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NUTRIENT REMOVAL BY OFF-SEASON GRAIN SORGHUM AS AFFECTED BY INTERCROPPING WITH RUZIGRASS AND FERTILIZATION LEVELS IN THE BRAZILIAN CERRADO

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Abstract – Sorghum is an off-season crop option in succession to soybean in the Cerrado region, but many producers underestimate the fertilization requirement, which can harm the productive performance of the system as a whole. The objective of this study was to quantify the uptake and removal of nutrients by grain sorghum in monocropping or intercropping with ruzigrass (*Urochloa ruziziensis*), with three levels of NPK fertilization (control without fertilization; replacement fertilization; and replacement + 30%) in a soil with built-up fertility. The experimental design was randomized blocks with four replicates. Sorghum plants were sampled at 33, 67, and 130 days after sowing, corresponding to eight-leaf stage, flowering, and physiological maturity. Nutrient accumulation throughout the sorghum cycle and the respective uptake and removal rates were assessed. Intercropping with ruzigrass in soil with built-up fertility reduces grain yield but does not influence the accumulation of most nutrients by sorghum. Fertilization increases sorghum biomass and nutrient accumulation even under high-fertility conditions, but without impact on grain yield. In off-season sorghum crops, nutrient uptake occurs essentially during the vegetative stages. Each ton of grain produced removes the equivalent of 14.5, 5.0, 3.5, 1.1, and 0.5 kg of N, P_2O_5, K_2O, Mg, and S, in addition to 2, 2, 25, 9, and 11 g of B, Cu, Fe, Mn, and Zn, respectively. The potential for soil nutrient depletion by grain sorghum is comparable to the patterns of off-season maize, highlighting the need for sufficient fertilization to replace the withdrawal by harvesting.

Keywords: *Sorghum bicolor*, *Urochloa ruziziensis*, nutritional requirement, nutrient uptake, off-season crop.

REMOÇÃO DE NUTRIENTES PELO CULTIVO DE SORGO GRANÍFERO SEGUNDA SAFRA NO CERRADO, SOB INFLUÊNCIA DO CONSÓRCIO COM BRAQUIÁRIA E NÍVEIS DE ADUBAÇÃO

Resumo - O sorgo é opção na segunda safra em sucessão à soja na região do Cerrado, mas muitos produtores subdimensionam a adubação para o seu cultivo, o que pode prejudicar o desempenho produtivo do sistema como um todo. Objetivou-se quantificar a absorção e a exportação de nutrientes pelo sorgo granífero em cultivos exclusivo e consorciado com braquiária, com três níveis de adubação NPK (controle sem fertilização; adubação de restituição; e restituição + 30%), em solo com fertilidade construída. O delineamento experimental foi o de blocos casualizados, com quatro repetições. Foram amostradas plantas de sorgo aos 33, 67 e 130 dias após a semeadura, correspondendo aos estádios de oito folhas, florescimento e após a maturação fisiológica. Calcularam-se os conteúdos de nutrientes acumulados ao longo do ciclo e as respectivas taxas de extração e de exportação. O consórcio com braquiária em solo de fertilidade construída reduz a produtividade de grãos, mas não influencia no acúmulo de nutrientes pelo sorgo. A adubação incrementa a biomassa do sorgo e o acúmulo de nutrientes mesmo sob condições de alta fertilidade, porém, sem reflexos na produtividade. No sorgo segunda safra, a absorção de nutrientes ocorre majoritariamente durante a fase vegetativa. Cada tonelada colhida de grãos exporta o equivalente a 14,5; 5,0; 3,5; 1,1 e 0,5 kg de N, P_2O_5, K_2O, Mg e S, além de 2, 2, 25, 9 e 11 g de B, Cu, Fe, Mn e Zn, respectivamente. O potencial de remoção de nutrientes pelo cultivo de sorgo é comparável aos padrões do milho segunda safra, evidenciando a importância das adubações de restituição das quantidades exportadas na colheita, de modo a conservar a fertilidade do solo.

Palavras-chave: *Sorghum bicolor*, *Urochloa ruziziensis*, exigência nutricional, marcha de absorção, safrinha.

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Sequential season and off-season crops constitute an important modality of land use intensification in the Cerrado region and have expanded mainly for improving profitability to producers, besides favoring the maintenance of the no-tillage system with a more significant annual input of crop residues on the soil surface. Grain sorghum (*Sorghum bicolor* L. Moench) is an alternative commercial crop for the off-season in succession to soybean, generally used in areas with later sowing after the ideal window of climatic risk zoning for maize, which has been the preferred option. In these circumstances, sorghum's main advantage is its higher tolerance to water stress when compared to other grain crops (Silva et al., 2009; Santos et al., 2014; Devnarain et al., 2016; Asadi & Eshghizadeh, 2021).

As sorghum cultivation is carried out in periods with a greater scarcity of rainfall, which usually limits the productive potential, producers tend to work with less investment in crop management and fertilization. This behavior, at least in part, also stems from the spread of a mistaken perception that sorghum is suitable for cultivation in low-fertility soils because of being a more rustic plant (Menezes, 2015). However, studies evaluating crops under irrigation, with conditions favorable to the optimal development of sorghum, have demonstrated its high capacity to uptake nutrients from the soil (Borges et al., 2016, 2018). Thus it is reasonable to deduce that the nutritional requirement must be as higher as the greater the productive potential of the environment where sorghum is grown. Therefore, when the climatic conditions in the off-season are more favorable, the quantities of nutrients removed by the harvested grains may be greater than those applied by many producers in sorghum fertilization. Consequently, there would be proportional depletion of the nutrient reserves available in the soil until the impoverishment of the system negatively interferes with the performance of soybean in the following season. Howeveer, according to Menezes et al. (2015), this problem does not occur when the producer follows the technical recommendations for sorghum fertilization.

Nevertheless, producers often claim that sorghum cultivation depletes the soil, harming the subsequent crop. Therefore, a reduction of nutrient availability can be expected due to removal by harvest (Marcelo et al., 2009). However, undesirable effects can also be associated with other factors, such as the initial nitrogen deficiency related to microbial immobilization induced by the high C/N ratio of sorghum straw. Other factors are the physical effect of straw covering the soil surface and hindering seedling emergence or the presence of allelopathic substances (Nunes et al., 2003; Denadai et al., 2016; Biesdorf et al., 2018; Farooq et al., 2020). Therefore, there is still controversy about the actual causes of possible negative impacts of off-season sorghum on the development of the following crop in the area.

Introducing tropical forage grasses as cover crops have been recommended to increase ecological diversity for sustainable intensification in grain production systems. One of the techniques consists of intercropping ruzigrass with off-season maize or, less often, grain sorghum. There are proven benefits of ruzigrass for soil quality, nutrient cycling, and productivity of the subsequent soybean cultivation in the no-tillage system (Crusciol et al., 2015; Andrade et al., 2017; Resende et al., 2021). However, crop management to avoid loss of yield of the intercropped species still poses challenges (Mateus et al., 2020; Simão et al., 2021). One of the aspects refers to the likely need for greater fertilization to meet the requirement of the two intercropped crops so that there is no competition for nutrients.

In this context, studies that provide information on the magnitude of nutrient uptake by grain sorghum under different conditions of cultivation in the off-season are necessary to demystify subjective impressions and support nutritional management strategies that preserve the productive potential of the system. In the present study, the objective was to quantify the uptake and removal of nutrients by sorghum cultivated after soybean, as affected by the intercropping with ruzigrass and levels of NPK fertilization in Cerrado soil with built-up fertility.

Material and Methods

The study was conducted in a crop field at Fazenda Decisão, municipality of Unaí – MG, Brazil (16º24’49” S, 47º18’7” W, altitude of 990 m), in a very clayey Yellow Red Latosol (Oxisol), with high built fertility (Table 1), according to the interpretation criteria proposed by Sousa and Lobato (2004). The experimental area has been cultivated in no-tillage for about twenty years, under rainfed conditions, with high technological investment. In the 2017/2018 crop season, soybean yielded 4.9 t ha^{-1} and, in the off-season, pearl millet (*Pennisetum glaucum* L.) and crotalaria (*Crotalaria ochroleuca* L.) were sown in intercropping, as cover crops.

The experiments with levels of NPK fertilization for the soybean/off-season sorghum succession were set up in 2018/2019. The factors evaluated involved two-grain sorghum cropping systems (monocropped and intercropped with ruzigrass) and three levels of NPK fertilization (control without any fertilization; replacement of the amounts removed by grain harvest; and replacement plus 30%). The plant samplings were performed to determine the nutrient uptake by sorghum. The total quantities of N, P_2O_5, and K_2O applied in the soybean/sorghum succession in each fertilization treatment are presented in Table 1.

The monocropped and intercropped systems were established in two adjacent areas, in which the three levels of fertilization were applied, arranged in randomized blocks with four replicates, thus constituting two experiments that totaled 24 plots. On October 27, 2018, the soybean cultivar M6210 IPRO was sown at a rate of 320,000 seeds ha^{-1}, which produced an average of 4.6 t ha^{-1} of grains, with no response to fertilization treatments. On February 22, 2019, the early-cycle hybrid sorghum cultivar Enforcer was sown using 200,000 seeds ha^{-1}, with a spacing of 50 cm between rows. On this occasion, ruzigrass (*Urochloa ruziziensis*) was included in the experiment with the intercropping, sown broadcast at a rate corresponding to 450-500 pure live seeds per hectare, using a distribution device attached to the front of the tractor that pulled the sorghum seeder.

Large plots (30 x 150 m) were used, as sowing, fertilizer application, and pesticide spraying were carried out with machinery equipped with satellite guidance and variable-rate distribution devices. Thus, starter and top-dressing fertilizations had the doses automatically varied in the plots, according to treatments, through the mentioned mechanisms. Phosphate fertilizer (monoammonium phosphate) was distributed in the sowing furrow. Potassium fertilizer (potassium chloride) was broadcasted before soybean sowing and after the sorghum emergence at phenological stage 1 (Kochenower et al., 2010). In this stage, top-dressing nitrogen fertilization with ammonium nitrate was also performed.

The crop management involving pesticide applications was performed as needed, based on the

Table 1. Chemical and granulometric characterization of the soil before the experiments, and total of N, P_2O_5 and K_2O applied in the fertilization treatments for the soybean/off-season sorghum succession, 2018/2019, in Unaí – MG.

Parameters	Soil Analysis		
	0-10 cm		10-20 cm
pH_{water}	6.6		6.1
$P_{Mehlich\ 1}$ (mg dm^{-3})	38		23
K (mg dm^{-3})	183		157
Ca (cmol$_c$ dm^{-3})	5.2		3.3
Mg (cmol$_c$ dm^{-3})	1.8		1.1
Al (cmol$_c$ dm^{-3})	0.0		0.0
H + Al (cmol$_c$ dm^{-3})	2.2		3.6
Cation exchange capacity – CEC (cmol$_c$ dm^{-3})	9.7		8.3
Base saturation (%)	77		57
B (mg dm^{-3})	0.5		0.4
Cu (mg dm^{-3})	0.9		0.9
Fe (mg dm^{-3})	25		31
Mn (mg dm^{-3})	35		26
Zn (mg dm^{-3})	9		9
Soil organic matter – SOM (g kg^{-1})	41		34
S (mg dm^{-3})*	5		22
Sand (g kg^{-1})**	60		
Silt (g kg^{-1})**	270		
Clay (g kg^{-1})**	670		
	Fertilization treatments***		
	Control	Replacement	Replacement + 30%
N (kg ha^{-1})	0	95	123
P_2O_5 (kg ha^{-1})	0	96	125
K_2O (kg ha^{-1})	0	204	265

* Sulfur: 0-20 and 20-40 cm layers, respectively. ** Particle size: average values of the 20-40 and 40-60 cm layers. *** Total of N, P_2O_5 and K_2O supplied, considering the sum of soybean/sorghum succession.

technical recommendations for sorghum (Menezes, 2015). Rainfall in the period that comprised the cultivation is shown in Figure 1, indicating the times of sowing, top-dressing fertilization, and plant sampling.

Nutrient uptake was determined in a simplified manner by sampling plants at three moments of the sorghum cycle. The first sampling was carried out 33 days after sowing (DAS), in phenological stage 5, when the plants had eight expanded leaves. At this stage, four random plants, were cut near the soil surface, close to the central points of the plots

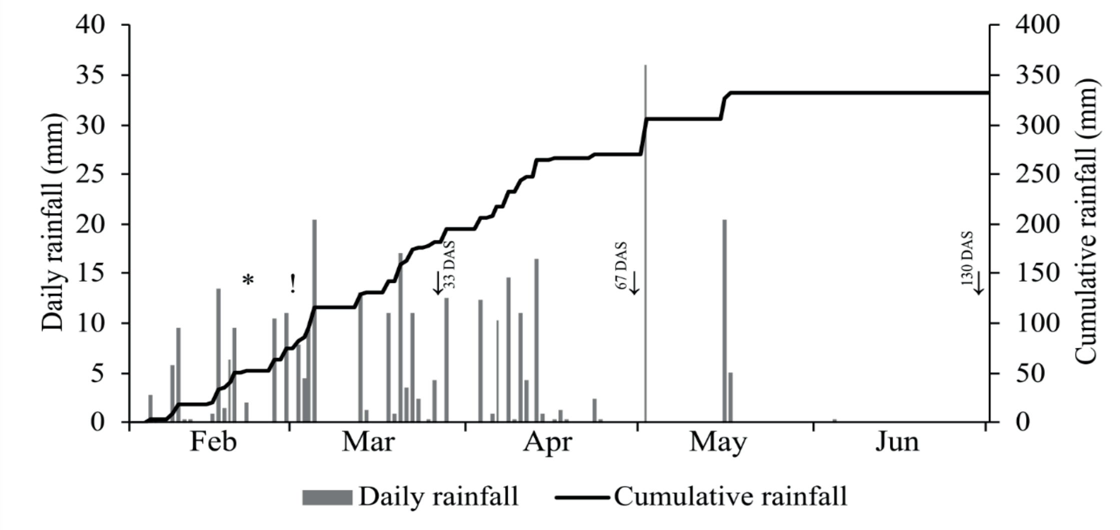

Figure 1. Daily and cumulative rainfall, from February to June 2019, in the experimental area of Fazenda Decisão. Unaí - MG. Symbology: *Sowing date; !Top-dressing fertilization with N and K; ↓Plant sampling for determining nutrient uptake; DAS – days after sowing.

(georeferenced), and processed without separating the leaves and stems. Then, at 67 DAS, phenological stage 10, corresponding to flowering, four other random plants were sampled around the central points of the plots. Afterward, the plants were fragmented into leaves, stems, and panicles. Finally, the last sampling was carried out after physiological maturity (stage 11.5), at 130 DAS, following the same procedures, except that the plants were separated into the compartments of leaves, stems plus rachis of panicles, and grains.

The plant compartments were quickly washed and dried in an oven at 65 °C until reaching constant weight. After being crushed in a knife mill, samples were analyzed for the concentrations of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn, according to the methodologies described in Silva (2009). The quantities of nutrients accumulated throughout the sorghum cycle were calculated considering the sampled compartments' dry biomass. The uptake was determined based on an average final stand of 178,500 plants per hectare. P and K uptake results were multiplied by 2.29 and 1.20, respectively, to express their equivalents in P_2O_5 and K_2O.

Grain yield was evaluated from the manual harvest of panicles in three 3-m long rows in the central portion of the plots, being expressed with moisture corrected to 13%. The harvest index was calculated by the relationship between the dry mass of grains and the total shoot dry mass of the plants sampled to evaluate the nutrient uptake.

The sorghum biomass and grain production data and total nutrient uptake at the end of the cycle were subjected to joint analysis of variance of the experiments with and without ruzigrass in intercropping. The significance of the sources of variation effects was assessed by the Fisher test ($p < 0.05$), and the means were compared by the Tukey test ($p < 0.05$).

Rates of nutrient uptake and removal per ton of harvested grains were calculated and correlated with yield. The nutrient requirements of sorghum were compared to those of maize, considering the removal values of off-season maize (Duarte et al., 2019). The relative removal and the difference in the amounts removed for a 6 t ha^{-1} yield were calculated by equations 1 and 2, respectively:

Equation 1:

$$\text{Relative nutrient removal (\%)} = \frac{\text{(Sorghum removal rate - Maize removal rate)}}{\text{Maize removal rate}} \times 100$$

Equation 2:

Removal difference (kg macronutrient or g micronutrient for 6 t ha^{-1} of grains) = (Sorghum removal rate x 6) - (Maize removal rate x 6)

Results and discussion

The intercropping with ruzigrass interfered in sorghum development, leading to significantly lower total shoot biomass production and grain yield than monocropping (Tables 2 and 3).

The low stature of grain sorghum plants, from 135 to 150 cm in height, measured at the flowering, allows light to enter the canopy, which favors ruzigrass, whose growth is stimulated by light intensity (Borghi et al., 2013), thus resulting in greater interspecific competition in the intercropping. The harmful effect found here diverges from the findings of studies (Crusciol et al., 2011; Mateus et al., 2011) that reported no reduction in the yield of sorghum intercropped with *Urochloa brizantha* (Marandu). However, in these studies, the maximum grain yield (6.2 t ha^{-1}) was still below the lowest average recorded among the treatments in the present study (7.3 t ha^{-1}), suggesting that competition may be more critical for reaching higher yield levels.

The increase in NPK fertilization did not compensate for the competition exerted by ruzigrass. Thus, the negative effect on the total biomass production and grain yield of sorghum in intercropping was not mitigated, denoting that the limitations were mainly due to competition for light or water. Contrasting, in monocropping, the total biomass production was higher with the increase in fertilization, but without resulting in a significant increment in grain yield, despite the difference of about 1.0 t ha^{-1} observed between the control and the replacement + 30% treatment (Table 3).

In this study, the average grain yield was higher than 8.0 t ha^{-1}, ranging from 7.3 to 9.2 t ha^{-1}, which corresponds to an outstanding performance for the off-season sorghum under rainfed conditions. This result confirms the favorable soil fertility conditions in the experimental area since the average yield of Minas Gerais State in the last five seasons ranged from 2.9 to 3.9 t ha^{-1} (Conab, 2021). Although the crop received only 279 mm of rain in the period between sowing and physiological maturity (Figure 1), the reserve of water available in the clay soil was probably sufficient to complete the water requirement of grain sorghum, which is about 400 mm (Albuquerque & Andrade, 2015). Therefore, the nutrient uptake patterns determined in the present study can be considered representative of crop fields with an excellent technological level in the Cerrado region.

The biomass partition among the plant compartments at the end of the cycle showed that the highest proportion of nutrients and photoassimilates was directed to grain formation (Figure 2), corresponding to an average harvest index of 0.55. This value is higher than the average index of 0.26 recorded by Goes et al. (2011) in a study on sorghum response to nitrogen fertilization in the off-season

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Table 2. Summary of the joint analysis of variance of the experiments (systems) with and without ruzigrass in intercropping , and NPK fertilization treatments, for grain yield, total shoot dry biomass and equivalent contents of macro- and micronutrients in the biomass of sorghum, in off-season cultivation, in Unaí – MG.

Source of Variation	D. F.	Mean Square							
		Grains	Biomass	N	P_2O_5	K_2O	Ca	Mg	S
System (S)	1	8679825.8**	5078317.2*	1296.5	119.0	711.4	0.72	8.9	0.33
Block [System]	6	125265.3	298398.4	205.3	42.5	65.6	2.41	32.6	0.13
Fertilization (F)	2	708927.8	3647814.9*	1560.0	179.3*	3085.6*	12.9	6.5	1.83*
S x F	2	443005.6	1488386.9	412.6	31.7	341.5	40.5**	133.3*	0.64
Error	12	383489.1	885128.1	1278.6	45.1	790.2	6.2	24.1	0.39
Mean (kg ha^{-1})		8077.2	12884.9	163.7	48.0	192.9	21.4	23.8	6.5
C.V. (%)		7.67	7.30	21.85	13.99	14.57	11.62	20.63	9.56

		B	Cu	Fe	Mn	Zn
System (S)	1	8.6	12.2	7892094.2**	3060.7	1658.0
Block [System]	6	54.8	232.3	368847.2	1157.0	3648.5
Fertilization (F)	2	188.9	914.4*	2482296.2*	425.9	18929.8*
S x F	2	254.6	225.8	2576553.8*	3576.7	2092.4
Error	12	69.5	225.5	507933.4	1599.3	4461.3
Mean (g ha^{-1})		58.9	47.7	1641.6	139.9	219.4
C.V. (%)		14.17	31.49	43.42	28.58	30.45

* and ** = significant at 5% and 1% probability levels by the F test, respectively.

Table 3. Total shoot dry biomass production and grain yield of sorghum cultivated in the off-season, under NPK fertilization levels, in monocropping or intercropping with ruzigrass.

Fertilization	Shoot biomass			Grains		
	Monocropping	Intercropping	Mean	Monocropping	Intercropping	Mean
	------------	------------	------------ kg ha^{-1}	------------	------------	------------
Control	12,133 bA	12,208 aA	12,171 b	8,148 aA	7,474 aA	7,811 a
Replacement	13,658 abA	12,284 aA	12,971 ab	8,702 aA	7,343 aB	8,022 a
Replacement + 30%	14,244 aA	12,783 aB	13,513 a	9,186 aA	7,611 aB	8,399 a
Mean	13,345 A	12,425 B	12,885	8,679 A	7,476 B	8,077

Means followed by the same lowercase letter in the column and uppercase letter in the row do not differ from each other by Tukey test at 5%.

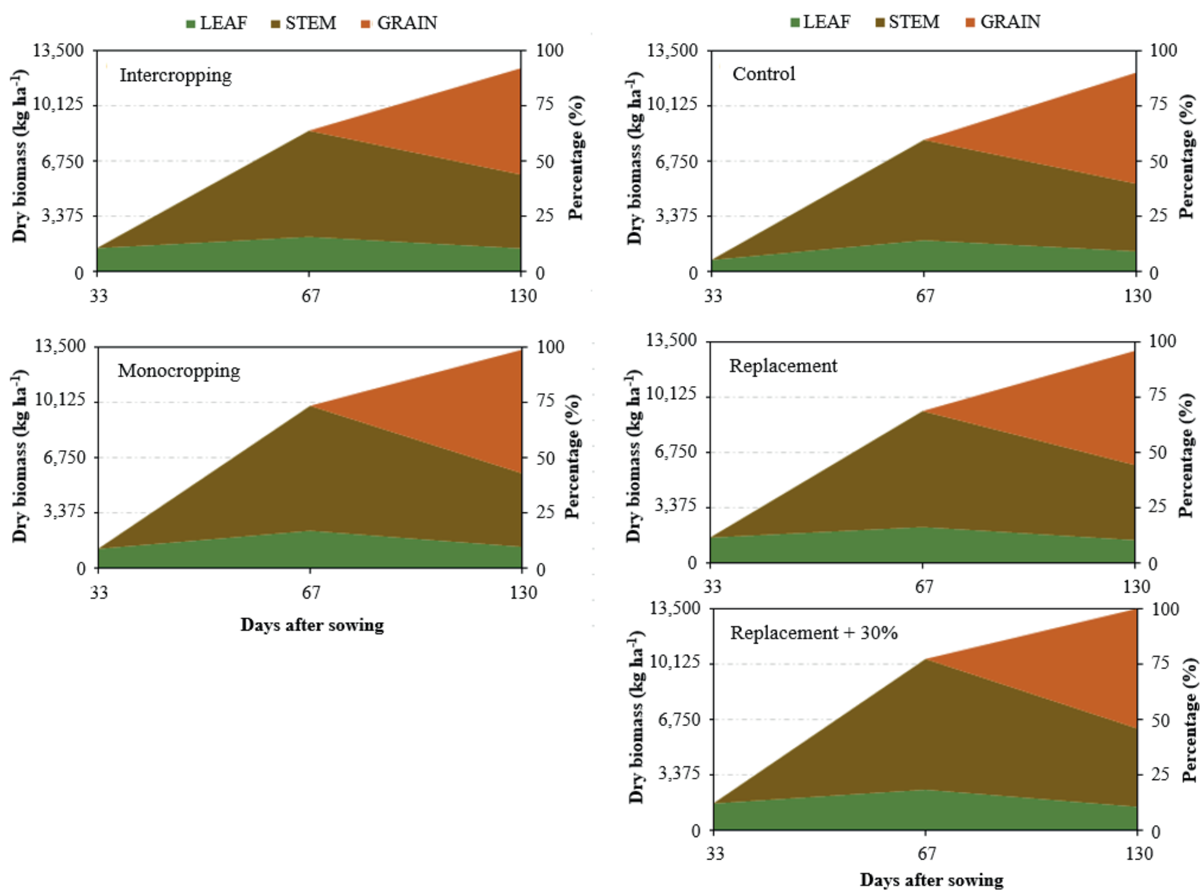

Figure 2. Dry biomass accumulation in shoot components along the sorghum cycle and percentage in relation to the total accumulation, when monocropped or intercropped with ruzigrass, and under fertilization treatments. Unaí – MG.

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and the index of 0.48 obtained by Borges et al. (2018), under irrigation in Northern Minas Gerais.

The nutritional requirement of sorghum, given by the nutrient accumulation quantified at the end of the cycle, was influenced variably by the treatments, according to the nutrient in question (Table 2). The uptake of N and equivalents in P_2O_5 and K_2O during the cycle are shown in Figure 3. There was no effect of the intercropping with ruzigrass or fertilization levels on N uptake by sorghum, which was increasing until physiological maturity, totaling, on average, 164 kg ha^{-1} of N in the last sampling (Figure 3). Indeed, the N credits from previous soybean cultivation contributed to minimizing possible differences, even regarding the control treatment without fertilization. Duarte et al. (2017) indicated a credit estimate on the order of 17 kg of N per ton of grains produced by the soybean, which would correspond to approximately 78 kg ha^{-1} of N derived from the crop preceding sorghum. Therefore, the remaining sorghum nutritional requirement could be met by soil-N in the control treatment and soil-N plus fertilizer-N in the fertilized treatments.

Until the flowering stage (67 DAS), 83% of N uptake occurred. This significant proportion can be attributed, in part, to the low volume of rainfall received after this stage (Figure 1), restricting nutrient absorption due to reduced soil moisture. As a result, about 71% of the N accumulated in shoots was translocated to grains (117 kg ha^{-1}), with a corresponding decrease in the leaves and stem levels (Figure 3, Table 4).

Phosphorus and potassium uptake by sorghum was not affected by the intercropping with ruzigrass, only by NPK fertilization (Table 2), being lower in the control treatment and not differing between replacement fertilization and replacement + 30%. At flowering, the accumulation was maximal in the case of P and reached 80% for K (Figure 3, Table 4). The mean values of total uptake corresponded to 48 kg ha^{-1} of P_2O_5 and 193 kg ha^{-1} of K_2O (or 21 kg ha^{-1} of P and 161 kg ha^{-1} of K).

Phosphorus was translocated in more significant proportion to the grains, which accumulated, on average, 83% of the total extracted by sorghum, equivalent to the removal of 40 kg ha^{-1} of P_2O_5 at harvest. Potassium, in turn, was the nutrient extracted in the most significant quantity, but only 14% was mobilized to the grains, which is equivalent, on average, to the removal of 28 kg ha^{-1} of K_2O. The internal dynamics of these two nutrients in the sorghum plant were similar to the patterns observed in maize (Silva et al., 2018), with a large proportion of P being removed in the grain harvest, while K remains mainly in the stover, and the stem is the main reserve compartment (Figure 3). Thus, sorghum stover represents a significant stock of K for cycling in the field, with the potential to meet a large part or even the total requirement of the subsequent crop.

Despite the significant effects observed in the analysis of variance, the accumulation of secondary macronutrients (Ca, Mg and S) and micronutrients (B, Cu, Fe, Mn, and Zn) showed less consistent trends in response to the treatments in addition to a high coefficient of variation in some cases (Table 2). Thus, the results are discussed below, presenting the average behavior in the experiments.

Among these nutrients, at least 70% of the total uptake occurred until the flowering stage, reaching 100% for S and Zn. The element removed in a minor proportion in grain harvest is Fe (12% of the total content), while S removal reaches 60% (Figure 4, Table 4).

As already mentioned, with the decrease in rainfall after flowering, the lack of moisture in the

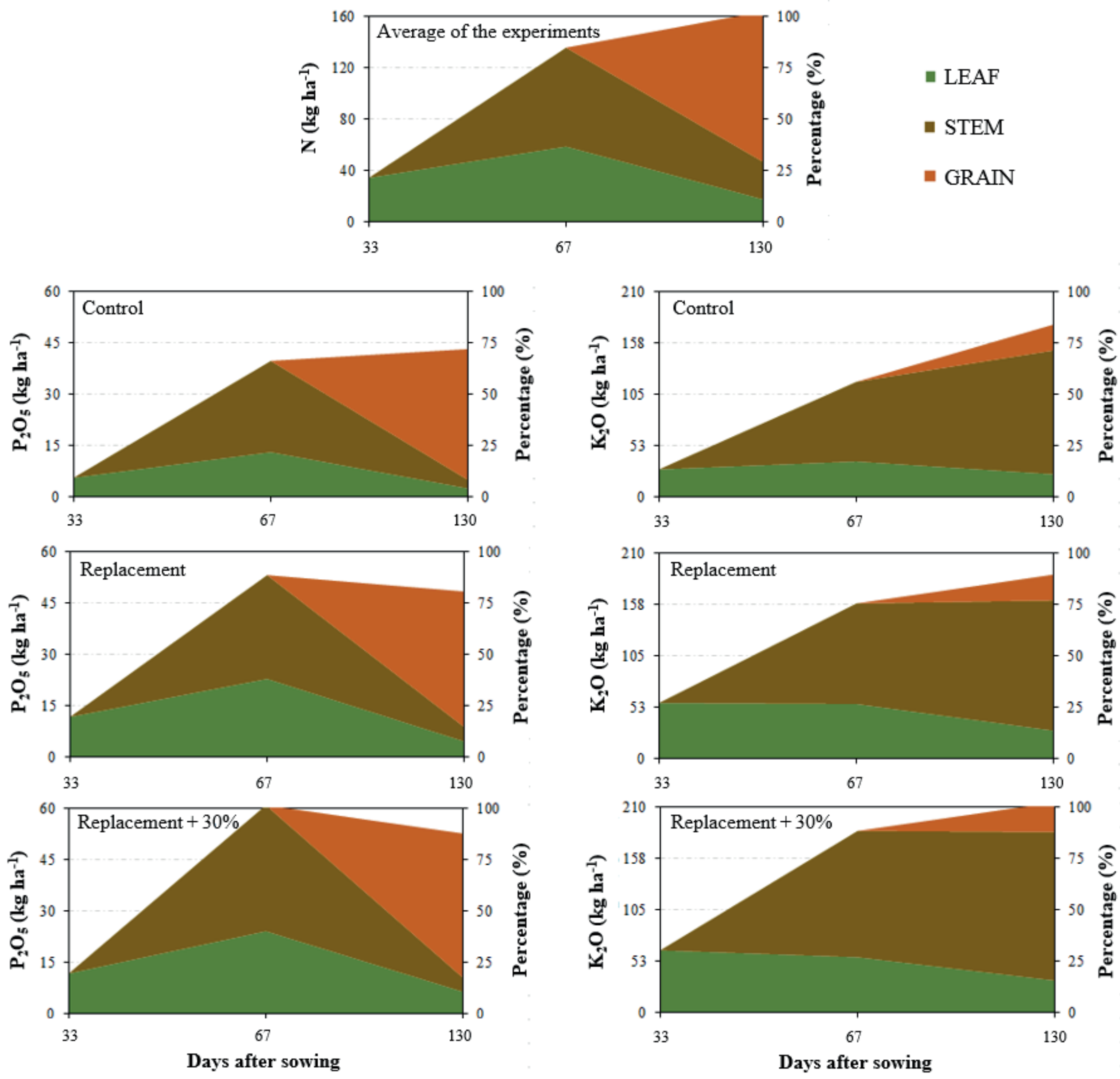

Figure 3. Accumulation of N and equivalents in P_2O_5 and K_2O in shoot components along the sorghum cycle and percentage in relation to the total accumulation. N: overall average response. P_2O_5 and K_2O: response to fertilization treatments on average of the monocropped and intercropped systems. Unaí - MG. To convert P_2O_5 into P and K_2O into K, divide the values by 2.29 and 1.20, respectively.

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Table 4. Indices related to nutrient uptake and removal by sorghum cultivated in the off-season in Unaí - MG, correlations with grain yield, and comparison with the nutrient requirements of off-season maize.

Nutrient	Proportional uptake until flowering	Proportional removal in grains	Uptake rate	Removal rate	Uptake rate x yield correlation	Removal rate x yield correlation	Relative removal compared to maize****	Removal difference compared to maize****
Macronutrients	(%)		(kg t^{-1} of grains)				(%)	(kg per 6 t of grains)
N	83	71	20.3	14.5	-0.47	-0.27	11	8.3
P_2O_5*	100**	83	6.0	5.0	-0.19	-0.11	3	0.7
K_2O*	80	14	23.9	3.5	-0.67	-0.52	-5	-1.0
Ca	80	33	2.6	<1.0***	-0.41	0.10	-	-
Mg	87	36	2.9	1.1	-0.45	-0.60	-4	-0.3
S	100**	60	0.8	0.5	-0.56	-0.51	-46	-2.5
Micronutrients	(%)		(g t^{-1} of grains)				(%)	(g per 6 t of grains)
B	87	32	7	2	-0.45	-0.01	-37	-8
Cu	82	36	6	2	-0.28	-0.23	11	1
Fe	70	12	203	25	-0.56	-0.70	86	68
Mn	91	53	17	9	-0.65	0.11	95	27
Zn	100**	42	27	11	-0.10	-0.11	-36	-39

* To convert P_2O_5 into P and K_2O into K, divide the values by 2.29 and 1.20, respectively.

** Value obtained at flowering higher than that quantified in sampling after physiological maturity.

*** Below the limit of detection by the laboratory calibration. Ca concentration in sorghum grains is usually low, with 0.18 kg t^{-1} as a reference value (Menezes, 2015).

**** Considering reference values of nutrient removal by maize cultivated in the off-season, means of 91 grain samples from experiments involving different cultivars, sites and years of cultivation (Duarte et al., 2019).

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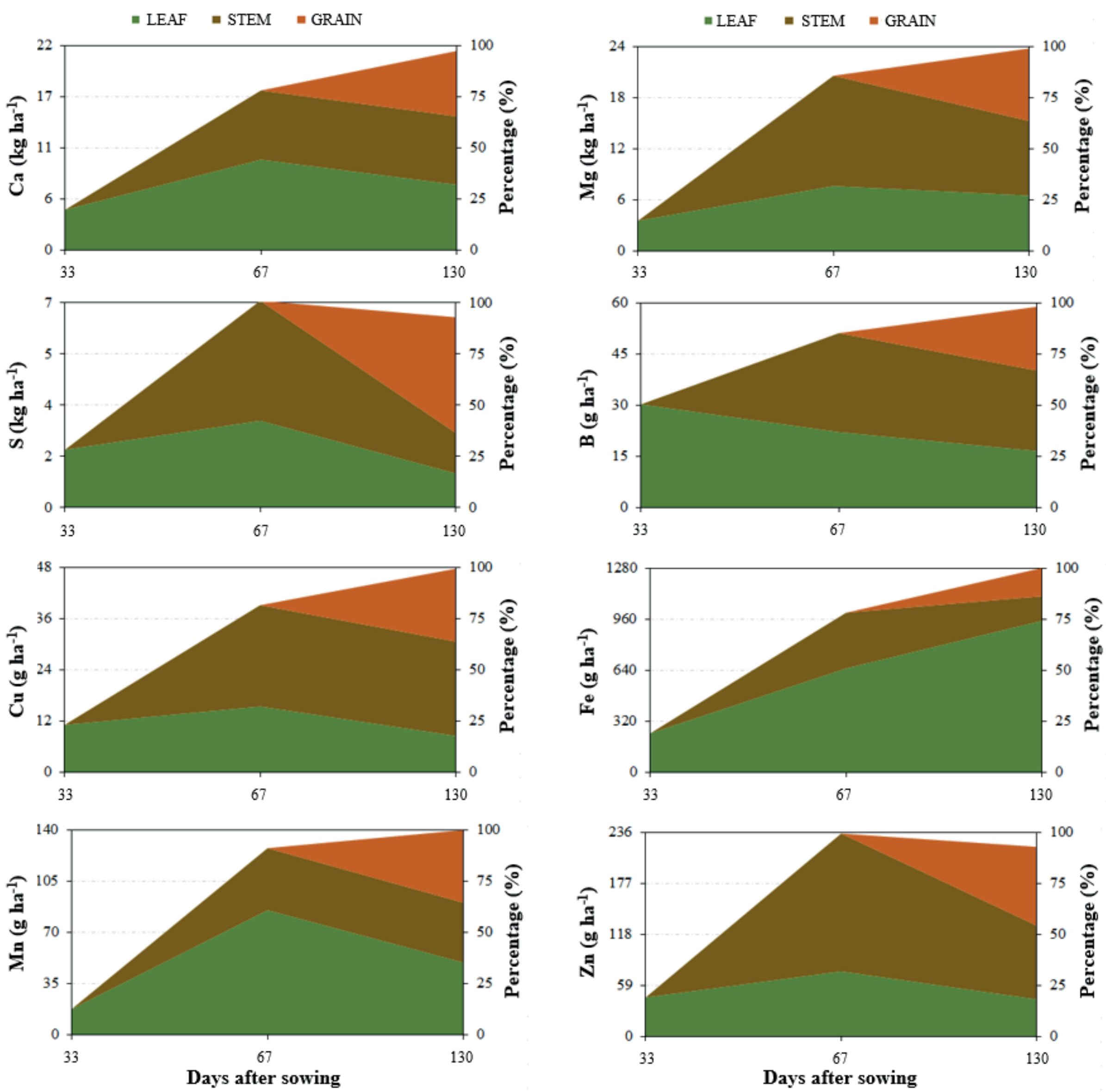

Figure 4. Accumulation of Ca, Mg, S, Cu, Fe, Mn and Zn in shoot components along the sorghum cycle and percentage in relation to the total accumulation. Average response in the experiments. Unaí - MG.

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soil limits root absorption in more advanced stages of plant development, even if there are nutrient reserves in the soil. In this case, the grain yield fundamentally depends on the nutrients accumulated in the vegetative stages. This aspect is evidenced by the decrease in the contents of secondary macronutrients and micronutrients (except Fe) in leaves and stems, between flowering and the end of the cycle, with concomitant mobilization for grain formation (Figure 4). Therefore, soil fertilization should be completed in the early stages of vegetative development for off-season sorghum, considering that late applications will be less efficient.

The uptake and removal of nutrients for each ton of grain produced in the present study (Table 4) were generally close to or lower than the values indicated by Menezes (2015), based on the behavior of the hybrid BRS 330 and grain yield of 6.0 t ha^{-1}. The present case observed higher uptake rates only for K and Cu. The uptake and removal levels of all macronutrients were also substantially lower than those of Borges et al. (2018) for the hybrid DKB 599, which produced 6.4 t ha^{-1} of grain under irrigation in Northern Minas Gerais. These divergences in results are not surprising, as variations in nutrient absorption are expected due to differences between cultivars, environments, and growing seasons, in addition to the fertilization used.

There was no correlation between uptake and removal rates and yield (Table 4), although yield varied from 7.3 to 9.2 t ha^{-1}. The absence of correlation denotes a certain constancy of these rates within this yield range, suggesting that, in the absence of local information, they can serve as indicators for nutrient balance calculations and definition of replacement fertilization in Cerrado soils with built-up fertility.

The nutritional requirement of sorghum is significant, reflecting patterns comparable to those of off-season maize, with proportionally higher removal rates for N, Cu, Fe, and Mn, similar rates for P, K and Mg, and lower rates for S, B, and Zn (Table 4). It can be verified that, for most nutrients, replacement levels for sorghum cultivation should not be below those recommended for maize, based on the potential for nutrient removal in the harvest of 6 t ha^{-1} of grains of both crops (Table 4).

Sorghum is recognized as more tolerant to water stress than other grain crops, being convenient for cultivation in periods of lower intensity and regularity of rainfall (Silva et al., 2009; Santos et al., 2014; Asadi & Eshghizadeh, 2021). However, it is mistakenly regarded as suitable for low-fertility soils (Menezes, 2015). As Resende et al. (2009) mentioned, the characteristic of sorghum's rusticity does not mean its nutritional requirement is low, especially when the goal is to obtain a high yield. The results observed here reinforce the importance of the correct fertilization strategy to replace the amounts of nutrients removed by sorghum so that its cultivation does not cause soil depletion or compromise the yield potential of subsequent crops and the system's performance as a whole.

Conclusions

Intercropping with ruzigrass in soil with built-up fertility interferes in sorghum development, resulting in lower biomass and grain production, but does not influence the accumulation of most nutrients. An increase in fertilization does not mitigate the effects of the competition exerted by ruzigrass.

Fertilization increases biomass production and accumulation of nutrients such as P and K by sorghum, even under high-fertility conditions, but with no effects on grain yield.

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From 70 to 100% of the accumulation of macro and micronutrients occurs until flowering, highlighting that nutrient uptake takes place essentially during the vegetative stages in the off-season sorghum.

For every ton of grain produced, the respective total uptake and removal of macronutrients (kg) and micronutrients (g) are N (20.3 and 14.5), P_2O_5 (6.0 and 5.0), K_2O (23.9 and 3.5), Mg (2.9 and 1.1), S (0.8 and 0.5), B (7 and 2), Cu (6 and 2), Fe (203 and 25), Mn (17 and 9), and Zn (27 and 11).

The proportional removal by grain harvest is higher for P, N, S, Mn, and Zn, corresponding to 83, 71, 60, 53, and 42% of the total accumulated in the shoot.

The potential for soil nutrient depletion by grain sorghum is comparable to the patterns of off-season maize, highlighting the need for sufficient fertilization to replace the withdrawal by harvesting in order to preserve soil fertility.

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