https://doi.org/10.1590/1678-992X-2023-0011

ISSN 1678-992X

Scientia Agricola

Research article

Decomposition of sorghum, grass, and sorghum intercropped with grass and soybean performance in integrated systems in the Cerrado

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Edited by: Lincoln Zotarelli

Received February 11, 2023
Accepted July 19, 2023

ABSTRACT: Previous cultivation of sorghum (*Sorghum bicolor*), Congo grass (*Urochloa ruziziensis*), and palisade grass (*Urochloa brizantha* cv. 'Marandu') may influence soybean (*Glycine max*) agronomic performance. The present work evaluated the decomposition of sorghum, grass, and sorghum intercropped with grass in the off-season to improve soybean yield in integrated crop systems in the Brazilian Cerrado and their dry matter production. This study was conducted in Planaltina, DF, in Central-West Brazil, on a Typical Acrustox soil from Mar 2010 until Feb 2012. The experimental design was a randomized block, with six crop systems before soybean: fallowing, sorghum, palisade grass (alone or intercropped with sorghum), and Congo grass (alone or intercropped with sorghum) with four replicates. Soybean agronomic performance, the crop systems' dry mass, and its decomposition rate were estimated over two years. Higher soybean grain yields were observed in cropping systems including Congo grass alone (3,349 kg ha^{-1}) or intercropped with sorghum (3,317 kg ha^{-1}). Sorghum intercropped with palisade grass produced 18,702 kg ha^{-1} of dry matter and 64.9 % (on average) of soil coverage during the soybean cycle. However, the highest lignin content was observed in sorghum intercropped with Congo grass (5.1 % on average). The results indicate that the cultivation of Congo grass, either alone or intercropped with sorghum, improves the agronomic performance of soybean in succession, compared to sorghum alone or palisade grass (alone or intercropped with sorghum). The intercropped systems provided the best nutrient efficiency use aiming at sustainable agriculture in the Cerrado region.

Keywords: *Glycine max*, *Urochloa*, integrated plant production, nutrient cycle, straw

Introduction

Intercropping systems under no-tillage during the dry season can increase soil surface coverage with amounts of residues, positively affecting the summer crop in the Brazilian Cerrado. Studies of plant species and crop systems which support water stress during the Cerrado off-season and provide a large amount of organic residues for the following crops are necessary (Ferreira et al., 2018; Oliveira et al., 2020) because of the potential benefits to soil physical protection and quality (Nascimento et al., 2019), and chemical and microbiological soil properties (Soares et al., 2019; Pavei et al., 2021).

Sorghum (*Sorghum bicolor* L. Moench) shows good perspectives for plant residue production prior to soybean (*Glycine max* L.) as the summer crop because of its higher accumulated biomass and tolerance to water stress (Borges et al., 2018). It can also be intercropped as an alternative to grazing during low pasture availability (Santos et al., 2018a). Furthermore, it produces good dry matter levels in integrated crop systems when cultivated with palisade grass (*Urochloa brizantha* cv. 'Marandu' (Hochst. ex A. Rich). R. D. Webster) (Nakao et al., 2018). Another forage that can be used for phytomass production, soil coverage, and intercropped with sorghum is Congo grass (*Urochloa ruziziensis* (R. Germ. and Evrard) Crins), on account of its adaptability to low rainfall in the off-season (Sousa Junior et al., 2020).

Decomposition dynamics of plant residues in tropical regions is essential due to the high temperatures that greatly accelerate this process (Muniz et al., 2021). The quantity of plant residues left on the soil – and its quality – must be considered when choosing the integrated crop systems since they influence the process of decomposition (Catuchi et al., 2019; Carvalho et al., 2023), improve soil physical and biological conditions, as well as facilitate nutrient cycling (Soares et al., 2019; Soratto et al., 2019).

Thus, the knowledge of the decomposition rate of sorghum, palisade grass, and Congo grass is necessary to adapt their use during the dry season before soybean in the summer. Crop rotation systems, including these species, have potential benefits for both pasture and companion crops (Muniz et al., 2021), especially for the recovery of degraded pasture soils, which are widespread in the Cerrado (Ayarza et al., 2022).

We hypothesized that plant residues of sorghum, grasses, and sorghum intercropped with grasses could improve soybean performance cultivated in integrated crop systems in the Brazilian Cerrado.

Materials and Methods

The study was conducted in Planaltina, Distrito Federal, Brazil, in an experimental area of Embrapa Cerrados (15°35′ S, 47°42′ W, 1,008 m altitude) on a Typical Acrustox soil (Soil Survey Staff, 2014). The climate is tropical Aw (Köppen), characterized by rainy summers and dry winters, and the average annual temperature from 22 °C to 27 °C (Alvares et al., 2013). The area was left fallow for two years before the experiment. Soil analysis in the: i) 0-0.2 m layer indicated 2.5 g kg^{-1} of organic matter; pH of 5.8 in water; 6.5 mg dm^{-3} of available P, and 52.4 mg dm^{-3} of available K (both extracted by Mehlich); 0.1, 2.8, and 0.9 cmol$_c$ dm^{-3} of exchangeable Al, Ca, and Mg respectively (extracted by KCl mol L^{-1}); 8.5 cmol$_c$ dm^{-3} CEC at pH 7.0, and 45 % base saturation; 334.7, 563.4, and 101.8 g kg^{-1} of sand, silt, and clay respectively; ii) 0.2-0.4 m layer: 2.1 g kg^{-1} of organic matter; pH of 5.7 in water; 1.1 mg dm^{-3} of available P, and 31.2 mg dm^{-3} of available K; 0.3, 2.0, and 0.6 cmol$_c$ dm^{-3} of exchangeable Al, Ca, and Mg respectively; 8.2 cmol$_c$ dm^{-3} CEC at pH 7.0, and 34 % base saturation; 365.5, 531.0 and 103.4 g kg^{-1} of sand, silt, and clay, respectively. Meteorological data (accumulated rainfall and air temperatures) were registered during the years of the experiment (Figure 1).

Experimental design and treatments

The experiment was performed in a randomized block design with four replicates. The treatments comprised six off-season cropping systems over two agricultural years: fallow; sorghum; palisade grass; Congo grass; sorghum intercropped with palisade grass; and sorghum intercropped with Congo grass. The dimensions of the plots were 5 × 8 m, with a useful area of 28 m^2 in each plot, totaling 1,120 m^2 of experimental area.

On 15 Mar 2010 and 17 Mar 2011, the treatments were sown under no-tillage system with a drag seeder, under row spacing of 0.5 m for grain sorghum 'BRS 304' (population of 300,000 plants ha^{-1} of this short-height and tannin-free hybrid), and in a row spacing of 0.25 m for palisade and Congo grass, at a rate of 14 kg of pure and viable seeds ha^{-1}, simultaneously sown with sorghum in

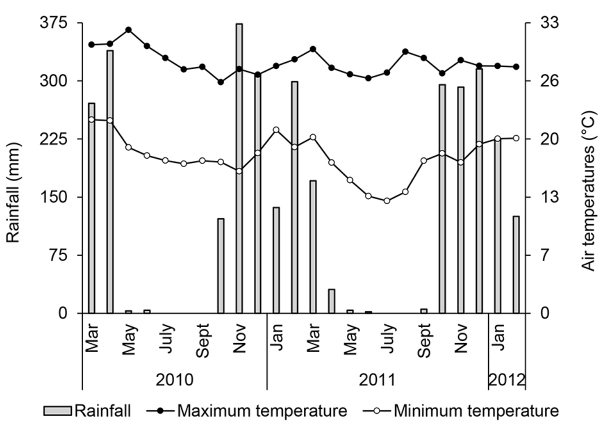

Figure 1 – Monthly accumulated rainfall and air temperatures (minimum and maximum) during the experimental period in Planaltina, DF, Brazil. Air temperatures measurement at 2-m height.

the intercropped systems, but not at the same crop lines. NPK 30-10-20 was applied in the sowing lines at a rate of 200 kg ha^{-1}, and 15 days after sowing, 50 kg ha^{-1} of urea was also distributed on the soil surface. On 30 June 2010 and 13 July 2011, sorghum was harvested. When the rainy season began (23 Sept 2010 and 15 Sept 2011), forage grasses and natural vegetation were desiccated using glyphosate (1,800 g of acid equivalent ha^{-1}, at a spray volume of 400 L ha^{-1}).

On 13 Oct 2010 and 10 Oct 2011, soybean 'BRS Favorita RR' was sown in a row spacing of 0.5 m (population of 320,000 plants ha^{-1}) under a no-tillage system using 400 kg ha^{-1} of NPK 00-20-20. Soybean seeds were treated with a peat-based powder with *Bradyrhizobium japonicum* (SEMIA 5079 and SEMIA 5080) using 500 g of product per 50 kg of seeds. At 28 days after soybean emergence (DAE), glyphosate was sprayed on all plots (1,800 g of acid equivalent ha^{-1}, at a spray volume of 400 L ha^{-1}). Pesticides were also sprayed to prevent the occurrence of diseases and pests. At 128 DAE, by the beginning of the R8 stage (grain drying in the pods and senescence of the leaves), soybean was desiccated with paraquat (400 g of active ingredient ha^{-1}, at a spray volume of 200 L ha^{-1}).

Soybean nutrient contents in the shoot, height, and grain yield

In Dec of both years, 20 soybean plants were collected from each plot to determine nutrient contents in the shoot at the flowering stage, at 59 DAE (stage R2 – completely flowering). In Feb, at 133 DAE, soybean's height was measured in five central rows of the plots. The grain yield was sampled in the same rows. Moisture content was adjusted to 13 % (wet basis) to obtain the weight of 100 grains and the grain yield.

Dry matter yield

Dry matter of sorghum plants was estimated in July of both years at 100 days after emergence (DAE), before its harvesting; grasses and natural vegetation (fallowing system) in Sept, at 166 DAE and before their desiccation; soybean plants in Dec, at 59 DAE. All plants were collected within 1-m^2 area in each plot for these purposes. Plants were dried at 60 °C for 72 h and weighed.

Decomposition and crop residues analyses

The dry sorghum, grasses, and natural vegetation materials were placed in 2-mm mesh nylon bags to calculate the decomposition rate during the rainy season. Each 0.2 × 0.2 m bag containing 20 g of dry plants was placed on the soil surface, according to the corresponding treatment. The bags representing the intercropping systems with sorghum and grasses contained 10 g of sorghum and 10 g of grass. Each plot comprised ten bags placed on the soil surface right after the soybean sowing operation, and the collections –

from 30 to 135 days after – took place over five months during the rainy season (spring/summer).

At each collection time, the plant residues were removed from the bags, dried for 72 h at 60 °C and weighed. After that, they were incinerated for 8 h in a muffle at 600 °C to determine the final inorganic content. The decomposed organic matter of the plant residues (*D* %) on the soil was obtained using the method described by Santos and Whitford (1981). Next, the remaining residues were calculated being the difference between the initial plant mass amount, considered as 100 %, and each rate per sampling period: 100 % – *D* %.

The composition of the cell wall of plant residues was analyzed for neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin (L) by the sequential method adapted from Robertson and Van Soest (1981). The hemicelluloses and cellulose contents were calculated as the difference between them: *NDF* – *ADF* and *ADF* – *L*, respectively.

Moreover, 1 g samples of soybean plants and plant residues were ground in a mortar and sieved (0.2-mm mesh) for subsequent determination of the total macronutrients by atomic absorption spectrophotometer (EMBRAPA, 2009). The Kjeldahl method was used to determine the total N concentration. The contents of N, P, and K released from the residues of the off-season crops during the flowering stage of soybean were used to estimate the fertilizer equivalents of N, P_2O_5, and K_2O (Dias et al., 2020).

Data analyses

Soybean and off-season crop data were analyzed using the general model Eq. (1).

$$y_{ijk} = \mu + S_i + U_j + C_k + e_{ijk} \tag{1}$$

where y_{ijk} = the response variable; μ, S_i, U_j, C_k, the general mean, the block effect, the year effect, and the treatment effect, respectively, and e_{ijk}, the experimental error (difference of plots within the same block), in which $e \sim N(0, \sigma^2)$, when null effects could be considered.

The t-test used the PROC GLM in SAS (Statistical Analysis System, version 9.3). The scheme was a factorial in a classical randomized block model with two levels of years and six levels of treatments, in which residuals are assumed to be normally distributed.

Plant residue data were analyzed using the general model Eq. (2).

$$y_{ijkl} = \mu + S_i + U_j + T_k + C_l + TC_{lk} + e_{ijkl} \tag{2}$$

where y_{ijkl} = the response variable; μ, S_i, U_j, T_k, C_l, TC_{ijkl}, the general mean, the block effect, the year effect, the time effect, the treatment effect, the time and treatment interaction respectively, and e_{ijkl}, the experimental error (difference of plots within the same block), in which $e \sim N(0, V)$, where V is the covariance matrix used to model the error dependence, since in experiments with repeated measures over time the assumption of error independence is relaxed. To choose the parameterization of V, the correlation matrix between times of collection (from 0 to 135 days) was calculated, and for all response variables studied, the unstructured one had the most suitable parameterization. To identify the difference between treatments within each time event, the t-test was performed using the PROC GLIMMIX in SAS (Statistical Analysis System, version 9.3).

In addition, models with one, two, and three parameters were tested. The exponential model was described to calculate the decomposition and lignin contents. The daily rates of decomposition and lignin release were calculated by applying the first derivative to the equations adjusted to the accumulated *D* % and *L*. The exponential model Eq. (3) was used to describe the rate of decomposition and the lignin contents.

$$y = x_0 e^{-kt} \tag{3}$$

where y = the amount of residues or the lignin content remaining after some time t, in days (from 30 to 135 days); x_0, the initial amount of the residues or the lignin content; and k, the constant for decomposition or the lignin content. With the value of k, the half-life time ($t_{½}$) Eq. (4) was calculated using the PROC GLM in SAS (Statistical Analysis System, version 9.3).

$$t_{½} = \frac{0.693}{k} \tag{4}$$

Results

The intercropped systems of sorghum and grasses improved soybean agronomic performance in succession and the nutrient content levels in the plants ($p < 0.01$). The crop systems including Congo grass increased soybean grain yield, either in intercropping with sorghum (3,349 kg ha^{-1}) or in sole cultivation (3,317 kg ha^{-1}). The highest persistence of plant residues covering the soil surface during the soybean cycle was observed for sorghum alone (70.5 % on average) or intercropped with palisade grass (64.9 % on average), with contents of hemicelluloses of 26.3 % and 26.1 % respectively, although the highest lignin content was observed when sorghum was intercropped with Congo grass (5.1 % on average). The highest nutrient equivalents were observed in the mix of plant residues in the collections taken at 60 days of decomposition.

Dry matter production

Dry matter production of the crop systems involving sorghum intercropped with grasses was higher than that of the fallowing and the monoculture grasses. The fallowing system produced 2,178 kg ha^{-1} of dry matter, which was considered low and did not differ from other sole cropping systems (Table 1).

Table 1 – Dry matter of different crop systems, and their residues' cellulose and hemicelluloses average contents during two years of assessment in Planaltina, DF, Brazil.

Crop systems	Sorghum	Grasses	Total	Plant residues	
	Dry matter			Cellulose	Hemicelluloses
	----------------------------------- kg ha^{-1} -----------------------------------			------------------------ % ------------------------	
Fallowing	-	-	2,178 c	13.0 b	24.3 d
Sorghum	13,685 a*	-	13,685 b	16.3 a	26.3 bc
Palisade grass	-	3,920 bc	3,920 c	12.5 b	28.8 a
Congo grass	-	5,620 a	5,620 c	13.0 b	26.9 bc
Sorghum with palisade grass	14,818 a	3,884 c	18,702 a	16.1 a	26.1 c
Sorghum with Congo grass	7,862 b	4,947 ab	12,809 b	15.8 a	27.5 b
Years					
1	15,760 a	2,632 b	11,879 a	12.9 b	26.2 a
2	9,316 b	4,761 a	9,224 b	15.9 a	25.4 b

*Means followed by different letters in the columns differ by the t-test (p < 0.05).

Palisade grass intercropped with sorghum produced 3,884 kg ha^{-1} of dry mass. In sole cropping, the dry matter production of palisade grass was 3,920 kg ha^{-1} and was not different from the intercropped system with this species. Congo grass produced 4,947 kg ha^{-1} of dry matter when intercropped with sorghum and 5,620 kg ha^{-1} in sole cultivation, values higher than those obtained with palisade grass (Table 1).

Decomposition and crop residues analyses

The interaction between crop systems, periods of collections, and lignin content was significant (p < 0.01). No interaction between crop systems and these periods was observed for cellulose and hemicelluloses contents, but differences between crop systems and between these periods occurred regardless of these parameters.

Single sorghum plant residues were the most persistent on the soil surface compared to the other crop systems. After 30 and 90 days on the soil, there was still 81.9 % and 60.9 %, respectively, of the initial amount of sorghum residues. At the end of the sampling cycle (135 days), sorghum plant residues on the soil represented 48.8 % of the initial amount and were not different from the other crop systems. The original palisade grass residue remaining on the soil surface after 60 days (56.6 %) was higher compared to Congo grass (49.3 %). The half-life of the residues of palisade grass was 92 days, less than 106 days for the fallowing system (Figure 2).

Congo grass showed the highest lignin contents between 60 and 135 days on the soil surface (Figure 3), but the residue amount was less, from 60 days (49.3 %) to 90 days (40.0 %) compared to the other species (Figure 2). The half-life of Congo grass was 76 days. Congo grass also showed less P content in the plant residues of intercropped systems, which led to higher P contents in soybean plants (Table 2). Therefore, Congo grass was more effective in recycling P for soybean plants during the summer. The lignin content of sorghum intercropped with grass residues did not differ from 30 to 135 days.

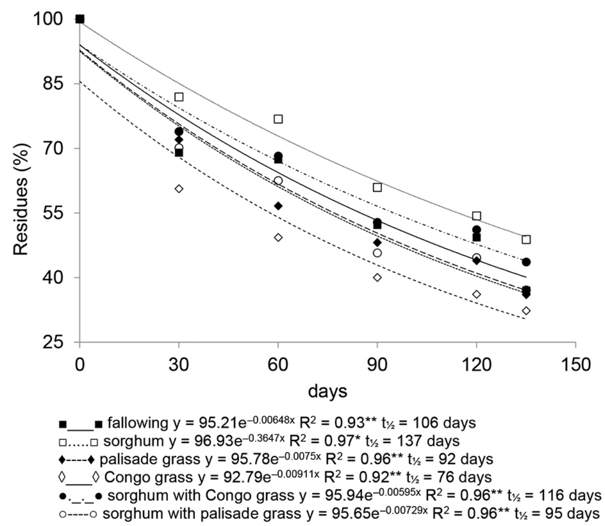

Figure 2 – Remaining residues on the soil surface of different crop systems including fallowing, sorghum, and grasses during soybean cycle in Planaltina, DF, Brazil. $t_{½}$ = half-life time. *, ** Significant (p < 0.05 and p < 0.01 respectively) by the t-test.

Higher contents of hemicelluloses (p < 0.05) were observed during the first year of assessment compared to the year after (Table 1). Hemicelluloses average contents differed between the crop systems and intercropped systems (p < 0.05), in the following order: palisade grass (28.7 %), Congo grass (26.8 %), sorghum (26.3 %), and fallow (24.3 %).

Soybean agronomic performance

Grass cultivation, single or intercropping, improved the agronomic performance of soybean in succession. The grasses affected the height of soybean plants, and the grain yields of this species. The previous crop system also affected soybean plants' nutrient content (Table 2).

Single sorghum and the fallow resulted in the lowest soybean plant height (Table 2). The average height of soybean plants was higher in the first year compared

Table 2 – Plant height, weight of grains, grain yield (133 DAE), dry matter and macronutrients contents of soybean plants during flowering (R2 phase – 59 DAE) in succession of different crop systems including fallowing, sorghum, and grasses in Planaltina, DF, Brazil.

Crop systems	Plant height	Weight of 100 grains	Grain yield	Dry matter	N	P	K	Ca	Mg	S
	m	g	------------ kg ha^{-1} ------------		------------ g kg^{-1} ------------					
Fallowing	0.57 e*	16.08 a	2,682 c	1,528 c	27.61 a	4.33 a	17.15 a	6.66 ab	1.99 ab	1.32 b
Sorghum	0.58 de	16.79 a	2,877 bc	1,877 bc	27.46 a	3.32 c	8.29 c	4.36 b	1.23 b	1.84 a
Palisade grass	0.68 abc	16.30 a	2,905 bc	1,845 bc	26.60 b	3.73 b	12.74 b	6.87 ab	1.77 ab	1.39 b
Congo grass	0.72 a	16.89 a	3,317 ab	2,795 a	25.84 c	3.74 b	15.16 ab	6.75 ab	1.98 ab	1.41 b
Sorghum with Palisade grass	0.63 cd	16.94 a	2,920 bc	1,631 bc	26.21 bc	4.11 ab	10.59 bc	7.02 a	2.09 a	1.71 a
Sorghum with Congo grass	0.70 ab	17.15 a	3,349 a	2,271 ab	26.93 ab	4.43 a	9.85 bc	5.58 ab	1.55 b	1.71 a
Years										
1	0.71 a	18.13 a	3,228 a	2,026 a	27.23 a	4.44 a	14.50 a	7.93 a	2.34 a	2.30 a
2	0.56 b	15.08 b	2,734 b	1,909 a	26.32 b	3.12 b	10.10 b	4.49 b	1.20 b	0.82 b

*Means followed by different letters in the columns differ by the t-test ($p < 0.05$).

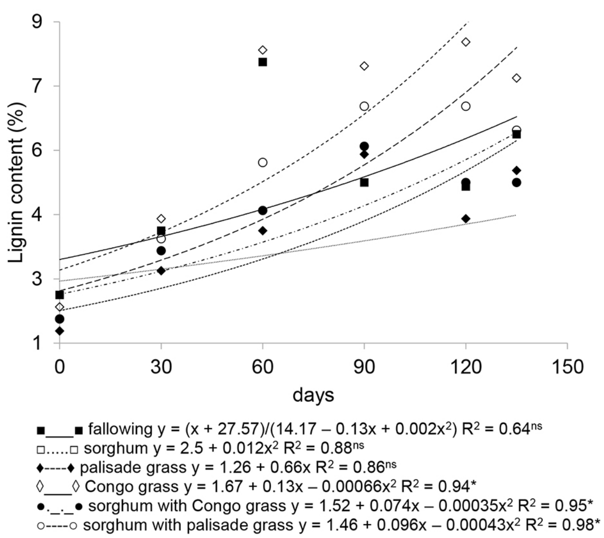

Figure 3 – Lignin contents of the residues of different crop systems including fallowing, sorghum, and grasses during soybean cycle in Planaltina, DF, Brazil. *, [ns] Significant ($p < 0.05$) and non-significant ($p > 0.05$) respectively, by the t-test.

to the second (0.71 m and 0.56 m, respectively). The lowest soybean plant height (0.57 m) and grain yield (2,682 kg ha^{-1}) were found in the fallowing system.

Soybean plants cultivated after Congo grass, sorghum, and even after fallowing showed differences in the amount of nutrients during the flowering period (Table 2). Although the fallow increased the N, P, and K levels in soybean plant tissues, this system did not increase soybean grain yields. The nutrient content of soybean plants varied between the assessment years ($p < 0.05$), with higher contents in the first year.

Discussion

The dry mass of sorghum in intercropped systems indicates a good adaptation of sorghum crop to the Cerrado off-season conditions (Table 1). These results show that even though the dry matter production of cover plants, such as Poaceae species, can be reduced during the autumn/winter (Oliveira et al., 2020), the dry mass produced by sorghum is still high and persistent for the Cerrado region, especially in the off-season. Low temperatures and water stress, common in this dry season, are the leading causes of the low production of dry matter by *Urochloa* species during the off-season in this region (Santos et al., 2018a; Carvalho et al., 2023).

The cultivation of sorghum in the Cerrado region during this time of the year has advantages compared to other cropping options, such as corn and wheat, due to its higher efficacy in converting water into dry matter. This pattern is related to specific plant biochemical and morphological mechanisms that endow sorghum plants with higher drought tolerance (Borges et al., 2018). In the present work, its dry matter production was not reduced when sorghum was sown immediately after the summer crop, characterizing it as potential fall/winter cropping.

The dry matter produced by palisade grass intercropped with sorghum can be considered a low value compared to those observed by other authors, with dry mass levels above 6,000 kg ha^{-1} (Dias et al., 2020; Oliveira et al., 2020; Sousa Junior et al., 2020). Although in the literature, values of dry matter above 6,000 kg ha^{-1} of grasses cultivated in the Cerrado off-season to provide soil cover are widely recommended, the persistent results observed showed that production levels of dry mass around 4,000 kg ha^{-1} are sufficient to provide a persistent soil coverage for the cultivation of soybean during summer under a no-tillage system (Table 1 and Figure 2).

Dry matter production must also be related to the plant's ability to retain residues on the soil due to the structural components of its tissues (Santos et al., 2018b), and, consequently, its persistence as straw. This is an important point about the fallowing system commonly in use in the Cerrado, and although it accumulates high amounts of dry matter, it is low-quality biomass. The fallow consisted of weed (Sodré Filho et al., 2022), which can be considered a poor producer of dry matter and, therefore, a low quality agricultural system.

The choice of plant species for off-season cultivation must consider the possibility of plant competition with soybean during the summer. Certain *Urochloa* species can become weeds, even after desiccation with herbicides, during the summer crop cycle due to their high re-growth capacity. No problem regarding the competition between off-season crops and soybean in succession was observed, mainly due to the effectiveness of the desiccation operation with glyphosate prior to soybean cultivation.

Palisade grass has a higher rate of decomposition than sorghum, and, consequently a lower persistence rate as a ground cover (Soares et al., 2019; Dias et al., 2020), unlike the result obtained in the present study. Although the fallowing system presented 67.4 % of the permanence of the residues (Figure 2), it was composed mainly of the Poaceae species (Sodré Filho et al., 2020), with a low recycling rate. The rates of sorghum residue decomposition in the Cerrado region can be higher in the first few days, so it is the mineralization during the soybean crop cycle (Nakao et al., 2019; Soratto et al., 2019).

Lignified plants with abundant stems generally show a low decomposition rate, as lignin content play a vital role in this process (Carvalho et al., 2023). On the other hand, the faster the decomposition process, the higher the cycling rate of nutrients and the shorter their permanence on the soil surface (Franscisquini Junior et al., 2020). The content of the structural components of plant cells also affects decomposition and nutrient release rates, mainly N (Soratto et al., 2019). Forage grasses with abundant stems have a high C:N ratio and lignin content, and, consequently lower decomposition rates (Carvalho et al., 2023). It is important to combine the fast release of nutrients from the straw to the soybean crop, that is, to synchronize it during the flowering phase for best agronomic performance. Soybean requires primarily N and P, especially within the 56 days after emergence (Balboa et al., 2018).

As regards the cellulose contents, the differences ($p < 0.05$) observed between sorghum – alone (16.3 %) or intercropped (26.8 %) – and the other crop species may be due to their unequal management: sorghum was harvested in July, after its complete senescence; palisade and Congo grasses (12.4 % and 12.9 % of cellulose average contents, respectively), and spontaneous plants of the fallowing system (13.0 %) were desiccated in Sept, while they were still alive (Table 1).

The amounts of accumulated rainfall and temperatures can also interfere with the rate of decomposition and the nutrients released by plant residues (Catuchi et al., 2019). It influenced the soybean agronomic performance since once the same cultivar was used in both years, the differences between the years of assessment can be explained from the rainfall periods that favored uptake in the first year due to its higher rainfall (Figure 1). The same phenomenon can explain the average height of soybean plants, probably due to climate conditions, although soybeans can also reach plant height values higher than those found. The crop grown on palisade grass residues can present an average plant height of 0.76 m, although this soil coverage cannot affect grain yields (Muniz et al., 2021). Plant height is among the factors that promptly influence crop losses and soybean grain yield (Rigon et al., 2018; Nakao et al., 2019).

Usually adopted by farmers in Brazil, the fallow presented several problems: weed species predominated as soil coverage in this system. Despite the use of herbicide to desiccate the plots, larger seed banks were formed in the soil during fallowing. Consequently, new weed seedling fluxes were observed during the soybean development, but only in this treatment (Sodré Filho et al., 2020). Weed interference with soybean was less intensive in other crop systems, due to the smaller weed seed soil banks' pressure and also by the effect of soil coverage on reducing weed plant development. Moreover, best soil coverage helps to maintain the soil moisture, increasing soybean plant development.

Considering the fertilizer equivalent, more significant amounts of N, P_2O_5, and K_2O were provided by the intercropped systems: sorghum with palisade grass or with Congo grass compared to other methods (Table 3). Grasses in integrated cultivation can afford large amounts of these nutrients to soybean crops and thus save chemical fertilizer applications, such as urea, phosphate, and potassium chloride (Muniz et al., 2021). Intercropping during the Cerrado off-season may

Table 3 – Released N, P, and K, and their equivalent contents of N, P_2O_5, and K_2O from the residues of different crop systems including fallowing, sorghum, and grasses during soybean flowering (R2 phase – 59 DAE) in Planaltina, DF, Brazil.

Crop systems	Released nutrients			Equivalent contents		
	N	P	K	N	P_2O_5	K_2O
	---------------------- g kg^{-1} ----------------------			----------------------kg ha^{-1} ----------------------		
Fallowing	2.40 a*	0.70 a	2.64 b	11.1 b	8.4 b	9.3 c
Sorghum	1.28 a	0.10 b	1.72 b	38.7 b	7.6 b	37.3 bc
Palisade grass	3.32 a	0.42 a	3.63 a	28.0 b	8.6 b	22.3 c
Congo grass	0.14 b	0.42 a	4.08 a	16.7 b	12.7 b	38.8 bc
Sorghum with palisade grass	2.53 a	0.51 a	3.12 a	109.2 a	52.7 a	100.5 a
Sorghum with Congo grass	0.35 b	0.13 b	3.27 a	100.4 a	9.3 b	69.8 ab

*Means followed by different letters in the columns differ by the Tukey-test ($p < 0.05$).

increase the nutrients cycling in the whole process, providing best agronomic performance of the summer crop, as observed for the soybean crop (Table 2).

The liberation of nutrients from plant residues relies on the microbial activity of the soil and other aspects related to vegetal species, such as its composition in lignin, lignin:N, and C:N ratio (Ribeiro et al., 2018; Catuchi et al., 2019; Carvalho et al., 2023). Factors that regulate the decomposition process are essential in managing cover crops and the productivity of integrated systems (Eberhardt et al., 2021). Suppose different plant species may have a similar capacity to absorb nutrients. However, there are many differences between them related to the phytomass production and the subsequent release of nutrients to the soil (Balboa et al., 2018; Catuchi et al., 2019). Thus, to choose a cover plant that will produce residues for a crop in succession, several factors must be considered, such as the quality of the residues and nutrient cycling, not just their persistence on the soil.

The high dry matter production of intercropping sorghum with grasses and its beneficial effects on soybean performance confirm the potential of this cropping system for the off-season in the Cerrado region. Off-season cropping systems can bring many advantages to the soybean in succession, increasing productivity and nutrient availability. The diversity of plant species – including the genus *Urochloa* prior to soybean – is essential during the off-season for the proper functioning of crop rotation under no-tillage systems.

In addition, the cultivation of sorghum, palisade grass, and Congo grass alone or intercropped can be helpful in farming management that seeks to fully off-season crop systems, with many advantages for soybean performance – such as plant height and grain yield – gaining the benefits of using agricultural diversification in an integrated crop-pasture practices.

Acknowledgments

This study was supported by Empresa Brasileira de Pesquisa Agropecuária (Embrapa Project N. 02.08.01.003.00), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

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