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RESEARCH

Residual Effect of Gypsum and Nitrogen Rates on Black Oat Regrowth and on Succeeding Soybean under No-Till

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Abstract

Under continuous no-till, gypsum has been successfully used to manage soil fertility and improve crop yield. Nitrogen (N) fertilization is critical for crop performance, however, since it is expensive and potentially pollutant, it must be correctly applied. Both subjects have been widely studied, yet there is a lack of information on the interaction between them, especially concerning crops in rotation or succession. The objectives of this study were to evaluate topdressing N fertilization (0, 50, and 100 kg N ha^{-1}) on black oat (*Avena strigosa* Schreb.) under no-till, inside a long-term gypsum experiment (0, 3, 6, 9, and 12 Mg ha^{-1}). We evaluated black oat regrowth after haylage harvest and nutrient concentration and uptake by aboveground biomass, as well as the effects of this system on the successor crop soybean (*Glycine max* (L.) Merr.) in terms of leaf nutrient concentration and grain yield over two growing seasons. The gypsum application, even up to 44 and 55 months earlier, presented a long-term effect when associated with N fertilization, causing black oat biomass to increase during the regrowth phase. Nitrogen fertilization increased black oat regrowth biomass, even without gypsum. Greater nutrient uptake by black oat regrowth occurred under higher gypsum rates and N fertilization, which may have been advantageous in the long term for the production system, once nutrient cycling may partially substitute fertilizer-derived nutrients. Soybean yield was not affected by either long-term gypsum or N applied at black oat tillering, even though some leaf nutrient concentrations were influenced.

Keywords *Avena strigosa* · *Glycine max* · Nutrient cycling · Cover crops

Introduction

In subtropical environments, such as Southern Brazil, black oat (*Avena strigosa* Schreb.) and soybean (*Glycine max* (L.) Merr.) are commonly cultivated in succession under no-till. Soybean is grown for grain production, while black oat may be used for cattle grazing or feeding and as a cover crop. To cope with the increasing global demand for food (Ray et al., 2013), improvements in the management practices and yield of these crops are constantly sought. Likewise, nitrogen (N) fertilization and gypsum application have been widely studied and used to manage soil fertility in subtropical conditions, but their interaction has been underexplored, especially in the long term.

In no-till, the soil permanent cover by plant biomass or residues reduces soil and nutrient losses, besides increasing soil organic matter, especially in tropical and subtropical environments (Nunes et al., 2011; Pereira et al., 2009). To avoid soil disturbance, crop residues and soil amendments

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are not incorporated into the soil by tillage. Thus, nutrients get concentrated near the soil surface, and a vertical fertility gradient builds up over time, with less available basic cations and phosphorus (P) in subsurface soil, which gets more acidic (Schlindwein et al., 2013; Zoca & Penn, 2017) and restrains root growth in depth (Bortoluzzi et al., 2014; Zandoná et al., 2015).

Gypsum application improves the distribution of nutrients in the soil profile, as it contains calcium (Ca^{2+}) and sulfur (S) in a soluble compost (2.5 g L^{-1}) and chemical form ($CaSO_4$) that allows percolation to subsurface layers (Zoca & Penn, 2017). The reaction of $CaSO_4$ with the soil reduces aluminum (Al^{3+}) activity, which alleviates subsurface acidity effects and redistributes basic cations like magnesium (Mg^{2+}) and potassium (K^+) from surface to subsurface layers (Caires et al., 2016; Ramos et al., 2013; Vicensi et al., 2020a, b). This change in soil chemical conditions enhances root growth (Caires et al., 2016; Vicensi et al., b) and crop tolerance to water stress (Dalla-Nora & Amado, 2013; Zandoná et al., 2015).

Some studies have reported that gypsum application increased biomass of black oat and other Poaceous crops (Soratto & Crusciol, 2008a; Vicensi et al., 2020a, b), besides improving soil fertility, especially in no-till soils (Caires et al., 2016; Ramos et al., 2013; Soratto & Crusciol, 2008a). In such conditions, N fertilization is also reported to increase black oat biomass (Bassegio et al. 2013; Menezes et al., 2013; Restelatto et al., 2014; Steiner et al., 2009) and quality (Basi et al., 2011), through higher nutrient uptake and concentration and lower C:N rate, which improves nutrient cycling (Restelatto et al., 2015; Santi et al., 2003).

The production of cover and forage crops in winter contributes to sustainable management, as it adds plant diversity to the production systems and organic matter to the soil, promoting nutrient cycling and improving soil quality (Balbinot Junior et al. 2009). Black oat may provide high-quality feed for cattle (Restelatto et al., 2014). Moreover, the plant residues can release significant amounts of N, P, and K, which are majorly available up to 30–40 days from crop management (biomass deposition on the soil surface) (Crusciol et al., 2008), benefiting grain yield of succeeding crops, such as soybean (Caires et al., 2017). When black oat is cultivated for forage in tropical and subtropical production systems, the plants can regrow for at least 40 days before planting the summer crops—sufficient time for a considerable biomass and nutrient accumulation (Vega-García et al., 2020).

Black oat is known for its hardiness and tolerance to poor soil conditions (Silva et al., 2006), having a strong root system (Burr-Hersey et al., 2017; Müller et al., 2001). It is cultivated in no-till areas for crop rotation, grazing, haying, silage, and grain production in Southern Brazil (Ziech et al., 2015). This crop has the potential to accumulate up to 7.8 Mg ha^{-1} of aboveground biomass (Michelon et al., 2019), or even more, depending on the environment and management practices. It serves as green manure since the absorbed nutrients are cycled, improving nutrient distribution in the soil profile and contributing to the efficiency of continuous no-till (de Faccio Carvalho et al., 2010).

Concerning N rates, in the subtropical areas of Southern Brazil, black oat biomass has been reported to increase with up to 120 kg N ha^{-1} (Bassegio et al. 2013; Steiner et al., 2009) and even 180 kg N ha^{-1} (Restelatto et al., 2014; Santi et al., 2003), depending upon production conditions. However, due to the high costs of N fertilization, growers apply none or much lower amounts of N than required, posing a presumable constraint to higher yields. In contrast, the negative effects of N loss processes are well known and there have been researching efforts focusing on N use efficiency (Zhang et al. 2015), so that lower and more environmentally friendly rates of N may be used, in consonance to economic viability and yield levels.

Since gypsum improves root growth of plants (Caires et al., 2016), including black oat (Vicensi et al., 2020b), and N can be easily leached through the soil profile in the nitrate (NO_3^-) form under normal aeration conditions (Bortolotto et al., 2012; Caires et al., 2015), we hypothesized that gypsum application could have a synergistic effect when associated with N fertilization on black oat regrowth and nutrient absorption, as well as positive effects on succeeding crops, such as soybean (*Glycine max* (L.) Merrill), the main cash crop in the summer season.

The objectives of this study were to evaluate topdressing N-fertilization on black oat under no-till, inside a long-term gypsum experiment, assessing black oat regrowth after haylage harvest and nutrient concentration and uptake by aboveground biomass, as well as the possible beneficial effects of this system in the successor crop soybean, in terms of leaf nutrient concentration and grain yield, over two growing seasons.

Materials and Methods

The experiment was set up in 2009, in Guarapuava, Paraná, Brazil (25º23′ S, 51º30′ W, altitude 1026 m), where the climate is humid subtropical mesothermic (Cfb—Köppen) (Alvares et al., 2013). The field was cultivated under the continuous no-till system for more than 11 years prior to the growing seasons of 2015 and 2016, which is the period considered for the present study.

In Oct. 2009, after the evaluation of soil morphology, clay content, and chemical attributes (Michalovicz et al., 2019), it was classified as very clayey Typic Hapludox (USDA, 1999), corresponding to *Latossolo Bruno* according to the Brazilian Soil Classification System (Embrapa, 2018), with low acidity in A horizon, low Al^{3+} levels up to 1.4 m, and no physical limitations (bulk density ≤ 1.1 Mg m^{-3}). The chemical analysis and clay determination of the soil diagnostic layer performed in Nov. 2009 is presented in Table 1. Soil chemical conditions up to 0.8 m just prior to 2015 and 2016 growing seasons were previously published by Vicensi et al. (2020b).

Experimental Design

The experiment was carried out in a randomized block design in a split-plot arrangement, with four replications. The main plots consisted of gypsum rates: 0 (control, G_0), 3 (G_3), 6 (G_6), 9 (G_9), and 12 (G_{12}) Mg ha^{-1} of dry weight, broadcasted on the soil surface and split into three equal annual applications, one third-rate each, in Nov. 2009, Nov. 2010, and Nov. 2011, just after sowing summer crops. These rates were calculated to provide 0, 33, 66, 100, and 133% of the required amount of Ca^{2+} to reach 60% of Ca saturation on the cation exchange capacity (at pH 7.0) of the A1 horizon of the soil (Michalovicz et al., 2019).

The subplots consisted of N-fertilization rates applied as top-dressings at the beginning of the black oat tillering stage: 0 (control, N_0), 50 (N_{50}), and 100 (N_{100}) kg ha^{-1} of N. The N source used was urea [($CO(NH_2)_2$), 45% of N]. The main plot size was 64 m^2 (10 × 6.4 m), and subplots had 21.31 m^2 (3.33 × 6.40 m).

Black Oat Crop

The black oat cultivar IAPAR 61 was sown on April 15 and April 17 in the 2015 and 2016 growing seasons, respectively, succeeding soybean in both periods. As additional information, the same variety was sown in the same experimental setup before this study, on April 15, 2014. The seeding rate was 360 seeds per m^2, with a row spacing of 0.17 m. The soil was fertilized with 40 kg ha^{-1} of P_2O_5 (triple superphosphate) in furrow and 40 kg ha^{-1} of K_2O (potassium chloride) broadcasted on the soil surface after sowing.

The plots were harvested (haylage) at 115 and 120 days after sowing in the 2015 and 2016 growing seasons, and black oat regrew for 30 days before the evaluation. After this period, a 0.51 m^2 area on each experimental unit was cut at 0.10 m from the soil surface to evaluate the aboveground biomass. Samples were oven-dried at 50 °C, ground (Wiley), and sieved (0.75 mm). Subsequently, they were analyzed for nitrogen (N), after sulfuric digestion (digestion block), and for phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) after nitric-perchloric digestion (Malavolta et al., 1997). N, P, and S were determined by Kjeldahl distillation, colorimetry, and turbidimetry methods, respectively. Ca and Mg were determined by atomic absorption spectrometry, while K was determined by emission flame photometry. Nutrient uptake by black oat regrowth was estimated by multiplying the nutrient concentration in the aboveground biomass (g kg^{-1}) by the biomass yield (kg ha^{-1}).

Soybean Crop

The soybean cultivar Syngenta 1561 was sown on Nov. 30 and Dec. 4 in the 2014/2015 and 2015/2016 growing seasons, respectively, succeeding black oat in both years. The seeding rate was 37.5 seeds per m^2, with a row spacing of 0.4 m. Basic fertilization was performed with 60 kg ha^{-1} of P_2O_5 (triple superphosphate) in furrow and 60 kg ha^{-1} of K_2O (potassium chloride) broadcasted on the soil surface after sowing. Using a turfy inoculant on the sowing day, seeds were inoculated with *Bradyrhizobium japonicum*, with ± 1.2 million viable cells per seed.

When soybean plants reached the R_2 growth stage (Fehr & Caviness, 1977), 30 recently fully expanded trifoliate leaves were collected with the petiole in each experimental unit. These samples were oven-dried at 50 °C, ground (Wiley), sieved (0.75 mm), and then, analyzed for the same nutrients and using the same methods as described for black oat biomass samples. At the R_8 growth stage, a 4.8 m^2 area in the center of each experimental unit was manually harvested to evaluate soybean grain yield. Grain mass was adjusted to 130 g kg^{-1} grain moisture.

Table 1 Soil chemical attributes and clay content of the stratified diagnostic layer (0–0.2 m) of the Typic Hapludox at the experimental site in Guarapuava, Paraná State, Brazil, 2009

Depth (m)	P (Mehlich-1) (mg dm^{-3})	Organic matter (g dm^{-3})	pH ($CaCl_2$)	Al^{3+}	H^++Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	CEC[a]	SBS (%)[b]	Clay (g kg^{-1})
				$cmol_c$ dm^{-3}							
0–0.1	20.7	49.8	5.3	0	4.8	4.9	2.6	0.3	12.6	61.8	720
0.1–0.2	19.7	49.5	5.3	0	5.1	4.5	2.4	0.3	12.3	58.3	720

[a]Cation exchange capacity at pH (H_2O) 7.0

[b]Soil base saturation

Meteorological Data

Daily meteorological data were obtained from a meteorological station (SIMEPAR/Brazil) located 200 m away from the experiment (Fig. 1). A sequential water balance proposed by Thornthwaite and Matter (1955) was calculated (Fig. 1a).

Over the black oat regrowth periods, the cumulative rainfall was 46 and 227 mm, and the average temperature was

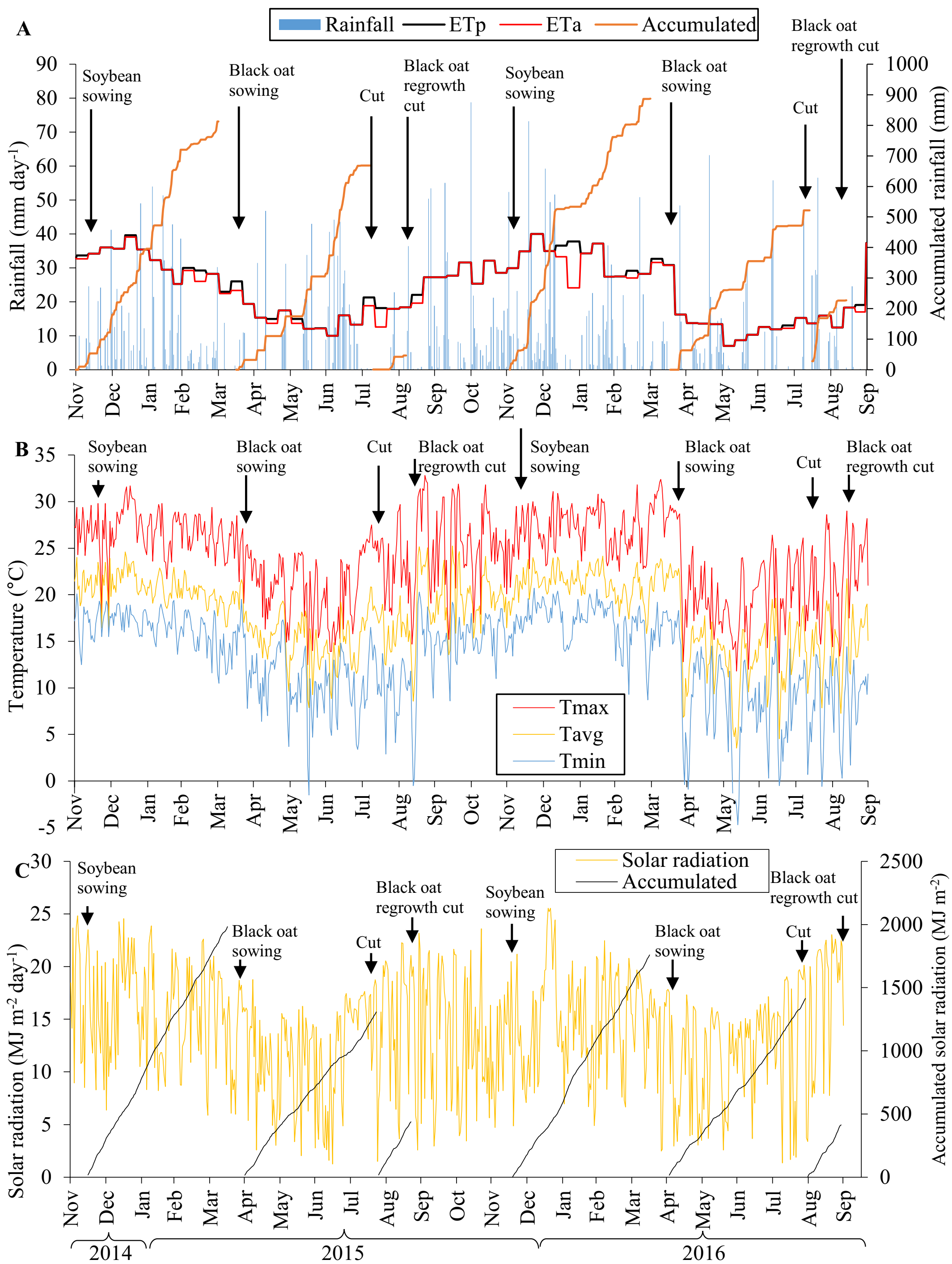


Fig. 1 Meteorological data from Nov. 2014 to Sep. 2016: **A** daily rainfall (blue bars), accumulated rainfall (orange line), potential evapotranspiration (ET_P, red line), actual evapotranspiration (ET_A, black line) across the growing seasons; **B** daily maximum (T_{MAX}, red), average (T_{AVG}, orange), and minimum (T_{MIN}, light blue) temperatures; **C** daily total solar radiation energy and solar radiation accumulated over the growing periods. Black arrows point to key dates

16.6 and 14.7 °C during the 2015 and 2016 growing seasons, respectively (Fig. 1a, b). The higher frequency of lower minimum temperatures in 2016 evinces the greater occurrence of frosts observed in this growing season (Fig. 1b). The accumulated solar radiation during black oat regrowth was similar in both periods (456 and 413 MJ m^{-2}) (Fig. 1c). The difference of actual evapotranspiration to potential evapotranspiration (ETa—ETp) had a negative balance of 63.5 and 0 mm during black oat cultivation in 2015 and 2016, respectively.

Concerning the soybean cropping seasons, the cumulative rainfall reached 813 and 887 mm, and the average temperature was 21.0 and 21.2 °C during the 2014/2015 and 2015/2016 growing seasons, respectively (Fig. 1a, b). The accumulated solar radiation were 1982 and 1759 MJ m^{-2} during these periods (Fig. 1c). The balance of ETa—ETp was negative, with values of −54.6 and −204 mm during the 2014/2015 and 2015/2016 soybean growing seasons, respectively (Fig. 1a).

Statistical Analysis

These data were submitted to the two-way analysis of variance (ANOVA) ($\alpha = 0.05$) in a split-plot scheme. The gypsum treatments were fitted to linear or quadratic regression models, based on the highest coefficient of determination (r^2) when significant at $p \leq 0.05$ by the F test. N-fertilization treatments were classified by the Tukey test ($\alpha = 0.05$) when significant. When interaction effects were detected, the degrees of freedom were unfolded.

Results

Black Oat Regrowth

An interaction effect was detected between gypsum and N-fertilization for black oat aboveground biomass after the regrowth period in both growing seasons (Fig. 2). In 2015, the interaction within N-fertilization was as follows: within $N_{0,}$ the regrowth biomass did not differ among gypsum rates; within N_{50}, a quadratic model fitted best the gypsum rate data, where the maximum estimated biomass yield was 2.55 Mg ha^{-1}, at an estimated gypsum rate of 6.26 Mg ha^{-1}, corresponding to 84, 96, 99, 97, and 87% of biomass yield achieved by G_0, G_3, G_6, G_9, and G_{12}, respectively; and within N_{100}, a linear model was the better-fitting model for gypsum rates, where the maximum biomass yield achieved was 3.02 Mg ha^{-1} at a rate of 12 Mg ha^{-1} of gypsum, corresponding to 73, 94, 84, 94, and 100% of biomass yield achieved by G_0, G_3, G_6, G_9, and G_{12}, respectively (Fig. 2a). As for the interaction within gypsum rates, the results were as follows: in G_0 $N_{100} = N_{50} > N_0$; in G_3 $N_{100} > N_{50} > N_0$; in G_6 $N_{100} = N_{50} > N_0$; in G_9 $N_{100} = N_{50} > N_0$; and in G_{12} $N_{100} > N_{50} = N_0$ (Fig. 2a).

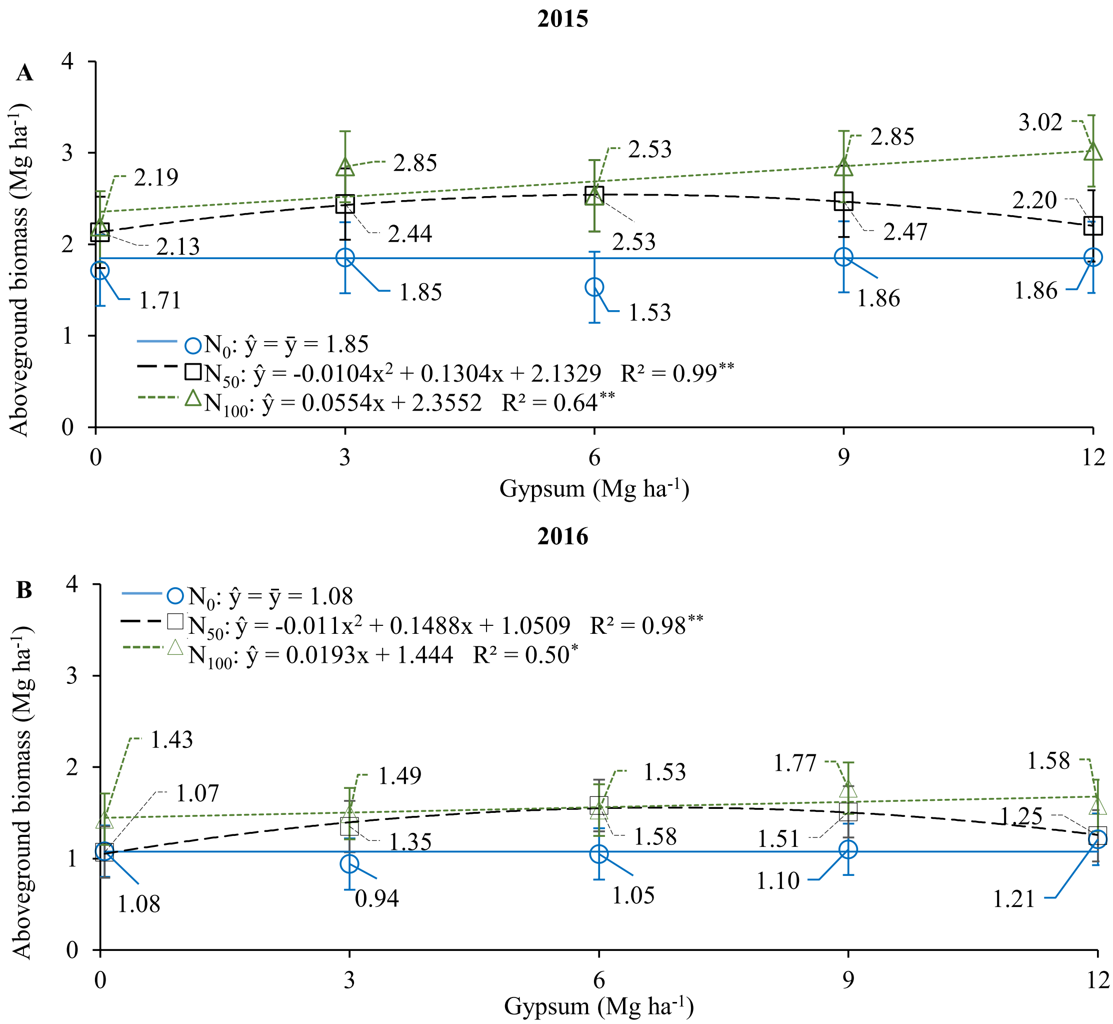
Concerning the 2016 growing season, looking at the interaction within N-fertilization, the interactive effects were as follows: within $N_{0,}$ the regrowth biomass did not differ among gypsum rates; within N_{50}, gypsum rate data fitted a quadratic model, where the maximum estimated biomass yield was 1.55 Mg ha^{-1}, at an estimated gypsum rate of 6.76 Mg ha^{-1}, corresponding to 69, 87, 102, 97, and 80% of biomass yield achieved by G_0, G_3, G_6, G_9, and G_{12}, respectively; and within N_{100}, a linear model was the better fit for gypsum rates, where the maximum biomass yield was 1.68 Mg ha^{-1} with 12 Mg ha^{-1} of gypsum, corresponding to 85, 89, 91, 106, and 94% of the biomass yield achieved by G_0, G_3, G_6, G_9, and G_{12}, respectively (Fig. 2a). Whereas for the interaction within gypsum rates, the results were as follows: within G_0 $N_{100} > N_{50} = N_0$; within G_3 $N_{100} = N_{50} > N_0$; within G_6 $N_{100} = N_{50} > N_0$; within G_9 $N_{100} = N_{50} > N_0$; and within G_{12} $N_{100} > N_{50} = N_0$.

Nutrient Concentration in Black Oat Biomass

The concentrations of N, P, K, Ca, Mg, and S in black oat regrowth biomass had no interaction between gypsum and N-fertilization in both growing seasons (Table 2). The biomass concentrations of N, P, and K were not influenced by gypsum rates, while Ca, Mg, and S concentrations were affected by gypsum in both growing seasons. Ca and S concentrations increased linearly with gypsum rates in both cultivation periods. Whereas Mg concentration decreased in a linear fashion in response to the increase in gypsum rates in 2015 and 2016 (Table 2). The concentrations of K, Mg, and S were not influenced by N-fertilization. N concentration between N_{50} and N_{100} produced no significant effect, and both were higher than N_0 in 2015. As for the 2016 growing season, N concentration increased according to the increase in N-fertilization ($N_{100} > N_{50} > N_0$). P concentration was lower in N_{100} than in N_0 in 2015. Whereas in 2016, P concentration did not differ between N_{50} and N_{100}, and both were lower in relation to N_0. Ca concentration was higher in N_{100} in relation to N_0 in both growing seasons (Table 2).

Black Oat Nutrient Uptake

The uptake of N, P, K, Ca, Mg, and S by black oat regrowth presented no interaction effect between gypsum and N-fertilization in both growing seasons (Table 3). Mg uptake was not influenced by gypsum rates. N uptake increased linearly with gypsum rates in 2015 and quadratically in 2016. P, Ca, and S uptake increased in a linear fashion with increasing gypsum rates in both growing seasons, and K uptake increased linearly in 2016 (Table 3).



p-value	Gypsum (G)	N	G × N	G × N_0	G × N_{50}	G × N_{100}	CV_G (%)	CV_N (%)
2014/2015	***0.016**	***0.000**	***0.009**				12	10
Linear				^{ns}0.409	^{ns}0.636	****0.000**		
Quadratic				^{ns}0.386	****0.004**	^{ns}0.412		
2015/2016	***0.022**	***0.000**	***0.025**				13	12
Linear				^{ns}0.102	***0.050**	***0.034**		
Quadratic				^{ns}0.155	****0.001**	^{ns}0.304		

Fig. 2 Black oat regrowth biomass 30 days after harvest (at the early heading stage) in (**A**) 2015 and (**B**) 2016 growing seasons, in response to the residual effect of gypsum applied between Nov. 2009 and Nov. 2011, and nitrogen rates (N_0, N_{50}, and N_{100}, corresponding to 0, 50, and 100 kg ha^{-1} of N) top-dressed at tillering, in a no-till field in Guarapuava, Paraná State, Brazil. *, ** and ^{ns} indicate significant values at $p \leq 0.05$ and $p \leq 0.01$, and non-significant values, respectively; bars represent the mean significant difference (MSD) by the Tukey test at $p < 0.05$ to compare N-fertilization treatments

Black oat regrowth uptake of N, P, K, Ca, Mg, and S were higher with N-fertilization in both growing seasons (Table 3). N, Ca, and Mg uptake increased with each further N rate ($N_{100} > N_{50} > N_0$) in 2015 and 2016. P, K, and S uptake between N_{50} and N_{100} produced no significant effect, and both were higher in relation to N_0 in 2015. In 2016, higher levels of P, K, and S were absorbed with each further N rate ($N_{100} > N_{50} > N_0$) (Table 3).

Leaf Nutrient Concentration in Soybean at R_2

Soybean leaf nutrient concentrations had no interaction effect between gypsum and N-fertilization in both growing seasons (Table 4). Leaf concentrations of N, P, and K were not influenced by gypsum rates, whereas Ca and S concentrations increased linearly with the increase in gypsum rates in both cultivation periods. In contrast, the

Table 2 Concentrations (g kg^{-1}) of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) in black oat regrowth biomass 30 days after harvest (at the early heading stage) in 2015 and 2016 growing seasons, in response to the residual effect of gypsum applied between Nov. 2009 and Nov. 2011, and N rates top-dressed at tillering, in a no-till field in Guarapuava, Paraná State, Brazil

	N		P		K		Ca		Mg		S	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Gypsum (Mg ha^{-1})												
0	47	42	2.8	4.3	27	32	3.9	4.4	2.0	1.54	2.0	3.0
3	46	39	2.7	4.4	28	36	4.5	5.1	1.8	1.52	2.6	3.1
6	49	43	2.8	4.2	29	35	4.2	5.2	1.7	1.49	2.6	3.2
9	45	45	2.8	4.3	27	36	4.6	5.5	1.6	1.48	2.6	3.3
12	47	41	2.8	4.3	28	37	4.8	5.4	1.5	1.45	2.9	3.5
N (kg ha^{-1})												
0	40 b	40 c	2.9 a	4.7 a	27	34	4.1 b	4.8 b	1.7	1.5	2.8	3.3
50	48 a	41 b	2.8 ab	4.1 b	28	35	4.4 ab	5.1 ab	1.7	1.5	2.5	3.3
100	53 a	45 a	2.7 b	4.1 b	28	36	4.7 a	5.5 a	1.7	1.5	2.4	3.1
Significance (*p* value)												
Gypsum (G)	^{ns}0.26	^{ns}0.40	^{ns}0.92	^{ns}0.67	^{ns}0.76	^{ns}0.12	*0.00	*0.02	**0.00	*0.05	**0.00	*0.05
Linear	–	–	–	–	–	–	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00
Quadratic	–	–	–	–	–	–	^{ns}0.28	^{ns}0.11	^{ns}0.15	^{ns}0.76	^{ns}0.10	^{ns}0.52
N	**0.00	**0.00	*0.02	**0.00	^{ns}0.12	^{ns}0.28	**0.01	**0.00	^{ns}0.14	^{ns}0.08	^{ns}0.07	^{ns}0.06
G×N	^{ns}0.78	^{ns}0.67	^{ns}0.99	^{ns}0.17	^{ns}0.15	^{ns}0.65	^{ns}0.95	^{ns}0.54	^{ns}0.88	^{ns}0.65	^{ns}0.94	^{ns}0.92
CV_G(%)	10	6	9	6	16	12	14	14	8	4	16	11
CV_N(%)	14	5	7	6	11	13	12	11	9	3	14	11

Equations	Ca (g kg^{-1})	Mg (g kg^{-1})	S (g kg^{-1})
Linear			
2015	$\hat{y} = 0.0633x + 4.02$ (r^2: 0.71)	$\hat{y} = -0.04x + 1.96$ (r^2: 0.97)	$\hat{y} = 0.2267x + 8.6$ (r^2: 0.77)
2016	$\hat{y}y = 0.08x + 4.64$ (r^2: 0.82)	$\hat{y} = -0.0073x + 1.54$ (r^2: 0.99)	$\hat{y} = 0.1433x + 11.64$ (r^2: 0.93)

Bold values are $p \leq 0.05$

Letters classify the averages by the Tukey test at 5% probability

*, ** and ns indicate significant values at $p \leq 0.05$ and $p \leq 0.01$, and non-significant values, respectively

concentration of Mg decreased linearly in response to the increase in gypsum rates in 2015 and 2016 (Table 4).

The leaf concentration of N, K, Ca, Mg, and S were not influenced by N-fertilization in the two seasons evaluated (Table 4). The concentration of P between N_{50} and N_{100} produced no significant effect, and both were lower in relation to N_0 in 2015. In 2016, P concentration in N_{100} was lower than N_0, while N_{50} did not differ from both rates.

Soybean Grain Yield

In both growing seasons, soybean yield was not affected by either gypsum or N-fertilization applied in prior black oat cultivation (Fig. 3). In the 2015/2016 growing season, soybean yield was 17% higher than in 2014/2015.

Discussion

Black Oat Regrowth

Overall, N-fertilization increased black oat aboveground biomass compared to the control, and in both growing seasons, N_{100} led to a greater increase than N_{50} when combined to low (G_0 and G_3) or high (G_{12}) gypsum rates (Fig. 2a, b). This crop accumulated more aboveground biomass in response to the long-term effect of gypsum depending on N-fertilization rate (Fig. 2a, b). In 2015, the aboveground biomass within N_{100} increased across gypsum rates in relation to G_0 from 16 to 37%. In 2016, the black oat aboveground biomass was 17 to 48% and 4 to 36% higher, within N_{50} and N_{100}, respectively, across gypsum rates in relation to G_0.

Table 3 Uptake (kg ha^{-1}) of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) by black oat aboveground biomass 30 days after harvest (at the early heading stage) in 2015 and 2016 growing seasons, in response to the residual effect of gypsum applied between Nov. 2009 and Nov. 2011, and nitrogen (N) rates top-dressed at tillering, in a no-till field in Guarapuava, Paraná State, Brazil

	N		P		K		Ca		Mg		S	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Gypsum (Mg ha^{-1})												
0	95	51	5.6	5.1	55	38	7.9	5.3	3.9	1.8	4.1	3.6
3	103	49	6.1	5.4	62	46	10	6.4	4.0	1.9	5.6	3.8
6	116	60	6.6	5.7	69	49	9.8	7.3	3.9	2.1	6.2	4.4
9	108	67	6.6	6.2	64	53	11	8.0	3.8	2.2	6.2	4.6
12	115	55	6.6	5.8	68	49	11	7.4	3.6	2.0	6.7	4.6
N (kg ha^{-1})												
0	74 c	43 c	5.3 b	5.0 c	50 b	37 c	7.6 c	5.2 c	3.1 c	1.6 c	4.9 b	3.6 c
50	112 b	56 b	6.5 a	5.5 b	67 a	48 b	10 b	7.0 b	3.9 b	2.0 b	5.9 a	4.4 b
100	136 a	70 a	7.1 a	6.4 a	73 a	57 a	12.3 a	8.6 a	4.5 a	2.3 a	6.4 a	4.9 a
Significance (*p* value)												
Gypsum (G)	**0.00	*0.00	**0.00	**0.01	^{ns}0.28	**0.00	**0.01	**0.00	^{ns}0.12	^{ns}0.10	**0.00	**0.01
Linear	*0.05	**0.01	*0.03	**0.00	–	***.000	**0.00	***.000	–	–	**0.00	**0.00
Quadratic	^{ns}0.29	**0.02	^{ns}0.29	^{ns}0.10	–	**.003	^{ns}0.44	**.005	–	–	^{ns}0.10	^{ns}0.27
N	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00	**0.00
G×N	^{ns}0.18	^{ns}0.40	^{ns}0.14	^{ns}0.26	^{ns}0.07	^{ns}0.09	^{ns}0.09	^{ns}0.32	^{ns}0.62	^{ns}0.06	^{ns}0.07	^{ns}0.09
CV_G(%)	12	16	10	11	21	12	20	15	15	13	17	16
CV_N(%)	18	13	14	12	18	17	18	17	17	13	20	13

Equations	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Linear			
2015	$\hat{y}=1.5x+98.4$ (r^2: 0.65)	$\hat{y}=0.0833x+5.8$ (r^2: 0.78)	–
2016	–	$\hat{y}=0.0733x+5.2$ (r^2: 0.65)	$\hat{y}=0.9667x+41.2$ (r^2: 0.67)
Quadratic			
2015	–	–	–
2016	$\hat{y}=-0.1905x^2+3.15x+47.8$ (r^2: 0.55)	–	–

Equations	Ca (kg ha^{-1})	S (kg ha^{-1})
Linear		
2015	$\hat{y}=0.24x+8.5$ (r^2: 0.83)	$\hat{y}=0.7333x+18$ (r^2: 0.79)
2016	$\hat{y}=0.1933x+5.72$ (r^2: 0.76)	$\hat{y}=0.3667x+14.2$ (r^2: 0.93)

Bold values are $p \leq 0.05$

Letters classify the averages by the Tukey test at 5% probability

*, ** and ns indicate significant values at $p \leq 0.05$ and $p \leq 0.01$, and non-significant values, respectively

Gypsum effects depend on the time course after application and the season conditions. In the same region of Paraná State, the biomass of white oat intercropped with ryegrass was not affected by gypsum applied 3 months prior to evaluation (Silva et al., 2015), possibly due to lack of time for the product to react in the soil. Under water deficit conditions, black oat presented a biomass yield 13% greater than the control in response to 2.1 Mg ha^{-1} of gypsum applied 10 months before the beginning of the experiment (Soratto & Crusciol, 2008b). Our results showed that gypsum has long-term effects, increasing black oat biomass after 44 and 55 months of the application of the last one-third of the rates (Nov. 2011).

Taking into account both seasons, N-fertilization with N_{50} and N_{100} at tillering increased black oat regrowth biomass by 30 and 49%, on average, respectively, in comparison with the control. Another study pointed out that N-fertilization (urea) increased black oat aboveground biomass by 63% with 100 kg N ha^{-1} and by 77% with 180 kg N ha^{-1} (Santi et al., 2003). Using the same cultivar of the present study,

Table 4 Leaf concentrations (g kg^{-1}) of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) in soybean at R_2 in 2015 and 2016 growing seasons in response to the residual effect of gypsum applied between Nov. 2009 and Nov. 2011, and nitrogen (N) rates top-dressed at black oat tillering, in a no-till field in Guarapuava, Paraná State, Brazil

	N		P		K		Ca		Mg		S	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Gypsum (Mg ha^{-1})												
0	35	41	4.3	5.3	19	18	6.0	9.0	1.87	1.90	2.9	2.9
3	36	40	4.1	5.1	20	19	6.6	9.5	1.73	1.85	3.1	2.9
6	33	40	4.3	5.2	20	18	6.7	9.8	1.62	1.83	3.1	3.1
9	35	41	4.0	5.4	19	20	6.8	9.8	1.62	1.81	3.4	3.1
12	35	39	4.4	5.3	20	18	7.3	10.1	1.59	1.81	3.7	3.2
N (kg ha^{-1})												
0	35	40	4.6 a	5.5 a	19	19	6.8	9.6	1.6	1.8	3.2	3.1
50	35	40	4.0 b	5.2 ab	20	18	6.7	9.7	1.7	1.8	3.2	3.0
100	34	41	4.0 b	5.1 b	20	18	6.6	9.7	1.7	1.8	3.3	3.1
Significance (*p* value)												
Gypsum (G)	^{ns}0.59	^{ns}0.66	^{ns}0.51	^{ns}0.56	^{ns}0.82	^{ns}0.44	****0.00**	****0.01**	****0.00**	***0.03**	***0.02**	***0.01**
Linear	–	–	–	–	–	–	****0.00**	****0.00**	****0.00**	****0.00**	****0.00**	****0.00**
Quadratic	–	–	–	–	–	–	^{ns}0.85	^{ns}0.26	^{ns}0.08	^{ns}0.37	^{ns}0.38	^{ns}0.97
N	^{ns}0.26	^{ns}0.93	****0.01**	***0.03**	^{ns}0.65	^{ns}0.13	^{ns}0.51	^{ns}0.74	^{ns}0.34	^{ns}0.60	^{ns}0.33	^{ns}0.54
G×N	^{ns}0.11	^{ns}0.46	^{ns}0.07	^{ns}0.99	^{ns}0.44	^{ns}0.15	^{ns}0.08	^{ns}0.95	^{ns}0.98	^{ns}0.94	^{ns}0.10	^{ns}0.24
CV_G(%)	9	9	14	10	15	11	7	6	5	2	16	7
CV_N(%)	8	7	14	8	15	9	9	6	11	2	10	10

Equations	Ca (g kg^{-1})	Mg (g kg^{-1})	S (g kg^{-1})
Linear			
2015	$\hat{y}=0.0933x+6.12$ (r^2: 0.86)	$\hat{y}=-0.0223x+1.82$ (r^2: 0.83)	$\hat{y}=0.0633x+2.86$ (r^2: 0.93)
2016	$\hat{y}=0.0833x+9.14$ (r^2: 0.87)	$\hat{y}=-0.0073x+1.884$ (r^2: 0.92)	$\hat{y}=0.0267x+2.88$ (r^2: 0.92)

Bold values are $p \le 0.05$

Letters classify the averages by the Tukey test at 5% probability

*, ** and ns indicate significant values at $p \le 0.05$ and $p \le 0.01$, and non-significant values, respectively

Steiner et al. (2009) observed that the application of 100 and 120 kg N ha^{-1} (urea) led to increases of 103 and 124%, respectively, in black oat aboveground biomass. Both studies (Santi et al., 2003; Steiner et al., 2009) assessed the trait at the grain formation phase, whereas this study evaluated the plants 30 days after haylage harvest at the early heading stage, focusing on black oat regrowth for soil cover and nutrient cycling for the successor crop.

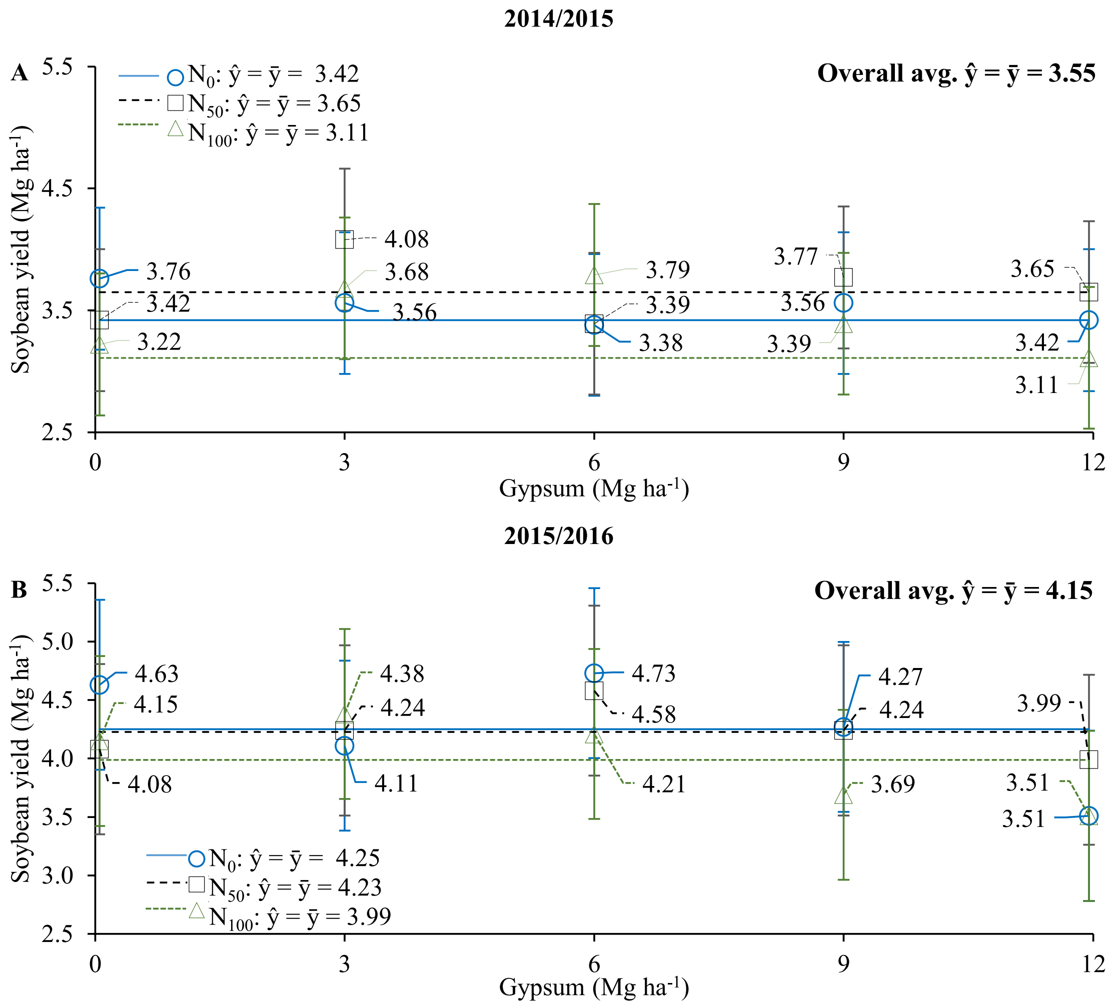
Black oat was preceded by soybean in both seasons in this study, and mineralized-N from soybean straw possibly has partially met the black oat N demand, which resulted in a lower relative response to N-fertilization than the observed in other studies, including the same rate of N_{100}. Soybean straw of a medium yield crop may reach 90 kg N ha^{-1} (Balboa et al., 2018), which will be made available through the mineralization process in the soil, providing N for the following crop (Siqueira-Neto et al., 2010). Black oat would possibly have a greater response to N fertilization if preceded by a crop with a higher C:N ratio, such as corn.

The 41% lower aboveground biomass yield in 2016 compared to 2015, considering the experimental average, may be partly explained by the different meteorological conditions between the growing seasons. In 2016, frost occurred more frequently along with lower average temperature and lower accumulated solar radiation in relation to 2015 (Fig. 1).

Nutrient Concentration in Black Oat Biomass

The concentrations of P, K, Ca, and S in the 2015 growing season showed average decreases of 34, 21, 14, and 20%, respectively, compared to the 2016 growing season. This may be partially explained by the dilution effect from plant growth, as the biomass in 2015 was, on average, 70% higher compared to the one obtained in the 2016 growing season.

The N concentration in 2015 was, on average, 12% higher compared to 2016 (Table 2). In 2016, the temperature during black oat regrowth was, on average, 2.5 °C lower than in 2015 (Fig. 1b), which may have reduced the mineralization



p-value	Gypsum (G)	N	G × N	CV_G (%)	CV_N (%)
2014/2015	^{ns}0.552	^{ns}0.174	^{ns}0.096	15	10
2015/2016	^{ns}0.086	^{ns}0.065	^{ns}0.110	16	9

Fig. 3 Soybean yield in response to the residual effect of gypsum rates applied in Nov. 2011 and black oat nitrogen (N) topdressing in (**A**) 2014/2015 and (**B**) 2015/2016 growing seasons, in a no-till field in Guarapuava, Paraná State, Brazil. Prior to soybean sowing, black oat was harvested at the early heading stage, regrew for 30 days, and burnt down by herbicide. ^{ns} indicates non-significant values; bars represent the mean significant difference (MSD) by the Tukey test at $p < 0.05$ to compare N-fertilization treatments

rate of soil organic matter and crop residues, decreasing N availability. In this condition, N uptake by plants depends more on N fertilizer, which may have favored the difference between N_{50} and N_{100} applied in black oat tillering in 2016. The reduction in P concentration due to N-fertilization rates may be due to a dilution effect from plant growth, as the increase in N-fertilization rates increased biomass produced from black oat regrowth (Fig. 2a, b).

It is possible that the absorption of N and Ca interacted synergistically, as these nutrients presented an equivalent response to N-fertilization. In few weeks after application, N from urea (used in top dressing) is transformed into NO_3^- in the soil through nitrification (Bremner & Blackmer, 1978). The non-antagonistic interaction between cations and anions promotes simultaneous transport (symport) of both ions through cell membranes, therefore, the absorption of NO_3^- enables the passive absorption of cations like Ca and K (Andres et al., 2016). N is related to photosynthesis and protein synthesis in plants, while Ca is necessary for cell division and expansion (Yong et al., 2010), so the higher availability of Ca and N, provided by gypsum and N-fertilization, explains the greater black oat growth evaluated by the aboveground biomass.

The reduction in Mg concentration in black oat biomass with the increase in gypsum rate is related to the competitive inhibition of Mg^{2+} absorption by higher levels of Ca^{2+} in the soil (Soratto & Crusciol, 2008a). N-fertilization is associated with Mg deficiency in plants, which has the potential to reduce plant development (Soratto & Crusciol, 2008b; Soratto et al., 2010). However, within the N-fertilization rates used in this study, up to 100 kg N ha^{-1}, this effect was not observed in black oat regrowth.

Higher regrowth biomass related to gypsum rates may also be due to higher S availability. In addition, Ca^{2+} from gypsum benefits nutrient uptake by roots (Siddiqui et al., 2013) and root growth and architecture (Cao et al., 2013), thus contributing to plant growth.

Black Oat Nutrient Uptake

Proving its hardiness (Silva et al., 2006) and strong root system (Burr-Hersey et al., 2017), black oat thrived in a 30-day period of regrowth after harvest and absorbed significant amounts of nutrients from the soil profile, especially of N and K (Table 3). Black oat roots reach 80 cm depth (Vicensi et al., 2020b), and even with only 46 mm of rain during the regrowth period in 2015, more nutrients were absorbed in this growing season by the aboveground biomass than in 2016, when the regrowth period was rainier but also colder.

The increase of black oat regrowth due to the residual effects of gypsum and N-fertilization resulted in greater nutrient uptake by aboveground biomass. Gypsum rates increased the black oat uptake of N, P, K, Ca, and S in both growing seasons (Table 3), even without affecting regrowth biomass concentrations of N, P, and K (Table 2), meaning that biomass yield was determinant. The biomass concentration of Mg was linearly decreased by gypsum rates (Table 2), but this effect was offset by concomitant biomass increase (Fig. 2) and Mg uptake was not affected by gypsum in both growing seasons (Table 3). These results show the importance of crop rotation and winter forage crops for nutrient cycling since sufficient time is given for plant regrowth.

N-fertilization at oat tillering increased the uptake of N, P, K, Ca, Mg, and S during the regrowth phase after harvest, even without affecting Mg and S concentration on the aboveground biomass. In other studies, N-fertilization at rates up to 100 or 120 kg ha^{-1} has also increased N, P, and K uptake by black oat, proportionally to biomass increase (Melo et al., 2011; Restelatto et al., 2015).

The beneficial outcomes of N-fertilization and residual effects of gypsum to the production system include better soil cover by larger straw deposition and improved nutrient availability to the following crops (Torres et al., 2008), with special advantages for crops with a surface root system (Fan et al., 2016). Nutrients on the aboveground plant residues are deposited on the soil surface for subsequent decomposition. The half-life time for nutrient release from black oat residue was calculated in 15.4, 10, 9, 7.8, and 8.7 days for N, P, K, Ca, and Mg, respectively, and the highest mineralization rate and release of nutrients occurred approximately 30 days after the deposition of the residues (Ferreira et al., 2014).

Leaf Nutrient Concentration in Soybean at R_2

Leaf N concentration ranged from 33 to 41 g kg^{-1} and remained above the leaf sufficiency range suggested by Urano et al. (2006), and below the ranges suggested by Malavolta et al. (1997) and SBCS/NEPAR (2019) (Table 5) in both growing seasons. No effect of black oat N-fertilization was detected and the equivalence in the comparison of N_0 with N_{50} and N_{100} shows that biological fixation was not affected, providing adequate N supply for soybean. Most of the soybean N is derived from the symbiotic nitrogen fixation (Hungria et al., 2006), and N concentration in soybean leaves is usually insensitive to either residual effects of N fertilizer in predecessor crops or gypsum rates (Caires et al., 2011; Vicensi et al., 2016).

As for leaf P concentration, values ranged from 4.0 to 5.5 g kg^{-1} and remained above the leaf sufficiency range suggested by Urano et al. (2006), Malavolta et al. (1997), and SBCS/NEPAR (2019) (Table 5) in both growing seasons. Although P concentration in soybean leaves remained above the leaf sufficiency range, it was reduced by N-fertilization rates. As N-fertilization increased P uptake by black oat regrowth, it possibly reduced available P in the soil, and black oat biomass P was not mineralized in time for soybean absorption. Furthermore, as urea-derived N is subjected to nitrification processes, the soil acidification side effect may have also decreased soil available P due to P fixation reactions in the soil (Jones, 2012; Viviani et al., 2010).

Leaf K concentrations ranged from 18 to 20 g kg^{-1} and remained within the leaf sufficiency range suggested by Urano et al. (2006) and Malavolta et al. (1997), and below the one suggested by SBCS/NEPAR (2019) (Table 5) in both growing seasons. As this last reference range is more recent, changes in the sufficiency limits may be the cause

Table 5 Leaf sufficiency range of soybean at R_2 found in literature and in this study

Reference	With petiole	N	P	K	Ca	Mg	S
Malavolta et al. (1997)	Not specified	45–55	2.6–5	17–25	2–4	3–10	2.5
Urano et al. (2006)	Yes	29–56.7	2.2–3.7	13–29	7.8–18	1.8–5	1.3–4.3
SBCS/NEPAR (2019)	Yes	41–49	2.8–3.6	22–27	8–11	3–4.8	2.5–3.5
Range of our results	Yes	33–41	4–5.5	18–20	6–11	1.6–1.9	2.9–3.7

of this variation. Since black oat was harvested for haylage and nutrients were exported from the field and K uptake by black oat regrowth was the second highest (after N), K availability may have been decreased in some soil layers during soybean first stages of growth. K fertilization for soybean was performed with 60 kg ha^{-1} of K_2O broadcasted on the soil surface after sowing. Considering the management conditions, K fertilization rate and application (broadcast or furrow) may be reviewed for the following crops.

Regarding leaf Ca concentrations in the 2015 growing season, values ranged from 6.0 to 7.3 and were below the leaf sufficiency range suggested by Urano et al. (2006) and SBCS/NEPAR (2019), and above the one suggested by Malavolta et al. (1997) (Table 5). In 2016, leaf Ca concentrations had values ranging from 9 to 11 g kg^{-1} and remained within or above the leaf sufficiency range suggested by Malavolta et al. (1997), Urano et al. (2006), and SBCS/NEPAR (2019) (Table 5). Higher gypsum rates increased Ca concentration linearly in both growing seasons (Table 4) just as occurred for black oat regrowth (Table 2).

For leaf Mg concentrations, numbers from 1.6 to 1.9 g kg^{-1} were observed and remained below or within the leaf sufficiency range suggested by Urano et al. (2006), and below the ones suggested by SBCS/NEPAR (2019) and Malavolta et al. (1997) (Table 5). The increase of gypsum rates decreased Mg concentration in a linear fashion (Table 4), which also occurred for black oat regrowth (Table 2). Gypsum mobilizes Mg^{2+} from surface layers to subsurface soil layers (Caires et al., 2011; Vicensi et al., 2020b). In the present study, Mg^{2+} levels were reduced in the soil up to 80 cm depth in response to gypsum (Vicensi et al., 2020a, 2020b). There is also competitive inhibition of Ca^{2+} supplied by gypsum over soil Mg^{2+} and K^+ (Jones, 2012). These results show that leaf Mg concentrations were predominantly below the leaf sufficiency ranges for soybean, especially when gypsum rates increased, evidencing that after many years of gypsum application, Mg is limiting crop yield and must be resupplied.

Concerning sulfur, leaf S concentrations ranged from 2.9 to 3.7 g kg^{-1} and remained within or above the leaf sufficiency range suggested by Malavolta et al. (1997), Urano et al. (2006), and SBCS/NEPAR (2019) in both growing seasons (Table 5). Increasing gypsum rates linearly increased S concentration in soybean leaves (Table 4), following the same pattern observed for black oat regrowth (Table 2). Gypsum provides Ca^{2+} and SO_4^{2-}-S to the soil, increasing Ca and S concentrations in plant tissues, as observed in other studies (Caires et al., 2011; Moda et al., 2013).

Our results of leaf nutrient concentrations compared to leaf sufficiency ranges (Malavolta et al., 1997; SBCS/NEPAR, 2019; Urano et al., 2006) evidence that K, Ca, and Mg for the 2014/2015 season and K and Mg in the 2015/2016 season may have limited soybean development and yield.

Among the elements evaluated in the diagnostic leaf (Table 4), only Mg was below or at the lower limit of the sufficiency range (Table 5), suggesting that this nutrient may have limited the performance of soybean, even though these plants showed no deficiency symptoms regarding this nutrient. The critical level of Mg^{2+} is 1 $cmol_c$ dm^{-3} in soil (SBCS/NEPAR, 2019) and after years of studies performed in this site, without liming and without Mg fertilization, Mg^{2+} levels were reported below or close to the critical level in gypsum and N treatments (Vicensi et al., 2020b), which corroborates the diagnostic leaf Mg concentration results.

Soybean Grain Yield

Soybean yield was not affected by either the residual effect of gypsum or N application at black oat tillering in both growing seasons. The lower soybean yield in 2014/2015 may be due to excess rainfall in February when soybean was in the reproductive stages. Excessive rainfall coupled with a higher incidence of cloudy days reduce plant photosynthetic activity, restrain nutrient absorption, and increase soybean flower abortion (Kokubun, 2011). In the 2014/2015 growing season, soybean presented lower leaf concentrations of N, P, and Ca than in 2015/2016, which are related to yield potential.

The overall averages of soybean grain yield in this study were 3.55 and 4.15 Mg ha^{-1} in 2014/2015 and 2015/2016 growing seasons, respectively. Both periods had higher yields than the average of Paraná state on the respective seasons, reaching 3.29 Mg ha^{-1} for 2014/2015 and 3.73 Mg ha^{-1} for 2015/2016 (CONAB et al., 2021).

Gypsum commonly has no effect on soybean yield under medium yield potential conditions (Pauletti et al., 2014; Somavilla et al., 2016; Vicensi et al., 2016) and under regular rainfall distribution or irrigation (Caires et al., 2006; Henry et al., 2018; Vicensi et al., 2016). However, in low yield potential conditions ($<$2.5 Mg ha^{-1}) with water deficit, gypsum may increase soybean yield (Henry et al., 2018; Schenfert et al., 2020). Under drought, an increase of 11.3% in soybean yield in response to a gypsum application of 2 Mg ha^{-1} was reported by Zandoná et al. (2015). Further studies are necessary to evaluate the applicability of gypsum in the soybean crop at different levels of magnesium above the critical level.

Soybean has a higher cation exchange capacity of roots when compared to Poaceous crops such as corn (Fernandes & Souza, 2006), which leads to a higher accumulation in the rhizosphere of soil divalent cations, such as Mg^{2+} and Ca^{2+}, favoring the absorption of these nutrients even under low availability in the soil. This feature may partly explain the different response of this crop to long-term gypsum when compared to black oat.

Conclusions

Our hypothesis that gypsum application associated with N fertilization could have a synergistic effect has been confirmed for black oat regrowth biomass, but not for soybean yield. The gypsum application, even up to 44 and 55 months earlier than the experiment, presented a long-term effect when associated with N fertilization, causing black oat biomass to increase during the regrowth phase. Nitrogen fertilization increased black oat regrowth biomass, even without gypsum. Nutrient uptake levels were greater for black oat regrowth due to higher gypsum rates and N fertilization, which may have been advantageous in the long term for the production system, once nutrient cycling may partially substitute fertilizer-derived nutrients. Despite their effects on soybean foliar diagnosis, soybean yield was not affected by either long-term applied gypsum or by N applied at black oat tillering.

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Declarations

Conflict of interest The authors declared that they have no conflict of interest.

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