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Cover Crops and Nitrogen Fertilization in Maize on the Productive Performance of Crop

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HIGHLIGHTS

- Nitrogen fertilization in maize impacts the phytomass of crops in succession.
- The oat+vetch+radish mix is a great alternative for winter production.
- The corn phytomass with N rates of 90 and 180 kg ha^{-1} was similar.
- The annual accumulated production of phytomass ranged from 10.0 to 28.6 Mg ha^{-1}.
- Winter cover crops and N rate affect corn grain production in years without drought.

Abstract: The use of conservation practices for sustainable agriculture production has grown in the last decades, mainly due to the no-tillage and the cover crops. The aim was to evaluate the productive performance of phytomass in three crop years with the effect of different winter cover crops and nitrogen (N) rates in succession maize. The study was carried out at the Federal Technological University of Paraná, in Dois Vizinhos, between 2020 and 2023, in a long-term experiment (2010). The treatments were a combination of three N rates applied to maize and eight winter cover crops. The annual cropping systems were buckwheat-winter cover crops-maize. The dry phytomass of buckwheat showed a significant difference between the residual N rates, but no difference to the cover crops. For the winter cover crops, mix and single oats showed a higher phytomass production, especially oats+vetch+radish, while common vetch had a lower production. Phytomass of maize was responsive to N addition, regardless of crop year; however, in a dry weather year, the cover crops showed no difference. Cumulative annual phytomass ranged from 10 to 28.6 Mg ha^{-1} and was related to the N rate and the winter crop. Maize grain yield was higher after vetch and lupine and with N fertilization. Therefore, winter cover crops and N fertilization can contribute to the productive development of all the crops in the cropping system.

Keywords: Buckwheat; Dry phytomass; Straw; No-tillage.

INTRODUCTION

The search for sustainable agricultural production is one of the challenges of the 21st century due to the context of climate change and the growing demand for food and environmental preservation [1]. Within this, soil has an important role, as it acts as a memory of the production systems, a potential sink of carbon , and a reservoir of nutrients since 9.4 to 18.5% of the residues are transformed into stored C in soil [2].

Sustainable agricultural production involves the use of conservation production systems. In this case, highlights the no-tillage system (NTS), which has three principles such as minimum soil mobilization, maintenance of soil coverage with straw or developing species, and crop rotation, associated with soil conservation practices [3]. NTS improves soil quality, soil protection from water erosion, temperature fluctuations, water retention, controls spontaneous species, among others [4], increases soil organic C and nutrient cycling [5]. Brazil has more than 33 million hectares cultivated in no-tillage [6], and only 10-20% uses the precepts of the NTS [3, 7] and in the Paraná state only 10% of the areas [8]. This difference is addressed mainly to the poor adoption of crop rotation, defined as the alternate and planned cultivation, in the same plot over time, of different plant species, due to the failures in crop planning, economic factors, and difficulties with crop management.

One of the techniques that can help in the construction of the NTS is the use of cover crops, which can improve the physical, chemical, and biological properties of the soil [9]. The diversity of cultivated species increases the cycling and availability of nutrients in the soil, improving aggregation and biological activity[10], given the relationship with soil organic matter [11]. In addition, the amount of phytomass generated by the cover crops is also important, as it ensures soil protection and increases C sequestration [12], benefiting the NTS quality. In the literature, it is possible to find minimum values of annual addition of straw for the maintenance of the system, values of 11 to 12 Mg ha^{-1} of dry phytomass [13]. These values changes according to the edaphoclimatic conditions where, in the subtropical region, 6 to 7 Mg ha^{-1} is recommended [14, 15].

And, as an alternative to increase the straw input and participate in the crop rotation, buckwheat (*Fagopyrum esculentum* Moench.) has been recently used. This crop is from the Polygonaceae botanical family, and stands out due to its short cycle, 35 to 50 days, and its adaptation to low fertility soils [9]. Buckwheat could be used in the human [16] and animal [17] alimentation, and as a cover crop in offseason [18]. Grain yield could be near 3 Mg ha^{-1} [19], while its dry phytomass could be higher than 8 Mg ha^{-1} [20].

The use of different cover crops for nutrient cycling has been the focus of several studies, mainly about nitrogen (N), the nutrient most used via fertilization [21–23]. Maize sown under vetch straw showed higher grain yield without N addition in top dressing, similar to the maize grain yield with an N rate of 120 kg ha^{-1} [24]. Cover crops increase maize grain yield however, leguminous species stand out due to the accumulated N concentration. Maize is a culture with a high N demand and is responsive to adding this nutrient [24], and the leguminous species fixed N through biological fixation [20]. In addition, the cover crops decomposition releases the nutrients for the use of succession maize, reducing N losses [25].

However, the search for efficiency in the use of fertilizers, as well as the reduction of losses, is a determining issue in a sustainable agricultural production [26]. Therefore, the use of legumes as winter cover crops prior to maize is expected to increase grain yield, reducing the need for N fertilizers, and increase the crop phytomass. The aim of this study was to evaluate the productive performance of phytomass of plants in three crop years, 2020, 2021, and 2022, under the effect of winter cover crops and nitrogen rates applied to maize.

MATERIAL AND METHODS

Experimental site

The long-term experiment is in the experimental area at the Federal Technological University of Paraná (UTFPR), in the municipality of Dois Vizinhos, Paraná, at geographic coordinates: 25º42'52” S, 53º03'94” W, with an altitude of 520 m. The region is characterized by a Cfa climate (humid subtropical), according to the Köppen’s classification [27], with an average rainfall of 2,010 mm per year [28]. During the study period, the observed rainfall is presented in Figure 1, with predominantly below-average rainfall, except for May, June, and August 2020; January and June 2021; and August and October 2022 [28]. The soil in the area was classified as a very clayey (773 g kg^{-1} clay, 224 g kg^{-1} silt, and 3 g kg^{-1} sand) Red Latosol [29] by SiBCS [30], equivalent to an Oxisol by Soil Taxonomy [31]. The initial soil chemical characterization, in the 0-0.20 m soil layer, was pH ($CaCl_2$) = 5.3; pH SMP index = 6.4; organic matter = 40.8 g kg^{-1}; P (Mehlich 1) = 4.3 mg dm^{-3}; K^+ = 0.2 cmol$_c$ dm^{-3}; Ca^{2+} = 6.0 cmol$_c$ dm^{-3}; Mg^{2+} = 2.8 cmol$_c$ dm^{-3}; H+Al = 3.8 cmol$_c$ dm^{-3}; sum of bases = 9.0 cmol$_c$ dm^{-3}; cation exchange capacity (CEC) = 12.8 cmol$_c$ dm^{-3}; and base saturation = 70%.

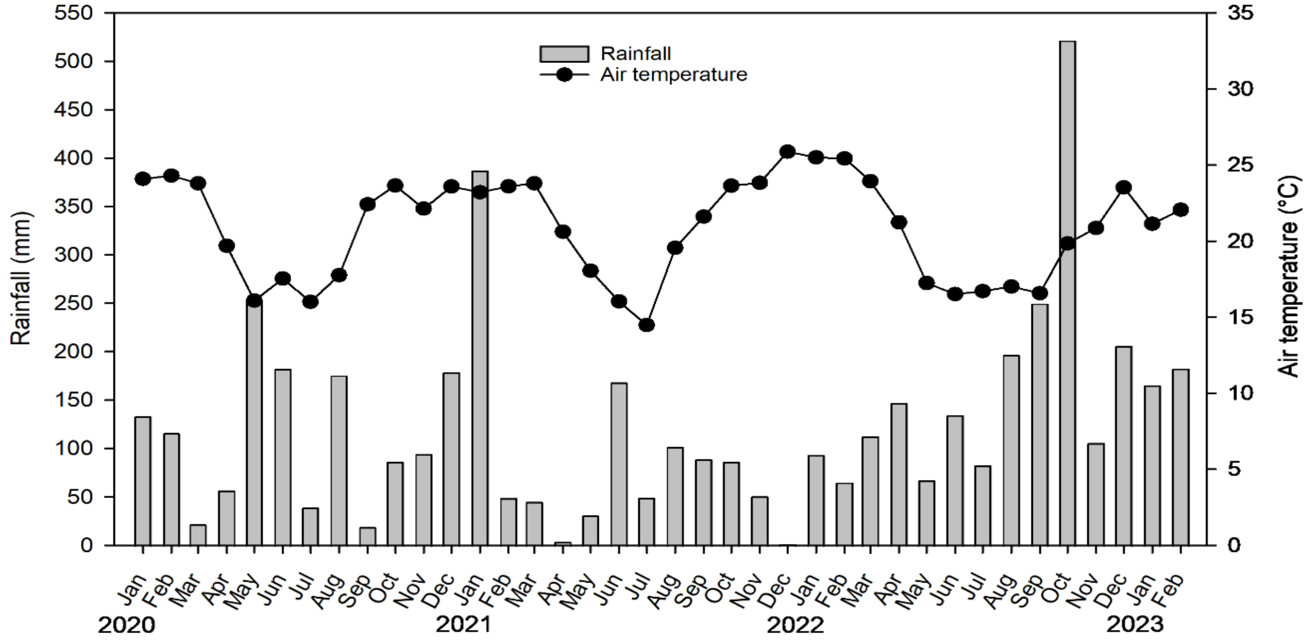

Figure 1. Monthly air temperature and monthly rainfall from January 2020 to February 2023.
Source: Instituto Nacional de Meteorologia (INMET) [27]; Grupo de Estudos em Biometeorologia (GEBIOMET) [28].

Experimental design and management

The experiment started in 2010 with the combinations between different winter cover crops and nitrogen rates of fertilizer in maize (*Zea mays* L.) managed in no-tillage. Buckwheat was added to the experimental crop year in 2019 as an alternative crop to the summer period. The evaluation period of the current study was from January 2020 to February 2023, with three crop years and annual cropping systems were buckwheat-winter cover crops-maize. The experimental design was a factorial scheme of subdivided plots, in randomized blocks, with three replications. The plots were eight combinations of winter cover crops, while the subplots were three different nitrogen rates. The total number of experimental units (subplots) was 72 with an area of 25 m^2 (5 x 5 m). Therefore, the cover crops used in the single plots were: oats (*Avena strigosa* Schreb.), rye (*Secale cereale* L.), forage pea (*Pisum sativum* subsp. Arvense L.) (added in 2020 in replace to radish), common vetch (*Vicia sativa* L.), lupine (*Lupinus albus* L.), and mix: oats + vetch (O+V), oats + vetch + radish (*Raphanus sativus* L.) (O+V+R), and white oats (*Avena sativa* L.) + forage pea + radish (WO+P+R). The N rates used in the subplots were: 0, 90, and 180 kg ha^{-1} N, applied to the maize crop.

Buckwheat was sown using a sowing density of 50 kg ha^{-1}, spaced 0.17 m between rows, under maize straw, on January 29, 2020; February 22, 2021; and February 14, 2022; without any crop fertilization. At the end of the crop cycle, buckwheat was managed with herbicide application and knife roller.

Subsequently, winter cover crops were implanted on May 11, 2020, June 10, 2021, and June 6, 2022, with a plot seeder with 0.17 m spacing between rows, without fertilizing. The management of cover crops was carried out with desiccation and lodging with a knife roller in a period close to maize sowing.

Maize sowing occurred with a precision seeder at 0.45 m spacing and an estimated population of 75,000 plants ha^{-1}, on September 23, 2020, September 22, 2021, and September 15, 2022, using a rate of 550 kg ha^{-1} of 2-20-20 N-P-K fertilizer for the 2020/21 crop year and 575 kg ha^{-1} of 2-18-18 fertilizer for the 2021/22 and 2022/23 crop years, at the sowing base, via furrow. Nitrogen fertilization was manually applied in cover on maize at the V4 stage, using urea (45% N). Mechanized harvesting was realized on February 5, 2021, February 11, 2022, and February 27, 2023.

To determine the dry phytomass of winter cover crops and buckwheat, samples of the aboveground matter of the plants were collected during the flowering stage with a metallic frame of 0.25 m^2 in each subplot. The material was dried at 55 ± 5 ºC until stabilization and then weighed. Buckwheat samples were collected in March 2020, and April 2021 and 2022, while for winter cover crops it was in August 2020, and September 2021 and 2022.

For the maize dry phytomass, sampling was realized at the physiological maturation stage, that is, in February 2021, 2022, and 2023, by collecting five plants in each subplot and drying them to constant weight, and then weighing them to estimate the total weight total in 10,000 m² (ha), according to the population obtained in the evaluation of grain productivity. The cumulative dry phytomass was calculated by adding the respective phytomass from a crop year (buckwheat, cover crop, and maize) to its treatments.

Determining maize grain yield, ears were manually collected in 2.7 m² of each experimental unit and processed in an electric thresher. The grains were weighed, and their moisture content was determined using an electronic determinator, to extrapolate the data to one hectare with moisture correction of 13% and obtain productivity.

Statistical analysis

The analyzed variables were dry phytomass of the crops separately and cumulative by crop year, and maize grain yield, for 2020/21, 2021/22, and 2022/23. Data were subjected to analysis of variance (ANOVA), following the experimental design of split-plots in a factorial scheme, and comparison of means by the Skott-Knott test ($p>0.05$), using the SISVAR software [32].

RESULTS

Dry phytomass

For buckwheat phytomass, there was no interaction between cover crops and N rates in any of the evaluated crop years (Table 1). In 2020, there was no difference between the cover crops and between the N rates. For the 2021 crop year, the mix (O+V, O+V+R, and WO+P+R) and the single leguminous vetch and lupine had the highest buckwheat dry phytomass values. Regarding N rates, the 0 and 180 kg ha^{-1} showed the highest phytomass production, 2.2 and 2.3 Mg ha^{-1}, respectively. As for the 2022 crop year, there was no difference between cover crops, nonetheless, for N fertilization, the 180 kg ha^{-1} rate showed higher phytomass production, 6.8 Mg ha^{-1}.

Table 1. Dry phytomass production of buckwheat in crop succession with winter cover crops and maize with nitrogen fertilization (0, 90, and 180 kg ha^{-1}) in the crop years of 2020, 2021, and 2022

N rate	**Winter cover crops**								**Mean**	**CV (%)**
(kg ha^{-1})	**Oats**	**O+V**	**O+V+R**	**WO+P+R**	**Rye**	**Vetch**	**Pea**	**Lupine**		
					Dry phytomass (Mg ha^{-1})					
					Crop year 2020					
0	1.1	0.8	1.0	1.3	1.1	1.0	1.5	1.0	1.1 ns	
90	1.2	1.0	1.0	1.1	1.1	1.0	1.5	1.2	1.1	23.3
180	1.2	1.1	1.0	1.4	1.1	1.2	1.3	1.6	1.2	
Mean	1.2 ns	1.0	1.0	1.3	1.1	1.0	1.4	1.3		29.3
					Crop year 2021					
0	1.9	2.1	2.9	2.0	1.7	2.4	2.2	2.8	2.2 A	
90	1.7	2.3	1.8	1.7	2.0	2.0	1.4	2.2	1.9 B	19.0
180	2.1	2.2	2.4	2.7	2.1	2.6	1.7	2.8	2.3 A	
Mean	1.9 b	2.2 a	2.4 a	2.1 a	1.9 b	2.3 a	1.8 b	2.6 a		19.9
					Crop year 2022					
0	4.3	4.9	5.7	6.2	5.1	6.5	5.9	4.8	5.4 B	
90	3.8	6.6	5.8	6.7	4.1	6.1	4.7	5.9	5.5 B	23.7
180	6.5	6.6	6.9	7.6	6.9	6.1	7.4	6.0	6.8 A	
Mean	4.9 ns	6.0	6.1	6.8	5.4	6.2	6.0	5.6		19.3

Means followed by the same capital letter in the column and lowercase letter in the row do not differ from each other by the Skott-Knott test ($p<0.05$). ns: not significant by the F test ($p<0.05$). CV: coefficient of variation. O+V: oats+vetch; O+V+R: oats+vetch+radish; WO+P+R: white oats+pea+radish.

Regarding winter cover crops, there was no factorial interaction in any of the evaluated crop years (Table 2). In 2020, the O+V+R mix had the highest dry phytomass production (6.5 Mg ha^{-1}), while the WO+P+R mix and the vetch had the lowest phytomass, 1.5 and 1.7 Mg ha^{-1}, respectively. As for the fertilizer rates, the absence of N (0 kg ha^{-1}) and the highest N rate (180 kg ha^{-1}) showed a phytomass production of 3.7 Mg ha^{-1}. In the 2021 crop year, the O+V+R and O+V mix showed the highest phytomass production, 2.1 and 2.2 Mg ha^{-1}, respectively, along with rye, with 2.4 Mg ha^{-1}. While in 2021, N fertilization did not interfere with the production of cover crops. In 2022, oats and mix had the highest phytomass production, and N fertilization (90 and 180 kg ha^{-1}) improved the phytomass production of winter cover crops.

Table 2. Dry phytomass production of winter cover crops in crop succession with buckwheat and maize with nitrogen fertilization (0, 90, and 180 kg ha^{-1}) in the crop years of 2020, 2021, and 2022

N rate	**Winter cover crops**								**Mean**	**CV (%)**
(kg ha^{-1})	**Oats**	**O+V**	**O+V+R**	**WO+P+R**	**Rye**	**Vetch**	**Pea**	**Lupine**		
				Dry phytomass (Mg ha^{-1})						
				Crop year 2020						
0	3.6	4.4	7.1	1.6	3.5	1.2	3.0	5.2	3.7 A	
90	3.5	2.5	5.3	1.4	2.3	1.5	2.0	4.1	2.8 B	23.5
180	4.2	3.1	7.3	1.7	3.3	2.6	3.0	4.3	3.7 A	
Mean	3.8 c	3.3 c	6.5 a	1.5 d	3.0 c	1.7 d	2.7 c	4.5 b		26.5
				Crop year 2021						
0	1.5	1.9	2.2	2.1	2.8	0.9	1.4	1.6	1.8 ns	
90	1.4	2.1	1.8	1.5	1.9	1.0	1.3	1.1	1.5	34.0
180	1.5	2.5	2.2	1.7	2.5	1.1	1.3	2.1	1.9	
Mean	1.5 b	2.2 a	2.1 a	1.8 b	2.4 a	1.0 b	1.3 b	1.6 b		26.1
				Crop year 2022						
0	4.2	5.3	4.8	5.6	2.6	1.4	2.4	3.6	3.7 B	
90	5.0	7.1	7.8	7.6	4.1	1.7	3.9	3.7	5.1 A	28.4
180	6.6	5.8	5.5	6.6	4.3	0.8	2.9	2.2	4.3 A	
Mean	5.2 a	6.1 a	6.0 a	6.6 a	3.7 b	1.3 c	3.1 b	3.1 b		30.2

Means followed by the same capital letter in the column and lowercase letter in the row do not differ from each other by the Skott-Knott test ($p<0.05$). ns: not significant by the F test ($p<0.05$). CV: coefficient of variation. O+V: oats+vetch; O+V+R: oats+vetch+radish; WO+P+R: white oats+pea+radish.

For maize phytomass production, in the 2020/21 crop year, the O+V and O+V+R mix, vetch, and lupine presented the highest phytomass with values above 11 Mg ha^{-1} (Table 3). For N fertilization, the highest productions were observed in the presence of N, with values of 11.3 and 11.7 Mg ha^{-1} for 90 and 180 kg ha^{-1}, respectively (Table 3). In the 2021/22 crop year, there was no difference in maize phytomass among the cover crops, but the addition of N, at both rates, promoted the highest phytomass. In the 2022/23 crop year, there was a factorial interaction in which there was a difference between the cover crops only for the N rate 0 kg ha^{-1}, with the mix, vetch, and lupine presenting higher phytomass maize production. For the cover crops, vetch and lupine, there was no difference between N rates, but for the other cover crops, rates of 90 and 180 kg ha^{-1} showed higher maize production.

Table 3. Dry phytomass production of maize in crop succession with buckwheat and winter cover crops with nitrogen fertilization (0, 90, and 180 kg ha-1) in the crop years of 2020/21, 2021/22, and 2022/23

N rate (kg ha^{-1})	Winter cover crops								Mean	CV (%)
	Oats	O+V	O+V+R	WO+P+R	Rye	Vetch	Pea	Lupine		
	Dry phytomass (Mg ha^{-1})									
	Crop year 2020/21									
0	7.1	9.5	9.5	7.5	8.3	10.4	8.4	11.4	9.0 B	
90	10.1	12.4	11.0	10.8	11.0	11.7	11.0	12.7	11.3 A	9.7
180	11.5	12.0	12.5	11.7	11.6	11.1	10.8	12.0	11.7 A	
Mean	9.6 b	11.3 a	11.0 a	10.0 b	10.3 b	11.1 a	9.9 b	12.1 a		11.7
	Crop year 2021/22									
0	9.4	7.7	7.9	8.2	11.3	7.1	7.1	7.7	8.3 B	
90	11.7	11.9	11.6	10.6	10.2	12.3	7.5	10.9	10.8 A	26.3
180	14.6	11.6	14.0	12.0	10.5	10.1	10.8	9.0	11.6 A	
Mean	11.9 ns	10.4	11.2	10.3	10.7	9.9	8.5	7.7		18.0
	Crop year 2022/23									
0	6.7 bB	10.3 aB	11.4 aB	9.4 aB	2.7 cB	13.0 aA	7.9 bB	9.8 aA	8.9	
90	13.0 aA	12.3 aA	14.8 aA	13.5 aA	11.0 aA	12.9 aA	12.7 aA	11.7 aA	12.7	13.3
180	14.0 aA	13.7 aA	16.1 aA	14.2 aA	12.2 aA	11.3 aA	11.3 aA	11.3 aA	13.1	
Mean	11.2	12.1	14.1	12.4	8.6	12.4	10.9	10.9		24.4

Means followed by the same capital letter in the column and lowercase letter in the row do not differ from each other by the Skott-Knott test ($p<0.05$). ns: not significant by the F test ($p<0.05$). CV: coefficient of variation. O+V: oats+vetch; O+V+R: oats+vetch+radish; WO+P+R: white oats+pea+radish.

Regarding annual cumulative phytomass production, in the 2020/21 crop year, the winter cover crops O+V+R mix and lupine had the highest production, with values of 18.5 and 17.9 Mg ha^{-1}, respectively (Table 4). Among the N rates, the cumulative phytomass was higher for the 180 kg ha^{-1} N rate. For the 2021/22 crop year, among the winter cover crops, the lowest cumulative phytomass was observed for pea (11.2 Mg ha^{-1}), differing from the others.

For N fertilization, the highest productions were observed in the presence of N, with values of 11.3 and 11.7 Mg ha^{-1} for 90 and 180 kg ha^{-1}, respectively (Table 3). In the 2021/22 crop year, there was no difference in maize phytomass among the cover crops, but the addition of N, at both rates, promoted the highest phytomass. In the 2022/23 crop year, there was a factorial interaction in which there was a difference between the cover crops only for the N rate 0 kg ha^{-1}, with the mix, vetch, and lupine presenting higher phytomass maize production. For the cover crops, vetch and lupine, there was no difference between N rates, but for the other cover crops, rates of 90 and 180 kg ha^{-1} showed higher maize production.

Regarding annual cumulative phytomass production, in the 2020/21 crop year, the winter cover crops O+V+R mix and lupine had the highest production, with values of 18.5 and 17.9 Mg ha^{-1}, respectively (Table 4). Among the N rates, the cumulative phytomass was higher for the 180 kg ha^{-1} N rate. For the 2021/22 crop year, among the winter cover crops, the lowest cumulative phytomass was observed for pea (11.2 Mg ha^{-1}), differing from the others.

Table 4. Cumulative dry phytomass production of buckwheat, winter cover crops, and corn with nitrogen fertilization (0, 90, and 180 kg ha^{-1}) in the crop years of 2020/21, 2021/22, and 2022/23

N rate	**Winter cover crops**								**Mean**	**CV (%)**
(kg ha^{-1})	**Oats**	**O+V**	**O+V+R**	**WO+P+R**	**Rye**	**Vetch**	**Pea**	**Lupine**		
	Dry phytomass (Mg ha^{-1})									
	Crop year 2020/21									
0	11.8	14.6	17.6	10.4	12.9	12.5	13.0	17.6	13.8 C	
90	14.8	15.9	17.3	13.3	14.3	14.2	14.1	18.1	15.3 B	9.2
180	17.1	16.3	20.8	14.7	16.0	14.9	15.1	17.9	16.6 A	
Mean	14.5 b	15.6 b	18.5 a	12.8 b	14.4 b	13.9 b	14.1 b	17.9 a		9.5
	Crop year 2021/22									
0	12.7	11.7	13.0	12.3	15.8	10.9	10.1	12.2	12.3 B	
90	14.8	16.3	15.2	13.7	14.0	15.6	10.0	14.2	14.2 A	20.2
180	18.2	16.3	18.7	16.4	15.0	14.0	13.6	13.9	15.8 A	
Mean	15.2 a	14.8 a	15.6 a	14.1 a	15.0 a	13.5 a	11.2 b	13.4 a		13.9
	Crop year 2022/23									
0	15.2 bC	20.5 aB	21.9 aB	21.2 aB	10.5 cC	21.9 aA	15.2 bB	18.2 aA	18.1	
90	21.8 bB	26.0 aA	28.3 aA	27.9 aA	19.1 bB	23.0 bA	19.1 bA	21.8 bA	23.3	10.3
180	27.1 aA	26.2 aA	28.6 aA	28.4 aA	23.4 bA	20.4 bA	20.4 bA	19.5 bA	24.3	
Mean	21.4	24.2	26.3	25.8	17.7	21.8	18.3	19.7		14.2

Means followed by the same capital letter in the column and lowercase letter in the row do not differ from each other by the Skott-Knott test ($p<0.05$). ns: not significant by the F test ($p<0.05$). CV: coefficient of variation. O+V: oats+vetch; O+V+R: oats+vetch+radish; WO+P+R: white oats+pea+radish.

Although, the 2022/23 crop year showed a significant interaction between the factors cover crops and N rates. For the N rate 0 kg ha^{-1}, the system with rye showed the lowest cumulative phytomass production, with 10.5 Mg ha^{-1}, while mix, vetch, and lupine showed the highest production. For the rate 90 kg ha^{-1}, the mix (O+V, O+V+R, and WO+P+R) showed higher cumulative production, with values above 26 Mg ha^{-1}, while for the rate 180 kg ha^{-1}, in addition to the mix and oats also showed the highest phytomass. Lupine and vetch did not show the effects of fertilization, not differing between the N rates, while for oats and rye there was an increase in production with the increase in the amount of N added; for vetch, the rate of 90 kg ha^{-1} showed higher cumulative phytomass production.

Maize grain yield

Maize grain yield in the 2020/21 crop year was higher on the cover crops vetch, lupine, and mix (O+V and O+V+R), with values above 5.5 Mg ha^{-1} (Table 5). Using N fertilizer increased maize grain yield, reaching 5.9 and 6.3 Mg ha$^{-1,}$ for 90 and 180 kg ha^{-1}, respectively. Although, for the 2021/22 crop year, there was no difference between cover crops and N rates. Grain yield in the 2022/23 crop year showed a factorial interaction. For the N rate 0 kg ha^{-1}, lupine, vetch, and O+V+R had the highest grain yields. In the 90 kg ha^{-1}, the O+V and O+V+R mix, and the single vetch and pea, showed higher grain yields. While with the N rate 180 kg ha^{-1}, there was no difference between winter cover crops. Regarding N rates, for WO+P+R and rye there was an increase in production with increasing N, but for vetch, there was no effect. In the others cover crops, the addition of N increased grain yield not differing between rates 90 and 180 kg ha^{-1}.

Table 5. Maize grain yield in crop succession with buckwheat and winter cover crops with nitrogen fertilization (0, 90, and 180 kg ha^{-1}) in the crop years of 2020/21, 2021/22, and 2022/23

N rate (kg ha^{-1})	**Winter cover crops**								**Mean**	**CV (%)**
	Oats	**O+V**	**O+V+R**	**WO+P+R**	**Rye**	**Vetch**	**Pea**	**Lupine**		
					Corn grain (Mg ha^{-1})					
					Crop year 2020/21					
0	2.2	4.3	4.3	2.5	3.3	5.1	3.4	6.1	3.9 B	
90	4.9	7.0	5.7	5.5	5.7	6.3	5.3	7.2	5.9 A	17.2
180	6.2	6.6	7.0	6.3	6.3	5.8	5.5	6.6	6.3 A	
Mean	4.4 b	5.9 a	5.7 a	4.8 b	5.1 b	5.7 a	4.7 b	6.6 a		20.8
					Crop year 2021/22					
0	0.8	1.0	0.9	1.3	1.0	1.2	1.2	1.0	1.0 ns	
90	1.3	1.0	1.0	1.1	1.9	1.1	1.2	1.5	1.3	38.8
180	1.1	1.0	1.0	1.3	1.5	0.6	1.2	1.8	1.1	
Mean	1.1 ns	1.0	1.0	1.2	1.5	1.0	1.2	1.1		42.2
					Crop year 2022/23					
0	1.5 bB	3.0 bB	4.9 aB	2.9 bC	1.2 bC	6.6 aA	3.0 bB	4.6 aB	3.4	
90	6.0 bA	8.8 aA	8.4 aA	6.3 bB	5.5 bB	7.8 aA	7.8 aA	6.5 bA	7.2	18.9
180	7.5 aA	8.4 aA	9.2 aA	8.3 aA	7.5 aA	7.1 aA	8.5 aA	7.8 aA	8.0	
Mean	5.0	6.7	7.5	5.8	4.7	7.2	6.4	6.3		24.6

Means followed by the same capital letter in the column and lowercase letter in the row do not differ from each other by the Skott-Knott test ($p<0.05$). ns: not significant by the F test ($p<0.05$). CV: coefficient of variation. O+V: oats+vetch; O+V+R: oats+vetch+radish; WO+P+R: white oats+pea+radish.

DISCUSSION

Effect of the use of winter cover crops and N fertilization on phytomass production

Buckwheat

Differences for buckwheat phytomass production, only in the 2021 crop year, cannot indicate that the cultivation of cover crops presented a residual effect on the system (Table 1). However, the use of single grass species, such as oats and rye, could not benefited buckwheat phytomass production due to the higher N immobilization of the Poaceae species, which may results in lower availability of nutrients when compared to Fabaceae, Brassicaceae species, or mix [33–35]. Buckwheat is a crop whose commercial adoption has occurred more systematically in recent years, so there are no records of information in the literature addressing the effect of cover crops on this commercial crop. The effect of using N on the maize crop to buckwheat phytomass production was observed in the 2021 and 2022 crop years. Maize crop has a high demand for N however, it was possible to visualize that the higher phytomass production with 180 kg ha^{-1} N rate may be due to the N cycling from the maize straw, mainly because of the continuous management over the 10 years.

Buckwheat showed great phytomass production in 2022 compared to the literature, with values above 6 Mg ha^{-1} [9, 18, 36]. Still, the highest phytomass production was close to the results of the studies using fertilizers [37] or soil correctives in pre-sowing buckwheat [38]. This higher production was also correlated with the crop year in which there was the highest accumulated rainfall in the months with buckwheat cultivation, 394 mm, while in the other crop years, they were 330 mm (2020) and 131 mm (2021), besides the rainfall volume distribution throughout the crop cycle which could resulted in decrease of dry aboveground phytomass [39].

On the other hand, when comparing the values of 2020 with the 2022 crop year, for a similar accumulated precipitation, there was an average increase of five times. One of the hypotheses refers to the residual effect of the N fertilizer used in maize, considering that in 2021/22, maize grain yield before buckwheat (Table 5) was very low due to the drought that occurred in the grain filling phase, but the phytomass production was similar to the year 2020 (Table 1). This normal phytomass productivity with low extraction/export via harvested grains may have enhanced the development of buckwheat due to the greater bioavailability of nutrients via maize straw cycling, showing the residual effect of fertilization not only between rates but in the whole system.

Winter cover crops

Among the different winter cover crops, the O+V+R mix showed the highest phytomass production in the three years evaluation, even in the 2021 crop year, in which climatic conditions were more limiting (Table 2; Figure 1). Mix are great alternatives due to the high phytomass production similar to oats and with accumulated N amount similar to or greater than leguminous, which confers a higher phytomass quality, resulting in a higher quality index of the residual phytomass [38], benefiting the system due to greater nutrient cycling [40], because the mix residue presents Ca = 1%; Mg = 0.56%; P = 0.33%; K = 3.28%; e N = 2.20% [34], with rapid N mineralization, contributing to increase the phytomass production [41]. The different species in the consortia present different strata of both light absorption and nutrient absorption, making systems more efficient in taking advantage of environmental conditions, such as light, water and nutrients for growth [42].

The lower production of vetch phytomass in all years was due to its longer flowering cycle, approximately 120-130 days, thus, at the time of evaluation, this species is not at the peak of phytomass production. However, even in this scenario, it is the cover crop that promotes higher maize yields in the absence of mineral N agreeing with [43]. Its efficiency can be increased by sowing at the end of April or at the beginning of May, thus, at the end of August it will have a 120-days cycle and at the peak of phytomass production, be able to add phytomass amounts greater than 4 Mg ha^{-1} and more than 85 kg ha^{-1} of N [41]. When comparing vetch phytomass production with different sowing rates, it also did not obtain results above 4 Mg ha^{-1} [44].

The phytomass of pea ranged between 4 and 7 Mg ha^{-1} [9], a value in contrast to the one obtained in the present study (Table 2), but compared with studies in the same area, the phytomass production was between 2.0 to 3 .5 Mg ha^{-1} [43], closer to the three crop years evaluated.

The different phytomass production between crop years is related to the precipitation, which was lower in 2021. Lower precipitation also affects the N availability in the soil, reducing the concentration in the soil solution, which also reduced its residual effect on phytomass production. Therefore, crops of similar species in similar soil and climate conditions of the present research, presented greater N accumulation when N fertilization is not used in maize [45], and an increasing concentration of N in leaf up to 180 kg ha^{-1} N rate [46], which justifies the higher phytomass, due to the correlation with the phytomass and the nutrients content, such as nitrogen [33], justifying the higher values for the residual rate 180 kg ha^{-1}.

Maize

For the 2021/22 crop year, there was no precipitation in December (Figure 1), however the phytomass production was not highly affected since this component was already more than 90% defined in the evaluation phase (R2), therefore, maize is less affected by water stress when it is grain filling than during the bolting period, negatively affecting grain productivity [47] (Table 3). Also, due to this lower precipitation, the cover crops had less influence on the maize phytomass production compared to 2020/21 and 2022/23, with N being a greater influence on the amount of phytomass produced.

N is among the elements with the greatest demand for maize [45], responding linearly with the N increase at least up to 200 kg ha^{-1}[48]. When maize is deficient in N, the plant develops chlorosis and leaf loss, causing lower growth [49], which reduces phytomass production, as observed for Poaceae species in the absence of mineral N for the 2022/23 crop year, in which the reduction of phytomass production to oats and rye was 50 and 77%, respectively, compared to the means of the respective systems that received N fertilization.

In the crop year 2022/23, only vetch and lupine produced phytomass as much as without N fertilization compared to the presence of N, indicating the greater capacity of these systems to supply N to the maize crop in succession. Although pea is a Fabaceae species and the same effect did not occur, as this treatment was included in 2020 (replacing radish), that is, its residual N fertilization effect on the soil by biological fixation is smaller when compared to the other leguminous. The radish cultivated previously provides approximately 81 kg ha^{-1} accumulated N [41], and with better N equivalence than Poaceae species, such as oats [50].

In the 2022/23 crop year, vetch, lupine, and mix may have released most of the N in the first 15 days after management, according [51], providing up to 56% of the N from the residue, as demonstrated by [43]. Comparing cover crops with spontaneous plants in the fallow system, the cover crops, presents greater N accumulation, K, and P in its phytomass [34], evidencing its importance. However, even in crop years with disadvantageous conditions, such as drought, it was possible to obtain the recommended minimum phytomass, which would be 7 Mg ha^{-1} for the crop [52], except for maize in succession of rye without the N addition, in the 2022/23 harvest, however, it could be considered an atypical result. Due to its C/N ratio, rye leads to N immobilization [50], influencing absorption by maize.

Cumulative annual phytomass

Nitrogen fertilization in the maize crop resulted in greater accumulated phytomass, with the increase in the N rate However, for systems with Fabaceae (except pea) the total additions of phytomass in the absence of mineral N were equivalent to those verified in the rates 90 and 180 kg ha^{-1} in the year 2022. At the same time, it can be seen when leguminous are used (single or mix), there is no increase in the cumulative phytomass for the rate 180 kg ha^{-1}, demonstrating that it is possible to work with half the applied rate (90 kg ha^{-1}) without compromising this variable.

In general, maize presents the greatest contribution to the addition of phytomass and C to the soil, representing 64% of the added phytomass, highlighting its importance in crop rotation systems. Cover crops added up to 36%, this result corroborated with those found by [53].

Even with crop years under conditions of low precipitation, the systems adopted in the present research made it possible to add adequate phytomass to maintain soil organic matter and, thus, avoid reducing the quality of the system. For subtropical regions, as in the present study, the authors state that between 4 and 6 Mg ha^{-1} of phytomass [2, 54] are necessary, but even when considering a higher value as ideal, which would be between 11 and 12 Mg ha^{-1} [13], most systems are able to supply this demand, considering the means dry phytomass production of cover crops (buckwheat and winter cover crops) of 4.5, 3.9, and 10.3 Mg ha^{-1}, and for cumulative phytomass of 15.2, 14.1, and 22.3 Mg ha^{-1}, for the crop years 2020/21, 2021/22, and 2022/23, respectively.

It should be noted that the results in the present study were obtained by the cumulative effect in the management during 13 years of research with conservationist practices, which at the same time demonstrates the importance of long-term experiments and the maintenance of long-term field production systems.

Effect of the use of winter cover crops and N fertilization on maize grain yield

Maize grain yield followed the same behavior verified for maize phytomass production and cumulative phytomass (Table 5). In the 2020/21 crop year, there is a distinction, with the greatest capacity to supply nitrogen to the maize crop for O+V, O+V+R, vetch, and lupine. Evaluating the productive capacity of maize and cover crops for three years, [19] observed higher yields for systems with blue lupine and mix, while higher maize yield was observed on white lupine, vetch, and radish, but not differing from mix for [54]. However, mix can be considered the most appropriate cover crop when the aim is to provide greater diversity and ecosystem benefits of soil protection and N release to the cropping system [41], combined with the reduction of production costs when considering the equivalence in N mineral, that is, considering its contribution and the cost of acquiring seeds, the economic return may be equal to or greater than the use of Fabaceae species.

However, in 2021/22, the effects of cover crops and N rates were not observed due to the water deficit during the crop cycle, which reduced grain yield to values below 1.5 Mg ha^{-1} (Table 5). The cumulative precipitation in the maize crop cycle was less than 350 mm (Figure 1), with only 2 mm in the month of December, while the climatological normal indicates accumulated rainfall for the region close to 900 mm [28]. Due to the low water availability, maize production can reach losses of up to 50%, and when the deficit occurs after fertilization, losses can range from 25 to 32% [55], since water is important for the development of the pollen tube [56]. In comparison with the other years evaluated, the loss of productivity reached 93.5%, which was also found in the other work, with loss greater than 80% [57]. The same authors obtained similar results to those of the present research when they presented drought in the critical period of maize development, with grain yield lower than 2.0 Mg ha^{-1}. Losses obtained in grain yield disagree with research carried out in similar conditions of climate and soil in which they claim to have a reduction of approximately 50% [58], since the present work presented greater losses.

When analyzing the interaction in the 2022/23 crop year, only the system with vetch presented grain yield in the absence of mineral N equivalent to 90 and 180 kg ha^{-1} N rates. So, it is possible to estimate the N equivalence of the cover crop systems used, between yield and applied N rates. For the vetch/maize system, the equivalence within its system is 167 kg of N ha^{-1}. This calculation was made, for example, considering that 7.1 Mg ha^{-1} is equivalent to 180 kg of N and 6.6 Mg ha^{-1} is equivalent to proportional kg of N. Still for the final equivalence, we must deduct the equivalence of a reference system, being used here oats and rye with an average yield of 1.35 Mg ha^{-1} in the absence of mineral N and an average of 7.5 Mg ha^{-1} at rate 180 kg. Thus, the average productivity of the Poaceae species in the absence of mineral N is equivalent to 32.4 kg ha^{-1} of N. Discounting the reference equivalence of the equivalence of the system with vetch/maize, we have that this system has an equivalence of 130 kg ha^{-1} of mineral N. Thus, we can infer the descending order of the capacity to supply N of cover crops used, following the order: vetch (130 kg of N); lupine (74 kg of N); O+V+R (64 kg of N); O+V (32 kg of N); pea (31 kg of N), and WO+P+R (30 kg of N).

Using crops in succession for several years allowed to identify the systems that promote greater maize production capacity and, in addition, to indicate that regardless of the system used, the additions of phytomass in the system are adequate for the maintenance and/or improvement of soil quality, highlighting the importance the inclusion of maize crops in rotation systems to ensure such results.

CONCLUSION

The production of buckwheat phytomass is influenced by the residual N applied in the maize crop, being improved using cover crops mix, pea, and lupine.

The highest phytomass production of winter cover crops was obtained using a mix, emphasizing O+V and O+V+R even in years affected by drought.

Maize phytomass production was not affected by the dry season, while grain yield was impacted with a reduction greater than 80%.

For annual cumulative phytomass, maize represents more than half of the total phytomass added, with the highest total additions verified in mix systems that also provide greater addition of biomass from cover crops.

The highest maize yields in the absence of mineral N are verified for the mix O+V+R with leguminous.

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