybeans in stage R5 allocate approximately 55% of their biomass to leaves, 31% to stems, and 14% to petioles (Litch, 2014). Cultivar with more leaves tend to have a higher biomass because nutrients are translocated from the leaves to the seeds and thus increase its weight (Bender et al., 2015). Higher seeds yield in soybeans are usually associated with higher biomass accumulation in stage R5 (Gaspar et al., 2017). However, although genetic improvement has focused on reducing the soybean crop cycle, modern cultivars present more than two-fold increases in the crop cycle compared to the cultivars used in past decades, especially in the harvest index (Rinker et al., 2014; Koester et al., 2014).

Significant differences in all measured macronutrient concentrations per DW (Table 3) were observed between the studied cultivars. The N concentrations varied from 22.0 to 29.3 g kg^{-1} DW, with an overall average of 26.3 g kg^{-1} DW. Cultivars BRS 8180 (22.0 g kg^{-1} DW), BRS 8280 (22.5 g kg^{-1} DW), TMG 1180 (23.3 g kg^{-1} DW), and ST-820 (24.0 g kg^{-1} DW) presented lower N concentrations than the remaining tested cultivars. Although the N concentrations were significantly different among cultivars, the values observed were similar to those reported by Bender et al. (2015) for two elite soybean cultivars grown in two locations in the American Midwest.

The P concentrations varied between 2.7 g kg^{-1} DW (BRS 8180) and 3.8 g kg^{-1} DW (CD-2737), with an overall average of 3.2 g kg^{-1} DW. Cultivars P 97R73, M 8766, W-791, P 98Y12, CD-2737, P 97R21, P 98Y30, and TMG-132 presented higher P concentrations than the remaining tested cultivars. The K concentrations behaved similarly, with the same cultivars (except W-799 and including M 8766 and BRS 8280) presenting higher K concentrations than the remaining tested cultivars. The K concentrations varied between 18.3 and 25.8 g kg^{-1} DW, with an overall average of 21.5 g kg^{-1} DW. The overall average Ca concentration was 7.6 g kg^{-1} DW, and two cultivars presented higher Ca concentrations than the remaining tested cultivars [TMG-132 (9.5 g kg^{-1} DW) and CD-2737 (10.1 g kg^{-1} DW)]. The overall average Mg concentration was 3.6 g kg^{-1} DW, and cultivars W-791, P 97R21, and P 97R73 presented higher Mg concentrations (4.0, 4.1, and 4.4 g kg^{-1} DW, respectively) than the remaining tested cultivars. The overall average S concentration was 1.9 g kg^{-1} DW, and cultivars P 98Y12, W-791, and CD-2737 presented higher S concentrations (2.2, 2.3, and 2.4 g kg^{-1} DW, respectively) than the remaining tested cultivars. Higher biomass nutrient accumulation is not always associated with higher nutrient removal, especially for nutrients with a low harvest index, such as Mg, Ca, and S (Fageria & Nascente, 2014). However, this relationship was inverse for N, with the increase in biomass leading to increased N removal (Table 3). Usually, the amount of N accumulated in soybean diagnostic leaves or even in the biomass is positively correlated with the seed yield (Fageria & Nascente, 2014).

Significant differences in plant micronutrient concentrations (Table 3) were observed between different cultivars only for Zn, Fe, and Mn. The Zn concentrations varied between 27 mg.kg^{-1} DW (ST-820) and 45 mg kg^{-1} DW (W 791), with an overall average of 35 mg kg^{-1} DW. The overall average Fe concentration was 203 mg kg^{-1} DW and was highest for cultivar P 97R21 (307 mg kg^{-1}). The Mn concentrations varied between 21 mg kg^{-1} DW (BRS 8180) and 42 mg kg^{-1} DW (P 98Y12), with an overall average of 32 mg kg^{-1} DW. The micronutrient recommendations for soybeans are based on the philosophy of safe fertilization, where nutrients are applied in the amounts necessary to correct soil concentrations plus nutrient removal for the biomass and seeds (Sousa & Lobato 2004). Barbosa et al. (2016) observed an Mn response in a soil similar to that used in the present study.

Significant differences in total macronutrient uptake per hectare were observed between the tested cultivars (Table 4). The overall average N uptake was 164 kg ha^{-1}; the uptake was lowest for cultivars BRS 8280 (82 kg ha^{-1}), CD-251 (102 kg ha^{-1}), M 8766 (108 kg ha^{-1}), BRS 8180 (125 kg ha^{-1}), and TMG-1180 (127 kg ha^{-1}) and highest for CD-2737 (255 kg ha^{-1}), P 97R21 (238 kg ha^{-1}), SYN-1279 (229 kg ha^{-1}), and P 98Y30 (216 kg ha^{-1}). P uptake varied between 10 kg ha^{-1} and 33 kg ha^{-1}, with an average of 20 kg ha^{-1}; P uptake was lowest for cultivars BRS 8280 (10 kg ha^{-1}), CD-251 (11 kg ha^{-1}), and M 8766 (13 kg ha^{-1}) and highest for cultivars CD-2737 (33 kg ha^{-1}) and P 97R21 (32 kg ha^{-1}). The overall average P uptake was 134 kg ha^{-1} and was highest for cultivars P 97R21 (212 kg ha^{-1}), CD-2737 (200 kg ha^{-1}), and SYN-1279 (185 kg ha^{-1}). The overall average Ca uptake was 48 kg t^{-1} and was highest for cultivar CD-2737 (88 kg ha^{-1}). The overall average Mg uptake was 22 kg ha^{-1} and was highest for cultivar P 97R21 (37 kg ha^{-1}). The overall average S uptake was 11.9 kg ha-1 and was highest for cultivar CD-2737 (21 kg ha^{-1}). These findings were in agreement with Kurihara et al. (2013), who studied ten soybean cultivars at 28 commercial farms in the state of Mato Grosso do Sul. However, plant nutrient use efficiency has increased with genetic improvement and varies widely between different soybean cultivars, especially those with different growth habits (Bender et al., 2015; Gaspar et al., 2017, Balboa et al., 2018).

Table 3. Soybean aboveground biomass, nutrient content in 17 soybean cultivars at R5 stage. Descriptive analysis of the soybean aboveground biomass and nutrient content†

Cultivar	Biomass	Nutrient content										
		N	P	K	Ca	Mg	S	Cu	Zn	Fe	Mn	B
	kg ha^{-1}	---------- g kg^{-1} ----------						---------- mg kg^{-1} ----------				
P 98Y30	5986 c	25.8 a	3.4 a	24.5 a	7.8 c	3.7 b	1.9 c	6.3 a	34 b	249 b	29 b	32 a
P 98Y12	7418 b	29.3 a	3.4 a	22.5 a	8.8 b	3.7 b	2.2 a	6.5 a	41 a	198 c	42 a	33 a
BRS 8180	5641 c	22.0 b	2.7 b	18.3 b	6.7 c	3.4 c	1.6 c	5.8 a	28 b	113d	21 c	29 a
M 8766	4200 d	25.8 a	3.2 b	22.5 a	7.3 c	3.4 c	1.9 c	5.8 a	34 b	233 b	29 b	36 a
W-799	5992 c	27.3 a	3.3 a	20.0 b	7.7 c	3.8 b	1.9 c	5.5 a	36 a	147 d	36 a	34 a
SYN-1279	8927 a	25.8 a	2.9 b	20.8 b	7.0 c	3.3 c	1.8 c	7.3 a	34 b	143 d	32 b	32 a
P 99R03	5427 c	27.7 a	3.0 b	18.7 b	6.9 c	3.3 c	1.8 c	6.3 a	37 a	241 b	30 b	33 a
TMG-132	6318 c	27.8 a	3.5 a	25.8 a	9.5 a	3.9 b	2.1 b	6.8 a	42 a	257 b	42 a	33 a
BRS 8280	3639 d	22.5 b	2.8 b	21.5 a	6.5 c	3.5 c	1.7 c	5.8 a	29 b	154 d	22 c	30 a
CD-2737	8661 a	29.0 a	3.8 a	23.0 a	10.1 a	3.2 c	2.4 a	6.8 a	35 b	244 b	40 a	34 a
CD-251	3560 d	28.5 a	3.2 b	20.3 b	7.8 c	3.7 b	2.1 b	6.3 a	38 a	256 b	33 b	35 a
TMG-1180	5445 c	23.3 b	3.0 b	18.5 b	6.7 c	3.6 c	1.6 c	5.3 a	28 b	203 c	23 c	27 a
W-791	5953 c	29.0 a	3.4 a	22.5 a	8.1 b	4.0 a	2.3 a	6.8 a	45 a	197 c	40 a	38 a
P 97R73	6135 c	26.2 a	3.3 a	22.3 a	8.3 b	4.4 a	2.0 b	6.5 a	41 a	216 c	37 a	33 a
SYN-1183	5800 c	26.6 a	3.1 b	21.0 b	7.0 c	3.3 c	1.8 c	6.2 a	33 b	192 c	30 b	33 a
ST-820	7083 b	24.0 b	2.8 b	19.8 b	6.2 c	2.8 c	1.8 c	5.3 a	27 b	115 d	25 c	29 a
P 97R21	8934 a	26.3 a	3.6 a	23.3 a	7.4 c	4.1 a	1.7 c	6.3 a	34 b	307 a	29 b	32 a
Minimum	*3278*	*20.5*	*2.4*	*15.0*	*4.8*	*2.6*	*1.5*	*4.3*	*20*	*96*	*18*	*21*
Maximum	*10892*	*33.2*	*4.0*	*29.5*	*11.5*	*4.5*	*2.7*	*9.5*	*54*	*347*	*47*	*45*
Mean	*6189*	*26.3*	*3.2*	*21.5*	*7.6*	*3.6*	*1.9*	*6.2*	*35*	*203*	*32*	*32*
Median	*6123*	*26.4*	*3.2*	*21.4*	*7.4*	*3.6*	*1.9*	*6.3*	*35*	*203*	*31*	*33*
SD§	*1702*	*3.0*	*0.4*	*2.7*	*1.2*	*0.5*	*0.3*	*1.0*	*7.0*	*59.8*	*7.7*	*4.4*
CV (%)	*27.5*	*11.4*	*12.2*	*12.7*	*16.3*	*12.8*	*14.7*	*15.7*	*20.0*	*29.5*	*24.2*	*13.5*

Note. † Means followed by the same letter in the column are not significantly different by Scott-Knott test ($P \leq 0.05$); § Standard deviation.

Significant differences in total micronutrient uptake per hectare were observed between the studied cultivars (Table 4). The Cu uptake varied between 22 g ha^{-1} (BRS 8280) and 65 g ha^{-1} (SYN-1279), with an overall average of 39 g ha^{-1}. The Zn uptake varied between 105 g ha^{-1} (BRS 8280) and 305 g ha^{-1} (CD-2737). The overall average Fe uptake was 1260 g ha^{-1} and was highest for cultivar P 97R21 (2754 g ha^{-1}), followed by CD-2737 (2101 g ha^{-1}). The overall average Mn and B uptakes were 200 kg ha^{-1}. Barbosa et al. (2016) observed that Mn was the micronutrient with the highest uptake. Notably, the soil in which the present study was performed presented concentrations of both macro- and micronutrients that were considered high. Because nutrients were not limiting for plant growth, the potential of each different soybean cultivar for nutrient uptake, translocation, and conversion into biomass could be observed. Kurihara et al. (2013) concluded that the amounts of nutrients accumulated in soybean stage R6 were similar to those calculated from the leaf analysis (R2). In the present study, all nutrient concentrations were within the adequate range for the interpretation of concentrations obtained in the leaf analysis.

Table 4. Soybean nutrient uptake and descriptive analysis in 17 soybean cultivars at R5 stage†

Cultivar	Nutrient uptake										
	N	P	K	Ca	Mg	S	Cu	Zn	Fe	Mn	B
	kg ha^{-1}						g ha^{-1}				
P 98Y30	153 b	20 c	146 c	47 c	22 d	11.1 d	38 b	204 b	1490 c	174 c	188 c
P 98Y12	216 a	25 b	167 b	65 b	27 b	16.3 b	49 a	301 a	1462 c	311 a	243 b
BRS 8180	125 c	15 d	106 d	38 d	19 d	8.9 e	33 b	159 c	638 d	119 d	166 c
M 8766	108 c	13 e	96 d	31 d	14 e	8.0 e	23 c	138 c	973 d	120 d	149 d
W-799	165 b	20 c	120 c	46 c	23 c	11.1 d	32 b	219 b	874 d	216 b	206 c
SYN-1279	229 a	26 b	185 b	62 b	30 b	16.1 b	65 a	300 a	1280 c	288 a	282 a
P 99R03	148 b	16 d	103 d	37 d	18 d	9.8 d	34 b	196 b	1318 c	160 c	180 c
TMG-132	176 b	22 c	163 b	60 b	25 c	13.3 c	42 b	267 a	1632 c	262 b	211 c
BRS 8280	82 c	10 e	79 d	24 d	13 e	6.2 e	22 c	105 c	555 d	82 d	107 d
CD-2737	255 a	33 a	200 a	88 a	27 b	21.0 a	59 a	305 a	2101 b	347 a	293 a
CD-251	102 c	11 e	73 d	28 d	13 e	7.4 e	22 c	135 c	911 d	118 d	125 d
TMG-1180	127 c	16 d	101 d	37 d	19 d	8.6 e	30 b	153 c	1103 c	124 d	146 d
W-791	172 b	20 c	133 c	48 c	24 c	13.4 c	40 b	265 a	1155 c	238 b	226 b
P 97R73	160 b	20 c	134 c	51 c	27 b	12.3 c	39 b	250 a	1325 c	229 b	203 c
SYN-1183	154 b	18 c	122 c	41 c	19 d	10.6 d	38 b	191 b	1098 c	173 c	191 c
ST-820	170 b	20 c	139 c	44 c	20 d	12.6 c	39 b	193 b	814 d	176 c	204 c
P 97R21	238 a	32 a	212 a	67 b	37 a	15.5 b	57 a	304 a	2754 a	263 b	283 a
Minimum	*72*	*9*	*61*	*21*	*11*	*4.9*	*18*	*84*	*504*	*63*	*88*
Maximum	*307*	*41*	*285*	*113*	*47*	*24.6*	*81*	*388*	*3556*	*442*	*356*
Mean	*164*	*20*	*134*	*48*	*22*	*11.9*	*39*	*217*	*1260*	*200*	*200*
Median	*161*	*20*	*134*	*45*	*21*	*11.2*	*36*	*212*	*1118*	*183*	*193*
SD§	*51.7*	*6.9*	*44.4*	*17.9*	*6.8*	*4.0*	*14.4*	*75.7*	*573.9*	*82.7*	*60.7*
CV (%)	*31.6*	*34.3*	*33.1*	*37.4*	*30.5*	*33.9*	*36.9*	*35.0*	*45.5*	*41.3*	*30.3*

Note. † Means followed by the same letter in the column are not significantly different by Scott-Knott test ($P \leq 0.05$); § Standard deviation.

Significant differences in soybean seeds yield were observed between the tested cultivars (Table 5). The overall average of soybean seeds yield was 3563 kg ha^{-1}. Cultivars BRS 8180 (3936 kg ha^{-1}), P 98Y12 (3957 kg ha^{-1}), and P 98Y30 (4015 kg ha^{-1}) presented the highest seeds yield, whereas P 97R21 (2961 kg ha^{-1}) presented the lowest. The observed overall average soybean seeds yield was higher than that reported for the state of Tocantins (2914 kg ha^{-1}) (CONAB, 2015) but was similar to the yield obtained in production areas adjacent to the experimental area and in the region of the experiment. Variability in soybean seeds yield occurs due to several factors, including the crop cycle length, growth habit, and resistance to pests and diseases. Similar results were reported by Peluzzio et al. (2010), who studied 17 cultivars in Tocantins.

Significant differences in all soybean seed macronutrient concentrations were observed between the tested cultivars (Table 5). The soybean seed N concentrations varied between 53.0 kg t^{-1} (ST 820) and 64.3 kg t^{-1} (BRS 8280), with an overall average of 60.1 kg t^{-1}. The average soybean seed P concentration was 5.4 kg t^{-1} and was highest for cultivars P 97R73 (5.7 kg t^{-1}), CD-251 (5.9 kg t^{-1}), BRS 8280 (5.9 kg t^{-1}), and ST-820 (6.1 kg t^{-1}). The soybean seed K concentrations varied between 6.2 kg t^{-1} (SYN-1183) and 9.8 kg t^{-1} (ST-820), with an overall average of 7.8 kg t^{-1}. The soybean seed Ca concentration varied between 1.6 kg t^{-1} (BRS 8180) and 2.9 kg t^{-1} (P 98Y30), with an overall average of 2.4 kg t^{-1}. The overall average soybean seed Mg concentration was 2.7 kg t^{-1} and was highest for cultivars P 97R73 (3.1 kg t^{-1}), BRS 8280 (3.1 kg t^{-1}), P 98Y30 (3.2 kg t^{-1}), and M 8766 (3.4 kg t^{-1}). The soybean seed S concentrations varied between 2.8 kg t^{-1} (ST-820) and 3.6 kg t^{-1} (P 97R73), with an overall average of 3.2 kg t^{-1}; the soybean seed S concentration was highest for cultivars W-791, TMG-132, BRS 8180 (both with 3.5 kg t^{-1}), and P 97R73 (3.6 kg t^{-1}).

Table 5. Soybean seeds yield and nutrient removal, and descriptive analysis of 17soybean cultivars †

Cultivar	Yield	Nutrient removal										
		N	P	K	Ca	Mg	S	Cu	Zn	Fe	Mn	B
	Kg ha^{-1}	--------------- kg t^{-1} seeds ---------------						------------- g t^{-1} seeds -------------				
P 98Y30	4015 a	58.3 b	5.3 b	7.8 a	2.9 a	3.2 a	2.9 c	11.0 b	47 a	84 a	24 a	24 d
P 98Y12	3957 a	61.3 a	5.2 b	6.9 b	2.6 a	2.7 b	3.3 b	9.5 c	47 a	80 b	24 a	26 c
BRS 8180	3936 a	63.8 a	5.2 b	6.9 b	1.6 b	2.6 b	3.5 a	11.5 b	47 a	93 a	20 b	31 a
M 8766	3698 b	55.8 b	5.3 b	8.1 a	2.5 a	3.4 a	2.9 c	12.3 b	44 b	81 a	23 a	26 c
W-799	3687 b	62.0 a	5.2 b	8.3 a	2.8 a	2.7 b	3.4 b	10.3 c	46 a	86 a	24 a	28 b
SYN-1279	3627 c	62.3 a	5.1 b	6.9 b	2.3 a	2.6 b	3.2 c	10.3 c	41 b	68 b	24 a	23 d
P 99R03	3605 c	61.3 a	5.3 b	6.4 b	1.9 b	2.4 b	3.0 c	9.0 c	41 b	73 b	21 b	25 c
TMG-132	3568 c	62.5 a	5.4 b	7.5 b	2.1 b	2.6 b	3.5 a	11.8 b	48 a	77 b	24 a	26 c
BRS 8280	3548 c	64.3 a	5.9 a	8.5 a	2.2 b	3.1 a	3.3 b	11.5 b	52 a	92 a	23 a	28 b
CD-2737	3522 c	58.5 b	5.0 b	9.1 a	2.6 a	2.8 b	2.9 c	8.8 c	43 b	88 a	26 a	22 d
CD-251	3513 c	60.0 a	5.9 a	7.5 b	2.3 b	2.5 b	3.2 b	10.0 c	48 a	76 b	26 a	29 b
TMG-1180	3476 c	58.8 b	5.3 b	8.1 a	2.5 a	2.8 b	2.9 c	9.8 c	42 b	74 b	22 b	23 d
W-791	3471 c	62.5 a	5.4 b	7.5 b	2.1 b	2.6 b	3.5 a	11.8 b	48 a	77 b	24 a	26 c
P 97R73	3460 c	64.0 a	5.7 a	8.4 a	2.4 a	3.1 a	3.6 a	10.8 c	47 a	77 b	26 a	27 c
SYN-1183	3313 d	60.4 a	5.0 b	6.2 b	2.1 b	2.4 b	3.1 c	9.2 c	42 b	70 b	22 b	25 c
ST-820	3295 d	53.0 b	6.1 a	9.8 a	2.6 a	2.6 b	2.8 c	15.5 a	47 a	84 a	25 a	24 d
P 97R21	2961 e	53.3 b	5.3 b	8.7 a	2.8 a	2.7 b	2.9 c	8.5 c	42 b	84 a	25 a	22 d
Minimum	*2693*	*28.1*	*4.6*	*5.0*	*1.6*	*2.2*	*2.6*	*7.2*	*38*	*64*	*19*	*20*
Maximum	*4269*	*66.8*	*6.6*	*11.1*	*3.3*	*3.8*	*3.9*	*20.6*	*56*	*117*	*32*	*34*
Mean	*3563*	*60.1*	*5.4*	*7.8*	*2.4*	*2.7*	*3.2*	*10.6*	*45*	*80*	*24*	*25*
Median	*3537*	*60.8*	*5.3*	*7.8*	*2.4*	*2.6*	*3.1*	*10.3*	*45*	*80*	*24*	*26*
SD§	*313.3*	*5.2*	*0.4*	*1.3*	*0.4*	*0.3*	*0.3*	*2.1*	*3.9*	*9.3*	*2.2*	*3.0*
CV (%)	*8.8*	*8.7*	*7.7*	*16.2*	*16.9*	*12.2*	*10.1*	*19.3*	*8.6*	*11.7*	*9.3*	*11.9*

Note. † Means followed by the same letter in the column are not significantly different by Scott-Knott test ($P \leq 0.05$); § Standard deviation.

Significant differences in all soybean seed micronutrient concentrations were observed between the tested cultivars (Table 5). The overall average soybean seed Cu concentration was 10.7 g t^{-1} and was highest for cultivar ST-820 (15.5 g t^{-1}). The soybean seed Zn concentrations varied between 41 g t^{-1} (SYN-1279) and 52 g t^{-1} (BRS 8280), with an overall average of 45 g t^{-1}. The overall average soybean seed Fe concentration was 80 g t^{-1}. The soybean seed Mn concentrations varied between 20 g t^{-1} (BRS 8180) and 26 g t^{-1} (P 97R73), with an overall average of 24 g t^{-1}. The overall average soybean seed B concentration was 25 g t^{-1} and was highest for cultivar BRS 8180 (31 g t^{-1}). The soybean seed nutrient concentrations observed in the present study were similar to those reported by Kurihara et al. (2013), who studied ten soybean cultivars in 28 commercial farms in the state of Mato Grosso do Sul. Thus, these concentrations may be used in mathematical models to calculate soybean nutrient demands.

Significant differences in the nutrient removal amounts required to produce one ton of soybean seed were observed between cultivars (Table 6). The overall average N removal was 106.6 kg t^{-1}; this amount was lowest for cultivars M 8766 (85.1 kg t^{-1}), BRS 8280 (87.7 kg t^{-1}), CD-251 (89.0 kg t^{-1}), TMG-1180 (95.1 kg t^{-1}), BRS 8180 (95.5 kg t^{-1}), and P 98Y30 (96.3 kg t^{-1}) and highest for SYN-1279 (125.4 kg t^{-1}), CD-2737 (131.1 kg t^{-1}), and P 97R21 (134.6 kg t^{-1}). The overall average P removal was 11.1 kg t^{-1}; this amount was highest for cultivar P 97R21, followed by CD-2737 (14.3 kg t^{-1}). The overall average K removal was 46.1 kg t^{-1}; this amount was lowest for cultivars CD-251 (28.3 kg t^{-1}), BRS 8280 (30.7 kg t^{-1}), BRS 8180 (34.0 kg t^{-1}), M 8766 (34.1 kg t^{-1}), P 99R03 (35.0 kg t^{-1}), and TMG-1180 (37.3 kg t^{-1}) and highest for P 97R21 (81.0 kg t^{-1}), followed by CD-2737 (65.9 kg t^{-1}). The overall average Ca removal was 16 kg t^{-1}; this amount was highest for cultivars CD-2737 (27.6 kg t^{-1}) and P 97R21 (25.6 kg t^{-1}), followed by SYN-1279 (19.5 kg t^{-1}), TMG-132 (19.3 kg t^{-1}), and P 98Y12 (19.0 kg t^{-1}). The overall average Mg removal was 9.1 kg t^{-1}; this amount was lowest for cultivars CD-251 (6.2 kg t^{-1}), BRS 8280 (6.7 kg t^{-1}), M 8766 (7.2 kg t^{-1}), P 99R03 (7.3 kg t^{-1}), and BRS 8180 (7.4 kg t^{-1}) and highest for cultivar P 97R21 (15.2 kg t^{-1}). The overall average S removal was 6.6 kg t^{-1} and was highest for cultivars CD-2737 and P 97R21 (8.9 kg t^{-1} and 8.3 kg t^{-1}, respectively).

Significant differences in the micronutrient removal amounts required to produce one ton of soybean seeds were observed between cultivars (Table 6). The overall average Cu, Zn, Fe, Mn, and B removal amounts were 21.7, 107, 442, 80, and 82 g t^{-1}, respectively. Significant differences in the ratios of nutrients translocated from the soybean aboveground biomass to the seeds were observed between cultivars (Table 7). The overall average ratio of translocated N was 57%; this ratio was lowest for cultivars P 97R21 (40%) and CD-2737 (44%) and highest for BRS 8280 (74%). Similar behavior was observed for the ratio of translocated P. The overall average ratio of translocated P was 50% and was also lowest for CD-251 (64%) and highest for BRS 8280 (67%). The ratio of translocated K varied between 11% (P 97R21) and 28% (BRS 8280), with an overall average of 18%. The overall average ratio of trweanslocated Ca was 16% and was highest for cultivars CD-251 (23%), M 8766 (23%), and BRS 8280 (25%). The ratio of translocated Mg was lowest for P 97R21 (18%) followed by SYN-1279 (24%) and was highest for M 8766 (47%) and BRS 8280 (47%), with an overall average of 32%. The ratio of translocated S varied between 33% (CD-2723) and 65% (BRS 8280), with an overall average of 50%.

Table 6. Soybean total nutrient removal (aboveground uptake plus seeds removal) amounts to produce 1,000 kg seeds, and descriptive analysis of 17 soybean cultivars on total nutrient removal[†]

Cultivar	N	P	K	Ca	Mg	S	Cu	Zn	Fe	Mn	B
	kg t^{-1} seeds						g t^{-1} de seeds				
P 98Y30	96.3 d	10.3 d	44.1 c	14.5 c	8.6 c	5.7 d	20.3 b	97 b	457 c	67 c	70 c
P 98Y12	115.9 b	11.6 c	49.0 c	19.0 b	9.6 c	7.4 b	22.0 b	123 a	450 c	102 b	87 b
BRS 8180	95.5 d	9.2 d	34.0 d	11.4 d	7.4 d	5.8 d	19.9 b	87 b	256 d	50 d	73 c
M 8766	85.1 d	8.9 d	34.1 d	10.8 d	7.2 d	5.0 d	18.3 b	81 b	345 d	56 d	67 c
W-799	106.8 c	10.5 d	41.1 c	15.3 c	8.9 c	6.4 c	18.9 b	105 b	323 d	83 b	84 b
SYN-1279	125.4 a	12.2 c	57.9 b	19.5 b	10.8 b	7.6 b	27.9 a	124 a	422 c	103 b	101 a
P 99R03	102.4 c	9.8 d	35.0 d	12.1 d	7.3 d	5.7 d	18.4 b	96 b	439 c	66 c	75 c
TMG-132	112.6 b	11.8 c	54.5 b	19.3 b	9.6 c	7.4 b	23.9 a	124 a	549 c	99 b	86 b
BRS 8280	87.7 d	9.9 d	30.7 d	8.8 d	6.7 d	5.0 d	17.5 b	81 b	248 d	46 d	59 c
CD-2737	131.1 a	14.3 b	65.9 b	27.6 a	10.5 b	8.9 a	25.3 a	129 a	684 b	124 a	104 a
CD-251	89.0 d	9.1 d	28.3 d	10.3 d	6.2 d	5.3 d	16.4 b	87 b	335 d	59 d	64 c
TMG-1180	95.1 d	9.9 d	37.3 d	13.1 d	8.3 c	5.4 d	18.4 b	86 b	391 c	57 d	65 c
W-791	112.2 b	11.3 c	45.8 c	16.0 c	9.4 c	7.4 b	23.4 a	125 a	410 c	93 b	91 b
P 97R73	110.1 b	11.6 c	47.1 c	17.2 c	10.9 b	7.1 b	22.0 b	119 a	460 c	92 b	86 b
SYN-1183	107.3 c	10.6 d	43.4 c	14.5 c	8.3 c	6.4 c	20.7 b	100 b	404 c	76 c	84 b
ST-820	104.6 c	12.2 c	52.3 b	15.9 c	8.7 c	6.6 c	27.1 a	105 b	331 d	78 c	86 b
P 97R21	134.6 a	16.3 a	81.0 a	25.6 a	15.2 a	8.3 a	27.8 a	146 a	1021 a	114 a	118 a
Minimum	*80.8*	*7.6*	*25.4*	*7.7*	*5.7*	*4.3*	*13.9*	*68*	*228*	*38*	*54*
Maximum	*149.6*	*18.3*	*99.2*	*33.1*	*17.6*	*9.7*	*34.8*	*182*	*1243*	*148*	*144*
Mean	*106.6*	*11.1*	*46.1*	*16.0*	*9.1*	*6.5*	*21.7*	*107*	*442*	*80*	*82*
Median	*105.6*	*10.9*	*44.7*	*15.1*	*8.8*	*6.3*	*21.2*	*101*	*386*	*75*	*80*
SD[§]	*16.3*	*2.2*	*14.9*	*5.6*	*2.3*	*1.3*	*4.7*	*23.3*	*193.3*	*25.3*	*18.2*
CV (%)	*15.3*	*19.9*	*32.4*	*34.9*	*25.1*	*19.3*	*21.5*	*21.8*	*43.7*	*31.5*	*22.1*

Note. † Means followed by the same letter in the column are not significantly different by Scott-Knott test ($P \leq 0.05$); § Standard deviation.

Significant differences in the ratios of nutrients translocated to the soybean seeds were observed between cultivars (Table 7). The overall average ratios of Cu, Zn, Fe, Mn, and B translocated to the soybean seeds were 50, 44, 21, 32, and 33%, respectively.

All overall average macronutrient uptake values were similar to those of previous reports (Table 8). N uptake was higher than the previously reported values of between 70 kg ton-1 (Osaki, 1991) and 83 kg t^{-1} (EMBRAPA 2011), indicating higher N demand by current cultivars. The P uptake (11.1 kg t^{-1}) was similar to that reported by Osaki (1991; 11.7 kg t^{-1}) and lower than that reported by EMBRAPA (2011; 15.4 kg t^{-1}). The K uptake (46.1 kg t^{-1}) was only lower than hat reported by Flannery (1986). The Ca uptake presented intermediate values compared to the previously reported values, between 12.2 kg t^{-1} (EMBRAPA, 2011; Borkert, 1986) and 27.2 kg t^{-1} (Flannery 1986). The Mg uptake (9.1 kg t^{-1}) was similar to the highest reported values of 9.1 kg t^{-1} (Bataglia et al., 1977) and 9.3 kg t^{-1} (Flannery, 1989). The S uptake (6.6 kg t^{-1}) presented intermediate values compared to the previously reported values, between 3.1 kg t^{-1} (Bataglia et al., 1977) and 15.4 kg t^{-1} (Borkert, 1986; EMBRAPA, 2011).

Table 7. Ratio of nutrients translocated from soybean cultivars aboveground biomass at R5 to soybean seeds at stage R8 and descriptive analysis†

Cultivar	Ratio of nutrients translocated to soybean seeds										
	N	P	K	Ca	Mg	S	Cu	Zn	Fe	Mn	B
	%										
P 98Y30	60 c	51 c	18 c	20 b	37 b	51 b	54 b	48 c	19 d	36 b	33 b
P 98Y12	53 d	45 c	14 d	13 c	28 c	44 c	44 c	39 d	18 d	23 d	30 b
BRS 8180	67 b	58 b	21 b	15 c	35 b	61 a	58 b	54 b	37 a	40 b	43 a
M 8766	66 b	60 b	24 a	23 a	47 a	57 a	66 a	54 b	24 c	42 b	39 a
W-799	58 c	49 c	21 b	19 b	31 c	53 b	54 b	44 d	27 b	30 c	33 b
SYN-1279	50 d	42 c	12 d	12 d	24 d	42 c	36 d	33 e	16 d	23 d	23 c
P 99R03	60 c	54 b	18 c	16 c	33 c	53 b	49 b	43 d	17 d	32 c	34 b
TMG-132	56 c	47 c	15 d	12 d	27 c	49 b	50 b	39 d	15 e	25 d	30 b
BRS 8280	74 a	67 a	28 a	25 a	47 a	65 a	65 a	64 a	37 a	51 a	49 a
CD-2737	45 e	35 d	14 d	10 d	26 c	33 d	35 d	34 e	13 e	21 d	21 c
CD-251	68 b	64 a	27 a	23 a	40 b	60 a	62 a	56 b	23 c	43 b	44 a
TMG-1180	62 c	53 b	22 b	19 b	33 c	54 b	53 b	49 c	19 d	38 b	36 b
W-791	56 c	48 c	16 c	13 c	27 c	48 b	51 b	39 d	19 d	26 d	29 b
P 97R73	58 c	49 c	18 c	14 c	28 c	50 b	49 b	40 d	17 d	28 c	32 b
SYN-1183	57 c	48 c	15 d	15 c	30 c	50 b	45 c	43 d	18 d	31 c	31 b
ST-820	49 d	50 c	19 c	17 c	30 c	42 c	56 b	45 d	25 b	32 c	29 b
P 97R21	40 e	33 d	11 d	11 d	18 e	37 d	31 d	30 e	8 f	23 d	19 c
Minimum	*35*	*28*	*9*	*6*	*15*	*30*	*25*	*24*	*7*	*17*	*15*
Maximum	*76*	*69*	*35*	*30*	*52*	*69*	*76*	*67*	*44*	*57*	*56*
Mean	*57*	*50*	*18*	*16*	*32*	*50*	*50*	*44*	*21*	*32*	*33*
Median	*58*	*50*	*18*	*16*	*30*	*49*	*51*	*44*	*19*	*31*	*32*
SD§	*9.1*	*9.7*	*5.8*	*4.9*	*7.8*	*9.4*	*10.8*	*9.6*	*7.8*	*9.1*	*9.0*
CV (%)	*15.9*	*19.3*	*31.5*	*30.2*	*24.7*	*18.8*	*21.4*	*21.8*	*38.0*	*28.6*	*27.6*

Note. † Means followed by the same letter in the column are not significantly different by Scott-Knott test ($P \leq 0.05$); § Standard deviation.

The overall average nutrient removal amounts required to produce 1 ton of soybean seeds (Table 8) were similar to those of previous reports. The average N removal required to produce 1 ton of soybean seeds (60.1 kg t^{-1}) was intermediate compared to the previously reported values, between 51.0 kg t^{-1} (Borkert, 1986; Flannery, 1989; Yamada, 1999; Embrapa, 2011) and 64.4 kg t^{-1} (Cordeiro et al., 1979). The average P removal required to produce 1 ton of soybean seed (5.4 kg t^{-1}) was similar to that of previous reports, except for the values reported by EMBRAPA (2011), which were higher than those in the remaining consulted studies (10 kg t^{-1}). The K removal required to produce 1 ton of soybean seed (7.8 kg t^{-1}) was lower than previous reports, possibly due to increased K use efficiency by the cultivars from the experimental region. K is taken up by plants in large amounts and performs functions in plant metabolism, assimilates translocation and storage and is required for turgor maintenance. Because it is not metabolized by the plants and forms easily reversible bonds with organic molecules (Marschner, 1995), K accumulated in the crop remains at the end of the crop cycle, and little K is translocated to the seed. Balboa et al. (2018) performed a global historical analysis and observed a 13% decrease in K translocation to the seed. This decrease may be related to K replacement by another ion, such as Na. Because the soil K concentrations were within the adequate range, luxury consumption could have occurred, especially when associated with high biomass production and nutrient uptake, which cause an internal imbalance in plants. Cultivars SYN-1279 and CD-2737 presented the highest aboveground biomass in stage R5 but differed in the amounts of K taken up (20.8 and 23.0, respectively; Table 3). This result shows that the cultivars present differences in K conversion into biomass, which may be associated with K translocation between organelles, cells, and other organs to regulate K within cells (Rangel & Damon, 2008). Calcium and S removal to produce 1 ton of soybean seed presented intermediate values compared to the previously reported values of 1.9 kg t^{-1} (Bundy & Oplinger, 1984; Tanaka et al., 1993) and 3.2 kg t^{-1} (Cordeiro et al., 1979) for Ca and 2.0 kg t^{-1} (Bataglia et al., 1977) and 5.4 kg ton^{-1} for S (EMBRAPA, 2011). Overall, the average Mg removal required to produce 1.0 t of soybean seed (2.7 kg t^{-1}) was higher than the previously reported values, which varied between 2.0 kg t^{-1} (Bataglia et al., 1977; Borkert, 1986; EMBRAPA, 2011) and 2.5 kg ton^{-1} (Flannery, 1989; Yamada, 1999).

Table 8. Nutrient uptake and nutrient removal amounts to produce 1,000 t of seeds from several authors in 40-years

Nutrient	Bataglia et al. (1977)	Cordeiro et al. (1979)	Bundy & Oplinger (1984)	Borkert (1986)	Flannery (1989)	Tanaka et al. (1993)	Osaki (1991)	Yamada (1999)	EMBRAPA (2011)	Present study
	Nutrient uptake (kg t^{-1} seeds)									
N	76.0	77.4	-	82.0	81.5	-	70.0	-	83.0	106.6
P	5.7	6.0	-	7.5	8.1	-	11.7	-	15.4	11.1
K	32.0	32.0	-	24.5	54.5	-	36.4	-	38.0	46.1
Ca	20.0	12.8	-	12.2	27.2	-	16.8	-	12.2	16.0
Mg	9.1	4.4	-	6.7	9.3	-	7.7	-	6.7	9.1
S	3.1	7.7	-	15.4	4.6	-	-	-	15.4	6.6
	Nutrient Removal (kg t^{-1} seeds)									
N	64.0	64.4	58.5	51.0	51.0	58.8	-	51.0	51.0	60.1
P	5.0	4.7	6.0	5.0	6.4	5.2	-	5.4	10.0	5.4
K	18.0	16.5	17.9	17.0	14.4	18.7	-	11.2	20.0	7.8
Ca	3.0	3.2	1.9	3.0	2.5	1.9	-	2.3	3.0	2.4
Mg	2.0	2.2	2.4	2.0	2.5	2.3	-	2.5	2.0	2.7
S	2.0	2.3	3.1	5.4	2.4	3.2	-	3.4	5.4	3.2

Significant differences (Mann-Whitney U test) in total nutrient uptake were observed between cultivars with determinate and indeterminate growth habits (Table 9). Cultivars with indeterminate growth habits presented higher uptake of all nutrients and an increased aboveground biomass. This information is important for the nutrient management of indeterminate growth cultivars because it indicates that they need higher amounts of nutrients for growth. Conversely, the ratio of nutrients translocated to the soybean seeds was similar for plants with both growth habits for most nutrients except P, Cu, Zn and B, which were translocated to the seed in higher amounts in the determinate growth cultivars, and Mn, which was translocated to the seed in higher amounts in the indeterminate growth cultivars. Therefore, the determinate growth cultivars presented higher nutrient use efficiency because they took up less nutrients and presented higher seed yields. The higher soybean seed yield and lower nutrient accumulation in the determinate growth cultivars may have resulted from lower biomass production, resulting in lower energy and nutrient expenditures by the plants and increased seed production (Fernandes & Souza, 2006). Soybean cultivars with indeterminate growth habits produce more nodes, fewer lateral branches, and fewer pods (Parvej, 2015; Parvez et al., 1989). Therefore, higher plant densities are needed to obtain satisfactory yields. However, this requirement results in higher energy and nutrient expenditures for stem formation, which account for up to 33% of the shoot dry mass and result in higher nutrient uptake requirements for nutrient allocation to the crop remains for the cultivars with indeterminate growth (Bender et al., 2015). There is evidence that cultivars with an indeterminate growth habit have an increased ability to recover from unfavorable growth conditions compared to cultivars with determinate growth habits (Kaschuk et al., 2016). The climate conditions during the present experiment were beneficial for soybean growth, and the cultivars with determinate growth presented higher average productivity than the cultivars with indeterminate growth (Table 10). In Brazil, farmers tend to use indeterminate growth soybean cultivars because their shorter crop cycles enable a second harvest, especially due to their higher resilience to water stress. Attention should be paid to their nutrient management because nutrient uptake is higher for these cultivars than for cultivars with determinate growth habits.

Table 9. Statistical analysis of soybean nutrient uptake and removal between determinate and indeterminate growth habit†

Nutrient	Nutrient uptake		P value	Nutrient removal		P value
	Determinate	Indeterminate		Determinate	Indeterminate	
N (kg t^{-1})	96	114	<0.001	61	61	0.989
P (kg t^{-1})	10	12	<0.001	5.4	5.2	0.016
K (kg t^{-1})	38	50	<0.001	7.5	7.9	0.456
Ca (kg t^{-1})	13	17	<0.001	2.4	2.5	0.146
Mg (kg t^{-1})	8.0	10.4	<0.001	2.6	2.7	0.806
S (kg t^{-1})	5.7	7.4	<0.001	3.2	3.2	0.192
Cu (g t^{-1})	20	23	0.002	10.9	9.8	0.007
Zn (g t^{-1})	92	119	<0.001	46	45	0.016
Fe (g t^{-1})	345	430	0.001	80	77	0.264
Mn (g t^{-1})	62	96	<0.001	23	25	0.007
B (g t^{-1})	70	93	<0.001	26	24	0.002
Seed yield (kg ha^{-1})	3655	3438	0.001	-	-	-
Biomass (kg ha^{-1})	5721	6523	<0.001	-	-	-

Note. † Mann-Whitney U test ($p < 0.05$).

4. Conclusion

The uptake of all nutrients, the aboveground dry biomass, and Ca translocation to the soybean seed were higher for cultivars with a shorter crop cycle. Potassium translocation to the soybean seed tended to decrease (45%). Nitrogen, P, and K uptake were higher than those in studies performed in the 1970s, 1980s, 1990s and 2000s due to genetic modification of cultivars to meet the demands of the production systems currently in use. Cultivars with determinate growth presented higher nutrient use efficiency. Because cultivars with indeterminate growth are becoming increasingly more common in intensive production systems, this factor should be considered in nutrient management to ensure that the amounts of nutrients applied meet the crop demands.

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