



An Innovative Corn to Silage-Grass-Legume Intercropping System With Oversown Black Oat and Soybean to Silage in Succession for the Improvement of Nutrient Cycling

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In the context of sustainable tropical agriculture, an innovative corn (*Zea mays* L.) to silage-grass-legume intercropping system can promote plant diversity, improve agronomic performance and land-use efficiency, and increase the yield of oversown black oat (*Avena strigosa* Schreb) and soybean [*Glycine max* (L.) Merr.] to silage in succession. Thus, during three growing seasons on a Typic Haplorthox in Botucatu, São Paulo State, Brazil, four treatments of a corn to silage production system were implemented in summer/autumn with black oat oversown in winter/spring: (1) corn intercropped with palisade grass (*Urochloa brizantha* “Marandu”) and black oat overseeded in lines; (2) corn intercropped with palisade grass and black oat overseeded in a broadcast system with superficial incorporation; (3) corn intercropped with palisade grass + pigeon pea [*Cajanus cajan* (L.) Millsp.] and black oat overseeded in lines; and (4) corn intercropped with palisade grass + pigeon pea and black oat overseeded in a broadcast system with superficial incorporation. During winter/spring, the black oat pastures were grazed by lambs, but results on forage allowance and nutritive value for animal grazing and on animal performance are not reported in the present manuscript. In the fourth growing season, the effect of soybean to silage intercropped with guinea grass (*Panicum maximum* “Aruana”), with only a residual effect of the four production systems from the previous three growing seasons, was evaluated. Despite greater interspecific competition of palisade grass and pigeon pea intercropped with corn, this more complex system produced better results. Thus, when analyzing this system as a whole, the triple intercrop (corn + pigeon pea + palisade grass) combined with oversown black oat in lines was the most effective option for silage production and for the improvement of

other elements of system productivity, such higher surface mulch quantity, leaf nutrient concentrations, and yield of soybean to silage intercropped with guinea grass. This intercrop also generated better nutrient cycling because an increased quantity of nutrients was retained in standing plant residue and surface mulch, which resulted in better land- and nutrient-use efficiency, with an emphasis on nitrogen and potassium.

Keywords: *Cajanus cajan*, integrated crop-livestock systems, *Urochloa brizantha*, *Zea mays*, land use efficiency

HIGHLIGHTS

- Corn to silage is not affected by intercropping with palisade grass and pigeon pea.
- Pigeon pea increased the surface mulch quantity and soybean to silage in succession.
- The triple intercrop generated better nutrient cycling.
- The land equivalent ratio exceeded 1, showing the advantage of double and triple intercropping.

INTRODUCTION

The adoption of the no-till system (NTS) is growing in different edaphoclimatic conditions around of the world. However, this system is highly dependent of crops for the production and maintenance of straw on the soil surface (Borghi et al., 2013a). Several cover crops have been researched and used in tropical conditions, being that forage grasses, intercropped or not, especially of the genus *Urochloa* (syn. *Brachiaria*) are standing out. In addition, the use of integrated crop-livestock system (ICLS) can provide grain production in the summer, pasture in the autumn/winter and straw in the spring for continuity of the NTS in tropical regions, such as in the Brazilian “Cerrado” and African “Savannah” (Mateus et al., 2012). It is also noteworthy that in Brazil, the problem of degraded pasture cause low forage yield and a low animal stocking rate (Pariz et al., 2011a). Thus, the ICLS is an option to recover these degraded areas, increasing animal production. Furthermore, ICLS can contribute to increased global food production in the future (Wirsenius et al., 2010; Franzluebbers and Stuedemann, 2014).

In this context, the intercropping of tropical forage grasses with grain crops could be a key strategy for enhancing the early establishment and successful production of a winter season (with low and irregular rainfall) forage for grazing (Costa et al., 2016; Crusciol et al., 2016; Pariz et al., 2016). Nevertheless, many of these studies did not utilize animal grazing. According Moraes et al. (2014a), approximately only 5% of studies about ICLS directly utilized animal grazing, alternating with cash crops. These authors also highlighted that a diversity of field studies is needed with ruminant livestock, including sheep (*Ovis aries*), to adequately characterize the impacts of ICLS on animal performance and crop yield because stocking rates and management approaches can alter crop residue and forage quantity and quality.

Furthermore, over the years, grass-only intercropping can compromise the sustainability of ICLS due to soil nitrogen deficiency (Costa et al., 2012; Garcia et al., 2016). Therefore, according Moraes et al. (2019), the “sustainable no-tillage

silage production systems are needed, especially those combined with promising ICLS production strategies, to improve overall agricultural functionality.” Thus, corn intercropped with legumes (i.e., pigeon pea) is an alternative to improve the diversification of agricultural activities in tropical regions (Baldé et al., 2011). Pigeon pea is grown by smallholder farmers as a sole crop or intercropped with corn, sorghum [*Sorghum bicolor* (L.) Moench] or other crops, with cereal being the main crop that is common in Africa and Asia (Senkoro et al., 2017). When a tropical perennial grass is included in corn or sorghum-legume intercropping, there is the advantage of later pasture formation, and this intercropping system with legumes represents an alternative for the grower to implement nitrogen biological fixation in the soil because pigeon pea can fix up to 235 kg ha⁻¹ of atmospheric N and can reduce the N fertilizer needed following cereal (Myaka et al., 2006) or pasture crops (Oliveira et al., 2011).

In general, results of Borghi et al. (2013a), Crusciol et al. (2014), Mateus et al. (2016), and Pariz et al. (2017c) demonstrated that in intercropping systems, the land equivalent ratio exceeded 1, showing the advantage in biomass production compared to sole crop systems. These results can be explained because companion crop stimulating the root growth of the grain crop (Hauggaard-Nielsen and Jensen, 2005). In addition, according Xiao et al. (2004), with the inclusion of legume intercropped with cereal crop (corn) and/or tropical forage grasses, it is also possible that the direct transfer of nitrogen from, e.g., a legume to a corn crop and grass. Results of Baldé et al. (2011) demonstrated that “high land equivalent ratio values provide evidence for the complementary and the high efficiency of use of available resources by the intercropped plants and thus the advantage of such systems to produce both corn grain and cover crop forage (pigeon pea and *Urochloa*.” The results presented by Ndungu-Magiroi et al. (2017) demonstrated that corn-bean (*Phaseolus vulgaris*) intercropping is more productive on a corn yield equivalent basis than monocropped corn, and the intercrop value is enhanced as bean to crop value ratios increase. Thus, despite several advances in research on intercropping systems, it is important to study the intensity of how each grain crop affects the growth of tropical perennial grasses and legumes in intercropping systems compared to monocropping systems (Brooker et al., 2015). The competition of crops in intercropping can be better explained by a land equivalent ratio (LER) (Mead and Willey, 1980), relative crowding coefficient (K) (Agegnehu et al., 2006), and aggressivity (A) (Takim, 2012).

Another good option in ICLS is the winter annual grazing grasses such as oat (*Avena*) (Moraes et al., 2014b). Results of Lopes et al. (2008) and Pariz et al. (2017b), demonstrated that in southern and central-southern Brazil, oversowing corn with oats

TABLE 1 | Rainfall, maximum and minimum temperatures, and radiation received at Botucatu, São Paulo, Brazil, during the study period and long-term averages.

Climate characteristics	Month											
	November	December	January	February	March	April	May	June	July	August	September	October
2013–2014												
Monthly rain, mm	45	65	74	116	104	99	72	1	26	19	96	37
Mean max. temp., °C	28.1	30.0	30.7	31.3	28.8	27.3	24.0	24.5	23.7	26.8	28.0	30.2
Mean min. temp., °C	17.3	19.0	19.7	20.4	18.8	16.7	13.9	13.5	11.7	11.5	12.5	13.4
Radiation received, MJ m ⁻²	600	696	735	541	432	497	424	399	407	531	551	717
2014–2015												
Monthly rain, mm	144	265	256	252	265	46	99	23	93	54	219	60
Mean max. temp., °C	28.1	28.6	31.7	28.4	27.1	27.0	23.4	23.5	22.6	26.7	27.3	28.7
Mean min. temp., °C	13.9	15.5	19.1	18.1	17.2	16.1	13.4	12.9	12.6	13.5	15.2	15.8
Radiation received, MJ m ⁻²	636	650	756	518	508	538	400	403	341	539	511	622
2015–2016												
Monthly rain, mm	186	299	492	367	134	29	146	127	0	86	0	160
Mean max. temp., °C	27.2	28.4	28.1	29.6	28.4	29.6	22.9	20.5	24.1	25.3	26.0	27.2
Mean min. temp., °C	15.7	18.3	18.2	18.4	17.9	16.0	13.1	11.8	12.8	12.7	14.5	14.4
Radiation received, MJ m ⁻²	516	545	630	567	573	512	369	369	455	491	558	616
2016–2017												
Monthly rain, mm	134	185	339	141	141	–	–	–	–	–	–	–
Mean max. temp., °C	27.9	27.9	26.4	29.8	28.0	–	–	–	–	–	–	–
Mean min. temp., °C	16.2	17.7	18.6	19.9	18.7	–	–	–	–	–	–	–
Radiation received, MJ m ⁻²	630	659	544	621	591	–	–	–	–	–	–	–
Long-term (60 year) avg												
Monthly rain, mm	185	224	203	141	67	76	56	38	39	71	127	133
Mean max. temp., °C	27.2	28.1	28.0	28.0	27.0	24.0	23.0	23.0	25.0	26.2	26.7	27.2
Mean min. temp., °C	16.4	17.1	17.4	19.0	17.0	15.0	13.0	13.0	14.0	12.4	14.2	15.1
Radiation received, MJ m ⁻²	603	636	663	548	517	500	378	362	405	502	524	605

is a viable alternative to increasing forage and meat production in winter/spring. However, the oversown of oat in the winter/spring with seeds planted in lines or seeds broadcast with superficial incorporation may alter the forage mass of pasture as well as nutrient cycling.

Thus, our objective was evaluated the effect of inclusion of pigeon pea in the intercrop of corn with palisade grass, as well as, the modalities of oversown of black oat on: corn and soybean leaf nutrient concentrations, agronomic characteristics and yields, intercropping competition factors, land-use efficiency, relative nutrient yields, mulching, straw decomposition, and nutrient release rates in an ICLS during four growing seasons in the Brazilian “Cerrado.”

MATERIALS AND METHODS

Site Description

The experiment was conducted in Botucatu in São Paulo, Brazil (48° 25' 28" W, 22° 51' 01" S; 777 m above sea level) over four consecutive growing seasons: 2013–2014, 2014–2015, 2015–2016, and 2016–2017. The soil was a clayey, kaolinitic, thermic Typic Haplorthox (FAO–Food Agriculture Organization of the United Nations, 2006) with 630, 90, and 280 g kg⁻¹ of clay, silt, and sand, respectively. For 4 years, until October 2010,

the field was fallow, with predominantly signal grass (*Urochloa decumbens* “Basilisk”) and annual broadleaf weeds (*Bidens* spp., *Sonchus oleraceus*, *Raphanus raphanistrum*, *Commelina benghalensis*, *Ipomoea grandifolia*, *Chamaesyce hirta*, *Euphorbia heterophylla*, *Desmodium tortuosum*, *Leonotis nepetifolia*, and *Sida rhombifolia*). In the growing seasons of 2010–2011 and 2011–2012, corn to silage was intercropped with palisade grass in the summer/autumn, and yellow oat (*Avena byzantina* “São Carlos”) was oversown, with grazing by lambs in the winter/spring (Pariz et al., 2017b). In the growing season of 2012–2013, soybean to silage was intercropped with guinea grass in the summer/autumn, and the pasture was cut in the winter/spring (Pariz et al., 2016, 2017a).

The climate of this area is Cwa, according to the Köppen climate classification system (Alvares et al., 2013). The long-term (1955–2015) mean annual maximum and minimum temperatures are 26.1 and 15.3°C, respectively, with a mean annual precipitation of 1,359 mm. The precipitation, temperature and incoming radiation were measured from 2013 to 2017 (Table 1).

The initial chemical characteristics of the soil [pH, organic matter, total acidity at pH 7.0 (H⁺, Al), exchangeable Al, available P and exchangeable Ca, Mg, and K] at depths of 0–0.20 and 0.20–0.40 m were determined (Table 2). The cation exchange capacity

TABLE 2 | Soil chemical characteristics at two depths in the experimental area before the initiation of the experiment.

Depth	pH	SOM ^a	P (resin)	H + Al	K _{ex}	Ca _{ex}	Mg _{ex}	CEC ^b	BS ^c
	CaCl ₂	g dm ⁻³	mg dm ⁻³			mmol _c dm ⁻³			%
0–0.20 m	5.1	38.1	12.2	41.4	1.0	31.5	15.8	89.7	53.8
0.20–0.40 m	4.8	38.0	5.5	59.6	0.7	21.9	11.4	93.6	36.3

^aSoil organic matter.

^bCation exchange capacity.

^cBase saturation.

(CEC) was calculated based on the sum of the concentrations of H⁺, Al, K, Ca, and Mg cations. The base saturation (BS) was calculated by dividing the sum of K, Mg, and Ca (the bases) by the CEC and multiplying the result by 100% (van Raij et al., 2001).

Experimental Design

The experiment had a completely randomized design as a function of soil fertility homogeneity, consisting of four treatments of corn to silage production system in summer/autumn with black oat oversown in winter/spring and twelve replications: (1) corn intercropped with palisade grass and black oat overseeded in lines; (2) corn intercropped with palisade grass and black oat overseeded in a broadcast system with superficial incorporation; (3) corn intercropped with palisade grass + pigeon pea and black oat overseeded in lines; and (4) corn intercropped with palisade grass + pigeon pea and black oat overseeded in a broadcast system with superficial incorporation. The cultivars used were: Marandu, Embrapa 29 and BRS Mandarim (palisade grass, black oat, and pigeon pea, respectively). During winter/spring, the black oat pastures were grazed by lambs, but results regarding forage allowance and nutritive value for animal grazing, as well as results regarding animal performance, are not reported in the present manuscript. The experiment was repeated in the same location for four growing seasons (2013–2014, 2014–2015, 2015–2016, and 2016–2017). Corn was ensiled in 2013–2014, 2014–2015, and 2015–2016, and soybean was ensiled in 2016–2017. The fourth growing season accounted for the residual effect of the crop systems from the previous growing seasons, as the same soybean crop system was applied to all plots. Each plot consisted of twenty 25-m-long rows spaced 0.45 m apart, thus providing a total area of 225 m². Monoculture plots of corn, palisade grass, or pigeon pea had the same size and number of replications as the other treatments. However, the corn, palisade grass, and pigeon pea monoculture plots were used only for determining the intercropping competition factors and land-use efficiency calculations.

Tillage, Crop Management, and Lamb Grazing Management

On 20 November 2013, plants comprising the remaining forage grasses and weeds were sprayed with glyphosate (1.44 kg acid-equivalent ha⁻¹) and 2,4-D amine (0.67 kg active ingredient ha⁻¹). On 09 December 2013, any weed regrowth was sprayed

with glyphosate (1.08 kg acid-equivalent ha⁻¹). Both herbicide applications used a spray volume of 200 L ha⁻¹.

Corn hybrid 2B587 PowerCore (Dow AgroSciences, Indianapolis, Indiana, USA) with early relative maturity was sown in all crop systems on 16 December 2013, 16 December 2014, and 14 December 2015 at a 4-cm depth, with a row spacing of 0.45 m and a density of 80,000 seeds ha⁻¹, using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, Rio Grande do Sul, Brazil). When intercropped with corn, palisade grass was simultaneously sown at 12.0 kg ha⁻¹ (pure live seed = 50%). Forage seeds were mixed with basic fertilizer (Pariz et al., 2016, 2017a) and sown at depths of 0.08 m below the soil surface, as described by Crusciol et al. (2012). Pigeon pea was first sown to a depth of 0.04 m using the same no-till seeding method (15 seeds per m) (~35 kg of seeds ha⁻¹), as recommended by Oliveira et al. (2011); then, the corn + palisade grass combination was sown. Therefore, pigeon pea emerged between the rows of corn + palisade grass. For all crop systems and in both growing seasons, basic fertilizer applied in the sowing furrows was 36 kg ha⁻¹ of N as urea, 126 kg ha⁻¹ of P₂O₅ as triple superphosphate, and 72 kg ha⁻¹ of K₂O as potassium chloride, following the recommendation of Cantarella et al. (1997).

Corn seedling emergence occurred 11, 7, and 4 days after sowing (27 December 2013, 23 December 2014, and 18 December 2015, respectively). Differences were due to the absence of rain after sowing in the growing seasons (Table 1). Pigeon pea seedlings emerged 17, 12, and 9 days after sowing (02 January 2014, 28 December 2014, and 23 December 2015, respectively). Forage grass seedlings emerged 25, 22, and 21 days after sowing (10 January 2014, 07 January 2015, and 04 January 2016, respectively). In all growing seasons, due to the large amount of straw on the soil surface, there was no emergence of annual broadleaf weeds, and herbicide application during post-emergence of the corn crop was not necessary. Furthermore, it was not necessary to decrease the initial growth of palisade grass with a herbicide subdose due to the different emergence times of corn and grass seedlings.

On 15 January 2014, 13 January 2015, and 13 January 2016, when corn had four expanded leaves (V4 stage), mineral fertilizer was broadcast with no incorporation at 150 kg ha⁻¹ of N as urea, 38 kg ha⁻¹ of P₂O₅ as triple superphosphate, and 150 kg ha⁻¹ of K₂O as potassium chloride, following the recommendation of Cantarella et al. (1997).

The average corn growing season length from emergence to grain production under 35% moisture was 104, 106, and 108 days

(10 April 2014, 08 April 2015, and 04 April 2016, respectively). Whole corn plants were harvested in each plot with a mechanical forage harvester (JF, model C-120, Itapira, SP, Brazil) at 0.45 m above the soil surface. Crops were chopped into particles with an average size of 1.0 cm, and knives were used to shred the corn silage grain. A two-row platform with reduced spacing (0.45–0.55 m between rows) was used to harvest the crops.

On 05 May 2014, 22 April 2015, and 13 April 2016, black oat was oversown in two modalities: (a) seeds were planted in lines to a depth of 3 cm at 65 kg ha⁻¹ pure live seed density with 0.17 m row spacing, using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, Rio Grande do Sul, Brazil); (b) seeds were broadcast (manually) at 120 kg ha⁻¹ pure live seed density, with superficial incorporation using a disk harrow (fully closed disks for minimum ground disturbance). Both oversown modalities followed the recommendation of Adami and Pitta (2012). In both oversown modalities, black oat seedlings emerged 24, 13, and 20 days after sowing (29 May 2014, 05 May 2015, and 03 May 2016, respectively). Differences in emergence were due to the absence of rain after oversowing during the growing seasons (Table 1).

In the first growing season, 48 (four crop systems × twelve lambs/crop system) uncastrated male crossbred Dorper, Texel and Ile de France lambs, with a mean age of 3 months and an initial body live weight of 27.0 ± 3.2 kg, were used. In the second growing season, 48 (four crop systems × 12 lamb/crop systems) uncastrated male crossbred Poll Dorset and Corriedale lambs with a mean age of 3 months and an initial body live weight of 24.4 ± 3.4 kg were used; 16 (four crop systems × four lambs/crop system) additional lambs were used to adjust the animal stocking rate. In the third growing season, 48 (four crop systems × 12 lambs/crop system) uncastrated male crossbred Dorper and Texel lambs with a mean age of 3 months and an initial body live weight of 26.4 ± 3.5 kg were used. The lambs were blocked based on weight variation and were randomly allocated to the crop systems. The management of lambs was conducted in accordance with the Ethics Committee on Animal Use (CEUA) of São Paulo State University (UNESP) at the College of Veterinary Medicine and Animal Science in Botucatu, São Paulo, Brazil, under protocol number 31/2014-CEUA.

The grazing method was rotational, with stocking at a fixed rate of 44, 55, and 44 lambs ha⁻¹ in the first, second and third growing seasons, respectively, in a semi-feedlot scheme. The initial stocking rates were 1.2, 1.5, and 1.2 Mg ha⁻¹ of body live weight, and the final stocking rates were 1.9, 2.2, and 1.9 Mg ha⁻¹ of body live weight in the first, second, and third growing seasons, respectively. The grazing period in each paddock was 3 days, and the rest period was 33 days, totaling 12 paddocks per treatment. Two cycles of grazing were carried out, 36 and 33 days (first and second cycles, respectively), totaling 69 days. Lambs were on the pasture throughout the day (from 6:00 h. to 18:00 h.).

On 17 September 2016, 2.0 Mg ha⁻¹ of dolomitic lime (CaCO₃, MgCO₃) with 28% CaO and 20% MgO was broadcast onto the soil surface, following the recommendation of Crusciol et al. (2016). On 02 December 2014, 16 November 2015, and 10 November 2016, plants composed of the remaining forage grasses and weeds were sprayed with glyphosate (1.44 kg acid-equivalent

ha⁻¹) and 2,4-D amine (1.34 kg active ingredient ha⁻¹). On 17 December 2014, 04 December 2015, and 25 November 2016, any weed regrowth was sprayed with glyphosate (1.08 kg acid-equivalent ha⁻¹) and on 02 December 2016, mulch was sprayed with paraquat (0.4 kg active ingredient ha⁻¹). All herbicide applications used a spray volume of 200 L ha⁻¹.

The soybean cultivar “AS 3610 IPRO—INTACTA RR2 PRO” (super early cycle, maturity group 6.1, and indeterminate growth rate) was sown on 06 December 2016 at a 4-cm depth at a density of 350,000 seeds ha⁻¹ and a row spacing of 0.45 m using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, Rio Grande do Sul, Brazil). The fungicide carboxin + thiram and the insecticide thiamethoxam were applied to soybean seeds at doses of 60 and 120 g of active ingredient (a.i.) to 100 kg of seeds, respectively. The soybean seeds were inoculated with *Bradyrhizobium japonicum* (SEMIA 5079—CPAC 15 and SEMIA 5080—CPAC 7) at 1,200 cells seed⁻¹. All soybean crop systems were fertilized in furrows, with 7 kg ha⁻¹ of N as urea, 70 kg ha⁻¹ of P₂O₅ as triple superphosphate and 70 kg ha⁻¹ of K₂O as potassium chloride. In all crop systems, guinea grass cv. Aruana was intercropped with soybean and planted at 15 kg ha⁻¹ (pure live seed = 32%). Forage seeds were mixed with basic fertilizer (Pariz et al., 2016, 2017a) and sown at depths of 0.06 m below the soil surface, as described by Crusciol et al. (2012). Soybean and guinea grass seedlings emerged 6 and 15 days after sowing, respectively (12 December 2017 and 21 December 2017, respectively). The herbicide glyphosate (0.54 kg acid-equivalent ha⁻¹) was applied 7 days after the emergence of the soybean seedlings. All crop systems were side-dressed 23 days after soybean emergence with 90 kg ha⁻¹ K₂O as potassium chloride, with incorporation using a row crop cultivator for NTS (Tatu Marchesan, model CPD, Matão, São Paulo, Brazil).

Soybeans were cultivated according to crop needs (Embrapa—Empresa Brasileira de Pesquisa Agropecuária, 2006). The application of phytosanitary products was as follows: insecticide thiamethoxam + lambda-cyhalothrin (21 and 16 g of a.i. ha⁻¹, respectively) during the V4 stage; the fungicide trifloxystrobin + prothioconazole (30 and 35 g of a.i. ha⁻¹, respectively) and insecticide thiamethoxam + lambda-cyhalothrin (28 and 21 g of a.i. ha⁻¹, respectively) during the R1 stage; the fungicide trifloxystrobin + prothioconazole (38 and 44 g of a.i. ha⁻¹, respectively) and insecticide acephate (600 g of a.i. ha⁻¹) during the R4 stage; and the fungicide azoxystrobin + benzovindiflupyr (60 and 30 g of a.i. ha⁻¹, respectively) and insecticide thiamethoxam + lambda-cyhalothrin (28 and 21 g of a.i. ha⁻¹, respectively) during the R6 stage. All fungicide and insecticide applications used a spray volume of 200 L ha⁻¹ and adjuvant mineral oil (65 g ha⁻¹).

The length of the soybean season (from emergence to growth stage R7—beginning of bean maturity and 50% yellow leaves), according to Fehr and Caviness (1977), was 95 days (16 March 2017). In this stage, whole soybeans and guinea grass plants were harvested according to the recommendation of Leonel et al. (2008) with a mechanical forage harvester (Model JF C-120 with 12 knives and total platform area of 1.30 m, Itapira, São Paulo, Brazil). The crops (soybean and guinea grass) were harvested at 0.15 m above the soil surface.

Sampling and Analyses

Corn and Soybean Leaf Nutrient Concentrations, Agronomic Characteristics, and Yield

Corn leaf samples were collected for nutrient analysis when 50% of corn plants were in the full flowering stage. Selection was randomized, with 30 plants chosen per plot. The fourth leaf with a visible sheath from the apex was collected following the methods of Cantarella et al. (1997). Soybean leaf samples were collected, i.e., the upper third trifoliate leaf from top to bottom at the R2 growth stage during full bloom (Fehr and Caviness, 1977). Petioles from 30 plants per plot were collected as proposed by Ambrosano et al. (1997). Leaf samples were washed, dried by forced-air circulation at 65°C for 72 h, grinding was carried out in a Willey mill (0.85 mm sieve) and analysis were carried out to determine the chemical composition. The concentrations of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn were determined using the methods described by Malavolta et al. (1997). Nitrogen was extracted with H₂SO₄, and the other nutrients were extracted with a nitro-perchloric solution. The nitrogen concentration in the digested solution was determined by Kjeldahl analysis. The concentrations of the other nutrients were determined using atomic absorption spectrophotometry.

The corn plant population and number of ears (NE) (i.e., number of plants and ears in the four central rows, excluding 1 m from the end of each side of the row of each plot, extrapolated to plants, and ears per hectare) were evaluated. The plant height (PH), main ear insertion height (MEIH), and basal stalk diameter (BSD) were also evaluated. From harvested whole corn to silage, palisade grass, and pigeon pea plants, a representative sample was dried by forced-air circulation at 65°C for 72 h to determine the forage mass (Mg ha⁻¹) and the proportions (%) of corn grains, palisade grass, and pigeon pea in the forage mass. Using the same plant evaluation methodology, current-year corn, palisade grass, and pigeon pea mulch were collected from the soil surface to determine the remaining straw (Mg ha⁻¹). Concentrations of macro and micronutrients were determined (same methods described for corn leaf nutrient). Nutrient concentrations were multiplied by the quantity of forage mass and mulch to determine the nutrient contents (kg ha⁻¹).

The soybean plant population (SPP) (calculated from the number of plants in the four central rows, excluding 1 m from the end of each side of the row of each plot, extrapolated to plants per hectare) was evaluated. The PH, height of the first pod insertion (HFPI), number of pods per plant (NPP), number of seeds per pod (NSP), dry weight of 100 seeds (W100), and dry weight of seeds per hectare were also evaluated. Soybean and guinea grass were harvested at 0.15 m above the soil surface. A representative sample was dried by forced-air circulation at 65°C for 72 h to determine the forage mass (Mg ha⁻¹). Using the same plant evaluation methodology, current-year soybean, and guinea grass mulch were collected from the soil surface to determine the remaining straw (Mg ha⁻¹).

Intercropping Competition Factors and Land-Use Efficiency

The relative nutrient yield was calculated as the N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn yield of the species in the mixture divided

by the nutrient yield of the species in the monoculture based on the harvested nutrient yields (crop yield multiplied by the % nutrient concentration of the aboveground biomass) according to Lüscher and Aeschlimann (2006). The land equivalent ratio (LER) was calculated according to Mead and Willey (1980). The relative crowding coefficient (*K*) and aggressivity (*A*) were calculated according to Agegnehu et al. (2006).

Surface Mulch Quantity, Decomposition, Nutrient Content, and Release Rates

After grazing by lambs, following pasture and weed desiccation with glyphosate herbicide, estimates were obtained for the plant material killed (i.e., mulch quantity). Along two diagonal transects in each plot, three evaluators placed metal grid squares (1 m²) on the ground in three areas per plot and cut all plant material to the ground level. The collected material was dried by forced-air circulation at 65°C for 72 h, weighed, ground, and reported in Mg ha⁻¹. Concentrations of macro and micronutrients were determined (same methods described for corn leaf nutrient). Nutrient concentrations were multiplied by the quantity of mulch to determine the nutrient contents (kg ha⁻¹). The lignin content was also determined according to the method described by Silva and Queiroz (2002) and was used to calculate the total lignin/N ratio.

To determine the rate of decomposition, fresh forage from each plot was placed in nylon bags (litter bags of 0.06 m², 0.3 × 0.2 m), proportionate to the standing mass (Pariz et al., 2011b). Litter bags were distributed and left on the soil for 15, 30, 60, 90, and 120 days. One litter bag per plot was removed at each sampling time as a function of days after desiccation (DAD) of pasture and weeds due to glyphosate herbicide following grazing. The contents of each litter bag were collected, purified by sieving, and rinsing with distilled water, and dried at 65°C to a constant weight to determine the dry weight. Subsequently, the concentrations of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn of the remaining forage residue per litter bag were determined according to the method proposed by Malavolta et al. (1997). The nutrient concentrations were multiplied by the amount of remaining residues, calculating the respective release rates for a period of 120 days (Pereira et al., 2016).

Statistical Analyses

All data were initially tested for normality with the Shapiro and Wilk (1965) test using the UNIVARIATE procedure of SAS Institute (2015, SAS Institute Inc., Cary, NC). All data were distributed normally ($W \geq 0.90$). The data were analyzed using the PROC MIXED procedure of SAS and Satterthwaite approximation to determine the denominator degrees of freedom for the test of fixed effects. The crop systems were considered fixed effects. A repeated statement was used with the growing season specified as the repeated variable. The covariance structure used in the analyses was autoregressive, which provided the best fit according to the Akaike information criterion. The results were reported as least square means and were separated by preplanned pairwise comparisons (PDIF). The mean separations were conducted using an LSD test. The effects were considered statistically significant at $p \leq 0.05$. Straw

TABLE 3 | Leaf nutrient concentrations at the full flowering stage in corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast in three growing seasons.

Treatments	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	g kg ⁻¹						mg kg ⁻¹				
Crop systems											
C + PG + BO line	29.0 ^{c§}	2.7 ^a	20.2 ^a	2.6 ^a	2.0 ^a	1.7 ^a	14.0 ^a	9.9 ^b	122.5 ^a	43.2 ^b	22.4 ^a
C + PG + BO broadcast	28.0 ^d	2.7 ^a	20.1 ^a	2.6 ^a	2.0 ^a	1.7 ^a	15.3 ^a	9.6 ^b	117.7 ^a	41.5 ^b	22.6 ^a
C + PG + PP + BO line	31.6 ^a	2.7 ^a	19.7 ^a	2.6 ^a	2.0 ^a	1.7 ^a	15.1 ^a	11.5 ^a	122.6 ^a	58.0 ^a	23.1 ^a
C + PG + PP + BO broadcast	30.6 ^b	2.7 ^a	20.3 ^a	2.7 ^a	2.1 ^a	1.7 ^a	14.8 ^a	11.7 ^a	125.8 ^a	57.7 ^a	22.6 ^a
Growing seasons											
First (2013–2014)	29.8 ^{a§}	2.8 ^a	19.9 ^a	3.3 ^a	2.4 ^a	1.7 ^a	17.9 ^a	10.3 ^a	122.0 ^a	53.5 ^a	22.5 ^a
Second (2014–2015)	29.6 ^a	2.6 ^a	20.5 ^a	2.5 ^b	2.1 ^b	1.7 ^a	18.6 ^a	11.0 ^a	122.5 ^a	47.9 ^a	22.8 ^a
Third (2015–2016)	30.0 ^a	2.7 ^a	19.9 ^a	2.2 ^c	1.5 ^c	1.8 ^a	7.9 ^b	10.7 ^a	122.0 ^a	48.9 ^a	22.8 ^a

§Means within a column of the same category (i.e., crop systems and growing seasons) followed by the same letter are not significantly different at $P \leq 0.05$.

decomposition and nutrient release rates were analyzed, as suggested by Wider and Lang (1982), with the litter bag method, using the PROC REG procedure of SAS, and the best adjustments chosen had the highest coefficients of determination (r^2) at $p \leq 0.05$. Error bars represent standard errors (SEs), and the means were determined using the PROC MEANS procedure of SAS.

RESULTS

Weather Conditions

The temperatures during the second (2014–2015) and third (2015–2016) growing seasons were relatively similar (Table 1) and appropriate for corn cultivation (Borghini et al., 2013b; Crusciol et al., 2013). According to Bergamaschi et al. (2004) and Araujo et al. (2011), the amount of precipitation would have allowed corn and intercropped forages to develop without water stress only during the second and third growing seasons (between 500 and 800 mm). In the fourth growing season (2016–2017), the weather conditions were also appropriate for soybean development (Crusciol et al., 2012, 2014). According to Embrapa—Empresa Brasileira de Pesquisa Agropecuária (2006), the amount of precipitation would have caused minimal water stress of soybean and intercropped guinea grass (between 450 and 850 mm).

In the first growing season (2013–2014), the rainfall (754 mm) was 45% lower than the historical average (1,360 mm), with low rainfall occurring in the summer (mainly from 17 January 2014 to 15 February 2014), which was associated with a greater mean maximum temperature than the historical average and caused severe water stress mainly during corn vegetative development, with precipitation around 300 mm between corn seedlings emergence until harvest (December 2013 to March 2014; Table 1). In the second and third growing seasons (2014–2015 and 2015–2016, respectively), rainfall amounts of 1,776 and 2,026 mm were 23 and 49% higher, respectively, than the historical averages, and the mean maximum and minimum temperatures were similar to the historical average. In the fourth growing season, the rainfall amount of 940 mm from November 2016 to March 2017 was 15% higher than the historical average

during this period (820 mm), and the mean maximum and minimum temperatures were similar to the historical averages. The radiation received by corn between seedling emergence and harvest was similar in all growing seasons (1,986, 2,142, and 2,065 MJ m⁻² in the first, second and third growing seasons, respectively), and in all months, the values were similar to the historical average. The radiation received by soybean between seedling emergence and harvest was 1,919 MJ m⁻² in the fourth growing season.

Between the harvesting of corn and stocking of lambs on pastures, rainfall amounts of 151, 232, and 302 mm occurred in the first, second and third growing seasons, respectively, and after the oversowing of black oat, rainfall amounts of 85, 189, and 302 mm occurred in the first, second and third growing seasons, respectively. The radiation received by pasture between the corn harvest and stocking of lambs was similar for all growing seasons (1,243, 1,231, and 1,050 MJ m⁻² in the first, second and third growing seasons, respectively).

Corn Leaf Nutrient Concentrations, Agronomic Characteristics, and Yield

The crop system affected the N, Cu, and Mn concentrations and the growing season affected Ca, Mg, and B concentrations of corn leaf tissue (Table 3). The crop system affected the standing plant residues, forage mass, and concentration of corn grains, and the growing season affected the corn plant population, NE per hectare, PH (corn, palisade grass, and pigeon pea), MEIH, bulk stalk diameter, standing plant residues, forage mass, proportions of corn grains, palisade grass, and pigeon pea (Table 4). Forage mass was also affected by the interaction between crop system × growing season.

Corn intercropped with palisade grass and pigeon pea had higher N, K, and Fe contents in the forage mass, and growing season affected only the N content in the forage mass (Table 6). Corn intercropped with palisade grass and pigeon pea had higher nutrient contents in standing residue than other crop systems, and growing season also affected all nutrient contents in standing residue.

TABLE 4 | Corn plant population (CPP), number of ears per hectare (NE), plant height (PH), main ear insertion height (MEIH), basal stalk diameter (BSD), standing plant residue (SPR), forage mass (FM), and proportions of corn grains (CG), palisade grass and pigeon pea in corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast in three growing seasons.

Treatments			PH			Concentration						
	CPP	NE	C	PG	PP	MEIH	BSD	SPR	FM	CG	PG	PP
	$n^{\circ} \times 1,000$				m		cm	$Mg\ ha^{-1}$		%		
Crop systems												
C + PG + BO line	75.0 ^{as}	82.3 ^a	2.0 ^a	1.0 ^a	–	0.9 ^a	21.7 ^a	2.2 ^b	14.1 ^b	50.0 ^a	1.2 ^a	–
C + PG + BO broadcast	74.7 ^a	81.2 ^a	2.0 ^a	1.1 ^a	–	0.9 ^a	22.3 ^a	2.4 ^b	14.0 ^b	50.5 ^a	1.3 ^a	–
C + PG + PP + BO line	75.9 ^a	81.8 ^a	2.1 ^a	1.1 ^a	1.6 ^a	1.0 ^a	21.4 ^a	3.1 ^a	15.0 ^a	47.5 ^b	1.1 ^a	6.4 ^a
C + PG + PP + BO broadcast	76.1 ^a	82.4 ^a	2.0 ^a	1.1 ^a	1.7 ^a	0.9 ^a	21.6 ^a	3.1 ^a	14.9 ^a	46.7 ^b	1.2 ^a	5.8 ^a
Growing seasons												
First (2013–2014)	70.1 ^{bs}	71.4 ^b	1.5 ^b	0.8 ^b	2.1 ^a	0.7 ^b	18.6 ^b	2.2 ^b	13.9 ^b	50.2 ^a	1.5 ^a	9.4 ^a
Second (2014–2015)	77.6 ^a	87.0 ^a	2.3 ^a	1.2 ^a	1.4 ^b	1.0 ^a	23.8 ^a	2.9 ^a	14.8 ^a	47.4 ^b	1.0 ^b	4.6 ^b
Third (2015–2016)	78.6 ^a	87.5 ^a	2.2 ^a	1.2 ^a	1.4 ^b	1.0 ^a	22.9 ^a	3.0 ^a	14.8 ^a	48.5 ^b	1.1 ^b	4.4 ^b

[§]Means within a column of the same category (i.e., crop systems and growing seasons) followed by the same letter are not significantly different at $P \leq 0.05$.

Intercropping Competition Factors and Land-Use Efficiency

Intercropping corn with palisade grass and pigeon pea increased the total LER in the three growing seasons compared to intercropping corn with palisade grass alone (Table 7). Intercropping corn with palisade grass and pigeon pea affected the *K*-value of corn and palisade grass in the three growing seasons compared to intercropping corn only with palisade grass and affected the *A*-value of corn in the three growing seasons as well as the *A* value of palisade grass only in the first growing season compared to intercropping corn only with palisade grass.

Surface Mulch Quantity, Decomposition, Nutrient Content and Release Rates

The inclusion of pigeon pea in the production system with intercropped corn and palisade grass provided an increase in the surface mulch, mulch cover and nutrient contents and caused a decrease in the lignin/N ratio, mainly with black oat oversown in lines (Table 9). The growing season also affected all these attributes except the lignin/N ratio.

With a lower lignin/N ratio than other treatments, surface mulch in the palisade grass plots generated during triple intercropping had greater initial decomposition [logarithmic (log 10) decomposition]; furthermore, with a higher lignin/N ratio than other treatments, surface mulch in the palisade grass plots generated during double intercropping had lower initial decomposition (Figure 1). The release rate of N was similar to that of surface mulch decomposition in all crop systems. The rate of release of P, K, Mg, and B contained in the plant residues was logarithmic over 120 DAD; however, there was no crop system effect (Figures 1–3). The release of Ca, S, Cu, Fe, Mn, and Zn from the plant residues was exponential at 120 DAD; however, without a crop system effect, and in the first 30 days, the release of these nutrients was slower than that of the other nutrients (Figures 2–4).

Soybean Leaf Nutrient Concentrations, Agronomic Characteristics, and Yield

The residual effect of corn intercropped with palisade grass and pigeon pea, mainly with black oat oversown in lines, resulted in higher N and K concentrations in soybean leaves (Table 10). Residual crop system effects were significant for the SPP, PH, HFPI, NPP, dry weight of 100 seeds, dry weight of seeds per hectare, forage mass, and standing plant residue, with higher values after triple intercropping than after double intercropping (Table 11).

DISCUSSION

Corn Leaf Nutrient Concentrations, Agronomic Characteristics, and Yield

In all crop systems, corn leaf nutrient concentrations were optimal under sufficient ranges (Cantarella et al., 1997), despite following a recommended seeding and side-dressing fertilization programme (Table 3). Previous studies have shown higher cash-crop leaf nutrient concentrations when these crops are intercropped with palisade grass (Crusciol et al., 2012; Borghi et al., 2013b). However, the inclusion of pigeon pea in intercropping increased corn leaf N, Cu, and Mn concentrations (increase of 9, 18, and 36%, respectively), demonstrating a direct transfer of these nutrients to the cereal crop (Xiao et al., 2004).

A reduction in corn leaf Ca and Mg concentrations over the three growing seasons suggested the absorption of these nutrients that depended on the effectiveness of the root systems and nutrient availability (Table 3). Monteiro et al. (1995) found that “the omission of Mg in nutrient solutions for cultivating palisade grass reduced the production of root dry matter by 70% compared to a treatment with adequate concentrations of Mg.” Although the levels of Ca and Mg in the soil were adequate before implementation of the experiment (Table 2), a short- to medium-term ICLS began in the growing season of 2010–2011 with dolomitic lime and agricultural gypsum application (Pariz et al.,

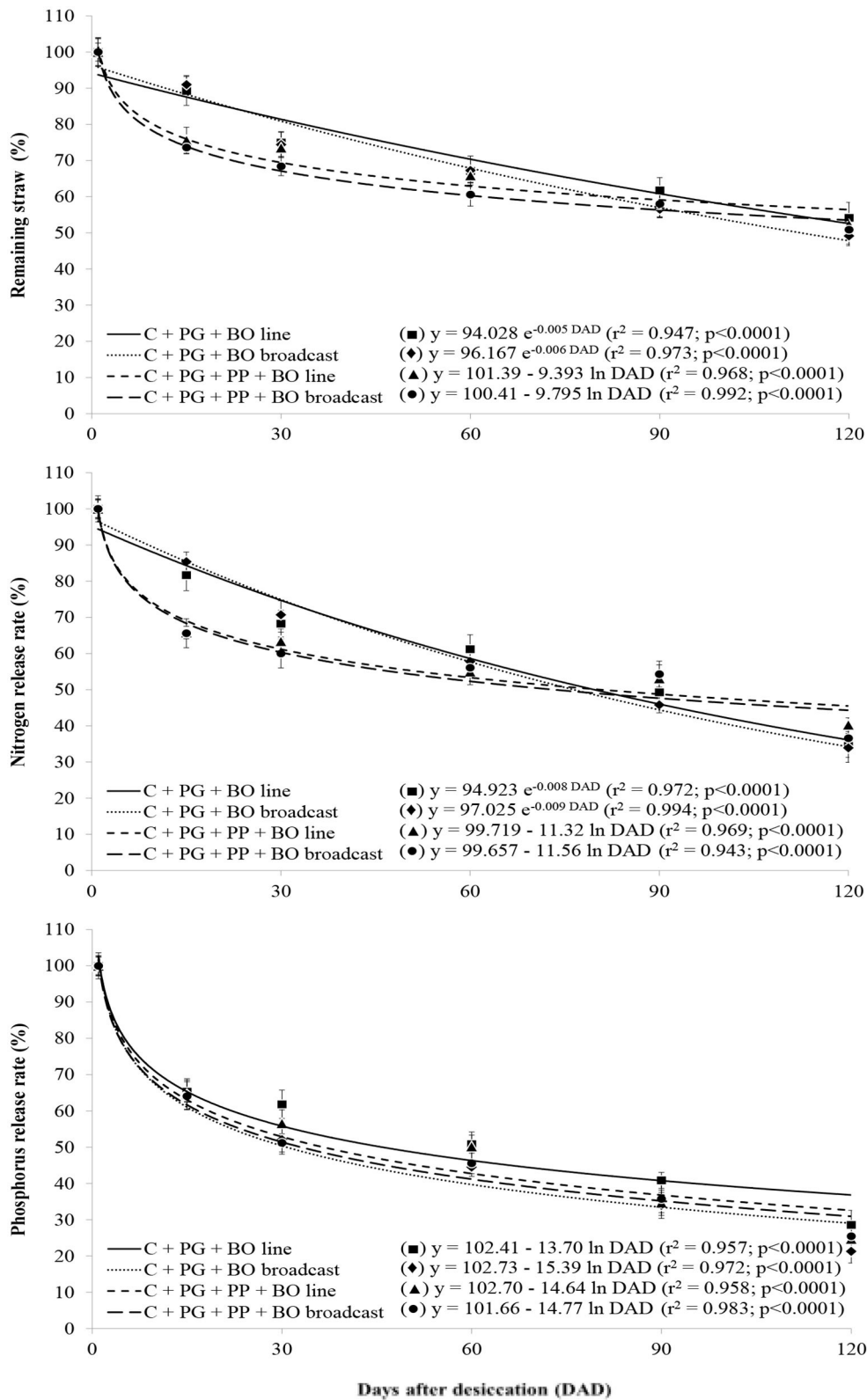


FIGURE 1 | Release rate of remaining straw, nitrogen, and phosphorus in palisade grass (PG) intercropped with corn (C) and with corn and pigeon pea (PP) to silage with black oat (BO) oversown in lines and broadcast after grazing by lambs as a function of days after desiccation (mean of three growing seasons). Values are the mean of 12 replicates, and the associated error bar is ± 1 SE. Days after desiccation (DAD): days after pasture and weed desiccation with glyphosate herbicide, after grazing by lambs.

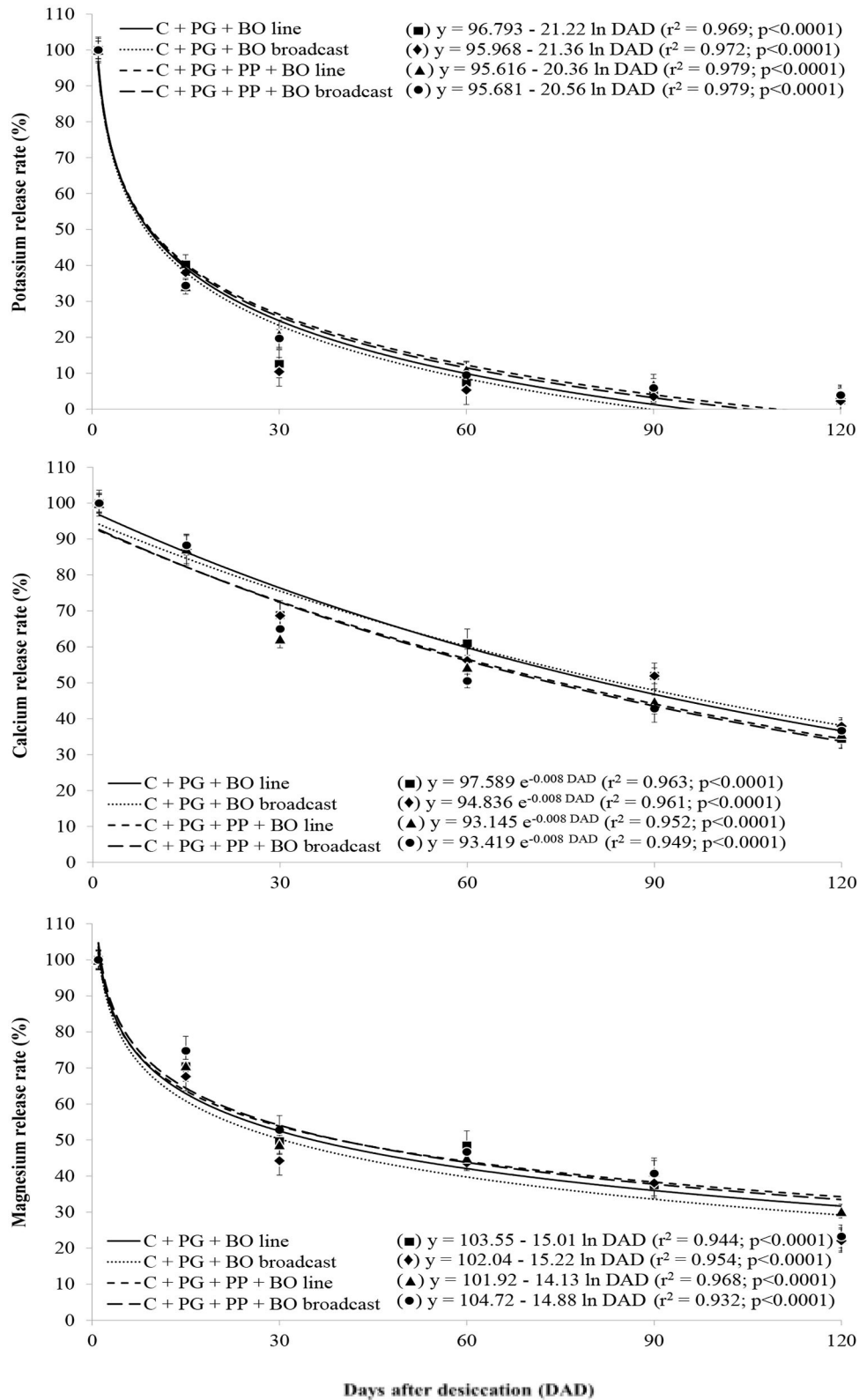


FIGURE 2 | Release rate of potassium, calcium, and magnesium in palisade grass (PG) intercropped with corn (C) and with corn and pigeon pea (PP) to silage with black oat (BO) oversown in lines and broadcast after grazing by lambs as a function of days after desiccation (mean of three growing seasons). Values are the mean of 12 replicates, and the associated error bar is ± 1 SE. Days after desiccation (DAD): days after pasture and weed desiccation with glyphosate herbicide, after grazing by lambs.

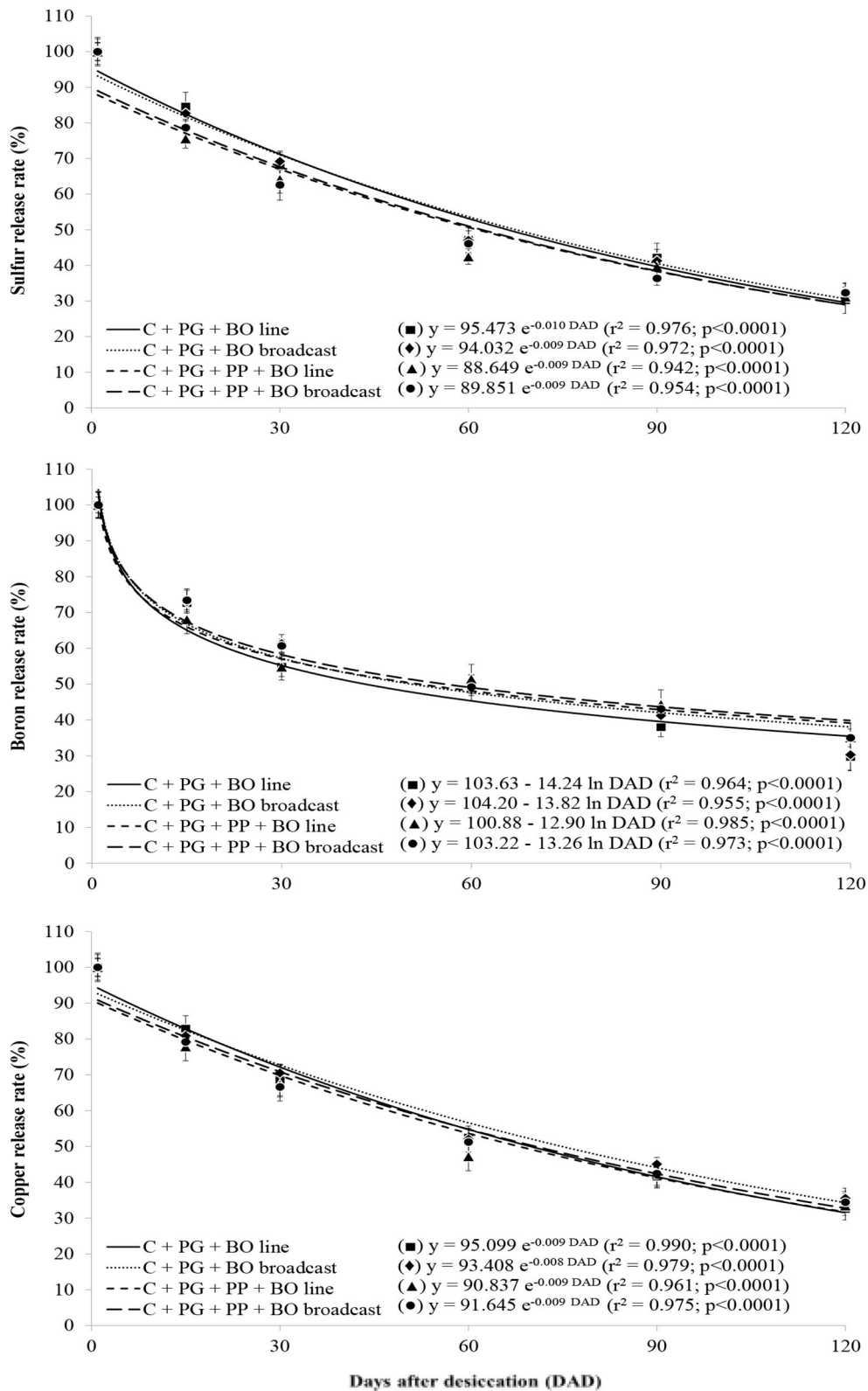


FIGURE 3 | Release rates of sulfur, boron, and copper in palisade grass (PG) intercropped with corn (C) and with corn and pigeon pea (PP) to silage with black oat (BO) oversown in lines and broadcast after grazing by lambs as a function of days after desiccation (mean of three growing seasons). Values are the mean of 12 replicates, and the associated error bar is ± 1 SE. Days after desiccation (DAD): days after pasture and weed desiccation with glyphosate herbicide, after grazing by lambs.

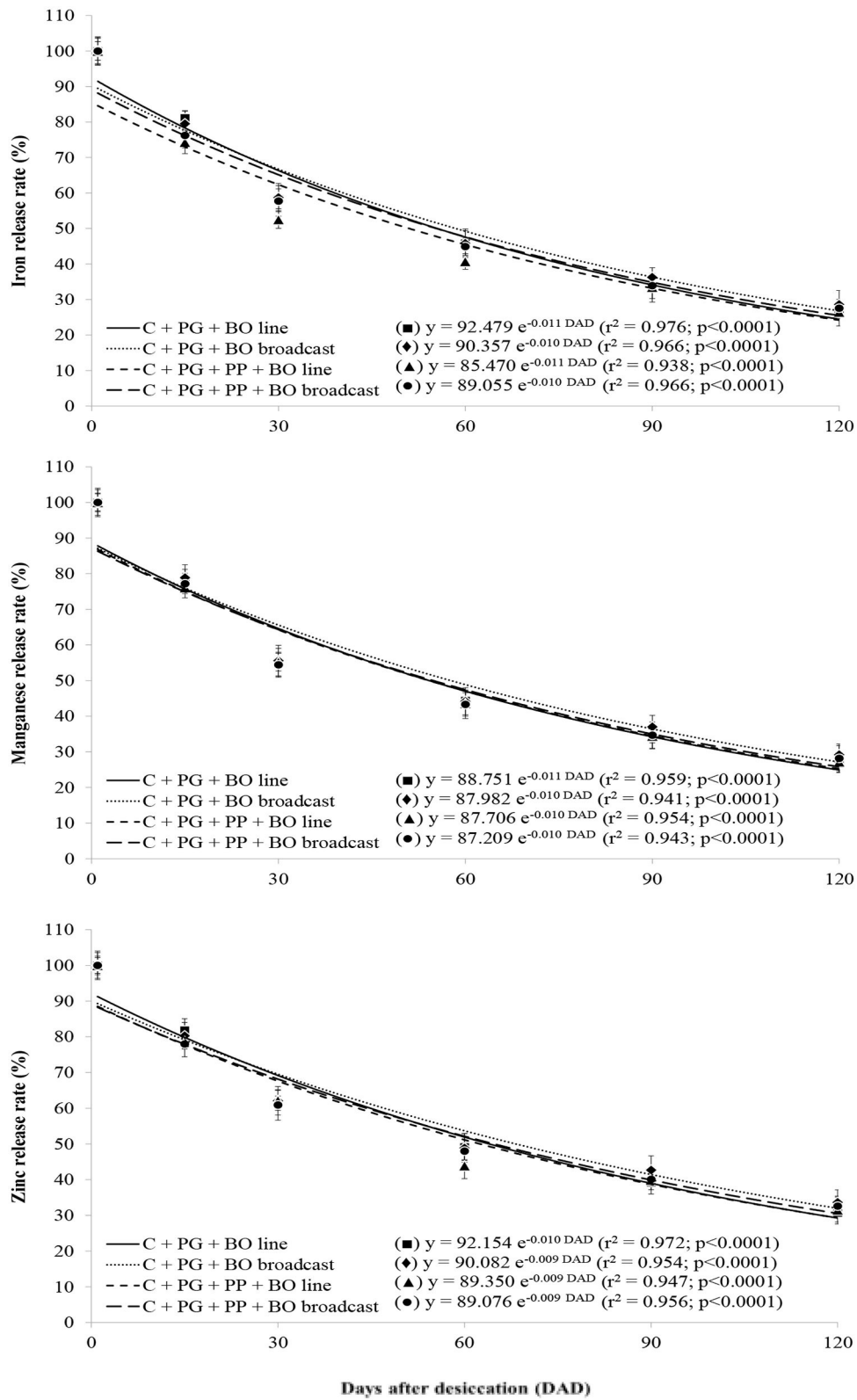


FIGURE 4 | Release rates of iron, manganese, and zinc in palisade grass (PG) intercropped with corn (C) and with corn and pigeon pea (PP) to silage with black oat (BO) oversown in lines and broadcast after grazing by lambs as a function of days after desiccation (mean of three growing seasons). Values are the mean of 12 replicates, and the associated error bar is ± 1 SE. Days after desiccation (DAD): days after pasture and weed desiccation with glyphosate herbicide, after grazing by lambs.

TABLE 5 | Forage mass of corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast in three growing seasons.

Treatments	Growing seasons		
	First (2013–2014)	Second (2014–2015)	Third (2015–2016)
	Mg ha ⁻¹		
Crop systems			
C + PG + BO line	12.9 ^{bBS}	14.6 ^{BA}	14.7 ^{BA}
C + PG + BO broadcast	12.8 ^{bB}	14.5 ^{BA}	14.7 ^{BA}
C + PG + PP + BO line	15.0 ^{BA}	15.0 ^{BA}	14.9 ^{BA}
C + PG + PP + BO broadcast	14.9 ^{BA}	15.0 ^{BA}	14.9 ^{BA}

^SMeans within a column followed by a different lowercase letter and within a line followed by a different uppercase letter are significantly different at $P \leq 0.05$.

2016, 2017a,b). In this context, the results of Crusciol et al. (2016) indicated that reapplication of lime to the surface of no-till soil can improve plant nutrition, dry matter production, crop yield, revenue and the long-term sustainability of tropical agriculture in the Brazilian “Cerrado.” Therefore, since this agricultural system has high nutrient exports, the availability of Ca and Mg in the soil should be monitored annually, with surface lime reapplications when necessary to prevent deficiency in plants. Accordingly, prior to soybean sowing, dolomitic lime was broadcast onto the soil surface. Another nutrient that supported this necessary annual monitoring is B because the concentration of this nutrient in corn leaves was lower in the third growing season than in the first and second growing seasons.

Greater standing plant residue with the incorporation of pigeon pea as an intercrop was due to the stems of this crop growing closer to the ground (Table 4). Corn intercropped with palisade grass had a lower forage mass than that of other crop systems during the first growing season (Table 5). This was a function of low rainfall in the summer, which was associated with higher mean maximum temperature than the historical average and caused severe water stress during corn vegetative development. Thus, the inclusion of pigeon pea in the production system intercropped with corn and palisade grass generated an increase of 16% in the forage mass during the first growing season, probably due to the development of the pivotal root system of pigeon pea (up to 1 m deep in relation to the soil surface), which resulted in greater water absorption, causing the crop to be more resistant to the water deficit. Therefore, the mass that was produced by the pigeon pea intercropped with corn and palisade grass allowed for the forage mass (~15 Mg ha⁻¹) to be similar to that produced during the other growing seasons without water deficiency. The inclusion of pigeon pea accounted for ~5.8–6.4% in the forage mass (Table 4), reducing the proportion of corn grains in the forage mass from 50.0–50.5% to 47.5–46.7%.

The severe water stress during corn vegetative development during the first growing season also reduced the corn plant population, NE, PH (corn and palisade grass), MEIH, BSD,

standing plant residue, and forage mass compared to the two other growing seasons (Table 4). However, as a function of the best resistance to the water deficit of pigeon pea previously discussed, associated with lower corn PH (greater incidence of light between the crop rows), the PH and proportion of pigeon pea in the forage mass were highest in the first growing season. Furthermore, it is noteworthy that after the flowering and pollination of the corn crop, the rainfall normalized, promoting adequate grain filling. Thus, as the corn plants had lower mass of leaves and stems, higher proportions of grains, and palisade grass were verified in the forage mass.

Considering that the proportion of pigeon pea in the forage mass was 9.4% in the first growing season and ~4.5% in the second and third growing seasons (Table 4) and that this legume had a higher N concentration than corn and palisade grass, this result demonstrates how the inclusion of legumes in crop systems promotes the accumulation of plant nitrogen via the biological fixation of atmospheric nitrogen (N₂) (Oliveira et al., 2011), which increases the content of this nutrient in the forage mass and in standing residue (Table 6).

Furthermore, silage with more protein, as is the case in a corn-legume intercrop system, can reduce the use of protein concentrates, which increase the cost of an animal’s diet. Also over the growing seasons [first (2013–2014) to third (2015–2016)], a greater accumulation of N occurred in the forage mass and in standing residue (Table 6), which can be considered an effect of the transition phase of NTS (between 5 and 10 years, considering that the experimental area has been managed since 2010). At this stage, the accumulation of straw on the soil surface begins, and N immobilization is similar to mineralization (Sá et al., 2009). A carryover effect of legumes may also occur in the crop system over the three growing seasons. The same carryover effect was also verified for all nutrients in standing residue, with higher contents in the second and third growing seasons than in the first growing season.

The higher N content in the forage mass and in standing residue from crop systems with oversown black oat in lines during the winter/spring compared to broadcast oversown black oat (Table 6) was due to the lower loss of soil nitrogen (emission of N₂O) in the line treatment because of the minimum ground disturbance under no-till seeding. In broadcast treatments, the superficial incorporation of black oat seeds using a disk harrow increased the pore space. High N₂O emission rates occur when the soil has a large proportion of water-filled pores, above 60%, which makes it difficult for O₂ to diffuse into the soil and favors the formation of anaerobic environments (Bateman and Baggs, 2005).

The higher K content in standing residue in the corn to silage systems likely provided significant K recycling and contributed to exchangeable forms in the soil (Garcia et al., 2008). Corn intercropped with palisade grass and pigeon pea also had a higher content of all nutrients in standing residue than other crop systems (Table 6). Thus, as a function mainly of stems that remained on the soil surface after harvest, pigeon pea had ~0.7–0.9 Mg ha⁻¹ more standing plant residue than that measured when there was no inclusion of this species in the cropping system (Table 4), which contributed to the greater accumulation

TABLE 6 | Nutrient content in forage mass and in standing plant residue of corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast compared to corn, palisade grass, and pigeon pea monoculture in three growing seasons.

Treatments	Nutrient content in forage mass										
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg ha ⁻¹						mg ha ⁻¹				
Crop systems											
C + PG + BO line	153.2 ^{c§}	24.0 ^a	113.4 ^b	18.0 ^a	24.3 ^a	18.8 ^a	121.9 ^a	68.8 ^a	630.0 ^b	448.9 ^a	251.7 ^a
C + PG + BO broadcast	143.5 ^d	23.9 ^a	112.5 ^b	17.9 ^a	23.5 ^a	16.9 ^a	112.4 ^a	62.4 ^a	596.8 ^b	432.5 ^a	237.2 ^a
C + PG + PP + BO line	173.7 ^a	25.6 ^a	125.8 ^a	18.8 ^a	25.4 ^a	18.1 ^a	135.2 ^a	66.7 ^a	1476.7 ^a	540.8 ^a	266.5 ^a
C + PG + PP + BO broadcast	163.5 ^b	22.6 ^a	124.8 ^a	18.5 ^a	27.0 ^a	17.7 ^a	135.8 ^a	62.2 ^a	1455.1 ^a	537.0 ^a	239.4 ^a
Growing seasons											
First (2013–2014)	148.2 ^{c§}	24.4 ^a	116.9 ^a	17.8 ^a	26.1 ^a	17.0 ^a	128.2 ^a	65.1 ^a	1046.8 ^a	506.8 ^a	266.6 ^a
Second (2014–2015)	158.7 ^b	23.6 ^a	120.1 ^a	18.1 ^a	23.5 ^a	18.6 ^a	122.7 ^a	64.2 ^a	1039.8 ^a	459.5 ^a	225.0 ^a
Third (2015–2016)	168.5 ^a	24.1 ^a	120.4 ^a	19.0 ^a	25.6 ^a	18.1 ^a	128.1 ^a	65.9 ^a	1032.4 ^a	503.1 ^a	254.5 ^a
Treatments	Nutrient content in standing residue										
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	kg ha ⁻¹						mg ha ⁻¹				
Crop systems											
C + PG + BO line	9.8 ^{c§}	1.2 ^b	52.3 ^b	5.4 ^b	7.8 ^b	2.5 ^b	37.8 ^b	4.8 ^b	762.6 ^b	156.2 ^b	24.7 ^b
C + PG + BO broadcast	8.4 ^d	1.2 ^b	50.7 ^b	4.9 ^b	7.0 ^b	2.4 ^b	34.1 ^b	4.6 ^b	818.3 ^b	149.5 ^b	22.2 ^b
C + PG + PP + BO line	14.6 ^a	2.2 ^a	63.1 ^a	8.8 ^a	9.6 ^a	3.4 ^a	48.6 ^a	7.8 ^a	1032.8 ^a	205.1 ^a	41.9 ^a
C + PG + PP + BO broadcast	12.3 ^b	2.2 ^a	61.7 ^a	8.6 ^a	9.3 ^a	3.5 ^a	52.1 ^a	7.6 ^a	1088.5 ^a	203.9 ^a	40.4 ^a
Growing seasons											
First (2013–2014)	8.7 ^{c§}	1.3 ^b	51.2 ^b	4.0 ^b	4.5 ^b	2.5 ^b	37.2 ^b	4.8 ^b	340.0 ^b	116.3 ^b	26.3 ^b
Second (2014–2015)	11.0 ^b	1.8 ^a	59.3 ^a	8.3 ^a	10.7 ^a	3.1 ^a	45.8 ^a	6.9 ^a	1335.5 ^a	218.3 ^a	35.5 ^a
Third (2015–2016)	14.0 ^a	1.8 ^a	60.3 ^a	7.0 ^a	10.0 ^a	3.2 ^a	46.4 ^a	6.8 ^a	1101.2 ^a	201.4 ^a	35.2 ^a

§ Means within a column of the same category (i.e., crop systems and growing seasons) followed by the same letter are not significantly different at $P \leq 0.05$.

of all nutrients in standing residue. Furthermore, considering that the soil of the experimental area is a Typic Haplorthox rich in magnetite (iron oxide), pigeon pea exhibited a strong capacity for Fe absorption and accumulation.

Intercropping Competition Factors and Land-Use Efficiency

As previously reported, the low rainfall in the summer of the first growing season (Table 1) caused severe water stress during corn vegetative development. Thus, in the first growing season, as a function of the best resistance to water deficit and of increased competition with corn and palisade grass, pigeon pea resulted in higher individual ($0.40\text{--}0.44 \times 0.19\text{--}0.23$) and total ($1.63\text{--}1.59 \times 1.28\text{--}1.31$) LER than in the two other growing seasons (Table 7). During the second and third growing seasons, corn may have competed with pigeon pea, slightly reducing the individual LER (~ 0.10). However, the LER of pigeon pea was ~ 0.20 , offsetting this reduction and resulting in a greater total LER.

In all growing seasons, palisade grass, and pigeon pea exhibited weak interspecific competition, but corn was strongly competitive in interspecific interactions (Table 7) because of the corn value ($-K$) and the palisade grass and pigeon pea value ($+K$) (Zarochentseva, 2012). However, the values of palisade grass and

pigeon pea were extremely low, and the value of corn was closer to zero when intercropped only with palisade grass. In the triple intercrop (corn + palisade grass + pigeon pea), the K -value of corn and palisade grass was far from zero, demonstrating that these crops had to be much more competitive in the presence of pigeon pea.

Over three growing seasons, all of the crop system A -values for corn were negative, whereas such values for palisade grass and pigeon pea were always positive (Table 7), indicating that these crops presented higher aggression to compete with corn as a function of the high rates of corn dry matter accumulation (Pariz et al., 2017c). In the three growing seasons, the intercropping of pigeon pea reduced the aggressivity of corn, and in the first growing season, as a function of the less favorable weather conditions already discussed, the aggressivity of palisade grass was also lower. However, in all cases, the A -values were extremely low, indicating that this aggressivity was minimal.

Concerning the individual relative nutrient yields, only the N of corn was affected by the cropping system (Table 8). In the same way as N in corn leaves (Table 3) and the N content in the forage mass and in standing residue (Table 6), the relative N yield was higher in crop systems with triple intercropping (corn + palisade grass + pigeon pea) than in systems with

TABLE 7 | Land equivalent ratio (LER) of corn, palisade grass, and pigeon pea monoculture, relative crowding coefficient (K) and aggressivity (A) of corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast in three growing seasons.

Crop systems	LER				K			A		
	Corn	Palisade grass	Pigeon pea	Total	Corn	Palisade grass	Pigeon pea	Corn	Palisade grass	Pigeon pea
First growing season										
C + PG + BO line	1.09a [§]	0.07 ^a	–	1.16 ^b	–5.55 ^b	0.16 ^b	–	–0.0013238 ^b	0.0013238 ^a	–
C + PG + BO broadcast	1.07 ^a	0.12 ^a	–	1.19 ^b	–8.87 ^b	0.24 ^b	–	–0.0013238 ^b	0.0013238 ^a	–
C + PG + PP + BO line	1.10 ^a	0.10 ^a	0.44 ^a	1.63 ^a	–25.61 ^a	0.64 ^a	0.60 ^a	–0.0036451 ^a	0.0003264 ^b	0.0033187 ^a
C + PG + PP + BO broadcast	1.11 ^a	0.08 ^a	0.40 ^a	1.59 ^a	–23.25 ^a	0.52 ^a	0.54 ^a	–0.0036451 ^a	0.0003264 ^b	0.0033187 ^a
Second growing season										
C + PG + BO line	1.14a [§]	0.02 ^a	–	1.17 ^b	–5.00 ^b	0.05 ^b	–	–0.0006853 ^b	0.0006853 ^a	–
C + PG + BO broadcast	1.17 ^a	0.03 ^a	–	1.19 ^b	–4.32 ^b	0.05 ^b	–	–0.0006853 ^b	0.0006853 ^a	–
C + PG + PP + BO line	1.06 ^b	0.02 ^a	0.20 ^a	1.28 ^a	–36.81 ^a	0.14 ^a	0.20 ^a	–0.0014979 ^a	0.0005580 ^a	0.0009399 ^a
C + PG + PP + BO broadcast	1.06 ^b	0.02 ^a	0.23 ^a	1.31 ^a	–36.48 ^a	0.12 ^a	0.24 ^a	–0.0014979 ^a	0.0005580 ^a	0.0009399 ^a
Third growing season										
C + PG + BO line	1.15a [§]	0.04 ^a	–	1.19 ^b	–4.37 ^b	0.08 ^b	–	–0.0003647 ^b	0.0003647 ^a	–
C + PG + BO broadcast	1.17 ^a	0.04 ^a	–	1.21 ^b	–3.85 ^b	0.07 ^b	–	–0.0003647 ^b	0.0003647 ^a	–
C + PG + PP + BO line	1.04 ^b	0.04 ^a	0.20 ^a	1.28 ^a	–80.53 ^a	0.25 ^a	0.17 ^a	–0.0007567 ^a	0.0003375 ^a	0.0004193 ^a
C + PG + PP + BO broadcast	1.03 ^b	0.06 ^a	0.19 ^a	1.28 ^a	–97.01 ^a	0.35 ^a	0.17 ^a	–0.0007567 ^a	0.0003375 ^a	0.0004193 ^a

[§]Means within a column of the same category in each growing season followed by the same letter are not significantly different at $P \leq 0.05$.

TABLE 8 | Relative nutrient yield (%) of corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast compared to corn, palisade grass, and pigeon pea monoculture (mean of three growing seasons).

Crop systems	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Corn											
C + PG + BO line	130.1 ^{c§}	124.3 ^a	61.1 ^a	46.0 ^a	64.1 ^a	95.1 ^a	59.2 ^a	91.7 ^a	51.3 ^a	34.5 ^a	117.8 ^a
C + PG + BO broadcast	122.2 ^d	122.8 ^a	61.6 ^a	38.4 ^a	60.1 ^a	95.0 ^a	54.2 ^a	90.1 ^a	56.3 ^a	30.2 ^a	115.0 ^a
C + PG + PP + BO line	149.6 ^a	122.4 ^a	59.9 ^a	40.2 ^a	60.3 ^a	95.9 ^a	56.5 ^a	91.0 ^a	65.0 ^a	35.7 ^a	120.3 ^a
C + PG + PP + BO broadcast	141.6 ^b	119.0 ^a	59.6 ^a	38.4 ^a	62.8 ^a	95.0 ^a	55.0 ^a	90.4 ^a	69.6 ^a	35.4 ^a	117.9 ^a
Palisade grass											
C + PG + BO line	4.9 ^{a§}	5.9 ^a	6.6 ^a	5.4 ^a	4.6 ^a	5.2 ^a	9.7 ^a	3.8 ^a	9.3 ^a	4.5 ^a	4.4 ^a
C + PG + BO broadcast	4.9 ^a	7.5 ^a	6.4 ^a	7.3 ^a	5.6 ^a	6.4 ^a	9.9 ^a	5.4 ^a	9.7 ^a	6.5 ^a	4.2 ^a
C + PG + PP + BO line	4.9 ^a	6.4 ^a	6.4 ^a	6.1 ^a	4.6 ^a	5.4 ^a	9.2 ^a	4.1 ^a	8.7 ^a	4.7 ^a	3.7 ^a
C + PG + PP + BO broadcast	5.3 ^a	6.7 ^a	6.2 ^a	5.9 ^a	5.0 ^a	5.3 ^a	10.2 ^a	3.9 ^a	12.2 ^a	5.8 ^a	3.6 ^a
Pigeon pea											
C + PG + BO line	–	–	–	–	–	–	–	–	–	–	–
C + PG + BO broadcast	–	–	–	–	–	–	–	–	–	–	–
C + PG + PP + BO line	27.0 ^{a§}	24.4 ^a	26.6 ^a	30.5 ^a	27.6 ^a	26.5 ^a	28.0 ^a	15.1 ^a	51.9 ^a	23.3 ^a	25.7 ^a
C + PG + PP + BO broadcast	23.4 ^a	20.6 ^a	25.9 ^a	26.0 ^a	25.6 ^a	24.4 ^a	24.8 ^a	13.2 ^a	40.3 ^a	15.7 ^a	18.6 ^a
Total											
C + PG + BO line	134.9 ^{c§}	130.1 ^b	67.5 ^b	51.5 ^b	68.7 ^b	100.3 ^b	68.9 ^b	95.5 ^b	60.6 ^b	39.0 ^b	122.1 ^b
C + PG + BO broadcast	125.1 ^d	130.2 ^b	67.7 ^b	45.8 ^b	65.7 ^b	101.4 ^b	64.1 ^b	95.6 ^b	66.0 ^b	36.7 ^b	119.2 ^b
C + PG + PP + BO line	181.5 ^a	153.1 ^a	92.9 ^a	76.8 ^a	92.5 ^a	127.9 ^a	93.7 ^a	110.2 ^a	125.6 ^a	63.6 ^a	149.7 ^a
C + PG + PP + BO broadcast	170.3 ^b	146.3 ^a	91.7 ^a	70.3 ^a	93.4 ^a	124.7 ^a	90.1 ^a	107.4 ^a	122.1 ^a	56.9 ^a	140.1 ^a

[§]Means within a column of the same category followed by the same letter are not significantly different at $P \leq 0.05$.

double intercropping (corn + palisade grass), mainly with black oat oversown in lines in winter/spring compared to oversown black oat that was broadcast, also reflecting a higher total relative N yield.

It should be noted that of all the nutrients, other than N, only P and Zn presented relative yields in corn plants >100% in all cropping systems (Table 8). Therefore, the results show that intercropping with palisade grass resulted

TABLE 9 | Surface mulch quantity, mulch cover, nutrient contents, and lignin/N ratio (Lig/N) in surface mulch of palisade grass intercropped with corn (PG + C) and with corn and pigeon pea (PG + C + PP) to silage with black oat (BO) oversown in lines and broadcast in three growing seasons after grazing by lambs.

Treatments	Surface mulch	Mulch cover	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Lig/N
	Mg ha ⁻¹	%	kg ha ⁻¹					mg ha ⁻¹						
Crop systems														
PG + C + BO line	5.2 ^{c§}	74 ^c	44 ^c	8 ^b	111 ^c	18 ^b	14 ^b	10 ^b	266 ^b	23 ^b	7,123 ^b	862 ^b	129 ^b	8.9 ^a
PG + C + BO broadcast	4.5 ^d	66 ^d	43 ^c	8 ^b	114 ^c	16 ^b	14 ^b	10 ^b	313 ^b	24 ^b	7,458 ^b	873 ^b	130 ^b	8.6 ^a
PG + C + PP + BO line	7.9 ^a	99 ^a	74 ^a	12 ^a	195 ^a	28 ^a	19 ^a	16 ^a	402 ^a	33 ^a	9,106 ^a	1,220 ^a	210 ^a	6.8 ^b
PG + C + PP + BO broadcast	6.1 ^b	86 ^b	60 ^b	11 ^a	141 ^b	28 ^a	18 ^a	14 ^a	382 ^a	30 ^a	9,365 ^a	1,308 ^a	190 ^a	6.4 ^b
Growing seasons														
First (2013–2014)	3.9 ^{c§}	59 ^c	38 ^c	7 ^c	93 ^c	15 ^c	11 ^c	8 ^c	227 ^c	18 ^c	5,578 ^c	709 ^c	109 ^c	7.5 ^a
Second (2014–2015)	6.1 ^b	86 ^b	59 ^b	10 ^b	145 ^b	23 ^b	17 ^b	13 ^b	350 ^b	28 ^b	8,309 ^b	1,088 ^b	169 ^b	7.8 ^a
Third (2015–2016)	7.7 ^a	97 ^a	69 ^a	13 ^a	183 ^a	30 ^a	22 ^a	16 ^a	445 ^a	36 ^a	11,002 ^a	1,400 ^a	216 ^a	7.7 ^a

§ Means within a column of the same category (i.e., crop systems and growing seasons) followed by the same letter are not significantly different at $P \leq 0.05$.

in an ~20% higher accumulation of these nutrients in the corn plants than monocropping. Tropical perennial grasses introduced into a cropping system resulted in a higher soil labile P content than fallow systems, probably because tropical perennial grasses can take up moderately labile soil P fractions that are recycled in the system, regardless of the P fertilization strategy (Almeida and Rosolem, 2016).

The relative yield of the other nutrients (K, Ca, Mg, S, B, Cu, Fe, and Mn) in the corn plants was <100% in all crop systems (Table 8). Among these nutrients, what surprised us was K, of which the accumulation reached approximately only 60% in all crop systems compared to monocropped corn. This is very good from the standpoint of extracting this nutrient in corn to silage production areas because the replacement management of K in these areas is a problem since the harvesting of corn to silage plants extracts large amounts of K from the soil (Pariz et al., 2016, 2017a). Thus, assuming that plants in all crop systems were adequately supplied with K (Table 3), we can hypothesize that monocropped corn presented extensive absorption of this nutrient, mainly from exchangeable forms in soil, which may exhaust this more available form of K in the soil over the medium to long term.

According to Rosolem and Steiner (2017) “regarding recommendations on sustainable fertilizer practices, sampling the 0–0.2-m layer seems to be insufficient, and increased rates of fertilizer K intensify K leaching below 1 m in tropical sandy clay loam soil.” In this context, the results of Garcia et al. (2008) demonstrated that “K recycling in intercropping systems is very important for plant growth to avoid losses in the soil profile. However, it must be emphasized that if K rates are underestimated in a fertilization programme, mainly corn to silage, soil K reserves may be depleted, as corn intercropped with palisade grass is very effective in recycling K, leading to increased exchangeable K contents in the surface soil layers; further, palisade grass is able to take up non-exchangeable forms of K in the soil. Ultimately, this K, after cover crop desiccation, is washed out of plant residues, and eventually,

more K is available for crops in succession.” Furthermore, corn to silage intercropped with palisade grass at greater heights, as performed in the present study (0.45 m above the soil surface), can contribute to K cycling from K contained in the lower internodes of plants (Pariz et al., 2016, 2017a). Therefore, the intercropping of palisade grass with corn becomes an excellent alternative in the cycling and maintenance of exchangeable K content in the soil, not allowing the extensive absorption of this nutrient by corn plants. The same analogy can be considered true for the other nutrients (Ca, Mg, S, B, Cu, Fe, and Mn) because the relative yield in corn plants was <100%, and the corn plants were well-fed (Table 8). Thus, we can also hypothesize that the contact of different intercropped crop roots can inhibit this expansive absorption of some nutrients by corn plants (Haugaard-Nielsen and Jensen, 2005).

The relative yield of all nutrients in palisade grass and pigeon pea plants was <100% and was not influenced by crop system (Table 8). However, the incorporation of pigeon pea in corn intercropped with palisade grass increased the total relative yield of all nutrients. Therefore, considering that the presence of pigeon pea in the triple intercrop did not interfere with the relative nutrient yields of corn and palisade grass, it can be inferred that this legume possibly absorbed and accumulated nutrients that might not be absorbed by corn and palisade grass plants, especially in deeper soil depths, as a function of the pivotal root system of pigeon pea (up to 1 m deep in relation to the soil surface).

Surface Mulch Quantity, Decomposition, Nutrient Content, and Release Rates

The higher surface mulch quantity, mulch cover, and N and K contents, mainly in the triple intercrop with black oat oversown in lines compared to double intercrop with black oat oversown in broadcast (increase of 75, 50, 72, and 71%, respectively), despite subsequent grazing by lambs (Table 9), was probably due to the nitrogen dynamics and soil decompaction under the development of the pivotal root system of pigeon pea. In addition, results of Costa et al. (2021) demonstrated that the inclusion of pigeon pea in the intercrop of corn with palisade grass efficiently

TABLE 10 | Soybean leaf nutrient concentrations at the R2 growth stage intercropped with guinea grass to silage in the fourth growing season in succession with corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast in the first three growing seasons.

Crop systems	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
2016-2017 growing season	g kg⁻¹						mg kg⁻¹				
C + PG + BO line	36.8 ^{c§}	3.1 ^a	26.9 ^c	7.1 ^a	3.4 ^a	2.1 ^a	31.6 ^a	10.5 ^a	81.5 ^a	54.2 ^a	38.4 ^a
C + PG + BO broadcast	36.5 ^c	3.0 ^a	26.5 ^c	7.0 ^a	3.3 ^a	2.0 ^a	31.4 ^a	10.6 ^a	81.7 ^a	53.7 ^a	38.0 ^a
C + PG + PP + BO line	45.1 ^a	3.3 ^a	30.1 ^a	7.6 ^a	3.6 ^a	2.2 ^a	32.3 ^a	10.5 ^a	85.8 ^a	55.8 ^a	39.8 ^a
C + PG + PP + BO broadcast	41.8 ^b	3.3 ^a	28.3 ^b	7.6 ^a	3.5 ^a	2.1 ^a	32.0 ^a	10.7 ^a	83.8 ^a	54.7 ^a	38.6 ^a

[§]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

increased the use of N fertilizer by corn, promoted greater N recovery in the soil, and increased total N in the crop system, thus decreasing unrecovered N from fertilizer in the plant-soil system, what according to Sprent (2007) can be explained because occurs symbiosis between plants and bacteria found in root nodules. In the case of oversown oats, the in-row modality provides better distribution, seed burial, and uniformity of the plant population than the broadcast modality. Furthermore, superficial incorporation into the soil using a disk harrow (fully closed disks for minimal ground disturbance) is necessary for better germination and to reduce the number of seeds vulnerable to consumption by birds. However, this mechanical operation can reduce the soil nitrogen concentration because it increases the porous space and breaks the stability of the soil organic matter, favoring greater N₂O emission.

However, in all crop systems, the mulch remaining 120 DAD was ~50–60% (Figure 1). Other nutrient (P, Ca, Mg, S, B, Cu, Fe, Mn, and Zn) contents were also higher when palisade grass was intercropped with corn and pigeon pea than when intercropped with other treatments; however, there was no effect of oversown black oat. The surface mulch quantity, mulch cover, and all nutrient contents increased in the third growing season compared with the second and first growing seasons, possibly due to a carryover effect and more time between the end of grazing by lambs and desiccation of the remaining plants.

The crop system affected the lignin/N ratio of the surface mulch of palisade grass (Table 9), which was lower in crop systems with triple intercropping than in those with double intercropping, because of the highest N content in plant surface mulch. Potassium was the nutrient with the highest accumulation in the mulch of palisade grass and exceeded 100 kg ha⁻¹ in all crop systems and nitrogen was the nutrient with the second highest accumulation in the mulch of palisade grass (Table 9); in general, the residues released ~50–60% of this nutrient at 120 DAD. The peak release of P, K, Mg, and B occurred in the first 30 days and in general, the residues released more than 60% of this nutrient prior to 120 DAD and at ~90 DAD, K had been completely released from the palisade grass residues (Figure 2). The remaining Mg (30–40%) was subsequently and gradually released as part of the structural plant compounds. In this way, at 30 DAD, ~50% of the Mg contained in the plant residues had been released.

Soybean Leaf Nutrient Concentrations, Agronomic Characteristics, and Yield

Concentrations of N in soybean leaves (Table 10) were slightly below a sufficiency level when previous crop systems were corn intercropped only with palisade grass (Ambrosano et al., 1997; Embrapa—Empresa Brasileira de Pesquisa Agropecuária, 2006). This result demonstrated that crop systems without the inclusion of legumes in intercropping or crop rotation over time may reduce the availability of N and consequently uptake by crops. The triple intercrop with black oat oversown in lines increased 23% the N content in soybean leaves compared to double intercrop with both black oat oversown systems. The differences in K concentrations in soybean leaves as a function of previous crop systems were possibly a function of the K content in the surface mulch (Table 9), demonstrating good nutrient cycling and a synchronized K release rate from mulch with absorption by soybeans during their growth cycle. The triple intercrop with black oat oversown in lines increased 13% the K content in soybean leaves compared to double intercrop with both black oat oversown systems. Despite no differences among crop systems with respect to other nutrients (P, Ca, Mg, S, B, Cu, Fe, Mn, and Zn), soybean leaf concentrations were within a range considered appropriate for soybean crops (Ambrosano et al., 1997; Embrapa—Empresa Brasileira de Pesquisa Agropecuária, 2006).

The higher values of SPP after triple intercropping (corn + palisade grass + pigeon pea) (Table 11) were a function of a higher quantity of surface mulch and the best mulch cover (Table 9), which reduced the bird attacks (mainly doves) on soybean seedlings. According to Yokomizo et al. (2000), the HFPI should be >0.12 m to enable proper mechanical harvesting of soybean. In our study, the HFPI of soybean was 0.13–0.15 m; therefore, mechanized harvesting was not a problem. The higher values of NPP, dry weight of 100 seeds (W100), dry weight of seeds per hectare, forage mass (FM), and standing plant residue (SPR) after triple intercropping can be explained by better mulch cover, N and K plant nutrition (Table 10) and possibly soil physical characteristics as a function of the root system of the pigeon pea and palisade grass discussed above, which favored the vegetative and reproductive growth of soybean. Thus, the combination of higher SPP, NPP, and W100 was reflected in ~1.0, 1.5, and 0.4 Mg ha⁻¹ more seeds, FM and SPR, respectively, than in crop systems with double intercropping (corn + palisade

TABLE 11 | Soybean plant population (SPP), plant height (PH), height of the first pod insertion (HFPI), number of pods per plant (NPP), number of seeds per pod (NSP), dry weight of 100 seeds (W100), dry weight of seeds per hectare, forage mass (FM), and standing plant residue (SPR) on the soil surface of soybean to silage intercropped with guinea grass in the fourth growing season in succession with corn to silage intercropped with palisade grass (C + PG) and with palisade grass and pigeon pea (C + PG + PP) with black oat (BO) oversown in lines and broadcast in the first three growing seasons.

Crop systems	SPP	PH	HFPI	NPP	NSP	W100	Seeds	FMS	SPR
2016–2017 growing season	n° × 1,000	m		n°		g		Mg ha ⁻¹	
C + PG + BO line	317 ^{b§}	73.5 ^b	13.2 ^b	42 ^b	2.5 ^a	13.1 ^b	4.4 ^b	9.4 ^b	1.1 ^b
C + PG + BO broadcast	319 ^b	73.0 ^b	13.0 ^b	41 ^b	2.5 ^a	13.1 ^b	4.3 ^b	9.2 ^b	1.0 ^b
C + PG + PP + BO line	337 ^a	79.2 ^a	15.3 ^a	45 ^a	2.6 ^a	13.4 ^a	5.5 ^a	11.0 ^a	1.5 ^a
C + PG + PP + BO broadcast	335 ^a	80.1 ^a	15.1 ^a	45 ^a	2.6 ^a	13.4 ^a	5.3 ^a	10.6 ^a	1.4 ^a

§Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

grass). Despite a lack of data on the N derived from the soil, pigeon pea may have provided some N (Baldé et al., 2011) to soybeans and guinea grass to enhance the seeds and FM (Table 11). The triple intercrop with both black oat oversown increased 24 and 16% the seeds and FM of soybean compared to double intercrop with both black oat oversown systems.

CONCLUSIONS

Our study revealed the potential for intercropping palisade grass and pigeon pea with corn in summer/autumn in the Brazilian “Cerrado” for produce forage mass and, subsequently, mulching in NTS. In addition, oversown black oat with palisade grass as a cover crop is also a good option for mulch production in the spring. Thus, with the inclusion of pigeon pea, maintaining long-term productivity would require fewer external N inputs. However, more constant monitoring of soil fertility, with an emphasis on the application of limestone, gypsum, phosphorus, and micronutrients, is necessary, especially because a majority of the biomass produced in these ICLS throughout the year is exported via the cutting of corn plants for ensilage.

Despite greater interspecific competition of palisade grass and pigeon pea intercropped with corn, this more complex system had better results. Thus, when analyzing this ICLS as a whole during the four growing seasons, the triple intercrop (corn + pigeon pea + palisade grass) combined with oversown black oats (mainly in lines) in the first three growing seasons was the most effective option for silage production and for the improvement of other elements of system productivity, such as higher surface mulch quantity (75%), leaf nutrient concentrations, mainly nitrogen and potassium (23 and 13%, respectively), and yield of soybean forage mass (16%) to silage intercropped with guinea grass in the fourth growing season. This type of intercropping also produced better nutrient cycling because it increased the quantity of nutrients retained in SPRs and surface mulch and provided better land- and nutrient-use efficiency, with an emphasis on nitrogen and potassium.

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DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The animal study was reviewed and approved by this study was conducted in accordance with the Ethics Committee on Animal Use (CEUA) of São Paulo State University (UNESP) at the College of Veterinary Medicine and Animal Science in Botucatu, São Paulo, Brazil, under protocol number 31/2014-CEUA.

AUTHOR CONTRIBUTIONS

CP, NC, and FA: experimental work, data analysis, results interpretation, and writing. CC, CACC, PM, JC, MA, and AF: results interpretation and writing. AC: data analysis, results interpretation, and writing. DS, IC, and VL: experimental work and writing. VP, JS, MP, VM, RS, DF, and LS: experimental work. All authors contributed to the article and approved the submitted version.

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