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SPATIAL AND TEMPORAL DISTRIBUTION OF CATTLE DUNG, NUTRIENT CYCLING AND SOYBEAN YIELD IN INTEGRATED CROP–LIVESTOCK SYSTEMS

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Thesis presented to Universidade Estadual de Ponta Grossa for obtain the Doctor (PhD) title in Agronomy – Concentration: Agriculture. Research area: Soil Use and Management.

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To my mother and my nephew
I DEDICATE

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ABSTRACT

CARPINELLI, S**. Spatial and temporal distribution of cattle dung, nutrient cycling and soybean yield in Integrated Crop–livestock Systems.** 2020. Thesis of doctorate degree in Agronomy - University State of Ponta Grossa.

Abstract: The aim of the present study was to (i) mapping the distribution of cattle dung in two ICLS, i.e., with and without trees, CLT and CL, respectively (ii) quantify nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) releases from cattle dung in two integrated crop-livestock systems (ICLS), either with pasture (black oats + ryegrass) and beef cattle during winter and soy or corn in summer (iii) evaluate the influence of the presence of cattle dung and trees on soybean nutrition and yield in ICLS. The experiment was divided into two periods: grazing period and soybean crop season. Grazing period: The experimental design was subplots were different times, comprising two ICLS (presence and absence of trees) and different times (0, 7, 14, 21, 28, 56 and 84 days after animal entry) with six replications. No differences were observed between systems for initial contents: 18.8 g kg^{-1} N and 7.3 g kg^{-1} S. However, significant differences were observed over time for N (9.7 g kg^{-1}), at the 84th assessment day. The ICLS did not affect N and S decomposition and release dynamics. However, total N and S released from the cattle dung and potentially available for the crops varied according to the ICLS, depending on the number of animals present during the grazing period and the amount of cattle dung. The CL system revealed a higher concentration of faeces at locations near the water points, gate and fences. The CLT affects the spatial distribution of the dung, causing uniformity. Soybean crop season: The experimental design was in a split–split plot, the main plots followed the CL and CLT systems, the subplots were the cattle dung input (presence and absence), and the sub-subplots were three positions between the tree rows (nested in the systems). In the CL system the plant height (+18.1%), the number of pods per plant (+51.2%) and grains per pod (+7.2%), pods per area (+50.6%), dry mass in V8 (+59%) and R2 (+60%), and grain yield of the soybean crop (+52.9%) were increased compared to the CLT system. The presence of cattle dung increased the availability of soil P (+30%) and potassium (K, +52.3%), as also the content of P (+4.3%), K (+5.2%), and S (+5.1%) as well as the grain yield (+22%). The light restriction, the competition for nutrients in the trees and drought periods were factors to be considered, to explain the difference in productivity between the CL and CLT systems.

Keywords: *Glycine max* (L.) Merrill; faeces patches; geostatistics; distribution pattern; plant nutrition

RESUMO

CARPINELLI, S. **Distribuição espacial e temporal de esterco bovino, ciclagem de nutrientes e produtividade da soja em Sistemas Integrados de Produção Agropecuária.** 2020. Tese de doutorado em Agronomia – Universidade Estadual de Ponta Grossa.

Resumo: O objetivo do presente estudo foi (i) mapear a distribuição de esterco bovino em dois SIPA, ou seja, com e sem árvores; (ii) quantificar a liberação de nitrogênio (N), fósforo (P), potássio (K) e enxofre (S), a partir das placas de esterco bovino, em dois sistemas integrados de produção agropecuária (SIPA), ambos com pastagem (aveia preta + azevém anual) e gado decorte durante o inverno e soja ou milho no verão (iii) avaliar a influência da presença de esterco de gado e árvores na nutrição e rendimento da soja em SIPA. O experimento foi dividido em duas fases: fase pasto e fase lavoura. Fase pasto: O delineamento experimental foi parcela subdivididas ao acaso com dois SIPA (presença e ausência de árvores) e sete épocas ao longo do tempo (0, 7, 14, 21, 28, 56 e 84 dias após a entrada dos animais) com seis repetições. Não foram observadas diferenças entre os SIPA para os teores iniciais: 18.8 e 7.3 g kg^{-1} de N e S, respectivamente. Contudo, diferenças significativas foram observadas ao longo do tempo apenas para os teores de N (9.7g kg^{-1}), aos 84 dias do período de avaliação. Os SIPA não afetaram a dinâmica de decomposição e liberação do N e S. No entanto, o macronutriente total liberado a partir das placas de esterco bovinos, e potencialmente disponível para as culturas, variou conforme o SIPA, pois dependeu do número de animais durante o período de pastejo e da quantidade de placas de esterco. O SIPA sem árvores apresentou uma maior concentração de fezes em locais próximos aos pontos de água, portão e cercas. O SIPA com árvores afetou a distribuição espacial do esterco, causando uniformidade. Fase lavoura: o delineamento experimental foi em uma parcela subdividida, as parcelas principais foram os sistemas SIPA com e sem árvores, as subparcelas foram a presença e ausência de esterco de gado e as sub-subparcelas foram três posições entre as linhas de árvores. No sistema SIPA sem árvores a altura da planta (+18.1%), o número de vagens por planta (+51.2%) e grãos por vagem (+7.2%), vagens por área (+50.6%), massa seca em V8 (+59 %) e R2 (+60%), e o rendimento de grãos da cultura da soja (+52.9%) foram maiores em relação ao sistema SIPA com árvores. A presença de esterco bovino aumentou a disponibilidade de P (+30%) e potássio no solo (K, +52.3%), assim como o teor de P (+4.3%), K (+5.2%) e S (+5.1%) assim como o rendimento de grãos (+22%). A restrição de luz, a competição por nutrientes com as árvores e os períodos de ausência de chuvas foram fatores a serem considerados para explicar a diferença de produtividade entre os diferentes SIPA.

Palavras-chave: *Glycine max* (L.) Merrill; manchas de fezes; geoestatística; padrão de distribuição; nutrição de plantas

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SUMMARY

INTRODUCTION

Integrated crop-livestock systems (ICLS) enable synergism between agricultural, livestock, and/or forestry activities carried out in the same area, focusing on the maximization of production factors. Changes in the ICLS microclimates and periods of shade can affect the deposition and decomposition of cattle dung, as well as nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) and nutrient cycling present in the system, as also, the distribution of feces in the sunny and shaded areas.

This study essentially researches the nutrient cycling process in integrated crop-livestock systems (ICLS), in order to increase the efficiency of the use of nutrients from cattle dung, and nutrient release patterns from these residues, to improve fertilization management. Our year of survey (2018–2019), therefore, provides new, to be published results about the interactive shading in ICLS with trees (CLT) and without trees (CL), with full sunlight, and the effects of cattle dung on the agronomic performance of forage crops, providing an outstanding contribution to advance the innovativeness in agronomy, as an inconsistent response has been reported in the literature about this.

We have assessed the impact of including trees in ICLS on nutrient cycling, because although cattle dung residues are rich in nutrients and can serve as biological sources of fertility, little is known of dung decomposition and its subsequent release into the succeeding crops in the typical ICLS of Southern Brazil (summer grain-crop and cattle grazing rotations) with trees. The main experiment was divided into two parts (winter 2018 and summer 2018–2019).

Therefore, a first original aspect of our study, we show the influence of the presence of trees on the spatial and temporal distribution of cattle dung and on the nutrient cycling in integrated crop–livestock systems. Another original aspect of our study is to assess the combined effects of shade and cattle dung distribution in two integrated crop–livestock systems (ICLS, i.e., with and without *Eucalyptus* trees) and we quantify the dry matter decomposition and nutrient release N, P, K and S the most commonly required nutrients in tropical and subtropical agriculture, which must be considered for fertilization management practices) from these residues in these two ICLS. Moreover, another original aspect of our study is to assess the combined effects of shade (CL and CLT), cattle dung input (presence and absence), and three positions between the tree rows (nested in the systems), on the agronomic performance of soybean nutrition and yield in natural conditions, that is, under the trees.

Our survey of one year provides new results on the interactive nature of the presence of trees and the effects of cattle dung on nutrient cycling and yield of soybean, giving an outstanding contribution to advance the state-of-the-art integrated systems with trees. Understanding nutrient release patterns from residues is necessary to improve fertilization management practices in the long-term, for ICLS conditions.

We highlighted the necessity of silvicultural interventions to increase land use efficiency for their long-term ecological sustainability. As such, this article should be of great interest to many readers, including those interested in integrated crop–livestock systems, as a strategy for sustainable land use and the use of trees, to increase the provision of ecosystem services, such as, carbon sequestration and soil stability, as well as to diversify the producer's income sources.

The results demonstrate that it is possible to employ ICLS, that is, sustainable technology, which contributes to the sustainability of agricultural and livestock activities in Brazil, reduce disturbing the environment. It also helps to keep its leading position in the ranking of countries, which may help prevent hunger in the world.

1 SPATIAL AND TEMPORAL DISTRIBUTION OF CATTLE DUNG AND NUTRIENT CYCLING IN INTEGRATED CROP–LIVESTOCK SYSTEMS

Abstract: Residue decomposition from cattle dung is crucial in the nutrient cycling process in Integrated Crop–Livestock Systems (ICLS). It also involves the impact of the presence of trees exerted on excreta distribution, as well as nutrient cycling. The objectives of this research included (i) mapping the distribution of cattle dung in two ICLS, i.e., with and without trees, CLT and CL, respectively, and (ii) quantification of dry matter decomposition and nutrient release (nitrogen − N, phosphorus − P, potassium − K, and sulphur − S) from cattle dung in both systems. The cattle dung excluded boxes were set out from July 2018 to October 2018 (pasture phase), and retrieved after 1, 7, 14, 21, 28, 56and 84 days (during the grazing period). The initial concentrations of N (~19 g kg^{-1}), P (~9 g kg^{-1}), K (~16 g kg^{-1}), and S (~8 g kg^{-1}) in the cattle dung showed no differences. The total N, P, K and S released from the cattle dung residues were less in the CLT system (2.2 kg ha^{-1} of N; 0.7 kg ha^{-1} of P; 2.2 kg ha^{-1} of K and 0.6 kg ha^{-1} of S), compared to the CL (4.2 kg ha^{-1} of N; 1.4 kg ha^{-1} of P; 3.6 kg ha^{-1} of K and 1.1 kg ha^{-1} of S). Lesser quantities of cattle dung were observed in the CLT (1810) compared to the CL (2652), caused by the lower stocking rate, on average, in this system (721 in the CL vs. 393 kg ha^{-1} in the CLT) because of the reduced amount of pasture in the CLT systems (−41%), probably due to light reduction (−42%). The density of the excreta was determined using the Thiessen polygon area. The CL system revealed a higher concentration of faeces at locations near the water points, gate and fences. The CLT affects the spatial distribution of the dung, causing uniformity. Therefore, these results strengthen the need to understand the nutrient release patterns from cattle dung to progress fertilization management.

Keywords: faeces patches; full sunlight system; geostatistics; heifers; distribution pattern; Thiessen polygon area

1.1 INTRODUCTION

Sustainable Intensification (SI) is the process in which agricultural production is expanded or saved while advancing environmental improvements (PRETTY, 2018). Among the strategies for the SI of land use, we highlight Integrated Crop–Livestock Systems (ICLS) (LAWSON; DUPRAZ; WATTÉ, 2019), including agro forestry systems (PRETTY, 2018), which are linked to the management of the soil conservation practices, such as the no-till system. ICLS include the development of a diversity of agricultural pursuits in the same area, ensuring several medium- and long-term advantages (DE FACCIO CARVALHO et al., 2010). Through ICLS, soil fertility and nutrient cycling can be improved, while promoting the sustainable intensification of land, like low fossil energy inputs, diversification of the producer’s income sources, high biodiversity and biomass production, consideration for animal welfare, and rational water use (LAWSON; DUPRAZ; WATTÉ, 2019; DE FACCIO CARVALHO et al., 2010).

ICLS with trees in pasture locations, in addition to providing shelter and shade, provide greater resilience to the system, as well as better pasture quality (NEELY and FYNN, 2012), as well as enhanced ecosystem services (LAWSON; DUPRAZ; WATTÉ, 2019). Trees also promote biodiversity, in an effort to recover nutritional security and global food yield (BÉLANGER and PILLING, 2019). In ICLS, the integration of trees may contribute to nutrient cycling by absorbing the nutrients present in the subsoil and releasing them into the topsoil (DE NOTARO et al., 2014). However, in shaded areas, the grasses exhibit physiological and anatomical changes to compensate for the low quantity and quality of light (CAVAGNARO and TRIONE, 2007), with observable impacts on the nutritive value and production (DA PONTES et al., 2016). These differences in the ingested forage, in terms of quantity and quality, may, consequently, alter the composition and quality of the cattle dung. Further, the tree component of the ICLS may influence the decomposition either directly or indirectly through microclimate or the decomposer communities (GUO and SIMS, 2001; QUINKENSTEIN et al., 2009). Although cattle dung residues are nutrient-rich and could be valuable organic sources (ASSMANN et al., 2017; BRAZ et al., 2002a; DUBEUX et al., 2014; RODRIGUES et al., 2008; DA SILVA et al., 2014; SOUTO et al., 2005; SUN et al., 2018; VENDRAMINI et al., 2007), little is known about dung decomposition and subsequent nutrient release in ICLS that include trees.

In the open pastures, i.e., systems without trees, the distribution pattern of cattle excreta and, consequently, in which the nutrients are returned to the pasture, is, in general, not homogeneous (DUBEUX et al., 2014; FERREIRA, 2011). As a result, crop performance is affected, particularly in ICLS, due an unequal distribution of cattle dung in the previous pasture (WHITE et al., 2001). For instance, studies showed that in areas with the largest presence of bovine dung in ICLS, the availability of phosphorus (P) and soil potassium (K) increased by 38% and 122%, and, consequently, the presence of these nutrients in the plant increased by 7% and 41%, respectively. These positive results increased the soybean yield by 23%, in areas with presence of dung input in relation to absence (DA SILVA et al., 2014). Therefore, this heterogeneous pattern of nutrient distribution from animal excreta and the occurrence of such returns in different areas increases the heterogeneity of nutrient return in the soils (DUBEUX et al., 2014; FERREIRA, 2011). Thus, the challenge is to address strategies to improve the spatial distribution of bovine dung production, to avoid the very concentrated occurrence of bovine dung in some attractive points of the field, as observed in the literature (WHITE et al., 2001; DA SILVA et al., 2014), regardless of the grazing intensity (DA SILVA et al., 2014).

Seasons can influence animal behavior and the spatial and temporal distribution of cattle dung. For instance, in the pasture-based dairy system, with evaluation performed during three different periods per year, (WHITE et al., 2001) observed that the concentrations of faeces and urine during three warm-season observations were higher next to the water tank. However, during the winter, the animals reduced their search for water (WHITE et al., 2001). Further, under tropical conditions, a few authors noted that, in the ICLS with trees (CLT), cattle deposit their faeces and urine in a more uniform distribution pattern (FERREIRA, 2011; CARNEVALLI et al., 2019). This occurs because, in CLT systems, thermal comfort features such as shade and tree trunks (scalers) are well distributed throughout the area (CARNEVALLI et al., 2019). In other words, with such good tree distribution, the tendency is towards a more uniform faeces distribution (FERREIRA, 2011; CARNEVALLI et al., 2019). This occurs because the animals prefer to remain in the shade of trees for all the daytime period, to avoid the high temperatures and solar radiation, especially observed for the animals in tropical zones (GIRO et al., 2019). However, since the stocking phase in a typical ICLS of South Brazil occurs during the winter, the frequency of animals searching for shade can be reduced, as for water troughs (WHITE et al., 2001). Therefore, additional studies are necessary to investigate the tree effect on cattle dung distribution at each season.

We hypothesized that, under subtropical conditions, in a typical ICLS of South Brazil (Cfb of Köppen), i.e., with summer crops, like soybean and maize, and cool-season pastures (e.g., ryegrass plus black oat) during the winter, trees may exert a smaller influence on cattle activities (i.e., the animals would reduce their search for shade during the winter, due to a lower heat load in this period) and, consequently, on the dung distribution. Further, the decomposition rate and nutrient release from the cattle dung could be affected by changes in the composition of the residues derived from the association with trees. Understanding of these factors will enable the ICLS managers to better synchronize the nutrient release with nutrient demand in the subsequent crops. The objective of this study was to assess the impact of including trees in the ICLS on the faeces distribution from heifers, during the winter, and, to quantify the dry matter decomposition and nutrient release (N, P, K and S are the most commonly required nutrients in tropical and subtropical agriculture) from these cattle dung residues in two ICLS (with and without eucalyptus trees).

1.2 MATERIALS AND METHODS

1.2.1 Characterization and History of the Experimental Area

A field experiment was conducted at the Rural Development Institute of Paraná (IDR): IAPAR – Emater (25°07′24.3′′S, 50°02′58.6′′W) in Southern Brazil. The local climate is humid subtropical (Cfb according to the Köppen Climate Classification), with frequent occurrence of frost. The mean annual temperature is 18.3 °C, ranging from 9.2 °C in July to 27.6 °C in February, with a mean annual rainfall of 1239 mm (Table 1). The soil is of the Typic Distrudept and Rhodic Hapludox variety (USDA, 1999) with 270, 30 and 710 g kg^{-1} of clay, silt, and sand, respectively, in the 0–20 cm layer. Chemical analysis of the soil revealed the following results: 4.9 pH ($CaCl_2$); 23.4 mg dm^{-3} of phosphorus (P; Mehlich–1); 0.2, 2.7 and 1.1 cmolcdm^{-3} of exchangeable potassium (K), calcium and magnesium, respectively; base saturation of 48.4%; and carbon (Walkley–Black) was 14.9 g dm^{-3}.

Table 1. Mean minimum–maximum monthly temperature (°C) and total rainfall (mm) during the experimental period (2018) and historical mean (HM).

Months	**Temperature (°C)**		**Total rainfall (mm)**	
	2018	**HM (1998–2018)**	**2018**	**HM (1998–2018)**
January	17.1–26.1	17.5–27.3	337.4	164.1
February	15.5–26.0	17.4–27.6	97.8	162.1
March	17.6–27.8	16.7–27.1	184.2	123.1
April	14.5–26.6	14.7–25.3	18.2	92.2
May	11.6–22.8	11.0–20.9	37.0	93.7
June	9.7–19.4	9.9–20.3	109.6	105.0
July	9.6–22.1	9.2–20.1	11.0	98.6
August	8.8–20.1	10.0–22.0	43.6	74.4
September	12.5–23.5	12.0–23.3	43.4	128.1
October	14.1–23.4	14.2–24.9	238.6	172.1
November	14.9–26.4	15.2–26.1	26.8	123.1
December	16.5–29.7	16.6–27.3	162.4	150.1

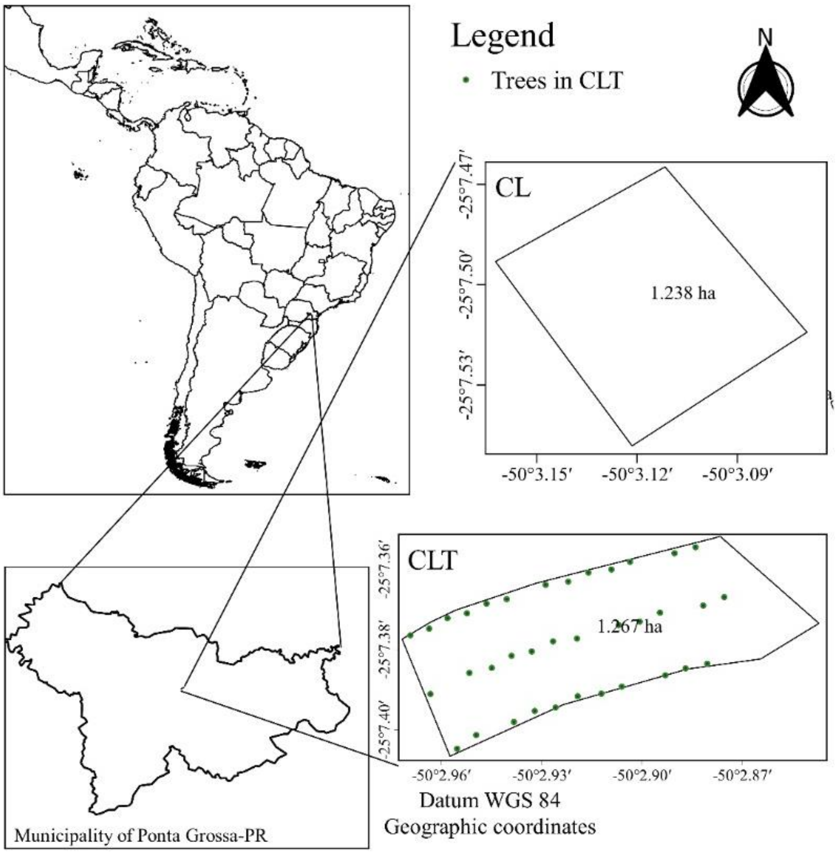
Source: SIMEPAR, station 25135001, localized in the municipality of Ponta Grossa—PR.

In 2006, three tree species (silver oak, *Grevillea robusta*, eucalypt, *Eucalyptus dunnii* and pink pepper, *Schinus mole*) were planted in the ICLS (with trees, CLT). The species were interspersed in the same rows, but running crosswise in relation to the slope, maintaining 3×14 m spacing (238 trees ha^{-1}); for more details see (CARPINELLI et al., 2020a). During the 2013 summer, the pink pepper trees were removed, as many of them had been damaged by cattle activity (PORFÍRIO-DA-SILVA et al., 2012). Furthermore, the tree density was reduced by thinning the silver oak in November 2014. Therefore, during the present study, the new tree arrangement was 9×28 m (~40 trees ha^{-1}), which comprised only eucalyptus. During the first three winters, i.e., in 2007, 2008 and 2009, black oat (*Avena strigosa*) was grown for soil cover, prior to soybean (*Glycine max*), maize (*Zea mays*) and sorghum (*Sorghum bicolor* × *Sorghum sudanense*) crops, respectively, in the summer, using no–tillage. Since the 2010 winter, the production system of integrated cattle grazing (Purunã beef heifers) on the cool-season pastures (ryegrass, *Lolium multiflorum* plus black oat). During the stocking phase, the pasture was managed in order to maintain a sward height (SH) constant, i.e., at 20 cm, by using continuous stocking and the put-and-take method (MOTT and LUCAS, 1952). Maize or soybean crops were cultivated alternately in the summer, in the same region.

In the current study, the black oat (cv. IPR 61) plus annual ryegrass (cv. São Gabriel) mixture was sown at a seeding rate of 45 and 15 kg ha^{-1}, respectively, in May 2018, and 400 kg ha^{-1} of commercial N–P–K fertilizer 04–30–10 ($N–P_2O_5–K_2O$) was applied. Dose of N was applied approximately 30 days after the pasture was sown, at the rate of 90 kg ha^{-1} (i.e., 18 June 2018). The experimental area (2.3 ha) was divided into two experimental units (see Figure 1): one experimental unit (1.2 ha) was used in the CLT system and another experimental unit (1.1 ha) in the CL. This experiment has been part of a long-term study protocol. For more details, see Da Pontes et al. (2018).

The mean percentage of light reduction under the tree canopy in the CLT system compared to that of the CL (treeless) was calculated in May (spring) 2018 and in December (summer) 2018, using two ceptometers (AccuPAR LP–80, Decagon Equipment Co., Pullman, WA). One was positioned under full sunlight, while the other was placed under the trees (Figure 1). Evaluations (one day per month, i.e., 29 May 2018 and 6 Dec. 2018) were done every 30 min, between 9:00 a.m. and 15:00 p.m. The decrease in the photosynthetically active radiation was calculated by the difference between the two values recorded by the ceptometers.

Figure 1. The experimental site at Ponta Grossa, Paraná, Brazil. CL: crop–livestock only; and CLT: crop–livestock with trees**.**



1.2.2 Experimental Design, Treatments and Performance of the Experiment

The split-plot randomized experimental design was used. The main plots included two types of ICLS systems (with and without trees, CLT and CL, respectively). The subplots were different times (at 1, 7, 14, 21, 28, 56 and 84 days after grazing commenced) and replicated six times.

During the winter (i.e., pasture measurements), the animals employed were Purunã (¼ Charolais, ¼ Caracu, ¼ Canchim, and ¼ Aberdeen Angus) cattle heifers with an age of ~10 months and weighing 216 ± 24 kg in 2018. Stocking season began on 05 July 2018, with grazing commencing at approximately 50 days after sowing, i.e., when all the paddocks reached at least 24 ± 1 cm height, on average. Heifers grazed until 17 October 2018 for a total of 104 grazing days. The short stocking with a variable number of animals periodically adjusted in the CLT in 2018 was caused by a severe drought in July (only 11 mm rainfall) that undermined the grassland productivity. All the animals has unrestricted access to shade in the CLT plots and clean water and mineral supplements throughout the experiments in the CLT and CL plots.

Herbage mass [kg dry matter (DM) ha^{-1}] was estimated at approximately every 21 days, with five cuts at ground level, in each experimental unit, within a quadrat of 0.25 m² (50 × 50 cm). The cuts were made at random inside each experimental unit. The samples were then oven dried (48 h at 60 °C) and weighed. In 2018, the cuts were done once every 21 days.

Animals were weighed every ~21 days (for a total of five stocking periods for 2018) after an approximately 15 h fasting from solids. The stocking rate (SR), kg ha^{-1}, was calculated by adding the average live weight (LW) of the test animals with the average LW of each put-and-take animal, multiplying by the number of days they remained in each experimental unit and dividing by the total number of grazing days during each period. The average daily gain (ADG), expressed in g $animal^{-1}$ day^{-1} was calculated as the difference between the final and initial weights of the test animals divided by the number of days in each stocking period. The gain per hectare (Gha), expressed in kg ha^{-1} was obtained by multiplying the animals ha^{-1} by the ADG of the test animals and the total number of grazing days.

1.2.3 Sampling and Chemical Analyses

Nutrient cycling (N, P, K and S) was evaluated from July 2018 up to October 2018, where the decomposition of DM bovine dung residue on N, P, K and S release were evaluated. At the beginning of the grazing period, 36 cattle dung from different experimental units were marked to accompany the natural degradation process and six cattle dung were collected immediately after defecation by the bovines and carefully transferred into a plastic bag in a thermal box with ice. To avoid any increase in the cattle dung decomposition via physical action, such as animal trampling, grazing exclusion boxes were used. At the time the representative cattle for dung in the ranging area in the experimental units were chosen, the boxes were allocated to protect the cattle dung. The box protected site was maintained without grazing for a period.

Each experimental unit of the CL and CLT systems had 36 cattle dung, during the beginning of the grazing period, for retrieval at 1, 7, 14, 21, 28, 56 and 84 days after grazing commenced. Total dung dry matter contents were oven-dried (60 °C) and weighed. The dry matter decomposition and nutrient release were determined from weight differences and nutrient concentrations among the periods. The cattle dung samples were ground in a Willey mill having a 1-mm mesh, for laboratory analysis. The macronutrient concentrations were determined according to Abreu et al. (2009). The N concentration was determined after digestion with sulphuric acid and distillation using the Kjeldahl method and measured to titration with sulphuric acid (H_2SO_4) 0.01 mol L^{-1} solutions. The P, K and sulphur (S) concentrations were determined after nitric–perchloric digestion. The P and S concentrations were measured by molecular absorption spectrometry and barium sulphate turbidity, and the K concentration was measured using flame emission spectrophotometry.

1.2.4 Spatial and Temporal Distribution of the Cattle Dung

The stocking phase in the 12th year after planting the trees occurred between July 5th and October 17th. During this phase, the dung input was georeferenced at 20-day intervals using the geodesic GPS (except for the first evaluation, which was evaluated one day after the grazing commenced). Experiments in these six periods were conducted at 1, 20, 40, 60, 80 and 104 days after grazing commenced. After each of the cattle dung was recorded, they were marked with lime for painting, so that each of the cattle dung was recorded only once throughout the experiment.

A digital map was produced based on the spatial and temporal distribution of the dung piled during the stoking phase, using the ArcView GIS 3.2 software. The cattle dung distribution in the earlier years was not evaluated. Paddocks were georeferenced using Trimble® R4 GPS receivers. The precision of the global positioning system (GPS) was 5 mm off the exact geographic point. The coordinate system used was the geographic coordinates (WGS84) and the geodetic reference system SIRGAS 2000 (Geocentric Reference System for the Americas). The dung patch distribution was mapped with the program Qgis.

On 13 July, 23 August, 12 September, 25 September, 3 October, and 17 October 2018, ten cattle dung were randomly selected in each treatment, where the major and minor semi-axes were measured to calculate the individual mean area of the cattle dung (a), considering them as an ellipse. In each evaluation, the cattle dung dry weight was determined. From the data collected by the GPS, it was possible to determine the total number of cattle dung in each sample, which was divided by the number of cattle in each experimental unit, in the interval of days between the samples. Thus, the number of cattle dung per day was estimated at each sampling interval.

The density of the cattle dung deposited in the pasture (D), according to the equation (Equation 1):

$$D = N \times a/A \tag{1}$$

Where, A is the total area of each paddock, N is the total number of cattle dung at the end of sampling and a is the average area occupied by each of the cattle dung. The value of the cattle dung density (*D*) was used to calculate the percentage of area covered by thefaeces (*P*), which is defined as (Equation 2):

$$P = 100 \times D \tag{2}$$

1.2.5 Geostatistics Analysis

For each position of the cattle dung (X and Y coordinates), the Thiessen polygon area was calculated (GOOVAERTS, 2000), in which the borders of the polygons are formed by the mediators of the lines that join two adjacent polygons (AUERSWALD; MAYER; SCHNYDER, 2010). The polygons were constructed using the computer program Qgis. To allow a comparison between the sampling periods and the study of the spatial dependence between the cattle dung, experimental semivariograms of the polygon areas were generated to quantify the spatial autocorrelations using the computer program Vesper 1.6. The spatial correlation of an attribute is quantified by the semivariogram (plot of semivariance *vs*. range) (FANCHI, 2010). Semivariance is a measure of the degree of spatial dependence between the points in space or values of attribute Z at 2 different locations (FANCHI, 2010). The lag h is the separation distance between the spatial points. The semivariance $\gamma(h)$ is a function of lag h between 2 observations $Z(xi + h)$ and $Z(xi)$ of the attribute Z; under these conditions:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i + h) - Z(x_i)]^2 \tag{3}$$

Where $N(h)$ is the number of data pairs that are approximately separated by lag h (FANCHI, 2010).

The points were fitted to the experimental semivariograms and, later, the Gaussian and Exponential Models were tested. The fit enabled the definition of the nugget effect (C_0), contribution ($C1$), spatial range and equivalent sill (C_0+C1). The criteria for choosing the best mathematical model adjusted to the experimental semivariograms were the lower values of the sums of the squares of the residuals (SQR) and the degree of spatial dependence (DSD) (BELTRAME et al., 2017). A ratio of <25% indicates a strong spatial dependence, a value of 25%–75% suggests moderate spatial dependence and a value >75% denotes weak spatial dependence (CAMBARDELLA et al., 1994).

1.2.6 Statistical Analysis

The data variability was scrutinized through visualization of the box plots and assumption of the normal distribution of the residuals using the Shapiro–Wilk test. The residuals were extracted employing the additive equation (Equation 4):

$$y_{ij} \sim \bar{X} + ICLS + e_{ij} \tag{4}$$

Whenever there were outliers or the normal distributions were not confirmed, mathematical transformation was performed using natural logarithm. An a priori analysis of variance was applied using the ICLS as a factor with the CL and CLT as the levels for each time of evaluation. A time series plot with confidence intervals is presented for each variable.

The data of the DM and nutrients remaining at each retrieval date were fitted to a nonlinear model for each system (i.e., CL and CLT) to reveal the decomposition characteristics. Non-linear regressions were done for each system, as we had a long-term experiment and systems were in a stable condition of land use. The exponential model was (Equation 5):

$$rem = res + act \times e^{-kt} \tag{5}$$

Where *rem* is the remaining constituent (DM and N–P–K and S) after *t* (days); *res* is the size of a resistant fraction showing no signs of decomposition during 120 days, *act* is the size of an active fraction decomposing during 120 days, and *k* is a non-linear decay constant of the active fraction. Unusual residuals greater than 3 in absolute value were excluded from the final model. The half–life residue ($t_{1/2}$), which represents the time needed for 50% of the DM (or N–P–K and S) to decompose (or release), was calculated by applying the following formula (Equation 6):

$$t_{1/2} = 0.693/k \tag{6}$$

Previously, in nonlinear models, data were analyzed by the interaction plot with Tukey intervals, using the Multifactor ANOVA procedure on Statgraphics Centurion XV. The cumulative N, P, K and S releases were estimated by the difference between the initial quantities of N, P, K and S in the residue and the quantities of N, P, K and S at each incubation period (i.e., the percent of N, P, K and S concentrations multiplied by the remaining DM obtained from the exponential model).

1.3 RESULTS

1.3.1 Residual Shoot Biomass and Animal Production

During the experimental period, the mean percentage of light reduction under the tree sward height (CLT) compared to the CL system ranged from 47% (May 2018, study commencement) to 36% (December 2018). The CLT showed lower herbage mass than did the treeless system (Table 2). Consequently, the ADG was also lower in this system (Table 2). These results were observed 12 years after the trees were planted, with 42% of light reduction under the trees. On average, differences in the sward height were observed between the two ICLS (Table 2). The shade provided by the 12-year-old trees in the CLT was as high as 42% in relation to the CL, which affected the grassland development (–41%).

Table 2. Values (means ± standard error) for the characteristics of animal performance in the beef cattle, i.e., stocking rate (SR), average daily gain (ADG) and live weight gain per hectare (Gha ha^{-1}) and agronomic attributes of the pasture (herbage mass, herbage accumulation rate and sward height) of *Lolium multiflorum* plus *Avena strigosa*, within each integrated crop–livestock system (CL, crop–livestock; CLT, crop–livestock–tree systems).

	CL	**CLT**	***P***
Stocking rate, SR (kg ha^{-1})	720± 267	393± 180	0.052
Average daily gain, ADG (kg day^{-1})	0.8 ± 0.3	0.5± 0.7	0.018
Gha ($kgha^{-1}$)	228± 23	109± 15	0.042
Herbage mass (kg ha^{-1})	988± 429	408 ± 303	0.002
Herbage accumulation rate (kg ha^{-1})	26± 13	24± 10	0.376
Sward height (cm)	23± 3	14 ± 4	0.007

1.3.2 Distribution of Cattle Dung

Between 2652 and 1810 of the total cattle dung were recorded in the different systems CL and CLT, respectively, during the evaluations (Table 3). The average frequency of defecation did not vary between the systems with 9 ± 0.6 ($p = 0.296$) defecations/animal per day and the average faeces weight at each defecation to showed no variations between the systems with a mean of 170 ± 18 g ($p = 0.549$) of DM.

The means of the area of dung patch density too did not vary between the systems, showing a mean of 0.03 ± 0.006 m^2 ($p = 0.072$). Considering the total number of cattle dung in each system (2652 in CL vs. 1,810 in CLT), the proportion of the total area covered by the accumulated cattle dung was 0.7 and 0.5%, for CL and CLT, respectively, considering all evaluations.

Table 3. Number of cattle maintained per system, in each cattle dung sampling (1, 20, 40, 60, 80 and 104 days, after grazing commenced). Total amount of excreta per livestock unit (n), and per day (n/a/d) in the different integrated crop–livestock systems (CL, crop–livestock and CLT, crop–livestock–tree systems).

Systems	**Sampling (days^{-1})**						**Total**	**Means**
	1	**20**	**40**	**60**	**80**	**104**		
CL								
Animals per ha	4	4	3	2	2	4		3
n	38	603	461	346	409	795	2652	
n/a/d	10	7	8	9	9	9.5		9
CLT								
Animals per ha	3	3	2	1	1	1		2
n	30	643	565	177	195	200	1810	
n/a/d	10	9	8.5	9	9	10		9

The density of the cattle dung was determined using the Thiessen polygon area to detect the distribution patterns (Figures 2, 3 and 4). The maps (Figures 2, 3 and 4), however, revealed substantial spatial variations and some similarities in the underlying pattern. The bovines deposited their excreta in different places each time, with no pattern of temporal distribution (Figure 2). In the full sunlight system, higher faeces patch concentrations were observed in places close to the gate, water tanks, mineral supplement points, and socialization areas (Figure 3). The CLT affects the spatial dung distribution, stimulating uniformity (Figure 4). The Thiessen areas varied between 0.04 and 46 m^2 and 0.13 and 43 m^2 for the CL and CLT, respectively, considering all the samples (Figures 3 and 4).

Figure 2. Digital map indicating the absence and presence of cattle dung in the different areas (CL, crop–livestock and CLT, crop–livestock–tree systems). Dark brown represents areas with high concentration of dung, whereas the white indicates areas without dung. Axes X and Y with UTM coordinate (in metres).

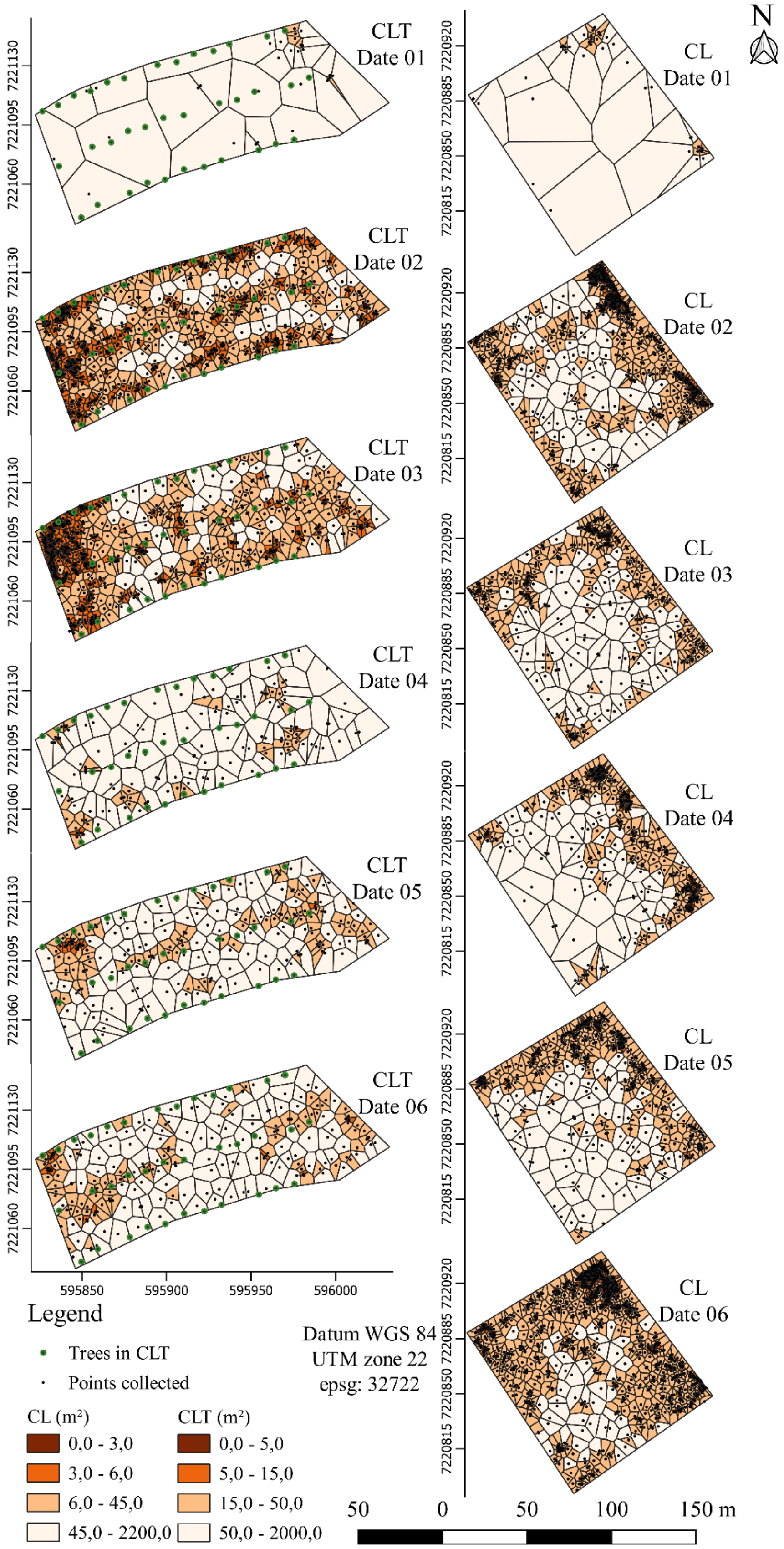


Figure 3. Thiessen areas of the spatial distribution of the dung, in the different systems: CL, crop–livestock, considering all samples. Dark brown represents areas with high concentration of cattle dung, whereas the white indicates areas without dung. Axes X and Y with UTM coordinate (m).

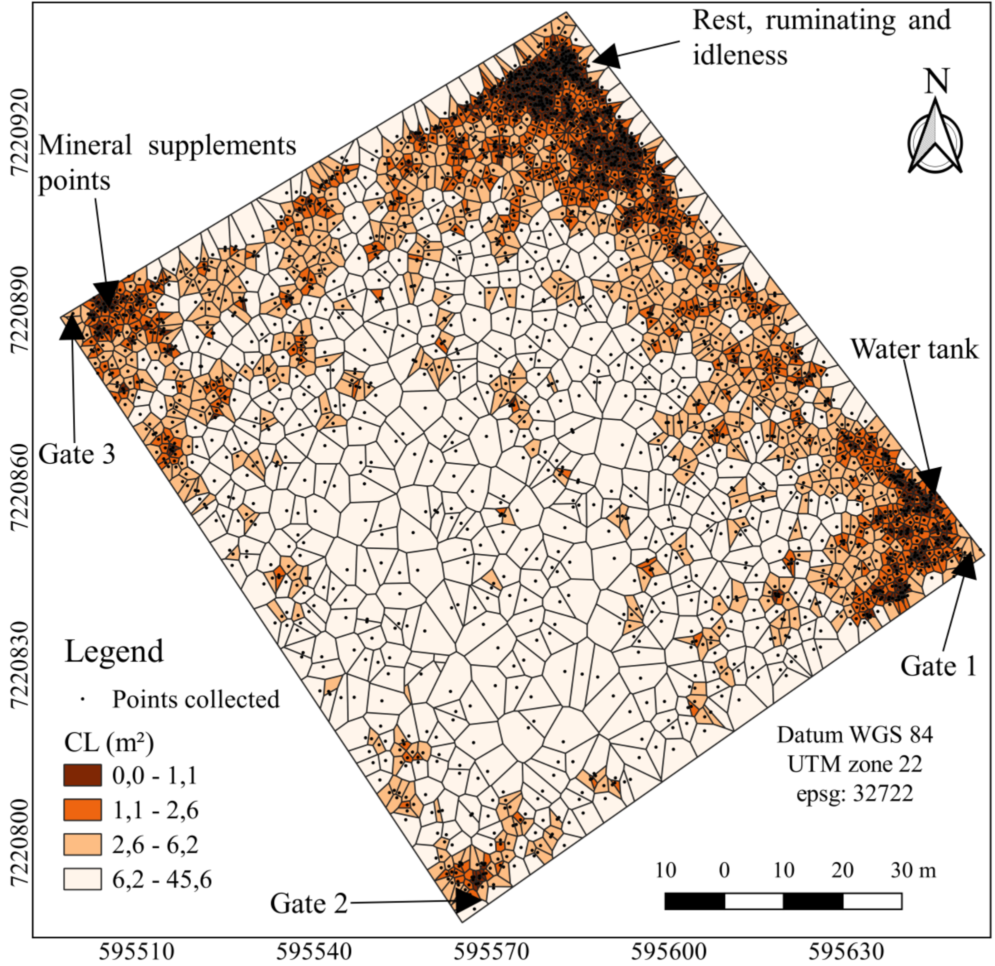
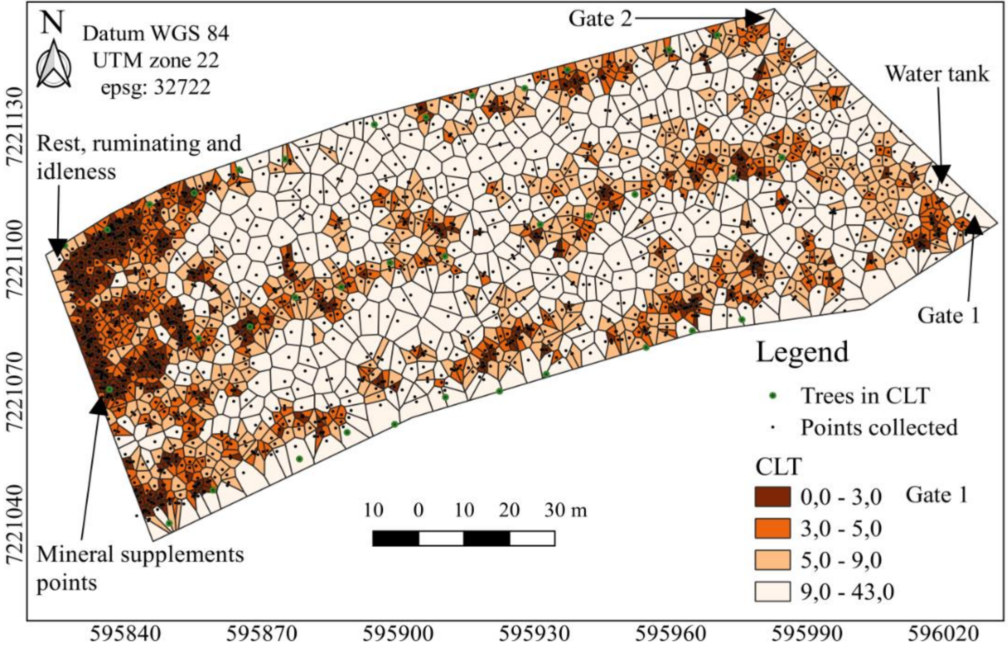


Figure 4. Thiessen areas of the spatial distribution of the dung, in the different systems: CLT, crop–livestock–tree systems, considering all samples. Dark brown represents areas with high concentration of cattle dung, whereas the white indicates areas without dung. Axes X and Y with UTM coordinate (m).



The geostatistical parameters of the Thiessen areas in the evaluations performed are shown, depending on the different ICLS (Table 4). It is observed that the data adjusted to the different models with a strong Spatial Dependence Degree (SPD). The range varied from 12 to 84 m, for the CLT (Table 4). It must be considered that Sampling 1 was performed one day after the animals entered. Considering all the samples, the range was 31 and 25 m for the CL and CLT, respectively. The semivariogram shows the spatial distribution of the cattle dung, considering all samples, in the different ICLS. A decrease is visible in the semivariogram over the short and long distances and an increase in the semivariogram is observed at medium distances.

Table 4. Geostatistical models of the Thiessen areas in each sampling period, in the different integrated crop–livestock systems (CL, crop–livestock and CLT, crop–livestock–tree systems).

Systems	Sampling	Model	C_0[1]	C_0+C1[2]	DSD[3]	Range (m)
CL	1	Gaussian	0.0	50000.0	1.00	53
	2	Gaussian	0.0	880.2	1.00	23
	3	Gaussian	15.9	1426.1	0.99	22
	4	Gaussian	12.8	5729.8	0.99	51
	5	Gaussian	60.7	2429.5	0.98	55
	6	Gaussian	20.0	338.3	0.94	25
CLT	1	Gaussian	0.0	50000.0	1.00	84
	2	Exponential	0.0	285.4	1.00	12
	3	Gaussian	91.4	583.4	0.84	35
	4	Gaussian	272.6	4273.3	0.94	16
	5	Gaussian	191.3	1498.1	0.87	16
	6	Exponential	0.0	1376.9	1.00	17

[1]C_0: nugget effect; [2]C_0+C1: Equivalent sill; [3]DSD: degree of spatial dependence (C_0/C_0+C1);

1.3.3 Initial Dry Matter of the Cattle Dung and Its Quality

No differences were observed between the systems for the initial N, P, K and S concentrations in the cattle dung (Table 5). In fact, N was the nutrient having the major initial concentrations in the cattle dung, regardless of the ICLS (Table 5). Potassium was the nutrient present in a lower concentration in the cattle dung at the end (84 days) of the grassland phase.

Table 5. Initial dry matter (DM) residue from the cattle dung and nutrient (N–P–K and S) concentrations (means ± standard error) for each system (CL, crop–livestock and CLT, crop–livestock–tree systems) and for time (1, 7, 14, 21, 28, 56 and 84 days after grazing commenced).

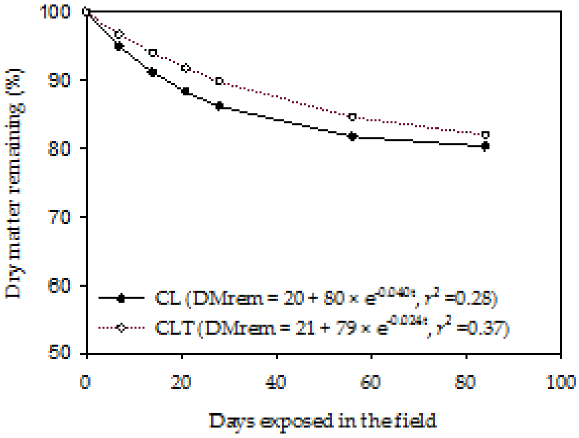
Source of Variation	**DM Cattle dung(g)**						
System	1 day	7 days	14 days	21 days	28 days	56 days	84 days
CL	177±84	153± 26	142± 22	133± 29	131± 34	124± 37	117 ± 30
CLT	161 ± 81	143± 28	141 ± 35	132 ± 33	127 ± 36	127 ± 39	118 ± 34
W^1	0.93	0.86	0.86	0.89	0.85	0.67	0.92
P^2	0.014	0.003	0.004	0.012	0.002	4.088	0.056
	Nitrogen (g kg^{-1})						
System	1 day	7 days	14 days	21 days	28 days	56 days	84 days
CL	19 ± 6	17 ± 6	17 ± 3	17 ± 2	14 ± 6	13 ± 3	10± 3
CLT	19 ± 5	18± 5	18± 6	15± 6	15 ± 4	13 ± 3	10± 4
W^1	0.86	0.89	0.97	0.86	0.89	0.96	0.89
P^2	0.052	0.128	0.853	0.051	0.133	0.733	0.101
	Phosphorus (g kg^{-1})						
System	1 day	7 days	14 days	21 days	28 days	56 days	84 days
CL	9 ± 1	9± 0.3	8± 1	8± 0.4	8± 0.3	7 ± 1	7 ± 0.4
CLT	9 ± 1	9± 0.4	8 ±0.4	8 ± 1	8± 1	7 ± 1	7 ± 0.2
W^1	0.92	0.97	0.98	0.92	0.96	0.93	0.95
P^2	0.289	0.838	0.979	0.277	0.769	0.423	0.567
	Potassium (g kg^{-1})						
System	1 day	7 days	14 days	21 days	28 days	56 days	84 days
CL	15 ± 2	12 ± 3	11± 2	10± 2	9± 1	8± 0.3	7± 1
CLT	16 ± 3	13± 3	11 ± 1	10± 3	9 ± 1	8± 0.4	6± 0.4
W^1	0.97	0.94	0.91	0.96	0.80	0.86	0.91
P^2	0.852	0.451	0.231	0.768	0.010	0.048	0.184
	Sulphur (g kg^{-1})						
System	1 day	7 days	14 days	21 days	28 days	56 days	84 days
CL	8 ± 1	7 ± 0.1	7 ± 1	7±0.4	7± 0.57	7± 0.4	6 ± 1
CLT	8 ± 1	8± 0.4	7 ± 0.3	7± 0.4	7± 0.89	7± 0.2	6 ± 1
W^1	0.93	0.93	0.93	0.98	0.89	0.96	0.90
P^2	0.396	0.365	0.362	0.966	0.133	0.736	0.167

*, **, ***, and ns denote significance at $p \leq 0.05, 0.01, 0.001$ and 'not significant', respectively. ^{1}W: Normality values (Shapiro–Wilk test); ^{2}P: The *p-value* statistic is a conditional probability of the Shapiro–Wilk test.

1.3.4 Dry Matter Decomposition of the Cattle Dung Residues and Nutrient Release

Dry matter loss from the cattle dung was described by the single exponential decay model for all systems (Figure 5). The *act* of the DM from the cattle dung residue that decomposed was ~80% (CL and CLT), and the *res* was ~20% (Figure 5). However, the k ranged from 0.04 (CL) to 0.02 (CLT) day^{-1}. Consequently, the $t_{1/2}$ of initial residue ranged from 17 (CL) to 29 (CLT).

Figure 5. Dry matter remaining (%) from the cattle dung residue, during exposure into the pasture (i.e., *Lolium multiflorum* + *Avena strigosa*) as affected by the systems (CL, crop–livestock and CLT, crop–livestock–tree). Dry matter or N, P, K and S remaining *(rem) = res + act* e^{-kt}. *res*, resistant fraction; *act*, active fraction; *k*, non–linear decay rate; *t*, time; r^2, coefficient of determination.

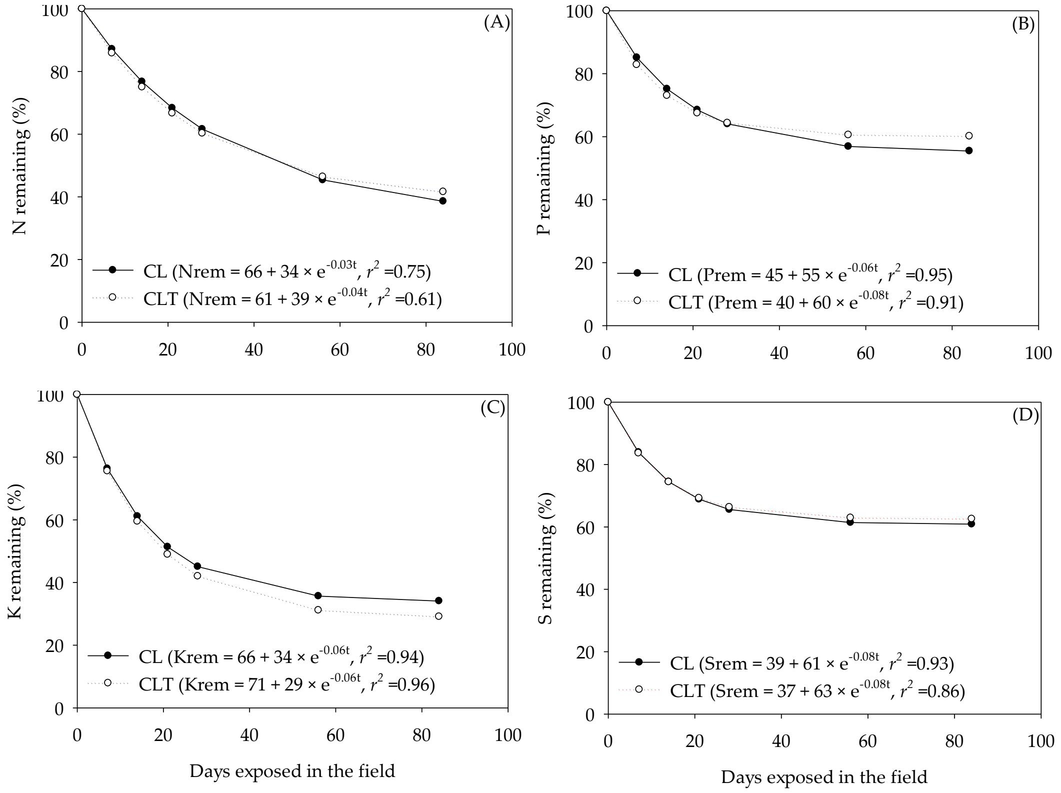


The *act* of N ranged from 34% (CL) to 39% (CLT) while the *k* of N ranged from 0.03 (CL) to 0.04 (CLT) day^{-1}, in the cattle dung residue (Figure 6). Consequently, the days required to release 50% of the initial N from the cattle dung residue ranged from 22 (CL) to 18 (CLT).

A few days were required to release 50% of the initial P and S, that is, the $t_{1/2}$ were 12 days (CL) and 9 days (CLT) for P, and 9 days (CL) and 8 days (CLT) for S (Figure 6) for the cattle dung residues. Phosphorus and sulphur were the nutrients showing high concentrations at the end (84 days) of the incubation period; this is, on average, 55% (CL) and 60% (CLT) for P, and 61% (CL) and 63% (CLT) for S (Figure 6) for the cattle dung residues.

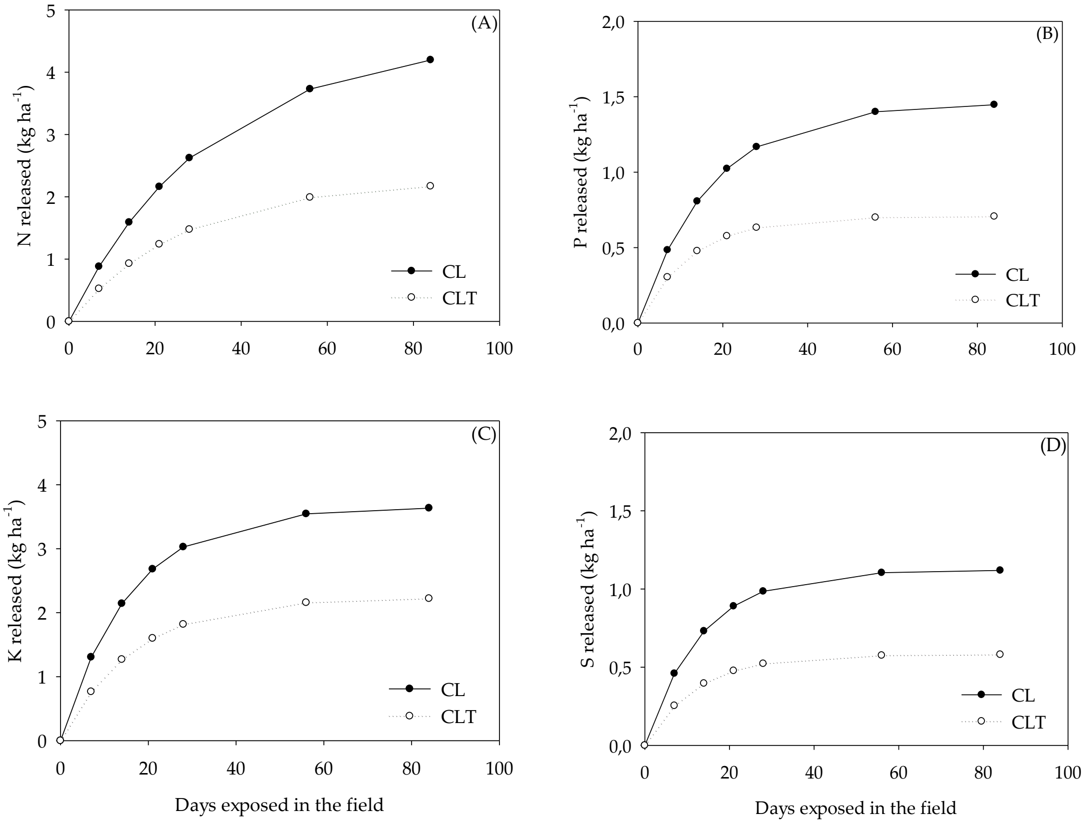
The $t_{1/2}$ of K ranged from 11 days (CL) to 12 days (CLT) for the cattle dung residue. Potassium was the nutrient showing a lower concentration at the end (84 days) of the incubation period, that is, on average, 34% (CL) and 29% (CLT) for the cattle dung residues.

Figure 6. Nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) remaining from the cattle dung residue, during exposure into the pasture (i.e., *Lolium multiflorum* + *Avena strigosa*; A, B, C and D) as affected by the systems (CL, crop–livestock and CLT, crop–livestock–trees). Dry matter or N, P, K and S remaining *(rem)* = *res* + *act* e^{-kt}. res, resistant fraction; *act*, active fraction; *k*, non–linear decay rate; *t*, time; r^2, coefficient of determination.



The largest nutrient releases occurred in CL (Figure 7). For instance, the total P released from the cattle dung (on day 84) and potentially available to the systems was about two times greater in the CL system (1.4 kg P ha^{-1}) than in the CLT (0.7 kg P ha^{-1}; Figure 7) due to the differences in the total quantity of cattle dung and number of animals (Table 2). The total N, P, K and S released from the cattle dung residues was lower in the CLT (2.2 kg ha^{-1}of N; 0.7 kg ha^{-1} of P; 2.2 kg ha^{-1} of K and 0.6 kg ha^{-1} of S), compared to that of the CL (4.2 kg ha^{-1} of N; 1.4 kg ha^{-1} of P; 3.6 kg ha^{-1} of K and 1.1 kg ha^{-1} of S) (Figure 7), i.e., a ICLS, and must be considered in the fertilization management.

Figure 7. Nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) released (kg ha^{-1}) from the cattle dung residue, during exposure into the pasture (i.e., *Lolium multiflorum* + *Avena strigosa*; A, B, C and D) as affected by the systems (CL, crop–livestock and CLT, crop–livestock–tree).



1.4 DISCUSSION

1.4.1 Pasture and Animal Production

The observation of a higher Gha in the CL, compared to the CLT systems (Table 2), can be explained by the greater herbage mass throughout the winter, increasing the pasture carrying capacity. However, in 2018, both in the CL and in CLT systems, the Gha fell far below the potential of the annual cool season pastures in the ICLS, due to the lower availability of rainfall during the winter (particularly in July, see Table 1). Values of ~490 kg LW ha^{-1} (LOPES et al., 2008) and 370 kg LW ha^{-1} (DA PONTES et al., 2018) have been observed for a mixture of black oat and ryegrass in the ICLS when the targeted SH was 20 cm.

Lower animal performance in the CLT systems could be linked to both the shade effect and difficulty in maintaining the target SH, particularly in the CLT system (14 cm of sward height). Periods with SH below the targeted SH (i.e., 20 cm), during periods with stress, could be responsible for lower animal performance through bite mass limitation

(CARVALHO et al., 2013). A lower SR was also observed under trees (Table 2). The presence of trees leads to changes in structural sward characteristics (e.g., reduction in tiller density), changing the relationship between herbage mass and SH (DA PONTES et al., 2017). The consequence is a lower herbage mass under trees than those systems without trees, regardless of the SH (DA PONTES et al., 2017). Therefore, in order to maintain the same SH in both systems (i.e., CL and CLT), with different herbage mass, the number of animals (i.e., SR) in the CLT system was reduced.

Therefore, to maintain a greater SR on the CLT system, it is necessary to manage the trees (thinning and pruning) over time to avoid very large impacts on pasture productivity, in order to maintain the targeted SH and optimize animal performance. Further, to increase the efficiency of the CLT, beyond moderate grazing (i.e., 20 cm), moderate shade: 35%–37%, according to (PANG et al., 2019) must be adopted e.g., by increasing the frequency of thinning (DA PONTES et al., 2017) in order to decrease the negative effects on pasture growth and animal performance (PANG et al., 2019).

After 12 years of introduction of the tree component, the greatest light restriction, caused by the tree growth was the determinant for the differences observed between the systems. Long–term studies in the ICLS, particularly with trees, are important to ascertain the system viability, as well as to determine the need for the management of the tree component (i.e., thinning), in order to maintain the production diversification and income generation of the agricultural property.

1.4.2 Distribution of Cattle Dung

The range of area covered by each cattle dung here (i.e., 0.03 ± 0.01 m^2) is below the values reported by other authors, which extended from 0.05 to 0.09 m^2 (HAYNES; WILLIAMS, 1993); ~0.05 m^2 (BRAZ et al., 2003) and 0.12 m^2 (DA SILVA et al., 2014). However, the percentage of the dung-covered pasture surface, considering all samples, was similar to the magnitudes observed in other experiments: <1% in 10 weeks of grazing (BRAZ et al., 2003). The area covered by faeces represented only 0.7 and 0.5% for the CL and CLT, respectively, of the total pasture area during the 14-week experimental period. These values are directly related to the stocking rate. Although dung patches may cover only little surface of the grassland, the associated high nutrient input induces pasture growth, and these regions may contribute to ~30 % of the annual pasture production (HAYNES; WILLIAMS, 1993).

The number of cattle dung per animal per day (9 ± 1defaecations/animal per day) does not differ between the systems; however, they are below the values reported by other authors, i.e., between 11 and 16 (HAYNES; WILLIAMS, 1993), 10.8 (WHITE et al., 2001); and 9.8 defecations per day (BRAZ et al., 2002b). The number of defecations per day can be influenced by the environmental factors and grazing conditions (HAYNES; WILLIAMS, 1993).

However, between 2,652 and 1,810 cattle dung were recorded in the CL and CLT systems, respectively, during the evaluations. It is known that the faecal production is correlated with consumption and this, in turn, with animal performance (DE FACCIO CARVALHO et al., 2010). In the CLT system, with a high level of light restriction, animal performance was reduced when compared to the CL system. The consequence of this was the great differences found between the systems for the total production of cattle dung.

As the average frequency of defecation was 9 ± 1defaecations/animal per day and the average dung weight at each defecation was of 170 ± 18 g DM, the estimated daily faecal excretion was 1.5 kg DM per animal per day. Thus, considering the stocking rate of three animals per hectare in the CL and two animals per hectare in the CLT system (Table 3), and the 105-day grazing period, in the present study, over the grazing period, the total dry mass of cattle dung deposited on the soil surface was 477 and 318 kg of DM in the CL and CLT systems, respectively.

The geostatistical analysis of the Thiessen areas adjusted different models to the semivariogram throughout the evaluations (Table 4), revealing that the animals deposit their dung in different positions during each period, also evidenced by the different ranges of spatial dependence of the data. The higher the range values (Table 4) the greater the spatial continuity in the distribution of cattle dung by the area, while, the lower the values, the less the spatial continuity conferred in the dung distribution, as explained by the dung deposition in attractive sites. Despite this, when all the samplings are considered, and the different models (Table 4) are added over time, a visual pattern is presented in the behavior of the spatial distribution of the cattle dung, among the ICLS. However, differences are observed in the semivariogram and distances, due to the different areas and paddock shapes. Validation studies of the semivariogram analysis enabled the observation that the deposition of cattle dung follows a clear distribution pattern in relation to the attractive points, as was also reported by other authors (WHITE et al., 2001; CARNEVALLI et al., 2019; AUERSWALD et al., 2010; HAYNES; WILLIAMS, 1993; BAILEY; WELLING; MILLER, 2006). In the CLT, the distribution was more uniform when trees were present (9 × 28 m), which is evident by the lower reach in the semivariogram adjusts for the CLT (25 m) in relation to the CL (30 m), when considering the Thiessen areas formed from the concentration points (Figures 3 and 4).

In tropical conditions, the trees available in the pastures affect spatial distribution of the dung, stimulating homogeneity (CARNEVALLI, et al., 2019). This behavior may be caused by the fact that the animals prefer to spend most of the day under the shade of the trees, in a tropical climate (GIRO et al., 2019), leading to homogeneous nutrient return and concentration in pasture areas, such as close to the shade and water areas (DUBEUX et al., 2014). Consequently, in the CLT system, the dung patches were distributed close to the shaded areas. These shaded places were the favorite places for the heifers to ruminate and idle away the time, when they defecated more (GIRO et al., 2019). In fact, the behavior of the animals observed in our study, i.e., in a subtropical region, was like that observed in the tropical climates, contrary to our initial hypothesis. Thus, shady areas in the pastures, with well distributed trees throughout these areas, are recommended for subtropical conditions to improve the spatial distribution of cattle dung in the area.

The CL system present higher concentrations of dung at sites near the rest areas (for ruminating and idleness), mineral supplement points, water troughs and fences opposite the gate. Consequently, the pattern in which nutrients are returned to the pasture, as the dung, is heterogeneous. Due to this uneven pattern, probably, a nutrient build-up is observed in these areas of the campsite (gates, water troughs, mineral supplements points and socialization areas) as well as depletion in the nutrient in the rest of the grassland. In order to minimize these effects, an option could be an increase in the frequency of changes in the positions of the gate, fences, water troughs and mineral supplement points.

Under our experimental and subtropical conditions, as the tree arrangement was 9 × 28 m (~40 trees ha^{-1}), there was a probably greater inclination for the animals to rest and ruminate near the trees; consequently, there is a more even distribution of dung over the experimental units, since trees were well distributed throughout the area. This probably reduces nutrient losses and favors more efficient cycling within the system.

1.4.3. Dry Matter Decomposition and Nutrient Release of Cattle Dung Residues

The cattle dung disintegration process, that is, the disappearance of DM, occurred in a restricted manner, since an 11-mm precipitation was observed (July 2018, in the study period, Table 1). Low precipitation could have delayed the physical disintegration of the cattle dung because this process is favored by the impact of raindrops (HAYNES; WILLIAMS, 1993), together with the microbiological activity, as the main factor responsible for the disintegration or decomposition of the dung. The low rate of cattle dung decomposition is also associated with the presence of recalcitrant constituents (~20%, Figure 5). Therefore, below 20% of the DM of the plates disappeared during the 84 days of the study. Further, in the current study, since the SH was maintained below 20 cm in CLT systems, the animals probably ingested low-quality plant parts (e.g., stem and leaf sheath, i.e., plant parts with a higher fibre and lignin content than leaves), when compared with animals in the CL system. This could help to explain the slightly difference between systems on dry matter decomposition of the cattle dung residues, with as lower degradation in CLT systems. A higher C:N ratio favors a slower decomposition.

Total quantities (kg ha^{-1}) of N, P, K and S released from the dung residue (Figure 7) and potentially available to the actual and subsequent crop were more likely related to the quantity of dung residues which were, in general, reduced in the CLT, rather than to any changes in the dung quality due the shading effect.

Nitrogen was the nutrient present at the greatest initial concentration in cattle dung (~19 g kg^{-1}, Table 5), probably because the more labile compartments are broken down in the animal rumen, a small amount is retained in the animal's tissue, and most is released with urine and dung (CARVALHO et al., 2013). However, because mineralization is microbially driven, several factors affect it, including temperature and soil moisture (EGHBALL et al., 2002). Nitrogen mineralization increases with the rising temperature under conditions found in agricultural soils (EGHBALL et al., 2002). For instance, the total N released from the cattle dung residue (at 84 days) and potentially available to the actual and subsequent soybean crop was about two times greater in the CL (4 kg N ha^{-1}) than in the CLT system (2 kg N ha^{-1}; Figure 7) due to differences in the total quantity of cattle dung (Table 3), since a higher number of heifers were present in the CL systems (3 cattle ha^{-1}), while a lower number (2 cattle ha^{-1}) were present in the CLT.

As N was the nutrient present in the highest initial concentration (Table 5), the greatest N release occurred from the cattle dung residue, regardless of the systems (Figure 7). However, we should take into account that the N values released in the pasture phase were related only to the N cycling by the decomposition of a single compartment (cattle dung), and not to the great potential of the N cycling of the whole system. Nitrogen release from cattle dung can be attributed to the easily decomposable fraction by microorganisms (low C:N ratio), quality (structure) and lignin content (SEMMARTIN et al., 2008; ASSMANN et al., 2015).

Rapid P releases had been reported by (ASSMANN et al., 2017). Moderate grazing also caused the speedier release of P from the dung, as indicated by the lower $t_{1/2}$, namely, 5 to 6 days in the labile fraction (ASSMANN et al., 2017). The rapid P releases from the dung have been related to the quality (structure) and lower lignin content (ASSMANN et al., 2017; SEMMARTIN et al., 2008). The phosphorus availability from cattle dung is high (>70%), as most of the dung P is inorganic and becomes plant-available (EGHBALL et al., 2002).

The $t_{1/2}$ of K released from the dung was similar to the report of (ASSMANN et al., 2017; HAYNES; WILLIAMS, 1993). This rapid release of K occurred because most of the K is in water-soluble form (ESSE et al., 2001). Between 60%–70% of the K ingested by animals returns to the soil system (RODRIGUES et al., 2008). These observations suggest the importance of the dynamics of K in the balance and maintenance of the system. Grazing animals significantly alter the cycling of K, mainly due to the spatial heterogeneity of K return via animal excreta (MATHEWS et al., 1994).

A few days were necessary for the release of 50% of the initial S, that is, the $t_{1/2}$ were 9 days (CL) and 8 days (CLT) for the cattle dung residue. In the initial stage, the pattern of release was rapid, after which it was constant up to 84 days. The dynamics of S is dependent on the dynamics of N. The rate of release of the available S content is dependent upon environmental conditions, initial concentrations and characteristics of the S, as well as the microbial population in the soils (DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY, 2017). It might be due also to the increase in the strength of mineralization and the increased microorganism activity during this period. These favorable conditions boost the S release. After 21 days, there was a slight reduction in the available S content, which might have been caused by the commencement of the immobilization and hampered mineralization, as well as the reduced microbial activity (DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY, 2017). Probably, the remaining material in the field is highly resistant, i.e., with a high content of lignin and fibre, which is more difficult to decompose (WHITEHEAD, 2000). It is important to highlight that urinary excretion present: 76–82% of N, P insignificant, 70–90% of K and 6–90% of S.

From these results, and considering 84 days after the entry of the animals, about ~60% of the N, ~42% of the P, ~68% of the K and ~38% of the S present in the cattle dung, in the active fraction, was completely released. This represents about 4 and 2 kg ha^{-1} of N; 1.4

and 0.7 kg ha^{-1} of P; 4 and 2 kg ha^{-1} of K and 1.1 and 0.6 kg ha^{-1} of S in the CL and CLT, respectively, released by cycling in the initial residue (Figure 7). Briefly, small quantities of N, P, K and S were cycled from cattle dung under a beef-cattle and soybean integration system but must be considered for fertilization management practices.

The nutrient cycling could have been much higher had it not been a drought winter (Table 1). For example, a study with the CL system in the subtropics, with different heights and 120 days of grazing, showed a cycling of around 3 to 8 kg ha^{-1} of P and 10 to 22 kg ha^{-1} of K cycled by dung (ASSMANN et al., 2017). Thus, for instance, it has been recommended to use simple specific fertilizer sources [e.g., monoammonium phosphate (MAP), diammonium phosphate (DAP), and potassium chloride (KCl)] in ICLS, that have a high concentration of specific nutrients, rather than N–P–K formulated fertilizers, which make it possible to achieve more technically adequate management and more economic efficiency for rural producers, avoiding losses and luxury consumption (BERNARDON et al., 2020), when also considering the nutrient cycling by residues.

Our results reinforce the importance of keeping the animals permanently in the area, in order to reduce the nutrients losses from animal excreta. Another factor that contributes to the reduction of losses from excreta is a more uniform distribution, in order to make better use by the intercropping. Further, an adequate management of grazing intensity allows greater biomass production, increasing the SR and excreta deposition. Our results, therefore, also reinforce the necessity to understand the nutrient release patterns from residues (animal, soil, plant, atmosphere and fertilizer addition) over the long term, for ICLS conditions, to improve fertilization management. Furthermore, it is imperative in the ICLS with trees to intensify silvicultural practices over time, to minimize the effect of the trees on intercropping productivity, to ensure a more constant addition of residues (from both the crop and stocking phases) and to promote productive, economic and sustainable stability of these systems (CARPINELLI et al., 2020a). Therefore, a few feasible silvicultural interventions need to be considered to avoid losses in pasture, thus maximizing the number of animals and nutrient cycling benefits.

In addition, it is recommended to use ICLS systems with trees because, in addition to contributing to nutrient cycling, these systems are particularly important to recovery of degraded areas, especially in steep areas, since tree lines contribute to soil conservation. Further, ICLS with trees makes it possible to increase income diversification for the producer, making more sustainable agriculture, and being a technology fully in line with the goals of the Brazilian government in the Low Carbon Agriculture (ABC) program.

1.5 CONCLUSIONS

The pattern in which the nutrients are returned to the pasture in the form of dung is no-nuniform for the crop–livestock system. The crop–livestock–tree system shows a more homogeneous spatial dung distribution, despite a few small points of concentration which continue to remain in areas, such as around the cow drinkers and the gate.

The integrated crop–livestock systems had no effect upon the decomposition and release dynamics for nitrogen, phosphorus, potassium, and sulphur from dung. However, the total of this nutrients released from the cattle dung and which was potentially available for the crops varied according to the integrated crop–livestock system, depending on the number of animals present during the grazing period and the quantity of the cattle dung.

2 EFFECT OF TREES AND CATTLE DUNG INPUT ON SOYBEAN YIELD AND NUTRITION IN INTEGRATED CROP–LIVESTOCK SYSTEMS

Abstract: In integrated crop–livestock systems (ICLS), grazing cattle influence the distribution of nutrients in the soil. When trees are present, they may affect the cattle dung distribution, as well as the nutrient cycling and crop yield. The objective of this experiment is to evaluate the influence of the presence of cattle dung and trees on soybean nutrition and yield in ICLS during 2018–2019. Two areas were used in this study, that is, with trees (CLT, 1.1 ha) and without trees (CL, 1.2 ha). Both areas have been considered as ICLS (soy–beef cattle), since 2009. The experimental design was in a split–split–plot, the main plots followed the CL and CLT systems, the subplots were the cattle dung input (presence and absence), and the sub-subplots were three positions between the tree rows. In the CL system the plant height (+18.1%), the number of pods per plant (+51.2%), grains per pod (+7.2%), shoot biomass (+60%) and grain yield (+52.9%) were increased compared to the CLT system. The highest values for plant height, shoot biomass, grain yield, grain weight, pods per plant, grains per pod, and phosphorus (P) concentrations in soybean, were observed in the central position among the tree rows, when comparing the positions nearest to the trees. However, in the position adjacent to the rows, an increased content of P in the soil was found and an increased content of sulfur (S) in the plant. The presence of cattle dung increased the availability of soil P (+30%) and potassium (K, +52.3%), as also the content of P (+4.3%), K (+5.2%), and S (+5.1%) in plant, and the grain yield (+22%). The great effect on soybean yield was due the trees presence (3.6 Mg ha^{-1} in the CL system vs. 1.7 Mg ha^{-1} in the CLT). The light restriction, the competition for nutrients with trees and drought periods were factors to be considered, to explain the difference in productivity between the CL and CLT systems.

Keywords: *Glycine max* (L.) Merrill, low carbon agriculture, light restriction, plant nutrition

2.1 INTRODUCTION

The Integrated Crop–Livestock Systems (ICLS) are categorized by exploring synergies between their components and by emerging properties (MORAES et al., 2014; CARVALHO et al., 2018). They constitute interactions planned at different space−time scales, which include the exploitation of agricultural crops and animal production in the same area that can be an alternative to reconcile conflicts of interest to society (CARVALHO et al., 2018).

The bovine in ICLS represents the entry of new flows (intensification of nutrient cycling) and interactions within the system, also increasing the economic resilience and soil quality (MORAES et al., 2014; CARVALHO et al., 2018). The presence of grazing animals is beneficial for the culture implanted in succession, as it influences the cycling and distribution of nutrients in the soil, via defoliation of plants, and their return to the soil, through excreta, such as dung and urine (DUBEUX et al., 2007).

Nutrients like nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) can undergo different transformations in the different compartments of the ecosystem (DUBEUX et al., 2007). These transformations can leave the element available for absorption and use by plants and microorganisms, as well as give more exposure to processes that result in the loss of these nutrients (DUBEUX et al., 2007). For example, a study with long-term soybean–cattle showed that in areas with dung, the levels of available P and K in the soil, as well as the number of pods per plant were considerably higher, increasing the grain yield of soybean in relation to the areas without cattle dung (DA SILVA et al., 2014).

The nutrients are not evenly distributed between the faeces and urine. The P, for example, practically returns only through feces; urine is the main pathway for the return of K; even as N and S are excreted in both forms (WILLIAMS and HAYNES, 1990). The amount of macronutrients released from cattle dung and potentially available for crops, current and subsequent, depends mainly on the number of animals during the grazing period (CARPINELLI et al., 2020b), age of the animals, and the amount of nutrients present (quality). Furthermore, due to the high concentration of dung in the rest areas and near water tanks, there is an increase in the levels of P and K in the soil in these areas (SANDERSON et al., 2010) and a heterogeneous distribution of cattle dung (CARPINELLI et al., 2020b).

When including trees (CLT) in pasture locations, in addition to enhancing environmental benefits, trees provide greater resilience to the system, as well as shelter and an improvement in pasture quality (JOSE and DOLLINGER, 2019). In general, C3 species, as soybean, are more tolerant to the shade than C4 species (LISTA et al., 2019). According to Magalhães et al. (2019), the soybean crop only shows a reduction in productivity due to the lower incidence of sunlight after the fourth year of implementation of the CLT system, while maize has shown a drop in productivity after the third agricultural year. Similarly, in CLT systems, grazing animals spend proportionally more time under the shade of trees, contributing to greater uniformity in the spatial distribution of excreta when the trees are well-distributed in the entire plot (CARPINELLI et al., 2020b).

The present study is based on the hypothesis that the nutrients that are returned to the soil via cattle dung would affect their availability in the area and positively impacts the grain yield of the crop implanted in rotation to pasture. Moreover, the more homogeneous distribution of cattle dung in wooded areas can contribute to minimizing the negative effects of shading on soybean production. The objective of the present study is to evaluate the influence of the presence of cattle dung and trees, in ICLS, on the contribution of the chemical attributes to the soil, soybean nutrition, and production.

2.2 MATERIALS AND METHODS

2.2.1 Local Characteristics, Experimental Design and Treatments

The present study was conducted at the Rural Development Institute of Paraná - IAPAR–Emater (25◦07'22"S, 50◦03'01"W) in Ponta Grossa, Paraná, Southern Brazil. The climate type was Cfb, humid subtropical, according to Köppen's classification. The mean annual temperature was 18.3 °C, ranging from 14.2 °C in July to 24.5 °C in February, with a mean annual rainfall of 1170 mm (Table 6). The soils were classified as Typic Distrudept and Rhodic Hapludox. The average soil chemical and granulometric attributes (0–20 cm layer) at the end of crop phase (May 2018) were: pH–$CaCl_2$= 4.9, P (Mehlich–1)= 23.4 mg dm^{-3}; 2, 28 and 11 $mmol_c$ dm^{-3} of exchangeable K, calcium (Ca) and magnesium (Mg); respectively; base saturation of 48.4%; carbon (Walkley–Black) was 14.9 g dm^{-3}; 270, 30, and 710 g kg^{-1} of clay, silt, and sand, respectively.

Table 6. Mean monthly temperature (°C) and total rainfall (mm) during the experimental period (2018-2019) and historical minimum–maximum (HM, 21–year mean).

Months	**Temperature (°C)**		**Total rainfall (mm)**	
	2018/2019	**HM**	**2018/2019**	**HM**
May (2018)	16.4	9.4 – 17.3	37.0	6.4 – 213.8
June	14.2	11.9 – 17.3	109.6	4.8 – 327.6
July	15.2	11.5 – 15.8	11.0	2.0 – 273.4
August	13.9	13.13 – 17.3	43.4	2.2 – 315.2
September	17.0	14.8 – 19.8	43.6	27.2 – 301.6
October	17.8	16.5 – 20.9	238.6	35.6 – 267.6
November	19.7	17.9 – 22.6	26.8	20.2 – 247.4
December	22.0	20.3 – 22.4	162.4	29.4 – 261.2
January (2019)	22.8	20.3 – 22.8	72.4	68.0 – 337.4
February	20.7	20.20 – 22.6	138.8	11.2 – 351.2
March	20.6	19.7 – 22.7	181.6	21.0 – 319.6
April	19.7	17.7 – 21.2	104.8	3.8 – 260.2

Source: SIMEPAR (station 25135001, situated about ~8 km southwest of the present study), Ponta Grossa – PR.

In 2006, three tree species (eucalypt, *Eucalyptus dunnii*; pink pepper, *Schinus molle*; and silver oak, *Grevillea robusta*) were planted in the CLT. The species were interspersed in the same rows, running crosswise in relation to the slope, 3 × 14 m spacing (238 trees ha^{-1}). The direction of the layout was predominantly facing Southwest–Northeast. After some thinning (see DA PONTES et al., 2020), during the present study, the new tree arrangement was 9×28 m (~40 trees ha^{-1}), with only eucalypt.

Since the 2010 winter, the production system integrated cattle grazing (Purunã beef heifers) cool-season pastures (ryegrass, *Lolium multiflorum* plus black oat, *Avena strigosa*), with a variable number of animals, periodically adjusted to maintain the desired sward height of 20 cm, i.e. the “put-and-take” method (Mott and Lucas 1952). Maize (*Zea mays*) or soybean (*Glycine max*) crops were cultivated alternately in the summer, in the same area, using no-till.

The experimental data collected in this study only refers to the twelfth pasture–crop rotation year. The black oat (cv. IPR 61) plus ryegrass (cv. São Gabriel) mixture was sown in rows with 45 and 15 kg ha^{-1} of seeds, respectively, at the end of May 2018. In addition, 400 kg ha^{-1} of commercial N–P_2O_5–K_2O fertilizer 04–30–10 was applied. On 18 June, 2018, 90 kg ha^{-1} of N was applied in the form of urea.

The statistical arrangement was a split-split-plot design with two ICLS (with and without trees, CLT and CL, respectively) and two cattle dung concentrations (presence versus absence of cattle dung), with six replications (Fig. 8). In the CLT, there were three positions between the two tree rows, namely: P3, the central position between two tree rows; P1, positions adjacent to the rows; and P2, the intermediate positions (Fig. 9), totaling 12 plots for CL and 36 plots for CLT.

Figure 8. Digital map indicating the absence and presence of cattle dung in the different areas (CL, crop–livestock and CLT, crop–livestock–tree systems). Dark gray represents areas with presence of cattle dung, whereas, the white areas indicate absence of cattle dung. Axes X and Y with Universal Transverse Mercator (UTM) (in meters).

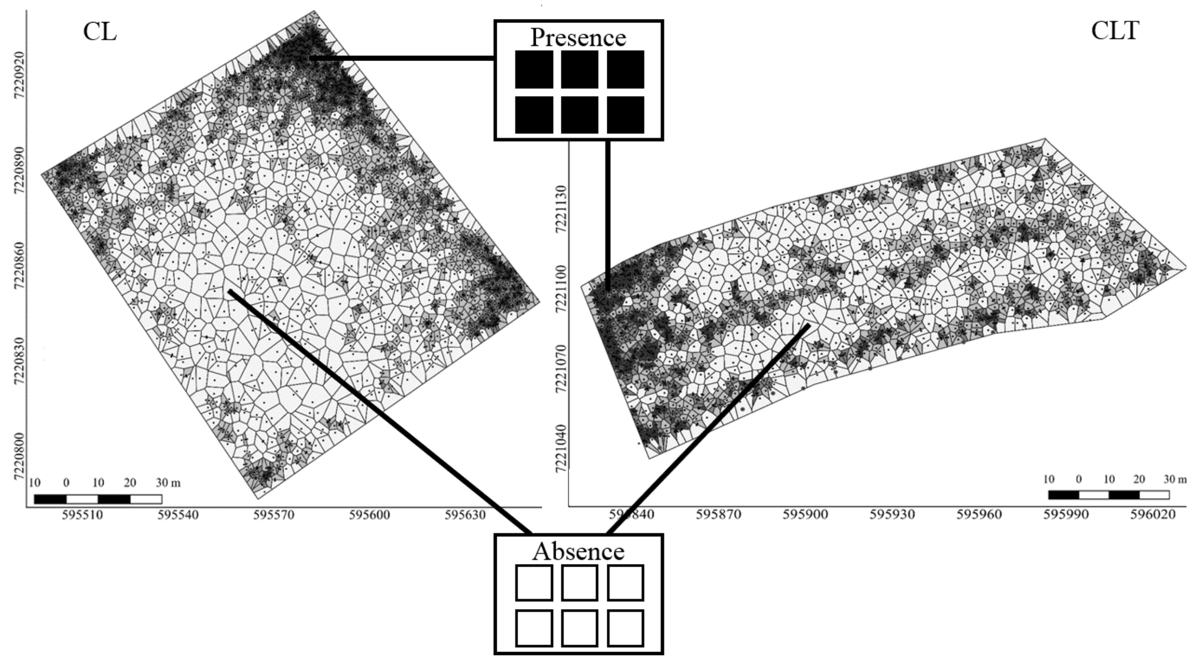
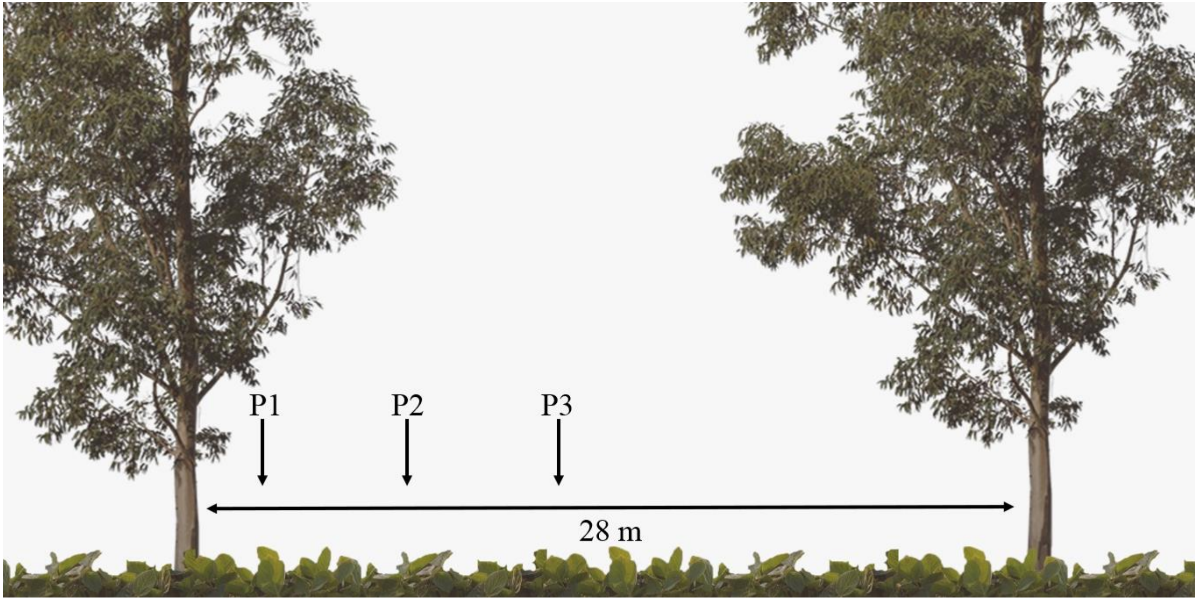


Figure 9. Positions between the tree rows in the crop–livestock system, namely: P3, the central position between two tree rows; P1, position adjacent to the rows; and P2, the intermediate position. At the start of the experimental period (December 2018), the mean percentage of light reduction under the tree canopy was 51% for P1, 38% for P2, and 22% for P3.



The experimental area (2.3 ha) was divided into two paddocks (see Fig. 8): one paddock (1.2 ha) was used since 2009 in the CLT system and another paddock (1.1 ha) in the CL. This experiment has been part of a long-term study protocol (e.g. see DA PONTES et al., 2018).

The grazing period in the current study occurred between July and October 2018, where in, the cattle dung input was geo–referenced every 20 days, using a geodesic GPS. A digital map was then created based on the spatial distribution of cattle dung accumulated during the grazing period using the ArcView GIS 3.2 software.

Prior to the soybean establishment, the plots were demarcated according to the dung spatial contribution digital map in each system, as represented in Fig. 8. Each plot consisted of 6 soybean rows, 3.0 m in length, spaced 0.4 m apart and totaling 7.2 m^2. The size of plots was defined based on the cattle dung congregation that is, with visual presence or absence of dung in the plots according to the treatment.

2.2.2 Soybean Management

The area was desiccated with glyphosate herbicide (2.3 L ha^{-1} of [1,1'–dimethyl–4,4'–bipyridinium] active ingredient [a.i.]) and mineral oil adjuvant (1 L ha^{-1}a.i.). After two days (on November 7, 2018), the soybean (Apollo – RR) seeds were inoculated with *Bradyrhizobium sp.* Stirps treatment, with 3–(2–chloro–1,3–thiazol–5–ylmethyl)–5–methyl–1,3,5–oxadiazinan–4–ylidene(nitro)amine (Thiamethoxam), and sown. The seeds were sown at a density of 10 seeds m^{-1} spaced 0.40 m between rows, and 230 kg ha^{-1} of the commercial NPK fertilizer 02–20–18 (N–P_2O_5–K_2O) + 16 kg ha^{-1} of S was applied (4.6 of N, 46 of P_2O_5 and 41.4 of K_2O).

On January 5, 2019, N–(phosphonomethyl) glycine (2.0 L ha^{-1}) was applied together with trifloxistrobina+tebuconazol (0.5 L ha^{-1}) and 0.3 L ha^{-1} of mineral oil (adjuvant). On January 29, 2019, azoxystrobin (200 g ha^{-1}) + clorpirifós (500 ml ha^{-1}), fungicide, and insecticides, respectively, and 250 ml ha^{-1} mineral oil (adjuvant) were applied. On February 20, 2019, the herbicides N–(phosphonomethyl) glycine (1.2 L ha^{-1}) + carfentrazone–ethyl (0.07 L ha^{-1}) were applied, together with the insecticides, imidaclopride+beta-ciflutrina (300 ml ha^{-1}); bifenthrin (60 ml ha^{-1}), and the fungicides trifloxistrobina+protioconazol (400 ml ha^{-1}); along with 250 ml ha^{-1} of mineral oil (adjuvant).

2.2.3 Sampling Procedures and Analyses

Soil samples from plots with and without cattle dung plus the respective positions between the tree lines were collected on January 14, 2019. From these samples the available P and exchangeable K was estimated, according to Pavan et al. (1992).

At the phenological stages V3 (FEHR and CAVINESS, 1977), 35 days after sowing, the initial plant population was evaluated in each plot (2 m linear). To determine the shoot biomass (stage V8 and R2), 10 plants were collected, cut above the surface of the soil, and dried at 50° C, until constant weight. After drying, the soybean samples were weighed, ground, and analyzed for the levels of N, P, K, and S, according to Malavolta et al. (1997).

At the R8 stage (full maturity), the following evaluations were recorded: the height of 20 plants, measured randomly, and the final plant population (2 m linear); and, in 10 plants per sub-subplots: pods per plant; grains per pod; insertion of the first pod and the weight of 1000 grains (estimated by the count of three samples of 100 grains). The weight values of 1000 grains and productivity were adjusted to the moisture content of 130 g kg^{-1}.

2.2.4 Statistical Analyses

Analysis of variance was performed for all parameters using the split-split-plot model in program RStudio (R CORE TEAM, 2019). The main plots were the systems (CL and CLT), subplots were cattle dung input (presence and absence), and sub-subplots were positions between the tree rows (P1, P2, and P3, nested in the systems). All the factors, except the blocks, were considered as fixed terms. The error term for systems was “block(system)” and for the subplot error was “dung*block(system)”. Interactions were checked for each variable and removed from the model if they had a p-value >0.05.

2.3 RESULTS

Plant height, shoot biomass, pods per plant, grains per pod, soybean yield and K content in soil were higher in the CL systems than CLT (Table 7). In contrast, the insertion of the first pod was higher in the CLT system (Table 7). The N, P, K, and S content in the soybean plant did not differ among the different ICLS (Table 7), as also the initial and final plant population, grain weight, and P content in the soil.

Table 7. Plant parameters and nutrient contents in plant and soil in relation to two Integrated Crop–Livestock Systems (ICLS) – (with and without trees, CLT and CL, respectively).

Parameter	**ICLS**	
	CL	**CLT**
Initial plant population at V3 (n◦ m^{-2})	18.9a	18.8a
Final plant population at R8 (n◦ m^{-2})	17.2a	17.4a
Plant height at R8 (cm)	58.7a	48.1b
Shoot biomass V8 (Mg ha^{-1})	46.3a	19.1b
Shoot biomass R2 (Mg ha^{-1})	111.5a	44.8b
Plant N at V8 (g kg^{-1})	32.9a	33.2a
Plant N at R2 (g kg^{-1})	28.8a	30.9a
Plant P at V8 (g kg^{-1})	2.0a	2.0a
Plant P at R2 (g kg^{-1})	1.9a	1.9a
Plant K at V8 (g kg^{-1})	36.2a	35.0a
Plant K at R2 (g kg^{-1})	24.2a	23.9a
Plant S at V8 (g kg^{-1})	1.7a	1.8a
Plant S at R2 (g kg^{-1})	1.6a	1.7a
Grain yield (Mg ha^{-1})	3.6a	1.7b
1000−grain weight (g)	143.7a	147.4a
Pods per plant (n◦)	88.9a	43.3b
Grains per pod (n◦)	2.4a	2.2b
Insertion of the first pod (cm)	8.6b	9.6a
Soil P (mg dm^{-3})	35.7a	39.1a
Soil K (mmol$_c$ dm^{-3})	5.7a	2.6b

Means followed by distinct letters on the line differ according to Tukey’s test ($P < 0.05$).

Greater values for soybean yield, grain weight, pods per plant and grains per pod, as well as, soil P and K contents were seen in areas with cattle dung input (Table 8). In contrast, soybean P, K, and S contents were affected by cattle dung input at V8, but not at R2 (Table 8). However, the initial and final plant population, plant height, shoot biomass, soybean N content and insertion of the first pod were not changed regarding the presence of cattle dung (Table 8).

Table 8. Plant parameters and nutrient contents in plant and soil in relation to the presence or absence of cattle dung in integrated crop–livestock systems.

Parameter	**Cattle dung**	
	Presence	**Absence**
Initial plant population at V3(n◦ m^{-2})	18.8a	18.9a
Final plant population at R8 (n◦ m^{-2})	17.5a	17.3a
Plant height at R8 (cm)	51.4a	50.1a
Shoot biomass V8 (Mg ha^{-1})	26.3a	25.6a
Shoot biomass R2 (Mg ha^{-1})	62.3a	60.6a
Plant N at V8 (g kg^{-1})	33.5a	32.7a
Plant N at R2 (g kg^{-1})	31.2a	29.6a
Plant P at V8 (g kg^{-1})	2.1a	2.0b
Plant P at R2 (g kg^{-1})	1.9a	1.9a
Plant K at V8 (g kg^{-1})	36.2a	34.3b
Plant K at R2 (g kg^{-1})	25.5a	22.4a
Plant S at V8 (g kg^{-1})	1.8a	1.7b
Plant S at R2 (g kg^{-1})	1.6a	1.7a
Grain yield (Mg ha^{-1})	2.5a	1.9b
1000−grain weight (g)	149.7a	143.3b
Pods per plant (n◦)	60.2a	49.3b
Grains per pod (n◦)	2.3a	2.2b
Insertion of the first pod (cm)	9.4a	9.3a
Soil P (mg dm^{-3})	45.0a	31.5b
Soil K (mmol$_c$ dm^{-3})	4.6a	2.2b

Means followed by distinct letters on the line differ according to Tukey's test ($P < 0.05$).

For the different positions between trees, in general, the shoot biomass, soybean yield, grain weight and pods per plant were higher at P3 (Table 9). The soybean plants height and the number of grains per pod were higher at P2 and P3 (Table 9). In contrast, soybean P and S contents differed among the three positions between the tree rows (Table 9). The P content was greater at P3; the opposite was observed for S, whereas, the greatest content was observed at P1 (Table 9). However, the initial and final plant population, the insertion of the first pod, plant N and K content, did not differ among the different positions (Table 9).

Regarding the positions of the trees, the soil K content did not change, but the soil P content displayed greater value at P1 (Table 9).

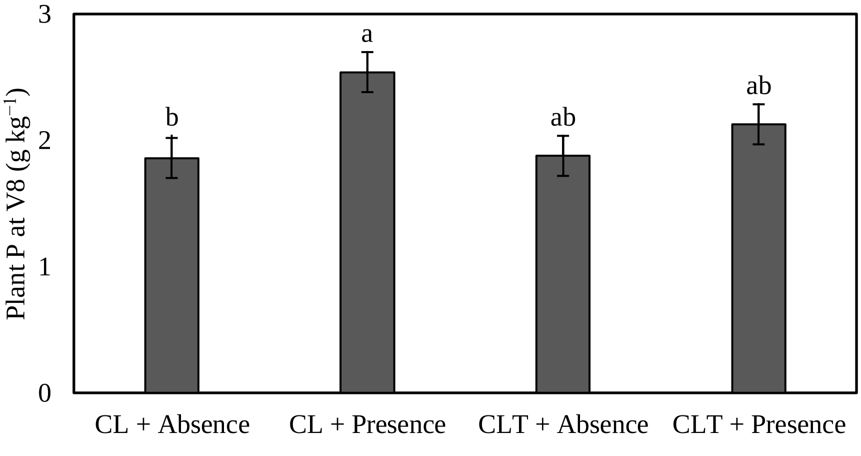
Table 9. Plant parameters and nutrient contents in plant and soil in relation to the three positions between the two tree rows in integrated crop–livestock systems, namely: P3, the central position between two tree rows; P1, positions adjacent to the rows; andP2, the intermediate positions.

Parameter	**Position (three positions between the tree rows)**		
	P1	**P2**	**P3**
Initial plant population at V3(n° m^{-2})	18.8a	18.8a	18.9a
Final plant population at R8 (n° m^{-2})	17.2a	17.5a	17.5a
Plant height at R8 (cm)	42.7b	49.4a	52.2a
Shoot biomass V8 (Mg ha^{-1})	14.9b	17.8b	24.6a
Shoot biomass R2 (Mg ha^{-1})	28.2c	41.7b	64.3a
Plant N at V8 (g kg^{-1})	33.0a	33.3a	33.1a
Plant N at R2 (g kg^{-1})	31.6a	30.8a	30.4a
Plant P at V8 (g kg^{-1})	2.0b	1.9b	2.3a
Plant P at R2 (g kg^{-1})	1.9b	1.9b	2.1a
Plant K at V8 (g kg^{-1})	33.6a	35.7a	35.5a
Plant K at R2 (g kg^{-1})	24.2a	23.9a	23.5a
Plant S at V8 (g kg^{-1})	1.9a	1.7b	1.7b
Plant S at R2 (g kg^{-1})	1.8a	1.6b	1.6b
Grain yield (Mg ha^{-1})	1.1b	1.5b	2.5a
1000−grain weight (g)	144.4b	141.4b	156.3a
Pods per plant (n°)	28.8b	40.9b	60.3a
Grains per pod (n°)	2.1b	2.2ab	2.2a
Insertion of the first pod (cm)	9.7a	9.8a	9.2a
Soil P (mg dm^{-3})	55.5a	27.1b	34.6b
Soil K (mmol$_c$ dm^{-3})	2.4a	2.2a	3.4 a

Means followed by distinct letters on the line differ according to Tukey's test ($P<0.05$).

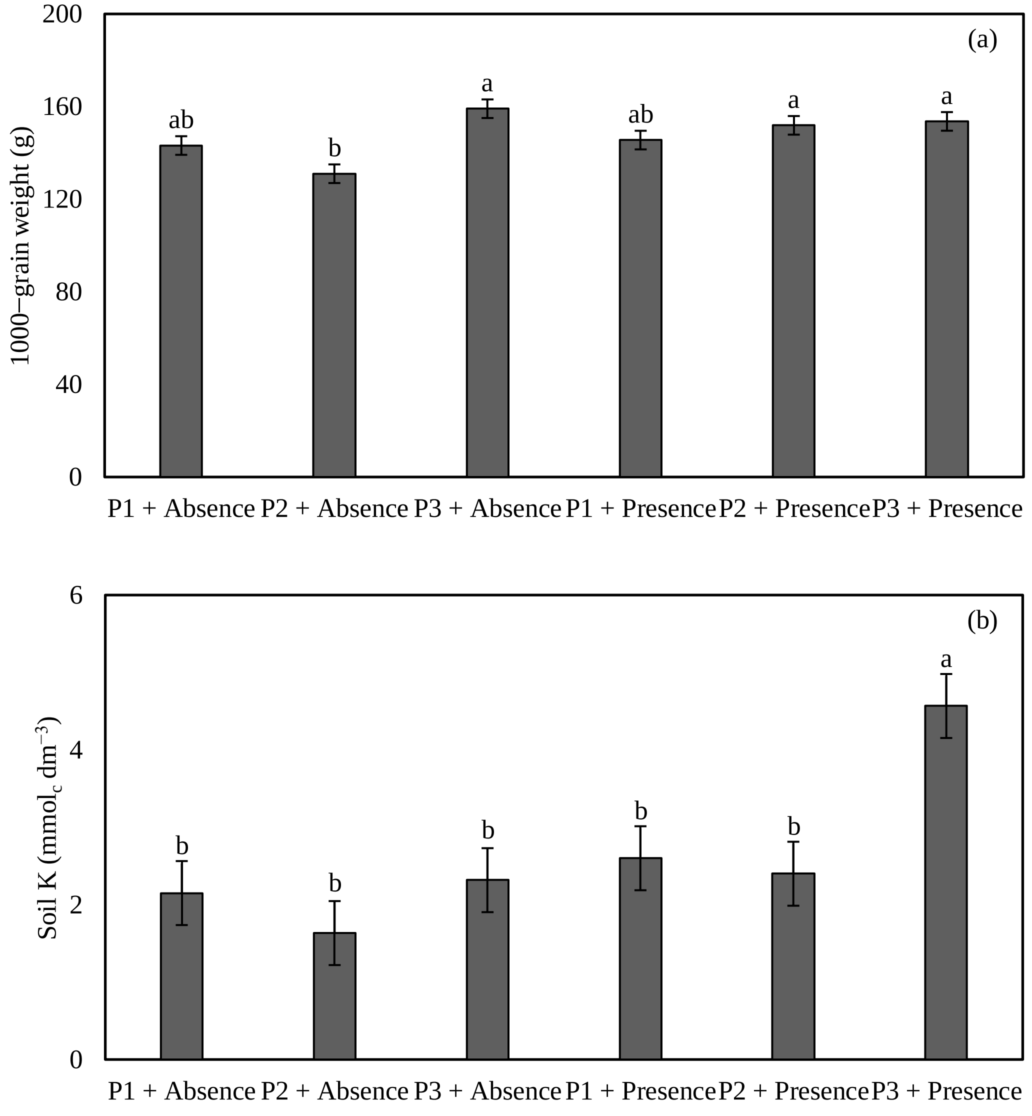
The biggest difference in P in plants, at V8 stage (Fig. 10), between ICLS occurred in areas without cattle dung.

Figure 10. Plant P from soybean residue, as affected by treatments (CL, crop–livestock *vs.* CLT, crop–livestock–trees systems; presence *vs.* absence of cattle dung). Means followed by the same lower case (compare cattle dung input within each system and compare systems for each cattle dung input) do not differ from each other by the Tukey's test ($P< 0.05$). Bars represent standard error.



Interactions between cattle dung and positions were observed only for grain weight and soil K content (Fig. 11). The grain weight varied between 145.5 (P1) and 153.6 g (P3) in the treatment with cattle dung and between 131.0 (P2) and 159.1g (P3) in the absence of cattle dung (Fig. 11a). The K content in the soil varied between 2.4 (P2) and 4.6 mmol$_c$ dm^{-3} (P3) in the treatment with cattle dung. In the absence of cattle dung, the K concentration in the soil remained at ~2.0 mmol$_c$ dm^{-3} regardless of tree positions (Fig. 11b).

Figure 11. Grain weight (a) and soil K content (b) from soybean residue, as affected by treatments (presence *vs.* absence of cattle dung; three positions between the two tree rows (see Fig. 2 for positions codes). Means followed by the same lower case (compare cattle dung input within each system and compare systems for each cattle dung input) do not differ from each other by the Tukey's test (*P* < 0.05). Bars represent standard error.



2.4 DISCUSSION

2.4.1 Available Soil with Phosphorus and Exchangeable Potassium

The P content in the soil did not differ among the different ICLS. Management practices that increase soil microbiota, that is, ICLS, can increase the availability of P and its uptake by plants increasing the recycling efficiency of this nutrient (SHARMA et al., 2013). However, differences were observed for the different positions, with the amount of P in the soil greater at P1. Our hypothesis is that animals in search of shade can directly interfere in the distribution of P returned by ruminants in CLT systems, making the concentration of P in the soil higher in areas closer to the shadows of the trees. It must be considered that long-term grazing cattle modify the soil environment, as cattle influence the decomposition of litter and accelerate the release of nutrients (SEMMARTIN et al., 2008). Another hypothesis is that the different amounts of tree residue that each position provides, will probably result in different amounts of nutrients being released over time. The shorter the distance from the trees (P1), the greater the proportion of branches and bark of the tree residue. Potassium in the soil was higher in the CL, as this nutrient returned very quickly to the system through animal excrement and plant residues (DUBEUX et al., 2007). Since the quantity of shoot plant residue and animal excrement were greater in CL system than CLT, due tree effect, a greater return of K by cycling is expected in CL (CARPINELLI et al., 2020a, b).

The P and K in the soil had higher concentrations in the area with the presence of dung input. The soil P nutrient content increased by 30% (45.0 mg dm^{-3}) in areas with dung, in relation to the absence of it. In relation to the beginning of the current study, P content in the soil in plots with dung input had an increase of 92.1% and the plots without this input, the increase was only 34.7%. The soil K content at the 12th year was 4.6 and 2.2 $mmol_c$ dm^{-3} in areas with and without dung, respectively. In relation to the beginning of the current study the K content in the plots with dung input had an increase of 130%. On the other hand, in the plots without dung the K increased by just 10%. Thus, cattle dung input contributes for a better soil fertility during the soybean cycle, since the mineral fertilizer input was the same for the presence and absence of dung input. These data agree with those reported by da Silva et al. (2014), where cattle dung increased the P content in the soil by 37.5%, even as the soil K content, was increased by 52.3% (4.6 $mmol_c$ dm^{-3}).

2.4.2. Soybean Nutrition

The N, P, K, and S content in the plant was not affected by the different system. The N is associated with the capacity of soybeans to make a symbiotic N fixation in the atmosphere, making the soy less dependent on the supply of N fertilizers and on N from animal excreta. The deposition of cattle dung and its spatial distribution resulted in variations in the attributes of plants, but not in the efficiency and capacity of the rhizobia in adequately nourishing the soy with N. Any practices that negatively influence biological soil fixation are unsustainable, and in ICLS, verified variations have not changed the N nutrition of soybeans.

However, regarding the different positions, the P content was higher in P3 (central line), and the opposite was observed for the S content, which was higher in P1 (closer to the trees). A study in the same area showed that the greatest P release from shoot biomass occurred in the central position between two tree rows (P3, 5.4 kg ha^{-1}) and the lowest release close to the trees (P1, 2.0 kg ha^{-1}, CARPINELLI et al., 2020a). The greatest nutrient cycling occurred, therefore, in the middle of the crop strip.

The P, K and S contents in the plant increased by 4.3%, 5.2% and 5.1%, respectively under dung presence in relation to absence (Table 8). These results are similar to the previous report by da Silva et al. (2014), which reported the positive effect of cattle dung on soybean nutrition. However, the N content in the plant was not affected by the presence of dung, because most of the N returned via urine, and little returned via cattle dung (HAYNES and WILLIAMS, 1993). This heterogeneous distribution of nutrients in the two via excreta returns (faeces and urine), and the occurrence of these returns in different areas, increases the heterogeneity of the nutrient returns in pasture soils, which can affect the absorption of these nutrients by the plant.

2.4.3 Effect of Trees on Soybean Yield

During the experimental period, the mean percentage of light reduction under the tree canopy (CLT) compared to CL ranged from 37% in the beginning of this study, that is, in December 2018, to 39.1% in March 2019. Despite C3 photosynthetic mechanism to be more tolerant to shading, since becomes light-saturated at approximately 50% of full sunlight (PANG et al., 2019), trees presence still affected the intercropping. The light restriction is only one resource that varies in CLT systems, with water, nutrients and probably soil biophysical properties also influencing plant productivity and development (REYNOLDS et al., 2007; JOSE and DOLLINGER, 2019).

The trees negatively affected the plant height, shoot biomass, pods per plant, grains per pod, and consequently grain yield. Also, these variables showed higher averages in the central position, than in the position close to the trees. Although other positions were not evaluated, they would probably have a curve with parabolic effect, with the apex of the parabola (i.e., greatest yield) occurring in the middle of the crop strip, with yield reduced nearest the tree row.

Further, a strong drought right after sowing probable contributed to increase the negative trees effect on soybean productivity. In addition, in the previous winter of 2018, the lack of rain in the months of May, July and August (37.0 mm, 11.0 mm, 43.4 mm, respectively) impaired the maintenance of the desired sward height (i.e., 20 cm, reducing biomass deposition, particularly in the CLT system, DA PONTES et al., 2020). Consequently, there was a reduction in the supply of nutrients via cycling, as the amount of biomass and cattle dung are the main factors affecting nutrient cycling (CARPINELLI et al., 2020a, b).

Areas with trees led to smaller soybean plants, but with larger first pod heights. Therefore, plants in CLT systems are probably less susceptible to grain depreciation caused by harvest. The average grain yield in CL (3.6 Mg ha^{-1}) is above the average for Brazil in the 2018-2019 harvest (CONAB, 2019), which was 3.2 Mg ha^{-1}, and in the Paraná State was 2.9 Mg ha^{-1}. It is important to highlight that the yield soybean in the CLT was extrapolated to hectares to facilitate a comparison with the results recorded under CL, when the soybean productivity per se was analyzed. The soybean occupied 85.7% of the area, with the remaining 14.3% being taken up by the trees, i.e., would be wood-producing. Thus, the real soybean yield achieved in 85.7% of the area of this association of soybean plus trees would be 1.5 Mg ha^{-1} of grains. Consequently, soybean yield with mature trees is compromised, even after a drastic thinning of the trees and a low tree density (~40 trees ha^{-1}) in the 12th experimental year. However, intercropping production in the CLT systems may be equal, or even higher, to that for open areas during some periods of tree developing (PORFIRIO-DA-SILVA et al., 2015), contributing to accelerate the cash flow when using ICLS as a strategy to recovery degraded areas.

2.4.4 Effect of Cattle Dung on Soybean Yield

The dung input increases the number of pods per soybean plant by 18.2% and the soybean yield by 22% in relation to the absence of dung, regardless the ICLS. These data corroborate with those observed by da Silva et al. (2014), that the presence of dung increase the number of pods per plant by 20% and soybean production by 23% when compared to the absence of cattle dung. The smaller number of pods per plant is considered as one of the main components of soybean crop yield, indicating its correlation with productivity (CARPENTIERI-PÍPOLO et al., 2005).

However, we found that these positives effects of presence of dung did not compensate or minimize with the tree effect, despite a better distribution of dung patches in CLT systems (CARPINELLI et al., 2020b). First of all, due the high losses in soybean yield with mature trees. Further, because dung patches, on general, cover only little surface of grassland (HAYNES and WILLIAMS, 1993; CARPINELLI et al., 2020b; DA SILVA et al., 2020). Thus, the 22% increase in soybean yield production in dung patches were not enough to overcome the differences between systems. However, our study contributes on investigation about the underlying mechanisms of CLT dynamics. Combining information of spatiotemporal patterns created by cattle, such as dung and urine distribution pattern (the latter still with scarce information), with the nutrients release patterns from residues (plant and animal) will help to define effective system fertilization strategy to improve the system's overall performance and efficiency.

2.5 CONCLUSIONS

The presence of cattle dung in the integrated crop–livestock systems increased the availability of phosphorus and potassium in the soil. By contributing to the increase in the levels of these nutrients in the plant, as well as S, it favored the yield components of the soybean crop, directly affecting productivity.

The soybean yield was higher in the crop–livestock without trees compared to the crop–livestock with mature tree systems. Light restriction, competition for nutrients with trees, periods of drought, are factors to be considered to explain the difference in productivity between these two integrated systems.

FINAL CONSIDERATIONS

The results show that significant amounts of nitrogen (N), phosphorus (P), potassium and sulfur (S) are cycled under these systems and the effect of trees is more related to the quantity of dung residues, rather than changes in residue quality and dynamics (e.g., no differences between systems were observed in the non-linear decay constant of active fraction – i.e. dry matter and macronutrient). Also, the significance of this is taken into account in the results of the fertilization practices for ICLS, as also the necessity of silvicultural interventions, to avoid losses in herbage mass, in order to increase the carrying capacity and N, P, K and S release from dung residues in systems with trees, thus, maximizing nutrient cycling benefits. Further, the positioning of the trees in integrated systems, can determine the concentration of dung deposition at certain locations.

The ICLS without trees (CL, full sunlight system) displayed a higher concentration of feces patches at sites near the gate, cow drinkers, and fences opposite the gate. The ICLS with trees (CLT, shaded area available in pastures) affected the spatial distribution of dung, stimulating uniformity (i.e., deposition of cattle dung did not only happen underneath trees, but also in places under their influence).

Further, our results demonstrate that the effect of cattle dung supply was more important in terms of the nutritive value of soybean than that of shade, particularly in terms of the content of N, P, K, and S in the soybean plant and the P content in the soil. However, the soybean yield, plant height, dry mass, and yield components of the soybean crop (i.e., pods per area, thousand grains weight, pods per plant, and grains per pod) was higher in the CL system compared to the CLT. The results indicate that the moderate shading level provided by trees in the CLT system, competition for nutrients with trees, and periods of absence of rain, affected pasture and soybean growth. The cattle dung input availability was not enough to overcome these differences.

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