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ORIGINAL ARTICLE

Production, nutrient cycling and soil compaction to grazing of grass companion cropping with corn and soybean

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Abstract Agricultural management systems are needed to simultaneously enhance production, promote plant diversity, improve nutrient cycling and reduce soil compaction. We investigated the effects of intercropped forage grass on production of corn (*Zea mays* L.) harvested for silage at 0.20 and 0.45 m height in the summer, as well as on production of subsequent forage, soybean [*Glycine max* (L.) Merr.] harvested for silage, nutrient cycling and soil responses on a Typic Haplorthox in Botucatu, São Paulo State, Brazil. Palisade grass cv. BRS Piatã [*Urochloa brizantha* cv. BRS Piatã] was the introduced companion crop with corn (Years 1 and 2), while signal grass [*Urochloa decumbens* cv. Basilisk] was the residual weedy species in comparison. Guineagrass cv. Aruãna [*Megathyrsus maximus* cv. Aruãna] was the introduced companion crop with soybean (Year 3), with only a residual effect of crop systems from the previous two years. After the corn silage harvest, pasture was grazed by lambs in winter/spring using a semi-feedlot system. When cut at 0.45 m compared with 0.20 m height, corn intercropped with palisade grass had greater leaf nutrient concentration, improved agronomic characteristics, forage mass of pasture for grazing by lambs, greater surface mulch produced, and greater quantity of N, P and K returned to soil. Greater soil organic matter, P, K and Mg concentration, and base saturation in the surface soil depth and lower soil penetration resistance at all depths occurred at 0.45 m than at 0.20 m corn silage cutting height intercropped with palisade grass. Analyzing the system as a whole, harvesting corn silage crop with palisade grass intercrop at 0.45 m height was the most viable option in this integrated crop-livestock system.

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Abbreviations

BS	Base saturation
CEC	Cation exchange capacity
DAD	Days after desiccation
HFPI	Height of the first pod insertion
ICLS	Integrated crop-livestock system
NE	Number of ears per hectare
NTS	No-till system
PP	Plant population
SPR	Soil penetration resistance

Introduction

The basic principle of the no-till systems (NTS) is use of technologies to protect the environment, such as no-till planting, erosion control, correct use of herbicides, maintenance of straw on the soil surface, crop rotation, and more recently, adoption of an integrated crop–livestock system (ICLS) (Borghi et al. 2013a). Currently, the practice of ICLS with NTS may be one of the best alternatives for farmers to gain income and simultaneously achieve sustainability and nutrient cycling in the tropical and sub-tropical region (Carvalho et al. 2010). With positive contributions to production, economics, and the environment, ICLS are being promoted as the "new green revolution in the tropics" (Mateus et al. 2012).

Crop and livestock activities can compromise the sustainability of agriculture, especially when they lead to declining grain yields, soil fertility, and carrying capacity of pastures, and increases in soil erosion and pasture degradation. In Brazil, ~80 million hectares (Mha) of degraded pasture exist, and nearly 50 Mha has severe degradation with low forage yield and low animal stocking rate (Pariz et al. 2011a). Potential exists for ICLS with NTS to recover these degraded areas, reduce production costs, and enhance utilization throughout the year, all of which could generate positive socio-economic and environmental outcomes (Tracy and Zhang 2008; Rufino et al. 2009; Carvalho et al. 2010; Crusciol et al. 2012; Franzluebbers and Stuedemann 2014).

According to FAO (2016), >1 billion people (about 15% of the human population) are hungry and living in poverty, and 75% of this population, as well as others in near poverty live in rural areas and depend on agriculture for their livelihood, mostly based on small-scale ICLS, including systems with long-term grazing. The demand for livestock-related food products (red and white meat, dairy products and eggs) is expected to grow significantly, thus providing small-scale farmers using ICLS the opportunity to generate income and employment.

Mixed farming systems involving ICLS account for approximately half of the food produced in the world, and in developing countries, crops such as corn, wheat, sorghum and millet are used for producing grain for human consumption and crop residues for animal feed (Herrero et al. 2010). These authors acknowledged that producers using mixed farming systems may value crop residues as much as grains, given that residues are a vital livestock feed in the dry season. Improvement of mixed crop and livestock production is crucial to elevate social and economic conditions for small-scale producers and mitigate human suffering.

Although NTS requires straw on the soil surface, cash crops alone often do not produce sufficient straw to adequately cover the soil throughout the year. This lack of straw, compromises nutrient cycling and increasing soil compaction. Soil coverage throughout the year and cover crops able to cycle nutrients also are extremely important for sustainable of tropical agriculture in the Brazilian Cerrado, where most soils are acidic, have low fertility and low cation exchange capacities (Mateus et al. 2016). In addition, regions with dry winters (low and irregular rainfall), such as the Brazilian Cerrado or African Savanna, have large risks in growing a successful dry-season crop, resulting in a long fallow period without productivity (Borghi et al. 2013a). In such warm conditions, straw decomposes rapidly (Pariz et al. 2011b), and negatively affects success of NTS. Thus, introduction of intercropped forages with grain crops could be a key strategy to enhance early establishment and successful production of a winter-season forage for grazing (Kluthcouski and Aidar 2003).

As it is a new cultivar, palisade grass cv. BRS Piatã [*Urochloa brizantha* (Hochst. ex A. Rich.) R. Webster 'BRS Piatã'], has not been studied much in ICLS. There is less competition when it is intercropped with grain cultivation due to the more upright and slower initial growth and size than palisade grass cv. Marandu [*Urochloa brizantha* (Hochst. ex A. Rich.) R. Webster 'Marandu'], which is of the same species and most commonly used in the intercrop system (Pariz et al. 2016), in addition to the considerable forage accumulation in the dry season, mainly leaves, after the crop has been harvested (Embrapa 2009).

Cutting height in corn silage production is often close to the ground, which could negatively affect intercropped forage survival and production. Low cutting height could remove valuable tillers, compromising pasture development and nutrient cycling. Silage harvest also has extensive traffic and heavy pressure from loaded equipment (Jaremtchuk et al. 2006). Silage harvest traffic could affect regrowth of grass and pasture formation, in addition to compacting soil. To reduce soil surface compaction, many farmers opt to use tillage after silage harvest, a practice which jeopardizes soil conservation. Therefore, developing sustainable no-tillage silage production systems is needed, especially if promising ICLS production strategies can be added to improve overall agricultural functionality.

There is currently a large array of studies with corn, sorghum [*Sorghum bicolor* (L.) Moench] and soybean production intercropped with tropical grasses in the Brazilian Cerrado (Pariz et al. 2010, 2011c, d, e; Crusciol et al. 2011, 2012, 2013, 2014, 2016; Mateus et al. 2011, 2016; Borghi et al. 2012, 2013a, b; Costa et al. 2012), but many of these have not utilized grazing animals in the system. A diversity of field studies is needed with ruminant livestock, including sheep and lambs (*Ovis aries*), to adequately characterize the impacts of ICLS on animal performance and crop yield, because stocking rate and management approaches can alter crop residue and forage quantity and quality, as well as affect nutrient cycling and soil compaction.

In addition, nitrification, a key process in the global nitrogen cycle that generates nitrate through microbial activity, may enhance losses of fertilizer nitrogen by leaching and denitrification. Certain plants can suppress soil-nitrification by releasing inhibitors from roots, a phenomenon termed biological nitrification inhibition (BNI). According Subbarao et al. (2009), within 3 years of establishment, *Urochloa* pastures have suppressed soil nitrifier populations, along with nitrification and nitrous oxide emissions. These findings provide direct evidence for the existence and active regulation of a nitrification inhibitor (or inhibitors) release from tropical pasture root systems. Exploiting the BNI function could become a powerful strategy toward the development of low-nitrifying agronomic systems, benefiting both agriculture and the environment.

Our objective was to evaluate the effects of intercropped forage grass on production of corn harvested for silage at 0.20 and 0.45 m height in the summer, as well as on production of subsequent forage, soybean harvested for silage, and soil responses during three years in the Brazilian Cerrado. Corn and soybean leaf nutrient concentrations, agronomic characteristics and yield, forage mass of pasture, mulching, nutrient contents in straw, straw decomposition, soil penetration resistance, and soil fertility were determined as response variables.

Materials and methods

Site description

The experiment was conducted in Botucatu in the State of São Paulo in Brazil (48°25′28″W, 22°51′01″S, 777 m above sea level), during three consecutive growing seasons: 2010–2011, 2011–2012 and 2012–2013. The soil was a clayey, kaolinitic, thermic Typic Haplorthox (FAO 2006) with 630, 90 and 280 g kg^{-1} of clay, silt and sand, respectively. For four years until October 2010, the field was in fallow, predominantly signal grass and annual broadleaf weeds.

Climate was Cwa, tropical with dry winters and hot and rainy summers, according to the Koeppen climate classification system (Alvares et al. 2013). Long-term (1956–2013) mean annual maximum and minimum temperatures were 26.1 and 15.3 °C, respectively, with mean annual precipitation of 1358 mm (Unicamp 2013). During the experimental period, rainfall and temperature were measured daily (Table 1), using a Professional Weather Station–Instrutemp ITWH-1080, located in the center of the research site.

Before initiating the experiment, soil compaction was evaluated at 20 points per hectare from soil penetration resistance (SPR) using an impact penetrometer (Model Stolf Reduced; Stolf et al. 2014). The ideal soil moisture condition for determination of SPR is between field capacity and 1/3 lower than field

Table 1 Rainfall, maximum and minimum temperatures, and photoperiod at Botucatu, São Paulo State, Brazil, during the study period and long-term averages

Climate characteristics	Month											
	December	January	February	March	April	May	June	July	August	September	October	November
2010–2011												
Monthly rain (mm)	243	712	188	164	127	17	50	7	25	0	360	103
Mean max. temp. (°C)	28.6	29.6	29.8	25.8	26.8	23.5	21.9	24.6	26.4	28.2	26.7	27.7
Mean min. temp. (°C)	18.3	19.6	19.6	18.3	15.9	12.9	10.9	12.2	14.3	13.4	16.7	15.7
2011–2012												
Monthly rain (mm)	143	357	167	59	250	78	228	23	0	51	159	104
Mean max. temp. (°C)	30.5	29.3	32.1	30.8	28.5	23.9	21.5	23.5	25.8	28.1	29.7	27.9
Mean min. temp. (°C)	17.8	17.5	20.1	18.4	17.7	13.9	14.2	12.6	14.4	15.6	18.1	19.2
2012–2013												
Monthly rain (mm)	419	392	161	267	126	97	115	57	0	88	106	54
Mean max. temp. (°C)	29.9	27.6	28.4	26.6	25.5	23.7	21.7	21.8	24.9	25.8	25.5	27.2
Mean min. temp. (°C)	21.4	20.0	20.9	20.1	18.5	16.9	14.0	12.4	12.2	14.2	15.0	17.3
Long-term (50 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
Photoperiod (h day^{-1})	13.3	13.2	12.7	12.1	11.5	10.9	10.7	10.8	11.2	11.9	12.5	13.1

Table 2 Soil fertility at 0–0.20 m depth of the experimental area before and after initiating the experiment, considering corn intercropped with palisade grass and corn only (signal grass weedy regrowth) after harvest for silage at two cutting heights and after grazing by lambs on pastures in first two growing seasons, and after cuts of guinea grass in third growing season

Treatments	Cutting height	pH $CaCl_2$	SOM[†] (g dm^{-3})	P (mg dm^{-3})	H + Al ($mmol_c$ dm^{-3})	K ($mmol_c$ dm^{-3})	Ca ($mmol_c$ dm^{-3})	Mg ($mmol_c$ dm^{-3})	BS[‡] (%)
Before initiation of experiment		4.7	46.5	8.2	45.7	0.8	21.4	11.2	42.2
After initiation of experiment									
Crop systems									
Corn + signal grass weedy regrowth	0.20	5.1a[§]	40.3b	11.8b	42.9a	1.0b	29.3a	15.3b	51.5a
Corn + signal grass weedy regrowth	0.45	5.1a	40.1b	12.0b	42.5a	1.0b	29.5a	15.3b	51.9a
Corn + palisade grass	0.20	5.1a	39.3b	11.8b	43.7a	1.0b	30.2a	15.6b	51.7a
Corn + palisade grass	0.45	5.1a	45.7a	17.1a	43.3a	1.5a	31.3a	17.5a	53.7a
Growing seasons									
First (2010–2011)	–	5.1a[§]	40.3a	10.1b	43.5a	1.1a	30.3a	15.0a	52.6a
Second (2011–2012)	–	5.1a	41.1a	15.4a	43.8a	1.2a	30.2a	16.8a	52.3a
2012–2013 growing season									
Corn + signal grass weedy regrowth	0.20	4.9a[§]	33.1b	10.9b	43.0a	1.0b	28.9a	12.1b	49.4b
Corn + signal grass weedy regrowth	0.45	4.9a	33.3b	11.9b	42.6a	1.1b	28.1a	12.5b	49.5b
Corn + palisade grass	0.20	5.0a	34.0b	11.3b	43.4a	1.1b	30.9a	12.9b	50.8b
Corn + palisade grass	0.45	5.0a	42.7a	17.5a	40.1a	1.7a	31.6a	18.1a	56.2a
Time of evaluations									
After corn harvest for silage	–	5.1a[§]	37.6b	12.9a	43.5a	1.1a	29.4a	16.1a	51.7a
After grazing by lambs	–	5.1a	43.0a	12.8a	43.7a	1.1a	31.2a	17.0a	53.0a

[†] Soil organic matter

[‡] Base saturation

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

capacity, as defined by Kiehl (1979). In practical terms, this occurs when soil volumetric moisture content is 0.22–0.33 m^3 m^{-3}. Soil penetration resistance was 0.63, 0.92, 1.51, and 1.93 MPa at 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m depths, respectively. These values are considered low (<1 MPa) to moderate (1–2 MPa) (Arshad et al. 1996), so we decided to implement the study with no soil disturbance. Chemical characteristics of the soil (0–0.20 m depth) were determined (Table 2). Soil pH was determined in 0.01 mol L^{-1} $CaCl_2$ suspension (1:2.5 soil/solution). Soil organic matter was determined via the colorimetric method using a sodium dichromate solution. Total acidity at pH 7.0 (H, Al) was extracted with 0.5 mol L^{-1} calcium acetate and determined through titration with 0.025 mol L^{-1} NaOH solution. Exchangeable Al was extracted with neutral 1 mol L^{-1} KCl at 1:10 soil/solution ratio and determined by titration with 0.025 mol L^{-1} NaOH solution. Available P and exchangeable Ca, Mg, and K were extracted using ion exchange resin and determined via atomic absorption spectrophotometry. Cation exchange capacity (CEC) was calculated from the sum of concentrations of H, Al, K, Ca, and Mg cations. Base saturation (BS) was calculated by dividing the sum of K, Mg, and Ca (the bases) by CEC and multiplying the result by 100% (van Raij et al. 2001).

Experimental design and treatments

The experiment was a randomized complete block design consisting of four crop systems and six replications. The crop systems consisted of (A) two intercropping systems for corn silage—without intercrop and volunteer signal grass only and with introduced palisade grass cv. BRS Piatã and (B) two cutting heights for silage—0.20 and 0.45 m above the soil surface. The experiment was repeated in the same location for three growing seasons (2010–2011, 2011–2012, and 2012–2013). Silage crop was corn in 2010–2011 and 2011–2012 and soybean in 2012–2013. The third year was a residual effect of crop systems from previous years 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 m^2.

Tillage and crop management

On 22 October 2010, residual weeds (signal grass and annual broadleaves) were sprayed with glyphosate [isopropylamine salt of *N*-(phosphonomethyl)glycine; 1.08 kg acid-equivalent ha^{-1}) and 2,4-D amine (2,4-Dichlorophenoxyacetic acid; 0.67 kg acid-equivalent ha^{-1}), using a spray volume of 200 L ha^{-1}. On 26 October 2010, plant material was cut using a plant residue horizontal crusher (Jan, model Tritton 3.000, Não-Me-Toque, RS, Brazil), leaving 8.5 Mg ha^{-1} of straw on the soil surface. On 3 November 2010, 2.5 Mg ha^{-1} of dolomitic lime ($CaCO_3 \cdot MgCO_3$) with 28% CaO and 20% MgO was broadcast on to the soil. On 4 November 2010, 1.5 Mg ha^{-1} of agricultural gypsum ($CaSO_4 \cdot 2H_2O$) with 17% Ca and 14% S was broadcasted, following the recommendation of Cantarella et al. (1997). On 7 December 2010, weed regrowth was sprayed with glyphosate (1.44 kg acid-equivalent ha^{-1}) and 2,4D amine (0.67 kg acid-equivalent ha^{-1}), using a spray volume of 200 L ha^{-1}, leaving 1.5 Mg ha^{-1} of additional straw on the soil surface.

Corn hybrid 2B587 HX (relative maturity–early) was sown for all treatments on 20 December 2010 and 21 December 2011 at 3-cm depth, row spacing of 0.45 m, and density of 80,000 seeds ha^{-1} using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, RS, Brazil). For all treatments and in both growing seasons, basic fertilization in the sowing furrows consisted of 36 kg ha^{-1} of N as urea, 126 kg ha^{-1} of P_2O_5 as triple superphosphate, and 72 kg ha^{-1} of K_2O as potassium chloride, following the recommendation of Cantarella et al. (1997). In the intercropping treatment, palisade grass was simultaneously sown at 10.8 kg ha^{-1} (pure live seed = 60%). Forage seeds were mixed with basic fertilizer (Mateus et al. 2007) and sown at depths of 8 cm below the soil surface, as described by Crusciol et al. (2012).

Corn seedling emergence occurred at 6 and 16 days after sowing (26 December 2010 and 6 January 2012, respectively). Differences were due to absence of rain after sowing in the second growing season (Table 1). Grass seedlings emerged at 11 and 18 days after sowing (31 December 2010 and 8 January 2012, respectively). On 7 January 2011 and 25 January 2012, nicosulfuron {[2-(4,6-dimethoxypyrimidin-2-ylcarbamoyl)sulfamoyl]-N,N-dimethylnicotinamide]; 8 g acid-equivalent ha^{-1}} and atrazine (6-chloro-N^2-ethyll-N^4-isopropyl-1,3,5-triazine-2,4-diamine; 1.25 kg acid-equivalent ha^{-1}) were applied using a 200 L ha^{-1} spray volume to reduce initial grass seedling growth and control the emergence of some annual broadleaf weeds.

When corn had five expanded leaves (V5), mineral fertilizer was broadcast with no incorporation (90 kg ha^{-1} of N as urea and 67 kg ha^{-1} of K_2O as potassium chloride in the first growing season and 150 kg ha^{-1} of N as urea and 90 kg ha^{-1} of K_2O as potassium chloride in the second growing season), following the recommendation of Cantarella et al. (1997). Greater rates of N and K_2O applied in the second growing season were due to nutritional deficiencies found in corn leaves in the first growing season. On 9 June 2011 and 1 June 2012, remaining forage was fertilized with 60 kg ha^{-1} of N as ammonium sulfate. On 14 December 2011 and 4 December

2012, remaining forage grasses were sprayed with glyphosate (1.44 kg acid-equivalent ha^{-1}), using a spray volume of 200 L ha^{-1}.

Soybean cultivar 'BMX Potência RR" (early cycle, maturity group 6.6) was sown on 20 December 2012 at 3-cm depth, row spacing of 0.45 m, and density of 300,000 seeds ha^{-1} using no-till seeding (Semeato, model Personale Drill 13, Passo Fundo, RS, Brazil). The fungicide carboxin (5,6-dihydro-2-methyl-1,4-oxathiin-3-carboxamide) + thiram (tetramethylthiuram disulfide) and the insecticide thiamethoxam (3-(2-cloro-tiazol-5-ilmetil)-5-metil-[1,3,5] oxadiazinan-4-ilideno-N-nitroamina) were applied to the soybean seeds at a dose of 60 and 120 g of active ingredient (a.i.) to 100 kg of seeds, respectively. Soybean seed was inoculated with *Bradyrhizobium japonicum* (SEMIA 5079–CPAC 15 and SEMIA 5080–CPAC 7) at 5 g inoculant kg^{-1} seed. Liquid formulation of cobalt (Co = 0.028 kg L^{-1}) and molybdenum (Mo = 0.284 kg L^{-1}) was added to soybean seed at 0.2 L ha^{-1}. All soybean treatments were fertilized in furrows with 26 kg ha^{-1} of N as urea, 90 kg ha^{-1} of P_2O_5 as triple superphosphate and 51 kg ha^{-1} of K_2O as potassium chloride.

In all treatments, guineagrass was the intercrop with soybean and planted at 10 kg ha^{-1} (pure live seed = 50%). Forage seeds were mixed with basic fertilizer (Mateus et al. 2007) and sown at depths of 8 cm below the soil surface, as described by Crusciol et al. (2012). Soybean and guineagrass seedlings emerged 5 and 12 d after sowing, respectively. The herbicides fluasifop-P-Butil [Butil (R)-2-(4-(5-trifluorometil-2-piridiloxi)-fenoxi)-propionato] and Clorimurom Etílico (Ethyl 2-(4-chloro-6-methoxypyrimidin-2-ylcarbamoylsulfamoyl) benzoate) were applied at 100 and 25 g a.i. ha^{-1}, respectively, at 22 days after emergence of soybean seedlings. All treatments were sidedressed 30 days after soybean emergence with 26 kg ha^{-1} of N as urea, 90 kg ha^{-1} of P_2O_5 as triple superphosphate and 51 kg ha^{-1} of K_2O as potassium chloride broadcasted without incorporation.

Lamb grazing management

In both growing seasons, 72 (four crop systems × six replications × 3 lambs/plot) uncastrated male crossbred Santa Inês lambs of three months mean age were stocked from August to December. Grazing method was continuous stocking with a fixed stocking rate of 133 lambs ha^{-1} in a semi-feedlot scheme. Initial stocking rate was 2.9 and 3.0 Mg ha^{-1} and final stocking rate was 4.3 and 4.8 Mg ha^{-1}, in the first and second growing seasons, respectively. Lambs were on the pasture throughout the day (from 6 a.m. to 6 p.m.), but at night (from 6 p.m. to 6 a.m.) they were moved into a corral located off on the plots, where they were supplemented with the same corn silage and same concentrate (ground corn, soybean meal, ground grain rice, vitamin mineral supplement and limestone) for all treatments. Grazing lasted 70 days in the first and second growing season (five 14-d periods). Estimated dry matter intake was 3.27 and 3.25% of live weight for an average daily gain of 100 and 132 g (NRC 2007) across periods, in first and second growing season, respectively. Greater average daily gain in the second growing season was because of greater forage dry matter yield of pasture, mainly from leaves, compared with the first growing season. Lamb diet was computer formulated using the Small Ruminant Nutrition System (SRNS) program based on the Cornell Net Carbohydrate and Protein System (2000) for sheep. In all treatments, pasture accounted for approximately 15% of dry matter intake; the remainder was provided from corn silage and concentrate according to daily need.

Sampling and analyses

Corn and soybean leaf nutrient concentrations

Corn leaf samples were collected for nutrient analysis when 50% of corn plants were in male full-flowering stage (VT stage: arrives when the last branch of the tassel is completely visible). Selection was randomized, with 30 plants chosen per plot. The fourth leaf with a visible sheath from the apex was collected, according to the methods of Cantarella et al. (1997). Soybean leaf samples were collected from the upper third trifoliate at the R2 growth stage, full bloom (Fehr and Caviness 1977). Petioles from 30 plants per plot were collected as proposed by Ambrosano et al. (1996). Leaf samples were washed and then dried under forced air circulation at 65 °C for 72 h before grinding and analyzing for chemical composition. Concentrations of N, P, K, Ca, Mg, and S were determined using methods described by Malavolta et al. (1997). Nitrogen concentration was determined using the Kjeldahl method. The P, K, Ca, Mg and S concentrations were determined by atomic absorption spectrophotometry.

Corn and soybean agronomic characteristics and yield

Average corn growing season length from emergence to grain with 33–34% moisture was 107 and 102 days in the first and second growing seasons, respectively. Whole corn plants were harvested in each plot with a mechanical silage forage harvester (Model JF C-120 with 12 knives, Itapira, SP, Brazil). Corn was chopped into average particles of 1.5 and 1.0 cm in the first and second growing seasons, respectively. We used a one-line platform (0.90 m spacing between rows) in the first growing season and a two-line platform with reduced spacing (0.45–0.55 m between rows) in the second growing season to harvest silage crops. In the second growing season, knives of the mechanical forage harvester shredded the corn silage grain.

Plant population (PP) 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 in each plot) were evaluated. From harvested whole corn plants as silage, a representative sample was dried in forced-air circulation at 65 °C to constant weight (approximately 72 h) to determine forage mass of silage (Mg ha^{-1}). Using the same plant evaluation methodology, current-year corn mulch from the soil surface was collected to determine remaining straw. Corn stalk samples were washed, dried in forced-air circulation at 65 °C to constant weight (approximately 72 h) and ground. Concentrations of N and K in corn stalk residue were determined according to the methods of Malavolta et al. (1997). Nitrogen concentration was determined using the Kjeldahl method, and K concentration was determined using atomic absorption spectrophotometry. Macronutrient concentrations were multiplied by quantity of corn stalk residue to determine macronutrient content in kg ha^{-1}.

Length of the soybean season (from emergence to growth stage R7–beginning maturity of the beans and 50% yellow leaves), according to Fehr and Caviness (1977) was 100 days. In this stage, whole soybean plants were harvested according to recommendation by Leonel et al. (2008), with a mechanical silage forage harvester (Model JF C-120 with 12 knives and total area platform of 1.30 m, Itapira, SP, Brazil). The crops (soybean and guinea grass) were chopped at 0.15 m above the soil surface. This was not repeated as in corn phase at 0.20 and 0.45 m levels. The third growing season was to evaluate residual effects from previous years.

Agronomic characteristics, including final plant population (calculated from the number of plants in the four central rows, excluding 1 m from the end of each side of the row in each plot), plant height, and height of the first pod insertion were evaluated. A representative sample was dried in forced-air circulation at 65 °C to constant weight (approximately 72 h) to determine forage mass of silage (Mg ha^{-1}).

Forage mass of pasture

During lamb grazing, forage mass of pasture was determined at the beginning of each 14-d period by cutting three representative 1.0 m^2 areas per plot to ground level using a mechanical rotary mower. Forage collected was dried by forced-air circulation at 65 °C to constant weight (approximately 72 h), weighed, and reported as Mg ha^{-1}. On 15 July 2013 and 21 October 2013 (103 and 201 days after soybean silage harvesting, respectively), forage mass of pasture (guinea grass) was evaluated in three representative 1.0 m^2 areas per plot by cutting at 25-cm stubble height with a mechanical rotary mower. Forage mass of pasture collected was dried by forced-air circulation at 65 °C to constant weight (approximately 72 h), weighed, and reported as Mg ha^{-1}.

Surface mulch quantity, nutrient content, and decomposition

After grazing by lambs, following pasture and weed desiccation with glyphosate herbicide, estimates were obtained of plant material killed (i.e. mulch quantity). From two diagonal transects in each plot, three evaluators placed metal grid squares (1 m^2) on the ground at three areas per plot and cut all plant material at ground level. The collected material was dried by forced-air circulation at 65 °C to constant weight (approximately 72 h), weighed, ground, and reported as Mg ha^{-1}. Concentrations of N, P, and K were determined according to the methods of Malavolta et al. (1997). Nitrogen concentration was determined using the Kjeldahl method, and P and K concentrations were determined using atomic absorption spectrophotometry. Macronutrient concentrations were multiplied by quantity to determine content (kg ha^{-1}). Lignin content was also determined, according to the method described by Silva and Queiroz (2002), and used to calculate lignin/N ratio.

To determine rate of decomposition, fresh forage from each plot was placed in nylon bags (litter bags of 0.06 m^2, 0.3 × 0.2 m), proportionally to the standing mass (Pariz et al. 2011b). Litter bags were distributed and left on the soil for 15, 30, 60, 90, and 150 days. One litter bag per plot was removed at each sampling time, as a function of days after desiccation (DAD) of pasture and weeds with glyphosate herbicide following grazing. Content of each litter bag was collected, purified by sieving and rinsing with distilled water, and dried at 65 °C to constant weight (approximately 72 h) to determine dry weight.

Soil penetration resistance and soil fertility

Soil penetration resistance and soil fertility methodologies at initial soil characterization were also used after corn harvest for silage and after lambs grazing in the first two growing seasons (2010–2011 and 2011–2012), and after the second cut of guineagrass (November, 2013) in the third growing season (2012–2013). Soil fertility was evaluated at these times at 0–0.20 m depth.

Statistical analyses

All data were initially tested for normality with the Shapiro and Wilk (1965) test from the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC). All data were distributed normally ($W \geq 0.90$). Data were analyzed using the PROC MIXED procedure of SAS and Satterthwaite approximation to determine denominator degrees of freedom for the test of fixed effects. Crop systems were considered fixed effects, and blocks were considered random effects. A repeated statement was used with growing season specified as the repeated variable and block × crop system specified as the subject. The covariance structure used in the analyses was compound symmetry (CS), which provided the best fit according to the Akaike information criterion. Time of evaluation also was considered a fixed effect for soil penetration resistance and soil fertility. Results were reported as least squares means and separated by preplanned pairwise comparisons (PDIFF). Mean separations were conducted using an LSD test. Effects were considered statistically significant at $P \leq 0.05$. Straw decomposition was analyzed as suggested by Wider and Lang (1982) by the litter bag method, using the PROC REG procedure of SAS, and best adjustments were chosen with greatest coefficients of determination (r^2) at $P \leq 0.05$. Error bars were presented as standard errors (SEs) and means were determined from the PROC MEANS procedure of SAS.

Results and discussion

Weather conditions

Temperature and precipitation during the two first growing seasons were relatively similar (Table 1) and appropriate for corn development (Borghi 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. In the third growing season, weather conditions were also appropriate for soybean development (Crusciol et al. 2012, 2014). According to Embrapa Soja (2006), the amount of precipitation would have caused minimal water stress for soybean and intercropped guineagrass.

In the first growing season, rainfall of 1894 mm was 39% greater than the historical average (1359 mm), and mean annual temperature of 21.2 °C was similar to the historical average (20.7 °C). In the second growing season, rainfall was 1896 mm and mean annual temperature was 22.2 °C, somewhat higher than the historical average. In the third growing season, rainfall was 1882 mm and mean annual temperature was 21.4 °C.

Rainfall of 61 mm on 12 April 2011, the first day of corn silage harvest, was exceptional, as was the absence of rain between 21 and 29 December 2011 following corn sowing. Precipitation of 712 and 357 mm in January 2011 and 2012, respectively (Table 1), hampered herbicide application and side-dress application of N and K fertilization for corn, which is why fertilization was performed manually in both growing seasons. It should be noted that 367 mm of rainfall occurred on 2–3 January 2011 alone. Rainfall between harvesting of corn for silage and stocking of lambs on pasture was 125 and 513 mm in the first and second growing seasons, respectively.

Minimum temperatures between May and July were lower in the first growing season than in the second growing season. Moreover, minimum temperatures of 2.8, 2.8, and 2.4 °C on 28 June 2011 and 4–5 August 2011, respectively, were recorded, which were very cold for this region in Brazil.

Corn leaf nutrient concentrations

Crop systems did not affect N, Ca and S concentrations of corn leaf tissue (Table 3). Corn leaf N concentration (17–26 g kg^{-1}) was suboptimal to the sufficiency range of 27–35 g kg^{-1} (Cantarella et al. 1997), despite following a recommended seeding and sidedress fertilization program. The N content of standing corn residue after harvest of silage also was lower in the first growing season (Table 4). Heavy rainfall in December and January during the first growing season (Table 1) likely contributed to N leaching from the root zone, and subsequent low N availability to corn. In the second growing season, level of N sidedressing fertilization (150 kg N ha^{-1}) also was higher than in the first growing season (90 kg N ha^{-1}). Further studies are warranted to determine optimum N fertilization of corn or other non-legume crops in complex cropping systems with intercropping and subsequent animal grazing of forage as compared with monoculture corn only (Costa et al. 2012; Mateus et al. 2016).

Highest leaf P concentration in corn intercropped with palisade grass at 0.45 m cutting height and in second growing season (Table 3) was reflected in greater P concentration in soil (Table 2). Palisade grass seems to be more effective in acquiring P relative to signal grass. Silva et al. (2003) found that soils with palisade grass had greater concentration of P in the labile fraction, and this encouraged uptake of P by plants.

Greater K leaf concentration and K content in standing corn residue when intercropped with palisade grass at 0.45 m cutting height than at 0.20 m cutting height and corn without intercrop (Tables 3, 4) likely provided significant K recycling and contribution to exchangeable forms in soil (Table 2) (Garcia et al. 2008). Thus, corn harvested for silage intercropped with palisade grass at greater heights can contribute to K cycling from K contained in lower internodes of plants (Nussio et al. 2001). Jaremtchuk et al. (2006) demonstrated that raising the cutting height of corn silage from 0.20 to 0.40 m reduced K removal by 19%. In our study, K remaining in corn residue intercropped with palisade grass when cut at 0.45 m height was increased by 25% (31.4 kg K ha^{-1}) compared to that at 0.20 m height (23.4 kg K ha^{-1}). Potassium recycling also was likely influenced by quantity of forage [greater K content in palisade grass than in signal grass plants residues when cut at 0.45 m than at 0.20 m height (Table 5)], quantity removed by grazing animals, and in corn silage removal.

Greater Mg leaf concentration in corn intercropped with palisade grass at 0.45 m rather than 0.20 m cutting height and corn without intercrop demonstrated the absorption ability of this nutrient due to the

Table 3 Corn leaf nutrient concentrations at male full-flowering stage in corn intercropped with palisade grass and corn only (signal grass weedy regrowth) at two silage cutting heights in two growing seasons

Treatments	Cutting height (m)	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	S (g kg^{-1})
Crop systems							
Corn + signal grass weedy regrowth	0.20	22a[§]	1.9b	16b	3.5a	2.5b	1.9a
Corn + signal grass weedy regrowth	0.45	21a	2.0b	15b	3.5a	2.4b	1.9a
Corn + palisade grass	0.20	21a	1.9b	15b	3.8a	2.5b	1.9a
Corn + palisade grass	0.45	22a	2.3a	18a	3.7a	3.0a	1.9a
Growing seasons							
First (2010–2011)	–	17b[§]	1.7b	16a	3.5a	2.9a	1.7a
Second (2011–2012)	–	26a	2.3a	16a	3.7a	2.3b	2.0a

[§] 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 $P \leq 0.05$

Table 4 Plant population (PP), number of ears per hectare (NE), forage mass of silage (FMS), standing corn residue (SCR), N and K content from SCR in corn intercropped with palisade grass and corn only (signal grass weedy regrowth) at two silage cutting heights in two growing seasons

Treatments	Cutting height (m)	PP n° × 1000	NE	FMS (Mg ha^{-1})	SCR (Mg ha^{-1})	N (kg ha^{-1})	K (kg ha^{-1})
Crop systems							
Corn + signal grass weedy regrowth	0.20	73.1a§	74.5a	14.1b	1.1b	2.8a	15.1 c
Corn + signal grass weedy regrowth	0.45	76.9a	74.5a	12.0 c	1.8a	3.1a	17.0 c
Corn + palisade grass	0.20	74.1a	75.0a	16.2a	1.1b	2.9a	23.4b
Corn + palisade grass	0.45	72.2a	69.9a	15.9a	1.6a	3.2a	31.4a
Growing seasons							
First (2010–2011)	–	72.7a§	71.1a	15.2a	1.5a	1.7b	27.6a
Second (2011–2012)	–	76.5a	75.9a	13.9a	1.2a	4.3a	15.8b

§ 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 $P \leq 0.05$

Table 5 Forage mass of pasture (FMP) during grazing by lambs in winter/spring, mulch cover, surface mulch, nutrient contents, and lignin/N ratio (Lig/N) in plants surface mulch of palisade grass intercropped with corn and signal grass weedy regrowth (corn only) at two silage cutting heights in two growing seasons, after grazing by lambs

Treatments	Cutting height (m)	FMP (Mg ha^{-1})	Mulch cover (%)	Surface mulch (Mg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Lig/N
Crop systems								
Corn + signal grass weedy regrowth	0.20	4.1c§	10.6c	1.4c	12.3c	2.0c	15.0c	7.1a
Corn + signal grass weedy regrowth	0.45	4.5c	15.0c	1.6c	15.7c	2.2c	15.5c	8.1a
Corn + palisade grass	0.20	6.3b	41.9b	2.3b	21.2b	2.8b	20.2b	7.7a
Corn + palisade grass	0.45	8.2a	64.4a	3.5a	31.1a	3.5a	29.0a	7.9a
Growing seasons								
First (2010–2011)	–	4.2b§	24.4b	1.7b	24.5a	2.2b	11.4b	3.7b
Second (2011–2012)	–	7.4a	51.6a	2.7a	20.7b	3.0a	28.4a	11.8a

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

greater effectiveness of their root systems (Table 3). Monteiro et al. (1995) found that omission of Mg in nutrient solution for cultivating palisade grass reduced by 70% dry root matter production compared to a treatment with adequate concentration of Mg.

Despite minor differences among growing seasons, corn leaf concentrations of P, K, Ca, Mg, and S were within sufficiency ranges (Cantarella et al. 1997). Previous studies have shown greater cash-crop leaf nutrient concentrations when intercropped with palisade grass (Crusciol et al. 2012; Borghi et al. 2013b).

Corn agronomic characteristics and forage mass of pasture

Cropping systems did not affect corn plant population and number of ears per hectare in either growing season (Table 4), despite palisade grass being more competitive than the signal grass regrowth (Pariz et al. 2011e) and has greater shade adaptability than signal grass, accumulates more forage mass in intercropping systems.

Corn only (with signal grass weedy regrowth) at 0.45 m cutting height had lower forage mass of silage than others crop systems. Despite greater interspecific competition of palisade grass with corn when intercropped simultaneously, corn showed greater forage mass of silage independent of cutting height (Table 4). This demonstrates the feasibility of intercropping corn with palisade grass for silage production. It is evident that the use of earlier corn hybrids favors these intercropped crops, as they present high rates of dry matter accumulation in its early development stages, with high interception capacity of photosynthetically active radiation, unaffected by competition with palisade grass (Crusciol et al. 2011). Furthermore, tropical forage grasses exhibit slow growth until approximately 50 days after seeding (Portes et al. 2000). This period usually coincides with the critical period of competition for annual grain crops. Kluthcouski and Aidar (2003) also reported that intercropping with tropical grasses did not affect the corn forage for silage and grain yield in different areas of the Brazilian Cerrado. However, the yield increase of corn intercropped with tropical grasses is not well understood in the literature. Therefore, additional multidisciplinary studies are needed to explain this outcome and to better evaluate the dynamics in the intercropped areas that result in equal or higher forage and grain yields than monoculture crops. Such multidisciplinary studies should involve chemistry, biochemistry, soil fertility, soil microbiology, soil–plant interactions, root exudation and plant physiology (Mateus et al. 2016).

Greater standing corn residue at 0.45 m than at 0.20 m cutting height was due to less silage harvested nearer ground level (Table 4). Palisade grass intercropped with corn appeared to recover rapidly following silage harvest, particularly at a cutting height of 0.45 m, resulting in greater forage mass of pasture in winter/spring (Table 5). In the intercropped system, palisade grass was sown at a time with high water availability and suitable temperature, resulting in sufficient initial leaf area to accumulate and proliferate after the corn silage harvest when rainfall becomes limiting for pasture development. Intercropping, therefore, appears to be a viable strategy to create a robust forage stand by the end of the corn-growing season to fully utilize residual soil moisture and limited precipitation during the winter/spring season. Better weather conditions with greater rainfall (Table 1) and no frosts after corn silage harvest likely contributed to greater forage mass of pasture for grazing by lambs in the second than the first growing season.

Mulch cover, surface mulch quantity, nutrient content, and decomposition

Crop systems did not affect lignin/N ratio (Table 5). In the second growing season, lignin/N ratio was lower than in the first growing season, because it had the highest N content in plant surface mulch. In the first growing season, surface mulch decomposition was exponential, independent of cropping system and cutting height (Fig. 1). In the second growing season, surface mulch decomposition was exponential in signal grass regrowth and logarithmic (log10) in palisade grass (regardless of cutting height of corn).

Sufficient surface mulch cover is key for successful implementation of NTS in the tropics to control weed emergence and maintain favorable conditions for successive planting. Mulch cover, surface mulch quantity, and N, P, and K contents were greater when palisade grass was intercropped with corn silage cut at 0.45 m than at 0.20 m height with signal grass regrowth (corn only), despite subsequent grazing by lambs (Table 5). Mulch cover, surface mulch quantity and P and K contents improved in the second growing season compared with the first, possibly due to a carryover effect. Several previous studies have assessed palisade grass surface mulch production as a function of intercropping with corn, but not with animal grazing (Pariz et al. 2011b; Costa et al. 2014; Mendonça et al. 2015). Therefore, additional studies with ICLS are needed to assess optimum grazing intensity, stocking rate (fixed or variable), and grazing method (continuous or rotational) on mulch cover, surface mulch quantity, and long-term system sustainability (Barth Neto et al. 2014; Savian et al. 2014).

Palisade grass had fewer geniculate stems at the plant base and from short stolons, which may have reduced lignin formation (Silva and Queiroz 2002). Greater lignin/N ratio has been associated with longevity of surface mulch (Pariz et al. 2011b). With lower lignin/N ratio in the first growing season, surface mulch had exponential decomposition with 60–70 and 20–30% mulch remaining at 30 and 150 days after desiccation (DAD), respectively (Fig. 1). In the second growing season, residue decomposition was similar, but palisade grass had logarithmic (log 10) decomposition with 30–45%

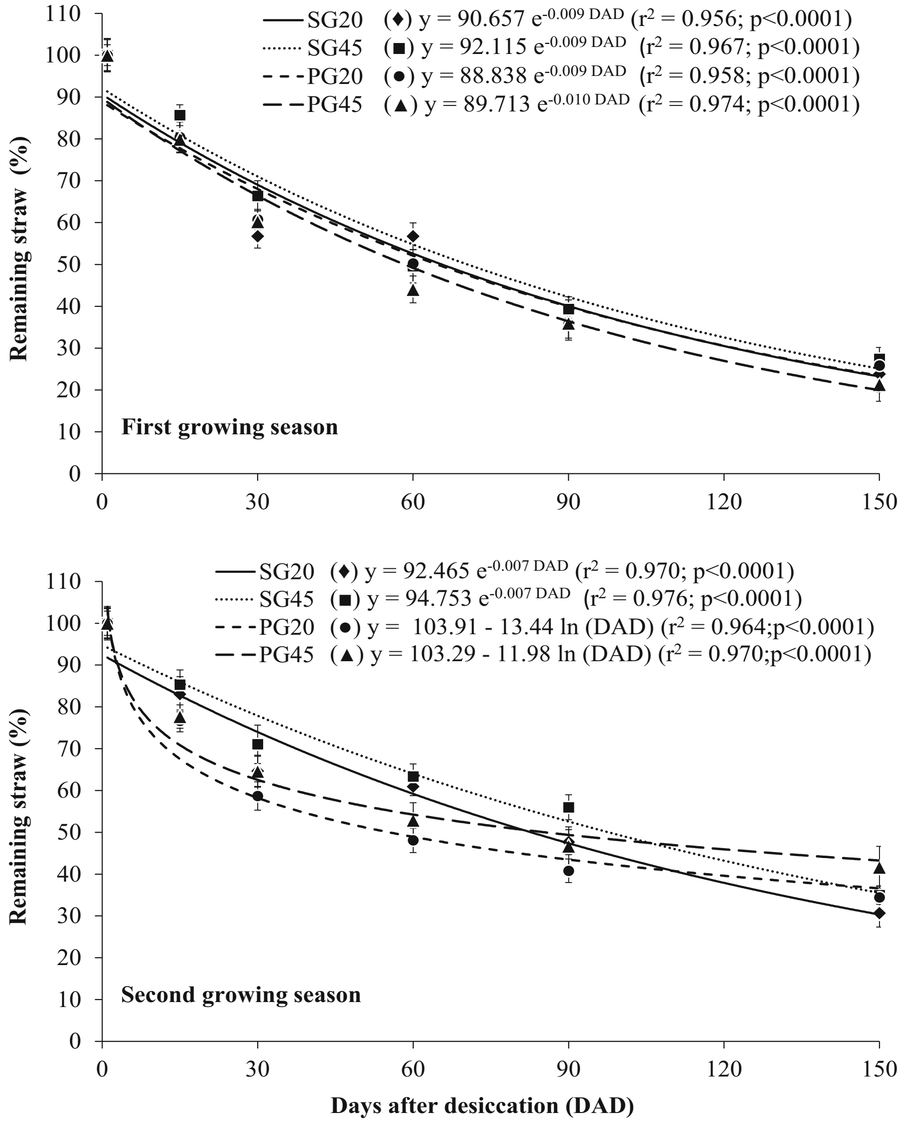


Fig. 1 Remaining straw of signal grass weedy regrowth (SG) and palisade grass (PG) after grazing by lambs on pastures, at 0.20 and 0.45 m cutting heights (20 and 45, respectively) of corn for silage and two growing seasons, in function of days after dessication. Values are mean of six replicates and associated *error bar* is ±1 SE. Days after desiccation (DAD): days after pasture and weed desiccation with glyphosate herbicide, after grazing by lambs

mulch remaining at 150 DAD. Greater mulch quantity of palisade grass could have reduced contact with the soil surface, resulting in slower decomposition (Pariz et al. 2011b).

Accelerated logarithmic (log 10) decomposition of palisade grass mulch 30 DAD in early November was found by Pariz et al. (2011b), Costa et al. (2014), and Mendonça et al. (2015). It is noteworthy that the high temperature in the spring/summer of this lowland Brazilian Cerrado environment may have caused accelerated surface mulch decomposition. In our study, slower decomposition was a function of milder temperature in December and January (Table 1). Thus, the Brazilian Cerrado has different climatic conditions depending on location in the country and altitude. Our study was conducted in the high altitude Brazilian Cerrado (777 m above sea level), a region with climatic conditions similar to more subtropical sites.

Soybean leaf nutrient concentrations

The residual effect of corn intercropped with palisade grass at 0.45 m silage cutting height resulted in greater N, P, K, and Mg concentrations in soybean leaves (Table 6). Concentrations of N, P, and K in soybean leaves were slightly below a sufficiency level when previous management was other than with palisade grass as intercrop and harvested at 0.45 m cutting height (Ambrosano et al. 1997; Embrapa Soja 2006). This result is supported by previous reports that demonstrated an increase in soybean leaf concentrations when intercropped with palisade grass (Crusciol et al. 2012, 2014). However, these authors did not explain why concentrations increased and we currently do not have an explanation for this response either. These results were associated with greater quantity of surface mulch and nutrients deposited on the soil surface after grazing by lambs (Table 5).

Soybean agronomic characteristics and forage mass of pasture

Soybean plant population was similar to that reported by Crusciol et al. (2012, 2014) for soybean intercropped with palisade grass (Table 7). Residual crop system effects were not significant for the height of first pod insertion (HFPI), as this feature is predominantly affected by genetics of the cultivar. According to Yokomizo et al. (2000), HFPI should be >0.12 m to enable proper mechanical harvesting of soybean. In our study, HFPI of soybean was 0.14–0.16 m, and therefore, mechanized harvesting was not a problem.

Plant height of soybean, forage mass of silage (soybean + guinea grass), and forage mass of pasture with guineagrass in two cuts were greater after corn intercropped with palisade grass at 0.45 m silage cutting height than at 0.20 m cutting height or without palisade grass as corn intercrop (Table 7). These results can be explained by better plant nutrition (Table 6). Results of Crusciol et al. (2012, 2014) inferred that simultaneous intercropping of soybean with palisade grass did not affect seed yield or its components. Therefore, results indicate that the appropriate time to sow palisade grass or guineagrass when intercropping will depend on the amount of forage desired, as it is likely that palisade grass sown earlier (i.e., nearer the soybean sowing date) will produce greater quantity of forage mass.

Grass height at the time of soybean harvesting was similar to soybean plant height. After cutting, the forage root system was already well established and forage could grow without soybean competition, allowing guineagrass to accumulate forage mass (Table 7). In mid-April (autumn), some rainfall (126 mm) and suitable temperature (18.5–25.5 °C) allowed guineagrass to quickly accumulate forage mass until the first cut. Lower temperature in July and August (12.4–21.8 °C and 12.2–24.9 °C, respectively) and reduced photoperiod, limited growth of guineagrass after the first cut (Müller et al. 2002). With the onset of spring, marked by more regular rain, increasing temperature, and adequate photoperiod, favorable conditions returned for guineagrass growth and dry matter accumulation until the second cut (Table 1).

Notably, a satisfactory amount of guineagrass was produced in both cuts, but significantly more so in succession to corn intercropped with palisade grass at 0.45 m silage cutting height, in which forage mass of pasture was >3.9 Mg ha^{-1} in both cuts compared with 2.3–2.9 Mg ha^{-1} in other crop systems (Table 7). The two cuts of guineagrass in succession to corn intercropped with palisade grass at 0.45 m silage cutting height was 8.3 Mg ha^{-1} of forage mass of pasture at a

Table 6 Soybean leaf nutrientconcentrations at R2 growth stage intercropped with guineagrass in third growing season in succession tocorn intercropped with palisade grass andcorn only (signal grass weedy regrowth) at two silagecutting heights in first two growing seasons

Cropping system	Cutting height (m)	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	S (g kg^{-1})
2012–2013 growing season							
Corn + signal grass weedy regrowth	0.20	33c[§]	2.3b	13b	7.0a	2.7c	2.0a
Corn + signal grass weedy regrowth	0.45	37b	2.4b	14b	6.7a	3.0b	2.1a
Corn + palisade grass	0.20	37b	2.3b	14b	6.5a	3.0b	1.9a
Corn + palisade grass	0.45	40a	2.6a	17a	6.8a	3.4a	2.0a

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

Table 7 Plant population (PP), plant height (PH), height of the first pod insertion (HFPI), and forage mass of silage (FMS) of soybean intercropped with guineagrass, and forage mass of pasture (FMP) in twocuts in the third growing season in succession tocorn intercropped with palisade grass andcorn only (signal grass weedy regrowth) at two silagecutting heights in first two growing seasons

Cropping system	Cutting height (m)	PP n° × 1000	PH (m)	HFPI (m)	FMS (Mg ha^{-1})	FMP firstcut (Mg ha^{-1})	FMP secondcut (Mg ha^{-1})
2012–2013 growing season							
Corn + signal grass weedy regrowth	0.20	280a[§]	0.61c	0.14a	4.9b	2.6b	2.9b
Corn + signal grass weedy regrowth	0.45	296a	0.67b	0.14a	5.3b	2.3b	2.6b
Corn + palisade grass	0.20	287a	0.68b	0.14a	5.2b	2.7b	2.9b
Corn + palisade grass	0.45	294a	0.75a	0.14a	5.8a	3.9a	4.4a

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

time when forage demand by grazing animals is typically not met (winter/spring). These observations are important for the Brazilian Cerrado and other regions, such as the African Savannas, where autumn/winter seasons are dry and cooler, limiting forage growth (Costa et al. 2005). Biomass produced by guineagrass provides sufficient quantity and quality for cattle or sheep to maintain or increase in body weight.

Despite lack of data on the N derived from the soil, soybean may have provided some N to guineagrass to enhance forage mass of pasture. According to Filizadeh et al. (2007), grass crop yield increases when following soybean, which is attributed to an increase in N availability from the rotation. Even without a precise measurement of the amount of N supplied from soybean to guinea grass, the forage did not display N deficiency symptoms. Guineagrass was grown without supplementary fertilization. New tropical grass seeds, cash crop fertilizer, and soil liming contribute to vigorous plant and root development by this forage, thereby allowing for year-long soil cover. Establishing year-round cropping systems can enhance cycling of nutrients, increase soil organic matter, improve soil water retention, reduce soil temperature oscillations, stimulate soil biological activity, suppress weed growth, and consequently, minimize herbicide use (Crusciol et al. 2014).

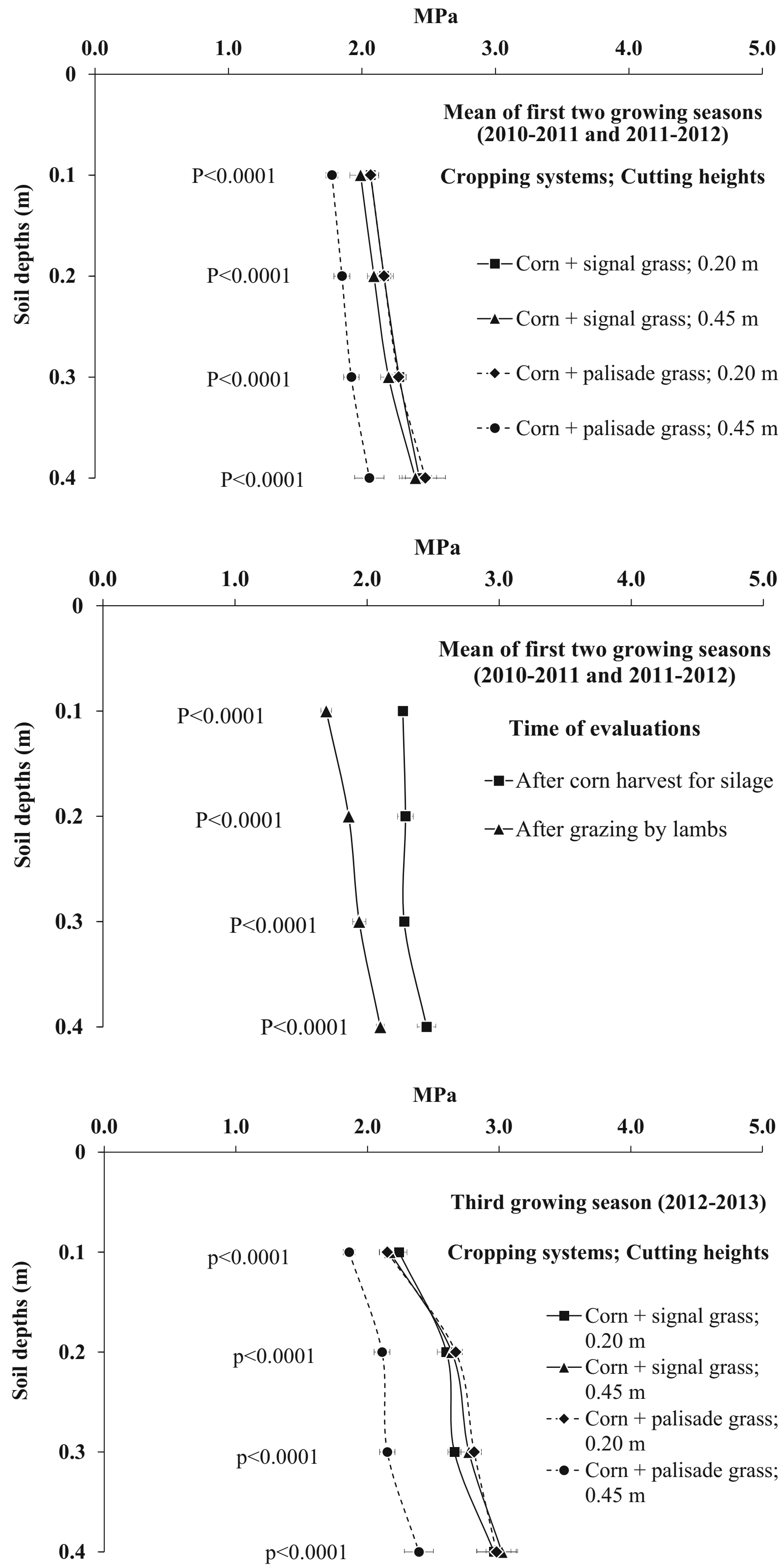
Soil penetration resistance and soil fertility

Lowest soil penetration resistance (SPR) occurred when corn was intercropped with palisade grass and cut at 0.45 m height, thereby demonstrating effectiveness of palisade grass roots compared with signal grass regrowth to improve soil condition (Fig. 2). Attributes contributing to lower SPR at all soil depths may have been from greater quantity of surface mulch (Table 4), greater forage mass of pasture to feed lambs over the entire grazing period in first two growing seasons (Table 5) and over two cutting period in third growing season (Table 7), and better mulch cover (Table 5).

Our results suggest that machinery traffic may compact soil more than lambs treading on the soil (Fig. 2), even when using a continuous grazing method with high stocking rate (2.9–4.8 Mg live-weight ha^{-1}). Grass roots of pasture managed with grazing by lambs in winter/spring were able to help resist soil compaction caused during corn silage harvest. Successful ICLS validates an alternative to farmers that often keeps soil fallow during the winter dry-season in the Brazilian Cerrado and African Savanna. Traditional crop farmers might also conventionally till soil after silage harvest to overcome soil compaction, which is not to be encouraged when considering soil conservation.

Greater soil organic matter under no-till reduces contact of soil colloids with phosphate, thereby reducing adsorption and allowing a gradual mineralization of organic P from soil and mulch to enhance availability of P for crop uptake (Mesquita Filho and Torrent 1993). We found greater soil organic matter and P concentration when corn was intercropped with palisade grass and cut at 0.45 m height compared with other cropping systems in three growing seasons (Table 2). Soil compaction also reduced the

Fig. 2 Soil penetration resistance (SPR) at different soil depths in corn intercropped with palisade grass and corn only (signal grass weedy regrowth) after harvest for silage at two cutting heights and after grazing by lambs on pastures in first two growing seasons and after guinea grass pasture intercropped with soybean in third growing season. Values are mean of twenty-four, forty-eight and six replicates(*panel above*, *middle* and *below*, respectively), and associated *error bar* is ±1 SE



availability of P in function of $H_2PO_4^-$ adsorption, reducing the contact with the plants roots and hence the crops uptake (Novais and Smith 1999). Thus, lowest SPR that occurred when corn was intercropped with palisade grass and cut at 0.45 m height (Fig. 2) can also improve soil P concentration and crops uptake (Tables 3, 6) compared to other treatments that presented highest SPR.

Greater amount of standing corn residue and surface mulch in corn intercropped with palisade grass at 0.45 m silage cutting height (Tables 4, 5) provided sources of organic matter and K to soil in three growing seasons (Table 2). Thus, this cropping system was the only one that maintained concentrations of soil organic matter and K greater at initial levels. Soil Mg concentration was also greater in this system, resulting in greater base saturation in third growing season. Thus, this cropping system demonstrated effectiveness in improving soil fertility over several years, as also reported by Crusciol et al. (2015) in a tropical region with palisade grass cover crops. Cycling efficiency of K corroborates the results of Garcia et al. (2008), in which an increase in exchangeable K was observed after desiccation of palisade grass intercropped with corn. These results are encouraging to enhance efficiency of corn silage production, which has high extraction and export of nutrients, especially K (Jaremtchuk et al. 2006).

Greater concentration of soil organic matter after grazing by lambs compared with corn harvest for silage only may have been due to deposition of animal manure and urine on the soil surface. Flores et al. (2008) highlighted the soil liming effect in the presence of grazing animals, which may be due to additional liberation of organic acids from manure and urine decomposition, as well as from exudation by grass roots.

Conclusions

Despite greater interspecific competition of palisade grass intercropped with corn, the more complex system had greater forage mass of silage. Greater cutting height at 0.45 m than at the traditional 0.20 m height left greater forage mass in the field. Our goal was to assess how intercropping and cutting height would change overall system productivity, nutrient cycling and soil characteristics; results that are not well defined in the literature. Thus, analyzing the system as a whole, the intercrop of corn with palisade grass harvested for silage at a cutting height of 0.45 m was the most effective option for silage production and improvement of other elements of system productivity, such as better soybean leaf nutrient concentration and greater forage mass of pasture available for lamb grazing. This intercrop also increased the quantity of nutrients retained in standing corn residue and surface mulch, avoided soil compaction, stabilized soil organic matter, and enhanced soil availability of phosphorus, potassium, and magnesium concentration.

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