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Phosphate and nitrogen fertilization interactions with different cover crops on the yield of main crops in a Brazilian Cerrado Ferralsol

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ABSTRACT: Growing off-season cover crops effectively enhances ecological diversity and improves nutrient cycling in agricultural systems, particularly when nutrient losses and low use efficiency are prominent. This study aimed to assess the interaction between different off-season cover crops and varying nitrogen (N) and phosphorus (P) application rates on common beans, soybeans, and corn yields, as well as on soil organic matter (SOM) and available P content (Mehlich-1) in a Cerrado loamy soil. The experiment was conducted as a strip-plot factorial design with three replications in Planaltina, Distrito Federal, Brazil, from 2017 to 2020 under a no-tillage system. A fallow control and different cover crops were assigned to the rows of the three blocks and cultivated during the off-season from February to May, including *Urochloa ruziziensis*, *Crotalaria spectabilis*, millet (*Pennisetum glaucum* L.), white oat (*Avena sativa*) and a mix of cover crops (white oat, millet, buckwheat [*Fagopyrum esculentum* Moench], and radish [*Raphanus sativus* L.]). Combinations of N and P rates were assigned to the columns of the blocks, and the effects of the interactions of the factorial were assessed on subsequently cultivated commercial summer crops, including soybeans (*Glycine max* L.) in the 2017/18, 2018/19, and 2020/21 seasons and corn (*Zea mays* L.) in the 2019/20 season. Furthermore, common beans (*Phaseolus vulgaris* L.) were grown during all winter cropping seasons from 2017 to 2020. Cover crops reduced the dependence of commercial crops on mineral N and P fertilizers, although response to increasing rates was still present. Moreover, the magnitude of this effect varied with the specific crop species and commercial crops. Among the cultivated species, *U. ruziziensis* and white oat; *U. ruziziensis*, white oat, millet, and the mix; and *U. ruziziensis* and *C. spectabilis* exhibited the greatest potential for increasing yield in beans; soybeans; and corn, respectively.

Keywords: fertilizer rates, cereals, Latossolo, efficiency, response curve.

INTRODUCTION

Phosphate and nitrogen fertilization are crucial in maintaining high productivity in Cerrado agricultural soils. The dynamics of these nutrients in the soil are poorly understood, and their use efficiency can be low in the absence of sustainable agricultural practices (Oliveira et al., 2019; Nunes et al., 2021). Moreover, misuse of these fertilizers can lead to erroneous application, resulting in nutrient losses or accumulation in soil fractions less available to plants, particularly phosphorus (P) (Pavinato et al., 2020).

Nitrogen (N) application in agriculture is associated with challenges related to losses, such as leaching or denitrification, posing environmental and economic concerns. Therefore, efficient management of N fertilization is essential (Zhao et al., 2019). On the other hand, excessive P fertilization has become increasingly common in highly weathered tropical soils, such as those found in the Cerrado, exceeding crop demands (Pavinato et al., 2020). Concerns regarding potential reductions in P availability due to the reaction dynamics of P with soil colloids may contribute to the low use efficiency of this nutrient (Fink et al., 2016).

Understanding how ecological intensification systems improve the efficiency of phosphate and N fertilization in the Cerrado is limited, despite several studies indicating the potential enhancement of N and P use through good agricultural practices (Zavalin et al., 2018; Oliveira et al., 2019; Nunes et al., 2021). Ecological intensification refers to the incorporation of a greater number of plant species in the production system through succession, rotation, or intercropping schemes (Albuquerque et al., 2013; Silva et al., 2013). In this context, the use of cover crops during the off-season is an intensification option available to farmers, improving the chemical, physical, and biological aspects of the soil environment (Gama-Rodrigues et al., 2007; Reinert et al., 2008; Carneiro et al., 2009). This practice can impact the metabolic and physiological processes of the main crop and influence the dynamics of plant nutrient absorption in subsequent crops (Rosa et al., 2009).

Benefits and impacts of cover crops on commercial crop yields and nutrient cycling vary depending on the species. For instance, leguminous species are used as cover crops mainly because they provide N to the soil (Pereira et al., 2012). On the other hand, grasses with deep root systems and high biomass production are crucial for enhancing soil organic matter and providing a long-term nutrient supply (Baptistella et al., 2020).

Therefore, the objectives of this study are: i) investigate how different cover crops influence yield potential in commercial crops such as beans, soybeans, and corn; ii) how they interact with N and phosphate fertilization; iii) test the responsiveness of corn and beans to direct N applications, and the responsiveness of soybeans to residual N; iv) evaluate the effects of these cover crops on soil organic matter and available P content. We hypothesized: i) the establishment of cover crops positively affects the yields of beans, soybeans, and corn, with specific cover crop species modulating these effects; ii) cover crop establishment reduces the responsiveness of commercial crops to N and phosphate fertilization; iii) bean and corn crops exhibit increased productivity with higher N rates, unlike soybean; and iv) cover crops affect soil P availability, with certain species demonstrating higher efficiency in enhancing its availability.

MATERIALS AND METHODS

Site description

The experiment was conducted in Planaltina, Federal District (DF), Brazil. It is located at coordinates 15° 36’ 14.90” S and 47° 42’ 52.65” W, with a 1,012 m elevation. The study took place between October 2017 and January 2021. The soil in the area is classified as a clayey Red Ferralsol (IUSS Working Group WRB, 2022), equivalent to Latossolo, according to the Brazilian Soil Classification System (Santos et al., 2013), and has a cultivation history of over 20 years with soybeans (*Glycine max* L.), common beans (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.). The property owner and technical staff declared a background of soil disease problems, mainly *Fusarium spp*. and *Rhizoctonia solani*, that affected especially the more sensitive common beans crops.

Macro and micronutrients deficiencies were corrected, and the area follows a no-till cultivation system with center-pivot irrigation. The ecological intensification system included the following commercial crops: soybeans in the summer cropping seasons (October to January) of 2017/18, 2018/19, and 2020/21, and corn in the summer cropping season of 2019/20. After each summer crop, the cover crops were sown and grown between February and May of each crop year from 2017 to 2020. Following each cover crop, common beans were sown as a winter crop (June to September), followed by the sowing of the subsequent summer crop (soybeans or corn). Before conducting the experiment, soil samples (n = 126, 21 per cover crop treatment) were collected from the 0.00-0.10 m depth layer and subjected to chemical and physical characterization. This layer was selected due to its high sensitivity to management practices and the fact that only broadcast fertilizations were performed in the area, including P application. In addition, due to the relatively short experiment duration, no significant chemical changes were expected below the depth of 0.10 m. Average values obtained were as follows: 6.28 for pH($CaCl_2$), 6.59 for pH(H_2O); H+Al(SMP) equal to 2.53 $cmol_c\ dm^{-3}$; K^+ (Mehlich-1) equal to 1.15 $cmol_c\ dm^{-3}$; P (Mehlich-1) equal to 103.5 mg dm^{-3}; Ca^{2+}(KCl) equal to 5.8 $cmol_c\ dm^{-3}$; Mg^{2+} (KCl) equal to 1.4 $cmol_c\ dm^{-3}$; soil organic matter (Walkley & Black) equal to 2.7 %; sum of bases (SB) equal to 8.4 $cmol_c\ dm^{-3}$; base saturation (BS) equal to 76.8 %; and contents of clay, silt and sand of 495, 225, and 281 g kg^{-1}, respectively.

Climatic aspects

Climatic data, including rainfall and air temperature, were collected throughout the study period using an automated gauge station near the study area. Accumulated annual rainfall values during the study period (Figure 1) were 1097.7 mm in 2017, 1105.4 mm in 2018, 1066.5 mm in 2019, and 1613.4 mm in 2020. Local water requirements vary between 400 and 600 mm for corn (Fancelli, 2015), and between 300 and 500 mm for beans (Cunha et al., 2013). Although the amount of rainfall received during the study period was generally sufficient for each crop, the Cerrado region experiences an irregular temporal rainfall distribution during the rainy season, necessitating additional irrigation in each crop year. Throughout the study period, supplemental irrigation was applied to the crops. Center-pivot irrigation system used in this study provided supplemental water during the wet season and complete irrigation during the dry season (May to September).

Experimental setup

The experiment was conducted in a 6 × 7 strip-plot factorial design, with three replications. The main factor comprised cover crops, which included spontaneous vegetation (fallow, control) (1), *Urochola ruziziensis* (2), white oat (*Avena sativa*) (3), sunn hemp (*Crotalaria spectabilis*) (4), millet (*Pennisetum glaucum* L.) (5), and a mix of species consisting of white oat, millet, buckwheat (*Fagopyrum esculentum* Moench) and radish (*Raphanus sativus*) (6). The secondary factor involved N and P fertilization rates for the summer crops (soybean and corn) and the winter crop (common beans), totaling 7 levels of fertilization (Table 1), which were applied perpendicularly to the cover crops in each of the three blocks. The fertilizer rates for each treatment were determined based on recommendations for each specific commercial crop (Table 1).

The cover crops were planted in plots that were 18 meters wide. In the transverse direction, the main summer and winter crops were planted in 5-meter-wide sections. Maintenance fertilization with potassium (K) involved applying 80 kg ha^{-1} K_2O per crop in the form of potassium chloride. Maintenance fertilization with N and P varied based on the specific treatment strategy. For the 100 % P treatment, a rate of 35 kg ha^{-1} of P was applied to soybean, corn, and common beans as a total rate before planting. For the 100 % N treatments, corn received a rate of 200 kg ha^{-1} of N (20 to 40 kg ha^{-1} of N at planting and 160 to 180 kg ha^{-1} of N as a topdressing on the fourth leaf), while beans received 80 kg ha^{-1} of N as a total rate before planting. Corn was inoculated with one dose of *Azospirillum brasilense* during planting.

At the end of each growing season for the commercial crops, grain yield was evaluated. Additionally, soil samples were collected annually from the 0 to 0.10 m layer after the harvest of the summer crop. Soil samples were analyzed for organic matter using the Walkley and Black method (1934) and for soil available P content using the Mehlich-1 method. Soil analyses were conducted at the Soil Analysis Laboratory located at Embrapa Cerrados, Planaltina, DF, Brazil.

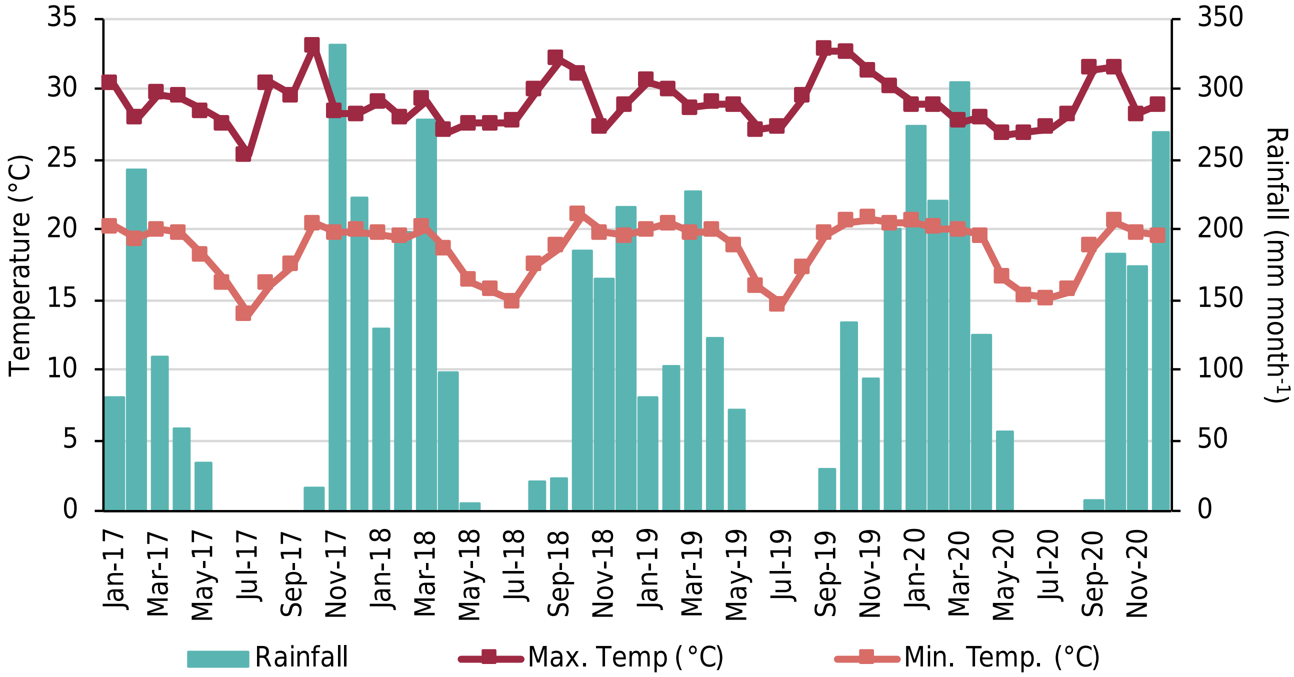


Figure 1. Maximum and minimum temperatures (°C) and monthly rainfall in the city of Planaltina-DF (Brazil) throughout the experiment period. Source: INMET (2022).

Table 1. Nitrogen and P fertilization rates applied to the commercial crops

Levels of N and P	N rate to common beans	N rate to corn	P rate to soybeans, common beans, and corn
	kg ha^{-1}		
P 0% + N 100%	80	200	0
P 25% + N 100%	80	200	9
P 50% + N 100%	80	200	17
P 100% + N 100%	80	200	35
P 100% + N 50%	40	100	35
P 100% + N 25%	20	50	35
P 100% + N 0%	0	0	35

Plant materials

Cover crops were sown in February of the years 2017, 2018, 2019, and 2020 at the following sowing rates: millet - 30 kg seed ha^{-1}, *Urochola ruziziensis* - 10 kg seed ha^{-1}, white oats - 130 kg seed ha^{-1}, crotalaria (*Crotalaria spectabilis*) - 35 kg seed ha^{-1}, and a plant mix (white oats - 50 kg ha^{-1}, millet - 7 kg ha^{-1}, buckwheat - 15 kg ha^{-1}, and radish - 3 kg ha^{-1}).

Dry matter production of the cover crops was evaluated at the end of each season. Before desiccation using herbicide application, the aboveground biomass was collected from a known area (1 m^2 per plot). Collected biomass was subsequently dried to a constant weight in a forced-air oven at 65 °C. Dry matter was determined and converted into kg ha^{-1}.

Statistical analysis

The results underwent analysis of variance using the F-test. When the F-test indicated statistical significance (p-value<0.01), the Tukey test was conducted to compare means (p-value<0.05) for the responses of both cover crops and commercial crops. Additionally, regression analyses were conducted to assess the relationship between yields and fertilization strategies.

RESULTS

Accumulation of dry biomass in cover crops

Millet consistently outperformed the other cover crops in all years in dry matter accumulation (Table 2), with significantly higher values. Compared to the means of the other cover crops, millet accumulated 44.2, 41.8, 68.6 and 112 % more dry matter in 2017, 2018, 2019 and 2020, respectively.

Soil organic matter and soil phosphorus content

Figure 2 presents the interaction between P rates and SOM, while figure 3 shows P rates and soil P content. There was a significant positive influence of P rates on SOM only when *C. spectabilis* was grown (Figure 2). No significant effects of P rates on dry matter production were observed, as the increases in SOM were primarily observed with the cultivation of *C. spectabilis,* one of the least capable species of inputting dry matter into the system. Control (fallow) treatment had SOM levels reduced with increasing P rates (Figure 2). However, when considering the mean responses of all cover crops regarding SOM to applied P rates, P application did not affect SOM accumulation (Figure 2).

Table 2. Average dry matter production values of cover crops preceding the summer cultivation in Planaltina – DF, Brazil (crop year from 2017 to 2020)

Cover Crop	2017	2018	2019	2020
	kg ha^{-1}			
U. ruziziensis	2167.1 b	5029.7 d	3390.4 b	1490.3 c
White oat	2467.2 b	6090.9 c	1421.0 d	1693.5 c
Millet	3521.7 a	8206.1 a	4475.1 a	3528.0 a
C. spectabilis	1745.8 b	4801.7 d	2382.5 c	1083.5 d
Mix	3389.7 a	7223.9 b	3425.3 b	2362.9 b
F-test	22.34***	476.26***	45.88***	170.47***
CV (%)	28.19	4.84	25.99	16.51
Means	2658.28	6284.12	3018.87	2031.64

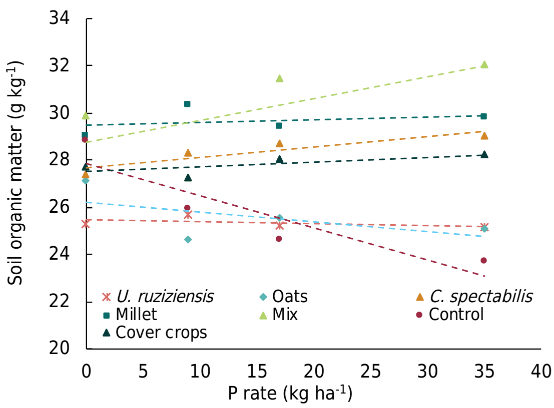
*** significant at 0.1 % probability; Means followed by the same letter in the columns do not differ from each other by Tukey's test at 5 % probability; CV: coefficient of variation.

There was an interaction between P rates and cover crops concerning soil P availability (Figure 3). Soil under most cover crops presented significant and positive linear responses to P addition, except for white oats, whose response was negative, although not statistically significant.

Yield of common beans

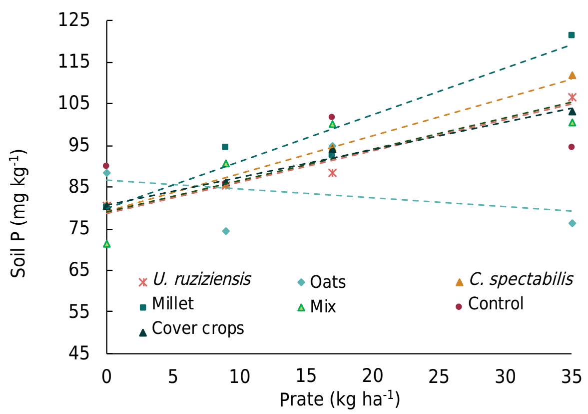
Figure 4 presents the yield responses of common beans to cover crops and N rates, considering the mean yields from 2017 to 2020. Generally, the highest yields were observed in common beans grown with white oats and *U. ruziziensis* as cover crops ($p<0.05$). The interaction between N rates and cover crops significantly influenced all evaluated species and the control (fallow) treatment (Figure 4). However, there was no significant effect in the interaction between P rates (Figure 5) with *U. ruziziensis* and the crop mix. Angular coefficients of the regression models indicate that using cover crops, approximately 1.9 times more P and 1.5 times more N was required to achieve a one-unit increase in the yield of beans compared to the model based on the control without cover crops use, i.e., soils under cover crops were less responsive to mineral fertilization.

Furthermore, when considering the prospect of increasing fertilizer rates, it is noteworthy that only at rates of 334 kg ha^{-1} of N or 321 kg ha^{-1} of P, which are approximately four times the recommended rates for both nutrients, the yield of beans in the control group would reach the same level as that achieved with cover crops. The models in figures 4 and 5 make evident that the angular coefficients for the response to N rates were higher compared to those for P rates.



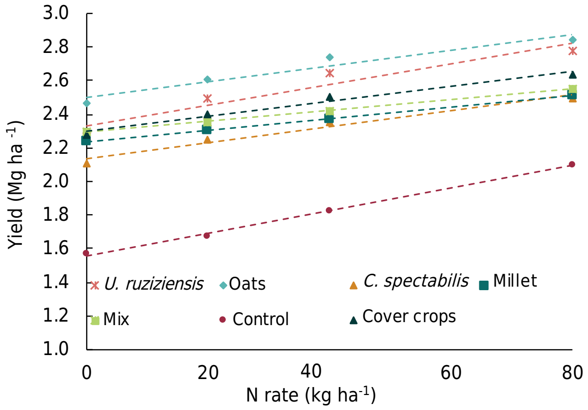
Cover Crop	Regression Model	$R^2_{adj.}$
Control	27.858 - 0.059P	0.75
Millet	29.490 + 0.004P^{NS}	-0.37
Mix	28.731 + 0.041P^{NS}	0.15
U. ruziziensis	25.480 - 0.003P^{NS}	-0.09
White oat	26.207 - 0.017P^{NS}	-0.03
C. spectabilis	27.677 + 0.019P	0.76
Cover crops	27.522 + 0.008P^{NS}	0.20

Figure 2. Soil organic matter contents as a function of the interaction between P fertilization with cover crops between 2017 and 2020 in the city of Planaltina, DF (Brazil). Values presented correspond to the means of three replications for each cover crop (n = 3).



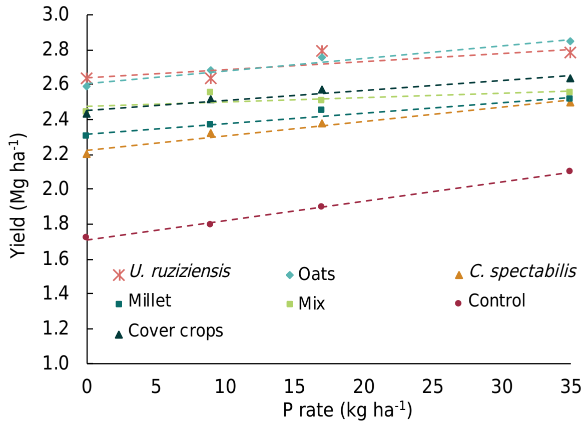
Cover Crop	Regression Model	$R^2_{adj.}$
Control	89.510 + 0.090P^{NS}	-0.17
Millet	79.98 + 1.223P	0.87
Mix	78.964 + 0.753P^{NS}	0.53
U. ruziziensis	78.707 + 0.751P	0.93
White oat	86.477 - 0.086P^{NS}	-0.36
C. spectabilis	79.165 + 0.907P	0.98
Cover crops	80.658 + 0.290P	0.98

Figure 3. Mehlich-1 P contents (mg kg^{-1}) as a function of the interaction between P fertilization with cover crops between 2017 and 2020 in the city of Planaltina, DF (Brazil). Values presented correspond to the means of three replications for each cover crop (n = 3).



Cover Crop	Regression Model	$R^2_{adj.}$
Control	1.560 + 0.0067N	0.99
Millet	2.236 + 0.0034N	0.99
Mix	2.298 + 0.0031N	0.99
U. ruziziensis	2.332 + 0.0061N	0.87
White oat	2.5 + 0.0046N	0.89
C. spectabilis	2.136 + 0.0047N	0.96
Cover crops	2.296 + 0.0045N	0.95

Figure 4. Yield of common beans as a function of the interaction between N fertilization rates with cover crops between the years 2017 and 2020 in the city of Planaltina, DF (Brazil). Values presented correspond to the means of three replications of N rates for each cover crop (n = 3).



Cover Crop	Regression Model	$R^2_{adj.}$
Control	1.709 + 0.0048P	0.99
Millet	2.313 + 0.0026P	0.93
Mix	$2.475 + 0.001P^{NS}$	0.19
U. ruziziensis	$2.639 + 0.002P^{NS}$	0.50
White oat	2.607 + 0.0031P	0.95
C. spectabilis	2.224 + 0.0035P	0.95
Cover crops	2.448 + 0.0025P	0.93

Figure 5. Yield of common beans as a function of the interaction P fertilization rates with cover crops between the years 2017 and 2020 in the city of Planaltina, DF (Brazil). Values presented correspond to the means of three replications of P rates for each cover crop (n = 3).

Soybean and corn yield

Supplementary Table 1 provides the analysis of variance for the average yield of soybean and corn during the summer cropping period, covering the years 2017/18 to 2020/21. In all the evaluated years, as well as in the combined analysis for the entire study period, the effects of cover crops and fertilizers acted independently. This means that for soybeans grown in the summer, there was no significant interaction between cover crops and P or N rates regarding productivity. Similarly, there was no significant effect ($p>0.05$) of the interaction between fertilizers and cover crops on corn yield in the 2019/20 season. Consequently, figures 6 and 7 present the results obtained based on the main effects of cover crops on the yields of soybean and corn.

Yield of soybeans was influenced by cover crops during the summer cropping from 2017 to 2021 (Figures 6a, 6b, and 6c) and in the overall means for the entire period analyzed (Figure 6d). Considering the yield means of the three soybeans crops (Figure 6d), all cover crops, except for *C. spectabilis*, exhibited improved yields compared to the control (fallow) treatment ($p<0.05$). On the other hand, in the 2019/20 summer corn crop, only *U. ruziziensis* and *C. spectabilis* resulted in significantly higher yields compared to the control group (Figure 7).

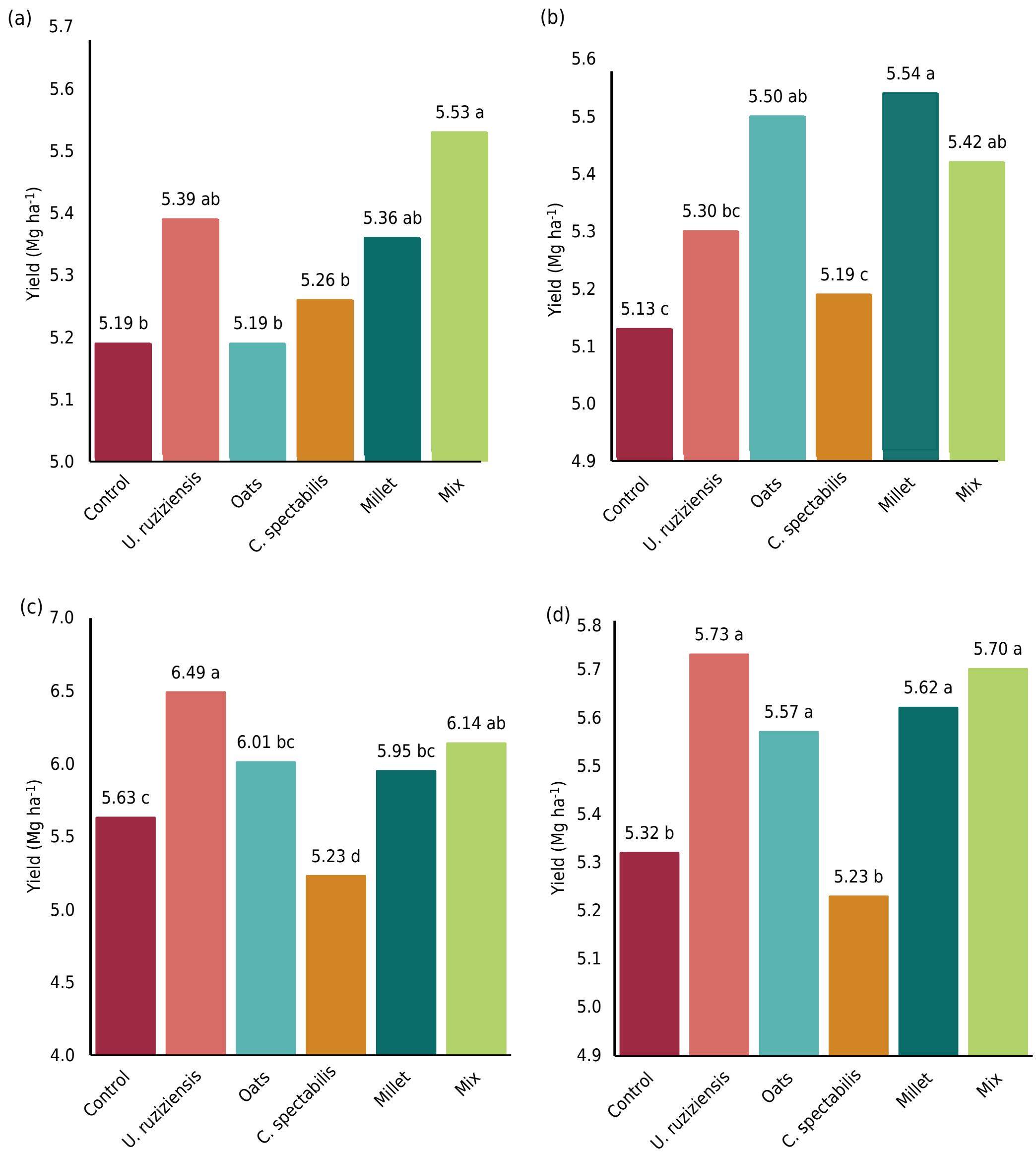


Figure 6. Soybean yield as a function of cover crops in the crop years 2017/18 (a), 2018/19 (b), 2020/21 (c), and means for the three soybeans crops between 2017-2021 (d) in the city of Planaltina, DF (Brazil).

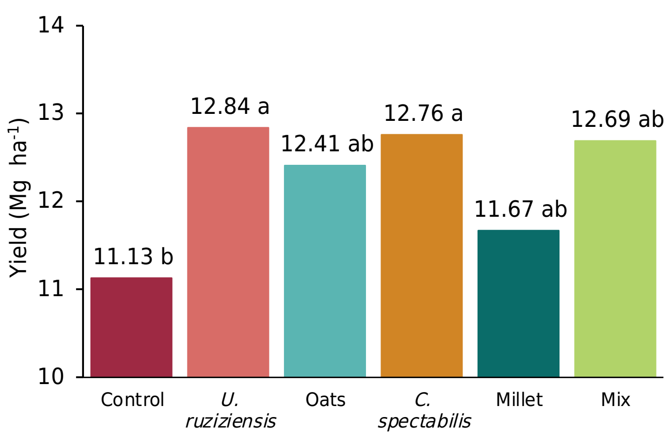


Figure 7. Corn yield as a function of cover crops (or fallow control) in the 2019/20 summer crop in the city of Planaltina, DF (Brazil). Values presented correspond to the means of three replications of N and P rates for each cover crop (n = 21).

DISCUSSION

Regarding the cover crop shoot dry matter, millet consistently outperformed the other cover crops across all the evaluated years. This superior performance can be attributed to its rapid growth, especially in the edaphoclimatic conditions of the Cerrado region, robust root system with high dry matter and nutrient cycling potential, as well as its ability to reduce disease and pest inoculum in the soil (Lima Filho et al., 2014). Similar findings were reported by Oligini et al. (2019) in a two-year study in the Paraná State, Brazil, where millet exhibited greater dry matter accumulations compared to *B. brizantha* and *C. spectabilis*.

The other cover crop species had varying shoot dry matter productions across different periods. This indicates that, except for millet, there was no consistent production pattern among the species. These results demonstrate that certain cover crops may perform diversely according to the cultivation year. Regarding the plant mix, its dry matter production was lower only than that of millet. Even though the relative short duration of the experiment, the high inputs of dry matter obtained by these two cover crop strategies reflected the highest soil organic matter values, although gains with P rates were only statically significant with *C. spectabilis* (Figure 2).

Soil under millet exhibited the highest response to P rates, being able to increase soil P availability by 1.2 mg kg^{-1} for each kg of P applied as fertilizer. Consequently, at the highest rate, millet resulted in a soil P availability of 122 mg kg^{-1}. Similarly, *C. spectabilis* and *U. ruziziensis* cover crops, at the highest rates, showed soil P availabilities of 110 mg kg^{-1} and 105 mg kg^{-1}, respectively, with coefficients of determination of 0.9 and 0.75. The observation of linear models relating Mehlich-1 P to P rates was partly expected due to the high initial levels found in the area, what happened for all crops except white oats. According to Barrow (2015), previous phosphate applications decrease soil P buffering capacity and improve the efficiency of later applications.

An increase in P availability with cover crop cultivation compared to fallow was observed by Soltangheisi et al. (2018), with white lupine being the most effective in enhancing P lability. The influence of cover crops on soil P availability can be attributed to their ability to alter soil P cycling and turnover, impacting its availability to subsequent crops. This can be attributed to different strategies of P acquisition by plants and varying labilities of P accumulated in plant tissues among cover crop species (Tiecher et al., 2012). Biomass production and exudation of organic materials by cover crops, along with its subsequent degradation, can enhance P availability by complexing Al^{3+} and Fe^{2+} in acid soils (Urrutia et al., 2014; Fink et al., 2016). This represents an important pool of slowly released P compared to soluble fertilizers (Martinazzo et al., 2007; Darch et al., 2014), while also stimulating soil biological activity and facilitating P assimilation into microbial structures (Yevdokimov et al., 2016).

The significant effect of the interaction between N rates and cover crops on the yield of beans is evident, as confirmed in the absence of N or P fertilization (0 kg ha^{-1}) with all cover crops compared to the fallow control. White oats and *U. ruziziensis* provided the highest yields of beans, with 2.33 and 2.50 Mg grain ha^{-1}, respectively, compared to 1.56 Mg grain ha^{-1} in the control (0 kg N and P ha^{-1} under fallow). *C. spectabilis* cultivation, which had the lowest dry matter production among the cover crops, still resulted in a 0.48 Mg ha^{-1} increase in grain yield compared to fallow. Gains observed with the use of grasses may be related to improved control of soil diseases that thrive under irrigated conditions, to which common beans are extremely susceptible (Toledo-Souza et al., 2012).

Considering the response curves obtained, it is noticeable that beans yields obtained with previous cover crops cultivation could only be potentially matched without cover crops if fertilization rates were about four times the recommended rates (334 kg ha^{-1} of N or 321 kg ha^{-1} of P). The models in figure 4 indicate that for N rates, angle coefficients were higher compared to those for P rates (Figure 5), suggesting that crops were more responsive to N rather than to P application. This could be attributed to beans' dependency on N input through fertilization (Pias et al., 2022), as well as the initially elevated levels of available P in the soil, which reduces its reliance on annual P input. However, the observed productivity responses to P rates were unexpectedly high, given the initially prominent levels of available soil P. Such discrepancy may be attributed to a background of root diseases in the experimental site, which could have limited root development and increased the crop's dependence on annual P fertilizer inputs.

In a study with *U. ruziziensis* cultivation alone and intercropped with other plants to assess its effect on bean productivity, Bettiol et al. (2015) found cover crops could recycle approximately 80 to 253 kg ha^{-1} of N, with the highest value observed in the intercrop between *U. ruziziensis* and *C. spectabilis*. In turn, Van Eerd (2018) observed that white oats resulted in higher bean yields compared to other cover crops such as hairy vetch, rye, and peas, leading to a 10.9 % increase in the yield of beans. Therefore, the choice of cover crop is highly dependent on the main crop, and selecting appropriate cover crops can have a significant impact on the main crop productivity.

Regarding the cover crop effect on P cycling, Maltais-Landry et al. (2014) concluded that P assimilation and subsequent release by cover crop residues have a more significant effect on P cycling than the release of organic acids and enzymes in the rhizosphere. While legumes have a greater capacity to produce organic acids and enzymes, grasses contribute more effectively to P cycling due to their higher biomass production. These findings align with the results presented here, demonstrating the ability of cover crops to enhance yields and reduce the dependence on N and P fertilizer inputs. This is achieved through the significant cycling of these nutrients by cover crops (Wendling et al., 2015; Hansen et al., 2022; Momesso et al., 2022), increasing their use efficiency based on different root system development profiles and soil profile use capabilities (Wendling et al., 2015; Hudek et al., 2021).

Cover crops play a vital role in nutrient assimilation, organic matter return to the soil, nutrient losses reduction and increased N (Abdalla et al., 2019) and P (Soltangheisi et al., 2018) availability. Their impact on nutrient uptake, rhizosphere acidification, and exudation profiles varies depending on the cultivated species (Vives-Peris et al., 2020), contributing to diverse microbial communities and enhanced nutrient cycling (Finzi et al., 2015). This, in turn, can lead to disease suppression (Mendes et al., 2018) and improved nutrient availability. The inhibitory effect of white oat extracts on the white mold (*Sclerotinia sclerotiorum*) in soybeans and even suppression of root diseases has been observed (Gebauer, 2017), with the species demonstrating increasing inhibitory activity with higher extract concentrations.

Summer yield of soybeans was influenced by cover crops. The results indicate that the plant mix, millet, and *U. ruziziensis* were the most promising cover crops for increasing soybean yields in most of the evaluated years. White oat also showed potential as a cover crop for enhancing soybean yields when considering the overall means across all years. Notably, *C. spectabilis* was the only cover crop that resulted in lower productivity than the control. On the other hand, Yokoyama et al. (2022) evaluated *U. ruziziensis* in soybean succession on a dystrophic Ferralsol in the subtropical region of Brazil and found that it increased soybean yield. These authors also reported that the benefits of cover crops are cumulative over time, which is evidenced by the higher yield of soybeans in the last year. Figure 6c shows that soybean yield in the *U. ruziziensis* and crop mix association were 20.5 and 11 % higher, respectively, than in the first year.

Statistically, all cover crops provided similar yields to each other ($p<0.05$) in the 2019/20 summer corn crop, with only *U. ruziziensis* and *C. spectabilis* showing significantly higher yields compared to the control (Figure 7). Millet yielded slightly lower than the average of *U. ruziziensis* and *C. spectabilis*, representing a 9 % decrease. This suggests that millet had the least positive effect on corn among the cover crops. Cultivation of *C. spectabilis* as a cover crop resulted in corn productivity similar to that of *U. ruziziensis*, despite *C. spectabilis* producing less dry matter in the 2019 crop (Table 2). This indicates that a legume cover crop has the potential to positively affect the productivity of a grass crop like corn. The legume cover crop may compensate for lower biomass production through other nutrient cyclings mechanisms, such as increased organic acid and enzyme production. Maltais-Landry et al. (2014) showed that the low C/N ratio provided by straw residuals favors nutrient mineralization in addition to biological N fixation during the cover crop cycle. The satisfactory yield performance of corn grown over grasses *U. ruziziensis* and white oats may also be due to relatively low N limitations in the soil system and the inoculation of corn with *Azospirillum brasilense*.

Potential use of legumes as cover crops before corn growing was also observed by Silva et al. (2020), who found higher corn yields with legume cover crops during the off-season in a Cerrado Ferralsol. Introducing these cover crops was equivalent to applying 80 to 108 kg ha^{-1} of N in the form of urea. In the absence of N fertilization, these authors noted that N recovery by the cover crops was 21.1 kg ha^{-1}, but the grain yield (6.41 Mg ha^{-1}) was equivalent to 60.5 kg ha^{-1} N application for corn grown after fallow in the off-season. Therefore, cultivating leguminous cover crops during the off-season can increase N recovery for the main crop and contribute to overall system yield improvement.

In general, the responses to increasing N and P rates throughout the evaluation period were linear and significant, except for the response of corn to phosphate fertilization in 2019/20, which showed no significant effect. Fontana et al. (2021) also found no reduction in N fertilizer requirements for soybeans, wheat, and corn rotated with cover crops, indicating that fertilizer remains essential for achieving satisfactory yields. However, the authors observed increases in most fractions of SOM and, especially, in microbial biomass C and N mineralization (43 % and 58 %, respectively) compared to the fallow control.

Although no N was applied to soybeans, the crop still responded significantly to residual N from common beans in all studied years (Table S1). This response may be attributed to restricted root development due to the presence of root pathogens in the soil (Figure S1) and soil compaction observed at depths below 20 cm (above 3000 KPa) (Table S2). This could have led to inefficient biological N fixation (Siczek and Lipiec, 2011).

CONCLUSIONS

Cover crops cultivation reduced the reliance of commercial crops on mineral fertilizers, i.e, crops were less responsive to N or P fertilization where cover crops had been cultivated. Nonetheless, response to mineral N and P fertilization rates was still noticeable on beans and corn, while soybeans also responded to residual N.

Not only dependence on mineral fertilizers was reduced with cover crops, but yield potentials were increased. *Urochloa ruziziensis* and white oat; *U. ruziziensis*, white oats, millet and the mix; and *U. ruziziensis* and *Crotalaria spectabilis* showed the greatest yield increases in common beans, soybeans, and corn, respectively.

Growing millet, *C. spectabilis* and *U. ruziziensis* during the off-season enhanced soil P availability, indicating their efficiency in cycling this nutrient compared to other species, thereby improving P use in Cerrado soils.

Interactions observed between commercial crops and cover crops, affecting yield and important soil parameters related to crop nutrition, underscore the need to further understand how cover crops, with their varied soil profile use and residue decomposition, influence yield and N and P dynamics in the soil.

SUPPLEMENTARY MATERIALS

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-49-spe1-e0240020/1806-9657-rbcs-49-spe1-e0240020-suppl01.pdf

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