# SHORT-TERM DYNAMIC OF SOIL FERTILITY FROM INTEGRATED CROP-LIVESTOCK SYSTEMS IN TROPICAL SAVANNA[1]

# [EFECTO A CORTO PLAZO DE LA FERTILIDAD DEL SUELO DE SISTEMAS DE INTEGRACIÓN AGRICULTURA-GANADERÍA EN UNA SABANA TROPICAL]

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## SUMMARY

The chemical attributes and the total organic carbon stock of the soil, from crop-livestock integration systems for renovation of degraded pasture, with fodder sorghum, were evaluated in torpical Savanna. The experiment was carried out in randomized block design with five replications, in plots of 200 $m^2$, in Brazilian Savanna. Treatments were (i) degraded pasture of *Brachiaria decumbens* cv. Basilisk; (ii) conventional renovation method for *B. brizantha* cv. Marandu (Control); (iii) Marandu sown in succession to sorghum monocrop for ensilage collected 0.45 m above the soil surface; and Marandu seeded simultaneously with the sorghum and harvested (iv) 0.15 and (v) 0.45 m above the soil surface. Carbon stock increases 19.9% in a short time (120 days) in the soil layer of 0.10-0.20 m for integrated crop-livestock systems treatments. All forms of renovation of pasture contributed to increases in macronutrients and reduction of Al in the soil. After 442 days, the higher soil fertility was observed for the Control tratamento indicating that this is a good method of renovation of pasture and it can be used where the crop-livestock can not.

**Keywords:** degraded pasture; carbon stock; sorghum; *urochloa*.

## RESUMEN

Se evaluó las propiedades químicas y del stock total de carbono orgánico del suelo de sistemas de integración agricultura-ganadería para la renovación de pasturas degradadas con el sorgo en la sabana tropical. El experimento se realizó en bloques al azar con cinco repeticiones, en parcelas de 200 $m^2$, en sabana brasileira. los tratamientos fueron (i) pastos degradados de *Brachiaria decumbens* cv. Basilisk; (ii) método de renovación convencional para pasto *B. brizantha* cv. Marandu (Control); (iii) Marandu sembrado en sucesión al monocultivo de sorgo para ensilaje recolectado 0.45 m por encima de la superficie del suelo; y Marandu sembrado simultáneamente con el sorgo para ensilaje recolectado (iv) 0.15 y (v) 0.45 m por encima de la superficie del suelo. El stock de carbono aumentó un 19.9% en un corto tiempo (120 días) en la profundidad de suelo de 0.10-0,20 m para los tratamientos integrados de sistemas de cultivo-ganado. Todas las formas de renovación de los pastos contribuyeron a aumentar los macronutrientes y la reducción de Al en el suelo. Después de 442 días, se observó una mayor fertilidad del suelo para el tratamiento Control indicando que éste es un buen método de renovación de pastos donde no se pueda usar la integracion agricultura-ganaderia.
**Palabras clave:** pastura degradada; secuestro de carbono; sorgo; *urochloa*.

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[1] *Submitted November 23, 2016 – Accepted March 24, 2017.* 

## INTRODUCTION

Inappropriate grazing management and low nutrient replenishment, associated with low technological investment, produce negative consequences to the sustainability of the livestock activity, e.g. low forage allowance, low performance rates, and low meat and milk production, besides causing degradation of pastures and consequently of soils (Balbino et al., 2011). For these reasons, it is essential to provide ideal conditions for the establishment and perenniality of pastures to ensure good soil cover and to reduce soil losses stemming from erosive processes.

Crop-livestock integration (CLI) systems involving the cultivation of annual crops and livestock production together have been a viable option for the recovery of pastures where the degradation process has been identified, generating satisfactory socioeconomic and environmental results (Allen et al., 2007; Franzluebbers, 2007; Tracy and Zhang, 2008).

The pasture produced by the CLI system provides the crop with a better structured soil, resulting from the abundant root system and the residual organic material left on the surface and subsurface of the soil (Loss et al., 2011), in addition to minimizing the use of pesticides by breaking pest, disease, and weed cycles (Vilela et al., 2008). As reported by Spera *et al*. (2009) in a study with rotation of grain production with perennial subtropical and temperate pastures, plant residues are rapidly transformed into organic matter due to their accelerated decomposition, typical of tropical soils.

In the CLI system, the intercrop of grain crops with forages is adopted when aiming to establish pastures and improve the soil cover for a no-till planting system. Because of their greater competition ability against forage grasses of the genus *Urochloa* spp. (syn. *Brachiaria* spp.) and *Panicum maximum*, in their initial stage of establishment, the corn and sorghum crops have been the most widely adopted plants for intercrops (Vilela et al., 2011). In this context, the fodder sorghum is a viable option to meet the demand of livestock farmers because of its chemical characteristics that meet the nutritional requirements of cattle reared on pasture on commercial farms and also because of their good fermentation capacity for being preserved in the form of silage. These facts, coupled with tolerance to drought (Vilela et al., 2011), make the sorghum crop a viable option for intercropping in regions with prolonged dry spells, as is the case of 'Cerrado' (Savanna) regions.

Strategies involving the harvest height for crops destined for ensilage may provide significant improvements to animal production and soil fertility, and higher cuts have yielded positive results. Despite the reduced dry mass harvested in this occasion, the benefits derived from improved silage quality have had a direct participation in increased animal production. In evaluating the quality of corn silage harvested at two heights in relation to the soil surface (0.14 and 0.45 m), Restle *et al*. (2002) observed that the silage produced from the high cut had a lower neutral detergent fiber content (42.6 vs. 52.2 %) and greater *in vitro* organic matter digestibility (63.7 vs. 53.6 %). The authors also observed that the increased corn harvest height did not interfere with the voluntary intake of dry matter, digestible energy, or average daily weight gain of feedlot cattle.

The effects of harvest height strategies on the silage quality and on cattle performance are better understood than the benefits from the soil perspective, whose information is still incipient. Some experiments conducted with corn indicate improvements in soil fertility as a result of nutrient cycling. Jaremtchuk *et al*. (2006) observed a 19.15 % decrease in potassium (K) extraction when the corn harvest height for ensilage was changed from 0.20 to 0.40 cm, corresponding to a savings of 21.37 kg $ha^{-1}$ KCl for the recovery of the K content extracted from the soil. In addition to K, other nutrients can be recycled by the adoption of higher harvest heights, such as N and P.

Another benefit that can be aggregated to the soil is the increment in the total carbon stock, though little is known about this benefit associated with the adoption of different harvest heights and the minimum time necessary for the accumulation to be positive. However, results of experiments with other goals (Silva et al., 2009) support the hypothesis that the sorghum harvested at greater heights may increase or at least maintain the carbon stock on superficial soil layers in a short period, mainly on degraded soils of the 'Caatinga' biome in Brazil, where high soil organic matter decomposition rates occurs due to the high air temperatures and low organic matter content of these soils.

Experimental studies aimed at evaluating the carbon/nitrogen (C/N) ratio of crops intended for green fertilization using sorghum and corn monocrops have shown that the sorghum dry mass displayed great carbon sequestration potential in the soil due to the high C/N ratio of the whole plant, of approximately 105, which is higher than that of corn (71), both analyzed 120 days after planting (Silva et al., 2009).

Most part of the carbon in forage plants is in the supporting tissues, which are naturally more fibrous (stem). As compared with corn, fodder sorghum has a larger proportion of stems in relation to the entire plant, and so it can contribute more significantly to elevate the carbon stock in the soil than corn. Flaresso *et al*. (2000) evaluated three corn and eight sorghum cultivars and observed that the stem represented, in the entire plant, approximately 34.2 % for corn and 43.3 % for sorghum. Considering that the most fibrous part of the stem is located near the soil (stem base), it is hypothesized that the mass remaining after the harvest can significantly contribute to increase the carbon stock in the soil in a short period, which can be potentiated by the dry mass originating from its regrowth or from the residue of a tropical grass grown in an intercrop that also has a high C/N ratio. The better understanding of this dynamics contributes both for practices aimed at soil improvement and in the context of greenhouse gas mitigation, thereby allowing a better understanding of CLI systems with sorghum.

Based on the above-mentioned considerations, this study was conducted to evaluate the chemical attributes and the total organic carbon stock of the soil under different options for renovation of a degraded pasture through the CLI system with fodder sorghum in a low-altitude Brazilian Savanna biome soil.

## MATERIALS AND METHODS

The study was carried out in Selvíria, MS, Brazil, in rainfed conditions, in a low-altitude Savanna (20º22' S and 51º22' W, 335 m asl). The soil was classified as Oxisol (Soil Survey Staff, 1999), where a non-supplemented cattle systems under continuous stocking (3 UA/ha) had been adopted for around 25 years, without any history of application of agricultural amendments or fertilizers.

According to the Köppen classification, the climate of study area is tropical humid Aw type, with rainy summers and dry winters and annual average temperature of 24.5 °C and average annual precipitation of 1,232 mm. Air temperature data were recorded daily in the period from 11/21/13 to 03/22/14 by an automated weather station in Ilha Solteira, SP, Brazil. The total rainfall during the experiment was 788.9 mm, recorded daily by a rain gauge located near the experimental area, while the average temperature and relative humidity of the air were of 27.3 °C and 76.2 %, respectively. The precipitation and minimum, mean, and maximum temperature data recorded during the experiment are shown in Figure 1.

The experiment was set up as a randomized block design with five replications. Treatments corresponded to the forms of renovation of pasture from signal grass (*Urochloa decumbens* (Stapf) R.D. Webster cv. ‘Basilisk’) to palisade grass (*Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webster cv. ‘Marandu’) with or without the use of fodder sorghum (*Sorghum bicolor* (L.) Moench cv. ‘Volumax’) as a companion crop. The following treatments were tested: (i) degraded signal grass pasture (Degraded); (ii) conventional renovation method to palisade grass monocrop ('Control'); (iii) palisade grass sown in succession to sorghum monocrop for ensilage collected 0.45 m above the soil surface ('Succession 45'); and palisade grass seeded simultaneously with the sorghum and harvested (iv) 0.15 ('Simultaneous 15') and (v) 0.45 m ('Simultaneous 45') above the soil surface for ensilage, totaling 25 experimental units arranged side by side and measuring 200 $m^2$ each with 2 m of edge.

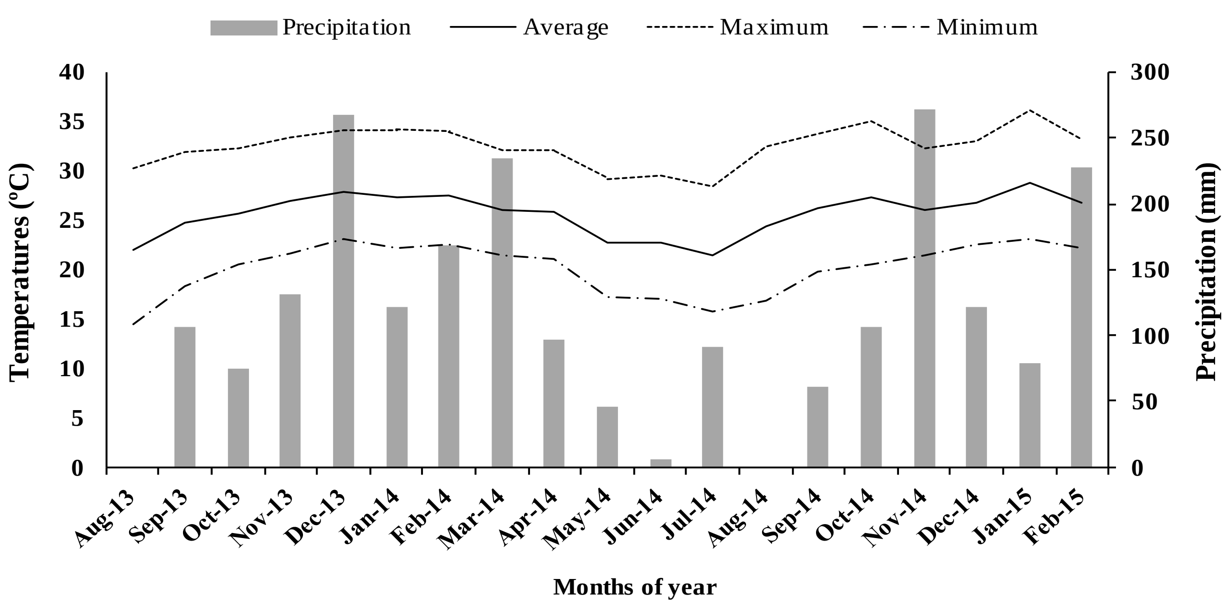


Figure 1. Precipitation and minimum, mean, and maximum temperature data of experimental site

Five samples for each experimental units (500 g) were collected for determination and evaluation of chemical attributes and carbon stock (E) in the region of greater root concentration of the tropical pastures in the soil. These were collected on three occasions, (i) prior to the implementation of the experiment (27/08/2013), (ii) 21 days after the sorghum harvest for silage (04/22/2014, 120 days after sowing), and (iii) 312 days after the sorghum harvest for silage (02/07/2015, 442 days after the implementation of the experiment), using a regular auger. For the first occasion, samples were taken at a depth of 0.00 to 0.20 m (soil characterization). For the other occasions, they were collected from the 0.00-0.10 and 0.10-0.20 m layers. After being collected, samples were air-dried, homogenized, and then sieved (2 mm) to obtain the air-dried fine earth for chemical analyses of soil fertility, as described in Anderson and Ingram (1993).

The estimated total organic carbon stock in the soil was calculated as shown in Eq. 1 (Carvalho et al., 2009), where E is the total C stock in the soil (Mg ha$^{-1}$); C is the total carbon content in the soil (g kg$^{-1}$); d is the apparent soil density (kg dm$^{-3}$); Dref is the apparent soil density of reference area and h is the thickness of the sampled layer (cm). To correct for errors intrinsic to the calculation of the C stock, arising from the variation in soil density values due to changes in land use, corrections were made to the original estimate for the same soil mass, using the 'Degraded' treatment as reference.

$$E = \frac{C.d.\left(\frac{Dref}{d}\right).h}{10} \qquad (1)$$

Results of the chemical analyses performed before the experiment was implemented revealed 5 mg dm$^{-3}$ P-resin; 3 mg dm$^{-3}$ S-$SO_4$; 20 g dm$^{-3}$ OM, 4.5 pH in $CaCl_2$; 1, 4, 6, 36, 19, 11, and 47 mmol$_c$ dm$^{-3}$ K, Ca, Mg, H+Al, Al, sum of bases (SB), and CEC, respectively; and 23% base saturation (BS). The micronutrient contents corresponded to 0.19, 2.7, 29, 10.8, and 0.1 mg dm$^{-3}$ B, Cu, Fe, Mn, and Zn, respectively. The soil particle size analysis resulted in 248, 64, and 689 g kg$^{-1}$ clay, silt, and total sand, respectively. For the carbon stock, before the experiment was implemented, treatments termed 'Degraded', 'Succession 45', 'Simultaneous 15', 'Simultaneous 45', and 'Control' had 17.19, 17.42, 17.30, 17.30, and 16.19 Mg ha$^{-1}$ in the 0.00-0.10 m layer, and 14.73, 16.86, 17.25, 16.45, and 14.93 Mg ha$^{-1}$ in the 0.10-0.20 m layer, respectively.

Prior to the implementation of the experiment, on 07/29/2013, the area was desiccated with application of glyphosate and carfentrazone-ethyl, respectively. Based on the soil analysis and aiming to elevate the base saturation to 60 % for the sorghum and 45 % for the Palisade grass monocrop (CFSEMG, 1999), 2.2 and 1.3 t ha$^{-1}$ dolomitic limestone (PRNT = 80 %), respectively, were applied (on two occasions for the Palisadegrass, 10/02/13 and 10/08/13), followed by incorporation with a harrow. In 'Degraded' treatment, liming was not applied, aiming to simulate the soil conditions observed in most part of the commercial farms in the Brazilian Savanna.

For the treatment in which the sorghum was grown as a monocrop, it was sown in rows spaced 0.45 m apart, aiming at a final stand of 130,000 plants ha$^{-1}$. Seeds were distributed at a depth of 0.04 m, together with the application with fertilizer (N-P-K+Zn). In the simultaneous growing system, the Palisadegrass was sown in the interrows of sorghum (0.45 m), keeping a distance of 0.22 m between rows, at a depth of 0.04 m, using 7 kg of pure, viable seeds per hectare, on 22/11/2013.

For the fertilization at planting of treatments 'Simultaneous 15' and 'Simultaneous 45', 370 kg of the 8-28-16+Zn formulation were applied, following CFSEMG (1999), whereas the 'Control' treatment received 404 kg ha$^{-1}$ of the 8-28-16+Zn formulation (CFSEMG, 1999). Nitrogen top-dressing was performed on 12/14/2013, when the sorghum plants had approximately four expanded leaves, using 100 and 80 kg ha$^{-1}$ N for 'Succession 45', 'Simultaneous 15 and 45', and 'Control' treatments, respectively, using urea as the source. The sorghum was collected aiming at silage production on 04/01/14, and the signal grass was subsequently sown mechanically at a depth of 0.02 m, in rows spaced 0.22 m apart.

The statistical analysis was performed using SISVAR software (Ferreira, 2011). For the variables without normality and homogeneity of the variances, the data were transformed using $(x+0.5)^{0.5}$. All data were subjected to analysis of variance, and means were compared by Tukey's test at 5% probability level.

## RESULTS AND DISCUSSION

The phosphorus (P) and organic matter (OM) levels in the 0.00-0.10 m soil layer 21 days after the sorghum harvest for silage did not differ between the treatments in the year 2014 (Table 1). In the analyses of chemical attributes one year after harvest, the P contents in the 0.00-0.10 m layer differed between treatments ($p<0.05$), with 'Succession 45' providing the highest amounts of this nutrient; an increase was observed after the sorghum was harvested for silage (Table 1). Phosphorus values increased after the experiment was conducted, by approximately 50 %.

Evaluating the use efficiency of P after *U. humidicola*, Sousa *et al*. (2007) observed greater productivity in the first crop of soy, after a cycle of nine years of pasture, as compared with the exclusive annual-crop system

($13^{th}$ soy crop) for the same P content in the soil, which demonstrates the greater use efficiency of this nutrient when the pasture was inserted in rotation. The lower critical level of P in the rotation from pasture to soy is likely due to the more efficient P cycling in the system; increments in the mineralization rate of the soil organic matter accumulated during the pasture period; or the blocking of P adsorption sites due to the greater accumulation of organic matter, which decreases the fixation of this element (Vilela et al., 2011). These results are indicative of the better use efficiency of P by the plants in systems with rotation from annual crops to pasture, although no similar result was found in the present study, possibly because the CLI system was not yet fully consolidated in the area, despite the average increase of 52 %, on average, provided by the treatments as a function of the degraded pasture.

In this regard, according to Martha Júnior *et al*. (2008), the main economic advantage of CLI in the livestock stage is the improved soil fertility (residual effect), which, despite depending on nitrogen fertilization, usually dispenses with P and K fertilization in the medium term.

The OM contents in the 0.00-0.10 m layer did not differ between treatments (Table 1), even after one year of cultivation. However, it is noteworthy that there was a 1.36 g $dm^{-3}$ increase in the OM content in the study period, which corresponds to a 6.6 % increase.

More diversified systems, like CLI, are important for replenishing and maintaining the soil OM and providing well-structured soils, as they increase the water infiltration rate and consequently its availability for crops, reducing the rainfall surface runoff, erosions, and pollution of water bodies. Additionally, they reduce the mechanical resistance to the penetration of roots into the soil profile, which augments the volume of soil exploited by the root system of the crops, thereby increasing the efficiency of use of water and nutrients (Franzluebbers, 2007).

In a study on rotation in grain production with subtropical and temperate perennial pastures, the authors observed that the plant residues were transformed into organic matter due to their mineralization (Spera et al., 2009), corroborating Nicoloso *et al*. (2008), who claimed that the soil under CLI has the potential to be a drain for atmospheric C and promote the accumulation of OM, unlike what was found in the present study.

The increased OM and better physical quality of the soil obtained with the introduction of pastures in agricultural areas with adequate fertility levels indicate that CLI has the potential to lessen the environmental impact of productive activities by positively contributing to the sequestration of atmospheric C in a short period with a consequent increase in the production stability of annual crops and better use of water and nutrients (Franchini et al., 2010). It should be mentioned that the increase in OM in high quantities obtained with CLI is a process that takes place after years of cultivations in the system, which would hardly occur in the conditions of the present study, in the first year of renovation of the area.

The C stocks (E) in the 0.00-0.10 m soil layer in 2014 ranged from 17.30 to 18.42 Mg $ha^{-1}$ in treatments 'Simultaneous 45' and 'Succession 45', which had the lowest and highest values respectively; no difference was detected between the other treatments (Table 1). Similarly, there was no difference in 2015, when the variation between treatments was 17.97 to 19.60 Mg $ha^{-1}$ in treatments 'Control' to 'Degraded, which had the lowest and highest carbon stock values, respectively (Table 1)

The values obtained in the present study were lower than those found by Macedo (2009), who studied E in the in layers from Oxisol soil in Campo Grande, MS, Brazil, subjected to management systems for 11 years (crops in a conventional system, crops in a no-till system, rotation of soy for one year and pasture (*U. brizantha*) for three years; rotation of soy for 4 years and pasture (*Panicum maximum*) for four years; permanent pasture *U. decumbens*); and permanent pasture (*U. decumbens*) intercropped with legumes and natural vegetation) and obtained carbon stock values of 23.4, 23.9, 27.6, 25.2, 28.1, 34.5, and 30.3 Mg $ha^{-1}$ in the 0.00-0.10 m layer; and 23.0, 23.5, 22.9, 22.7, 25.4, 24.1, and 23.7 Mg $ha^{-1}$ in the 0.10-0.20 m layer, respectively. However, these higher values were obtained in a clayey soil, where the soil colloids form complex of greater stability, protecting the OM from mineralization, whereas in the present study the soil with 248 g $kg^{-1}$ clay is classified as of medium texture, with lower OM protective capacity.

It is worth noting that difference in E values is due mainly to the time for implementation and consolidation of the productive systems. The accumulation and the greater uptake of carbon by the soil slowly increases over the years, and it is a long process, which explains the lower carbon stock values in the area of the present study, with one year of implemented system, as compared with systems consolidated over 11 years.

Table 1. Descriptive analysis of chemical properties in the 0.00-0.10 m soil layer for the treatments

| Variables | Years | Treatments | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Simultaneous | | | |
| | | Degraded | Succession 45 | 15 | 45 | Control | S. D. |
| P (mg $dm^{-3}$) | 2014 | 3.00a | 4.20a | 5.00a | 5.00a | 5.60a | 1.58 |
| | 2015 | 6.60b | 10.20a | 5.80b | 6.00b | 5.60b | 1.78 |
| O.M. (g $dm^{-3}$) | 2014 | 20.40a | 21.20a | 20.40a | 20.00a | 21.80a | 1.33 |
| | 2015 | 24.00a | 22.40a | 21.40a | 21.80a | 21.00a | 1.66 |
| E (Mg $ha^{-1}$) | 2014 | 17.53a | 18.42a | 17.64a | 17.30a | 17.65a | 1.42 |
| | 2015 | 19.60a | 19.47a | 18.51a | 18.85a | 17.97a | 1.06 |
| pH ($CaCl_2$) | 2014 | 4.58c | 5.62ab | 5.96a | 5.42b | 5.20b | 0.25 |
| | 2015 | 4.62b | 5.56a | 5.58a | 5.70a | 4.70b | 0.19 |
| K ($mmol_c$ $dm^{-3}$) | 2014 | 1.38a | 0.60c | 0.70c | 0.78bc | 1.08ab | 0.18 |
| | 2015 | 1.78ab | 1.16bc | 0.64c | 0.90bc | 2.16a | $0.17^f$ |
| Ca ($mmol_c$ $dm^{-3}$) | 2014 | 3.00c | 11.00ab | 15.40a | 9.60b | 12.00ab | 2.88 |
| | 2015 | 6.80b | 15.20a | 13.40a | 14.80a | 10.80ab | 2.51 |
| Mg ($mmol_c$ $dm^{-3}$) | 2014 | 4.00c | 13.80ab | 18.40a | 11.80b | 12.80b | 3.25 |
| | 2015 | 8.00b | 17.40a | 16.60a | 16.40a | 9.80b | 2.28 |
| H+Al ($mmol_c$ $dm^{-3}$) | 2014 | 36.80a | 21.80bc | 19.00c | 24.00bc | 27.20b | 2.85 |
| | 2015 | 36.60a | 22.80b | 21.60b | 20.40b | 24.80a | 3.92 |
| Al ($mmol_c$ $dm^{-3}$) | 2014 | 4.80a | 0.20b | 0.00b | 0.20b | 0.60b | $0.26^f$ |
| | 2015 | 2.80a | 0.00b | 0.00b | 0.00b | 2.80a | $0.32^f$ |
| SB ($mmol_c$ $dm^{-3}$) | 2014 | 8.38c | 25.40ab | 34.50a | 22.18b | 25.88ab | 4.96 |
| | 2015 | 16.58c | 33.76a | 30.64ab | 32.10ab | 23.08bc | 5.39 |
| CEC (mmolc $dm^{-3}$) | 2014 | 45.18b | 47.20ab | 53.50a | 46.18b | 53.08a | 3.27 |
| | 2015 | 53.18a | 56.56a | 52.24a | 52.50a | 56.54a | 5.58 |
| BS (%) | 2014 | 18.44 c | 53.47 ab | 64.15 a | 47.50 b | 48.12 b | 7.76 |
| | 2015 | 31.20 b | 59.60 a | 58.40 a | 61.00 a | 40.80 b | 6.29 |
| m (%) | 2014 | 35.40 a | 1.20 b | 0.00 b | 1.40 b | 3.20 b | $3.55^f$ |
| | 2015 | 15.00 a | 0.00 b | 0.00 b | 0.00 b | 9.60 a | $2.01^f$ |
| B (mg $dm^{-3}$) | 2014 | 0.13 a | 0.08 b | 0.08 b | 0.10 ab | 0.12 a | 0.01 |
| | 2015 | 0.17 a | 0.09 b | 0.10 b | 0.09 b | 0.14 ab | 0.03 |
| Cu (mg $dm^{-3}$) | 2014 | 2.64 a | 2.30 ab | 2.04 b | 2.36 ab | 2.16 b | 0.19 |
| | 2015 | 3.22 a | 2.78 ab | 2.58 b | 2.66 b | 2.66 b | 0.27 |
| Fe (mg $dm^{-3}$) | 2014 | 26.00 a | 16.80 b | 14.20 b | 16.20 b | 18.00 b | 2.65 |
| | 2015 | 41.20 a | 23.40 b | 18.60 b | 20.80 b | 25.60 b | 5.09 |
| Mn (mg $dm^{-3}$) | 2014 | 8.16 a | 9.40 a | 7.38 a | 9.90 a | 8.30 a | 1.30 |
| | 2015 | 15.40 a | 14.06 a | 11.34 a | 12.68 a | 13.36 a | 2.37 |
| Zn (mg $dm^{-3}$) | 2014 | 0.30 c | 0.40 bc | 0.40 bc | 0.60 b | 0.90 a | 0.13 |
| | 2015 | 1.92 a | 0.66 b | 0.46 b | 0.38 b | 1.42 a | $0.12^f$ |

Means followed by common letters in the line do not differ according to Tukey's test at 5 % probability level. $^f$Data corrected by the equation $(x+0.5)^{0.5}$. Actual means presented with letters by Tukey's test as a function of the statistics with corrected data. S. D.= standard deviation.

The highest accumulation rates and the highest E in the soil occur in systems with permanent pasture, whereas the lowest are found in systems with crops; intermediate values, however, occur in systems like CLI, mainly because of the greater availability of plant material provided by the pasture (Salton et al., 2011). This result was not found in the present study due to the little time for implementation of the Control grass pasture and the advanced degradation stage of the *Urochloa* ssp., which, in addition to not meeting the carbon demand through the uptake of plant material, would require adequate conditions of fertility and physical attributes of the soil to be able to develop satisfactorily, and this would take a few years until the production system was consolidated.

The pH in the 0.00-0.10 m layer was influenced by the treatments ($p<0.05$) both at 21 days and one year after the sorghum was harvested (Table 1). Treatment 'Simultaneous 15' was superior to 'Simultaneous 45', 'Control', and 'Degraded', but did not differ from 'Succession 45' in the year 2014. The increase in pH for treatment 'Simultaneous 15', which had the highest pH values, was 30.1 %, whereas the increase in the overall mean of the treatments was 17.0 %. In 2015, treatments 'Succession 45', 'Simultaneous 15', and 'Simultaneous 45' had higher values than treatments 'Control' and 'Degraded'. The pH increase from 'Degraded' to treatment 'Simultaneous 45', which provided the highest values, was 23.4%, whereas the increase in the overall mean of the treatments was 9.0 %.

The K, Ca, and Mg contents in the 0.00-0.10 m layer were influenced by the treatments ($p<0.05$) after the harvest in 2014 and one year after the harvest in 2015 (Table 1). After the harvest, treatment 'Simultaneous 15' had higher levels of Mg than treatments 'Simultaneous 45', 'Control', and 'Degraded', but did not differ from 'Succession 45'. In 2015, treatments 'Succession 45', 'Simultaneous 15', and 'Simultaneous 45' showed higher values than 'Control' and 'Degraded'.

For the K content, 'Degraded' was superior ($p<0.05$) to 'Succession 45', 'Simultaneous 15', and 'Simultaneous 45' treatments and did not differ from the 'Control' treatment after the harvest. 'Degraded' treatment showed, on average, a 34% higher K content in the soil as compared with the other treatments. Greater accumulation of K in the plants occurs when K is highly available in the soil; in this situation, plants absorb an amount larger than their metabolic needs, which is accumulated in the plant cell organelles (e.g. chloroplasts, mitochondria, and, especially, in the vacuoles), characterizing the "luxury consumption", and later removed with the harvest of the plant remnants, as occurs in crops used for silage (Gommers et al., 2005).

Potassium is a mobile element in the soil that is exported by plants in large amounts; thus, the intensification of cultivation benefits the extraction of this nutrient in the soil, which explains the low K values in the superficial soil layer (0.00-0.10 m) for the treatments with high transfer of dry mass via silage when compared with 'Degraded' (Table 1).

In the year 2015, the K contents in the 0.00-0.10 m layer were similar among treatments 'Degraded', 'Succession 45', and 'Simultaneous 45', differing only from 'Simultaneous 15', in which greater extraction of this nutrient occurred because of the shorter harvest height. Thus, the increased dry matter yield of the crops provided by the improved fertility and good use of the soil intensifies K cycling (Rosolem et al. 2012), generating a positive balance to the system. In this way, in integrated systems like CLI, both K cycling and K losses are expected to increase as the harvest intensity is increased (Ferreira et al., 2011), as was found in the current experiment

The Ca contents 21 days after the harvest were higher in the 'Simultaneous 15' treatment was compared with 'Degraded' and 'Simultaneous 45', but similar to 'Succession 45' and 'Control'. On average, treatment 'Simultaneous 15' showed a 51 % higher Ca content than the other treatments. Because treatments Succession 45', 'Simultaneous 15', and 'Simultaneous 45' received higher limestone doses as compared with 'Control' and 'Degraded', these treatments might show higher Ca and Mg contents and pH in the superficial layer and not differ from each other.

One year after the harvest, the lowest Ca content in the 0.00-0.10 m layer was observed for 'Degraded', while the other treatments did not differ. A significant increase was noted from one year to the other in the availability of Ca, because liming was performed only once before the experiment was implemented.

A similar result was found by Carneiro *et al*. (2009), who did not observe variations in the chemical attributes of a Brazilian Savanna soil under different use and management systems, where the H+Al and $Al^{3+}$ levels were higher and concentrations of Ca, Mg, and P were lower in the areas covered with Brazilian Savanna vegetation in relation to the managed areas.

As regards the potential acidity, aluminum saturation (m%), and Al content in the soil in the 0.00-0.10 m layer, 'Degraded' treatment displayed higher values than 'Simultaneous 15' and 'Control' for H+Al and than treatments 'Succession 45', 'Simultaneous 15', 'Simultaneous 45', and 'Control' for m% and Al content of the soil. The opposite result was observed for SB and BS, for which 'Degraded' treatment had lower values than the others (Table 1). 'Degraded' treatment had, on average, 30, 75.8, and 76.7 % higher potential acidity, Al content, and m%, respectively, than the other treatments. Treatment ‘Simultaneous 15’ showed higher SB, CEC, and BS contents (Table 1) than ‘Simultaneous 45’; higher SB and CEC in relation to ‘Degraded’; and higher BS than treatments ‘Simultaneous 45’, ‘Control’, and ‘Degraded’.

One year after the harvest, there was no difference for potential acidity and Al values (Table 1) among ‘Succession 45’, ‘Simultaneous 15’, and ‘Simultaneous 45’ treatments, but these differed from ‘Control’ and ‘Degraded’. As for the SB values, there were differences between treatments ($p<0.05$) ‘Succession 45’ and ‘Degraded’, although they did not differ from the others. These results are a reflection of the neutralization of Al and the active soil acidity caused by liming, as well as the availability and Ca and Mg, especially in the superficial layers - in general terms, potential acidity, Al content, and m% decreased, SB increased, and consequently CEC, BS, and pH increased in relation to the degraded pasture (‘Degraded’).

In regard to the average contents of the micronutrients B, Cu, and Fe in the 0.00-0.10 m soil layer, ‘Degraded’ treatment showed higher values than ‘Succession 45’ and ‘Simultaneous 15’ for B; higher Cu levels than ‘Simultaneous 15’ and ‘Control’; and higher Fe content than all treatments (Table 1).

Treatment ‘Control’ had higher Zn contents in the soil than ‘Degraded’, ‘Succession 45’, ‘Simultaneous 15’, and ‘Simultaneous 45’. Treatment ‘Simultaneous 45’ did not differ from ‘Simultaneous 15’ and ‘Succession 45’ treatments, but was superior to ‘Degraded’. The latter showed, on average, a 73.3 % lower Zn content as compared with the other treatments. For the Mn contents, no influence of the treatments was observed. However, in ‘Degraded’ treatment, the Mn content increased by 5.6 %.

The availability of cationic micronutrients is negatively influenced by an increase in pH; nevertheless, this response was not observed in the present study. The increase in PH up to approximately 5.9 in $CaCl_2$ benefits the availability of B in the soil (Malavolta et al., 1997); however, the opposite was observed in the 0.00-0.10 m layer, in which treatments ‘Degraded’, ‘Control’, and ‘Simultaneous 45’, which had lower soil pH than ‘Succession 45’ and ‘Simultaneous 15’, showed higher B contents

For the P, OM, and pH levels in the 0.10-0.20 m soil layer, no differences were observed among the treatments (Table 2). However, in ‘Degraded’, P, OM, and pH increased ($p<0.05$) by 40.0, 1.0, and 8.6 %, on average (Table 2). As regards E in the 0.10-0.20 m layer, the highest values in 2014 were obtained with treatment ‘Simultaneous 15’ (14.66 Mg $ha^{-1}$) as compared with ‘Degraded’ (12.23 Mg $ha^{-1}$), but ‘Simultaneous 15’ did not differ from the other treatments. In 2015, there was no difference between treatments, although the variation in E was 13.59 to 14.67 Mg $ha^{-1}$ between treatments ‘Control’ and ‘Simultaneous 15’ and ‘Succession 45’ with the lowest and highest obtained values, respectively.

In addition to agronomic efficiency, production systems must generate environmental gains, such as lower emission of greenhouse gases and sequestration of atmospheric C (Salton et al., 2011). Thus, the impact caused by the use of a crops-pasture rotation system may cause retention of C in the soil at a rate of 0.40 and 0.80 Mg $ha^{-1}$ per year, considering the stocks in the 0.00-0.20 m layer, the range corresponding to the E increment in the 0.00-0.20 m soil layer obtained in the present study, with 1.92 Mg $ha^{-1}$.

After the harvest, the K content in the 0.10-0.20 m layer for treatment ‘Simultaneous 45’ was higher than that of treatment ‘Simultaneous 15’, although it did not differ from ‘Degraded’, ‘Succession 45’, or ‘Control’ treatments (Table 2). One year after the harvest, treatment ‘Control’ provided higher K contents than the other treatments at the soil depth of 0.10-0.20 m.

The Mg content in the 0.10-0.20 m layer in ‘Degraded’ was lower as compared with the other treatments, which did not differ from each other in both years. In 2015, there was a significant increase in Mg values, because Ca values also increased at both depths of 0.00-0.10 m and 0.10-0.20 m ($p<0.05$). No difference was detected between treatments for the Ca contents after the harvest; however one year after the harvest, treatment ‘Control’ was superior to ‘Degraded’, which did not differ from ‘Succession 45’, ‘Simultaneous 45’, and ‘Simultaneous 15’ treatments (Table 2); this response is explained by the liming applied at the onset of the experiment.

The Al content in the 0.10-0.20 m layer was not influenced by the treatments after the harvest or one year later (Table 2). For potential acidity, there was no difference between treatments in the year 2014. In 2015, ‘Degraded’ had higher concentrations of this element than the other treatments including sorghum, but did not differ from ‘Control’.

Regarding the SB and BS, ‘Degraded’ had lower values than ‘Succession 45’, ‘Simultaneous 15’, ‘Simultaneous 45’, and ‘Control’, treatments mainly because of the greater Ca and Mg contents in the soil in the other treatments. By contrast, in 2015, ‘Control’ was superior to the other treatments, which did not differ in the 0.10-0.20 m layer (Table 2).

Cation-exchange capacity and m% did not differ from the other treatments in 2014 (Table 2). In 2015, 'Control' was superior to the other treatments for CEC, while for m%, 'Degraded' showed higher values than 'Simultaneous 45' and 'Control' treatments, but did not differ from 'Simultaneous 15' or 'Succession 45'. For BS, both after the harvest and one year later, 'Degraded' had the lowest results. From one year to another, we can observe an increase in CEC and BS values and a decrease in m% values, indicating that even in a short period (one year of implemented system), the soil profiles start to develop with better soil fertility, demonstrating the efficiency of integrated systems aimed at renovating productive areas in a sustainable manner.

The levels of micronutrients B, Cu, and Fe in the 0.10-0.20 m layer did not change with the treatments. For the B contents one year after the harvest, 'Degraded' treatment showed a higher value than those including sorghum, but did not differ from 'Control'. 'Degraded' treatment also had higher Cu contents than 'Simultaneous 15' and 'Simultaneous 45', but did not differ from 'Succession 45' or 'Control'. The Mn content in the 0.10-0.20 m layer (Table 2) was not changed by the treatments in either year. For Zn, there was no difference between treatments in the year 2014, but in 2015 treatments 'Degraded' and 'Control' were superior to the others.

The micronutrients Cu, Fe, and Mn and the pH had higher mean values than the 0.3-0.8, 5-12, and 1.3-5 mg $dm^{-3}$ and 5.1-5.5 reported as adequate by Raij *et al*. (1997). For Ca and Mg, the mean contents were within the range of 4-7 and 5-8 $mmol_c$ $dm^{-3}$, respectively, recommended by Raij *et al*. (1997) as adequate. The nutrients P, K, B, and Zn and BS showed lower mean contents than the adequate ranges of 15-40 mg $dm^{-3}$, 1.6-3.0 $mmol_c$ $dm^{-3}$, 0.21-0.6 and 0.6-1.2 mg $dm^{-3}$, and 51-70 recommended by Raij *et al*. (1997), respectively. Analyzing the nutrient contents by depth, in the 0.00-0.10 m layer, the P content was very low; K, B, Zn and BS were low; Ca, Mg, Cu, Fe, and Mn were high; and acidity was medium. In the 0.10-0.20 m layer, the P content was very low; K, Ca, Mg, B, Zn, and BS were low; Cu, Fe, and Mn were high; and acidity was high.

Overall, the soil fertility varied according to the sampling depths ($p<0.05$), showing more favorable conditions for plants in the uppermost layer (0.00-0.10 m) and a decrease in this condition as the soil profile became deeper (0.10-0.20 m), even one year after liming (Table 3). There was a large variation in results of the soil fertility analysis compared with the results of the initial soil sampling. The fact that this sampling was performed after deep plowing, with incorporation of several plant residues not yet mineralized, besides the liming and the different soil layer samples, might have interfered with the results.

Soil fertility attributes that are positively correlated with plant growth, such as P, OM, pH, K, Ca, Mg, SB, CEC, BS, Fe, Mn, and Zn, had their values significantly decreased as the analyzed depth was increased. By contrast, the attributes related to soil acidity (Al, H+Al, and m%) and the B content showed opposite results, i.e., as the analyzed depth was increased, the contents of these evaluations also increased (Table 3).

Similar results were obtained by Santos *et al*. (2009), who studied the effect of CLI production systems (wheat/soy and pasture of grasses intercropped with black oat, white oat, vetch, rye, and millet, and a fragment of subtropical forest) on soil fertility in a no-till system on Haplortox soil and found more favorable conditions to the development of plants on the superficial layer over the lower ones. According to those authors, differences in soil fertility are largely due to the depths sampled.

Overall, the CLI strategies benefited the soil fertility. Grazing, in a CLI system, may improve soil fertility as a result of the accumulation of OM, the alteration in nutrient cycling (Flores et al., 2008), improvement in the use efficiency of fertilizers, and differentiated nutrient absorption capacity (Carvalho et al., 2010). Similarly to the chemical attributes of the soil, E was influenced by the analyzed layers — in the 0.00-0.10 m layer, there was greater C accumulation than in the 0.10-0.20 m layer, due mainly to the greater uptake of organic material in the superficial layers, increasing the uptake of C on the surface as compared with the subsurface layers (Table 3), corroborating Salton *et al*. (2011), who studied different CLI strategies in long experiments and found that the C content was higher in the superficial layers of the soil and decreased with its depth.

It is noteworthy that in the period of one year of implemented system, E increased in the 0.00-0.10 and 0.10-0.20 m layers from 17.71 to 18.88 and 13.43 to 14.18 Mg $ha^{-1}$, respectively (Table 3), suggesting that the adoption of CLI systems, even in an initial period in a medium-texture soil, may be beneficial to the management of the soil/plant system, with a positive impact on production systems, corroborating Carvalho *et al*. (2010), who stated that CLI has shown a considerable potential for carbon accumulation in the soil. These authors observed, in the Brazilian Savanna, an increment in the carbon stocks of the soil in CLI systems as compared with traditional systems.

Table 2. Descriptive analysis of chemical properties in the 0.10-0.20 m soil layer for the treatments

| Variables | Years | Treatments | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | Simultaneous | | | |
| | | Degraded | Succession 45 | 15 | 45 | Control | S. D. |
| P (mg dm$^{-3}$) | 2014 | 1.20a | 2.00a | 1.40a | 1.80a | 2.00a | 0.30$^{f}$ |
| | 2015 | 3.60a | 5.00a | 3.80a | 4.20a | 4.00a | 1.21 |
| O.M. (g dm$^{-3}$) | 2014 | 16.60a | 16.60a | 17.00a | 15.60a | 18.00a | 1.64 |
| | 2015 | 18.80a | 17.40a | 17.20a | 17.00a | 18.20a | 1.14 |
| E (Mg ha$^{-1}$) | 2014 | 12.23b | 13.99ab | 14.66a | 12.83ab | 13.44ab | 1.07 |
| | 2015 | 13.85a | 14.67a | 14.66a | 14.14a | 13.59a | 0.79 |
| pH ($CaCl_2$) | 2014 | 4.32a | 4.86a | 4.94a | 4.62a | 4.70a | 0.48 |
| | 2015 | 4.40a | 4.90a | 4.78a | 4.78a | 4.88a | 0.31 |
| K (mmol$_c$ dm$^{-3}$) | 2014 | 0.56ab | 0.48ab | 0.46b | 0.78a | 0.62ab | 0.15 |
| | 2015 | 0.76b | 0.74b | 0.50b | 0.62b | 1.52a | 0.06$^{f}$ |
| Ca (mmol$_c$ dm$^{-3}$) | 2014 | 1.20a | 2.80a | 3.60a | 3.20a | 3.40a | 0.68$^{f}$ |
| | 2015 | 3.20c | 5.40bc | 6.20ab | 5.60bc | 9.60a | 0.76$^{f}$ |
| Mg (mmol$_c$ dm$^{-3}$) | 2014 | 1.40b | 4.60a | 4.80a | 4.20a | 4.20a | 1.26 |
| | 2015 | 3.40b | 6.60a | 6.80a | 7.00a | 9.20a | 0.81$^{f}$ |
| H+Al (mmol$_c$ dm$^{-3}$) | 2014 | 36.20a | 27.60a | 30.20a | 29.40a | 30.80a | 5.00 |
| | 2015 | 38.00a | 27.40b | 28.60b | 26.20b | 31.20ab | 4.01 |
| Al (mmol$_c$ dm$^{-3}$) | 2014 | 6.80a | 2.60a | 2.40a | 4.00a | 3.60a | 1.47$^{f}$ |
| | 2015 | 4.80a | 2.00a | 2.20a | 1.80a | 2.80a | 0.83$^{f}$ |
| SB (mmol$_c$ dm$^{-3}$) | 2014 | 3.16b | 7.88a | 8.86a | 8.18a | 8.22a | 1.28$^{f}$ |
| | 2015 | 7.36b | 12.74b | 13.50b | 13.22b | 20.32a | 3.25 |
| CEC (mmolc dm$^{-3}$) | 2014 | 39.36a | 35.48a | 39.06a | 37.58a | 39.02a | 3.97 |
| | 2015 | 45.36b | 40.14bc | 42.10bc | 39.42c | 51.2a | 2.72 |
| BS (%) | 2014 | 8.02b | 22.59a | 22.57a | 21.69a | 21.54a | 3.88$^{f}$ |
| | 2015 | 15.88b | 31.70a | 32.14a | 33.53a | 40.21a | 7.29 |
| m (%) | 2014 | 68.00a | 24.20a | 22.60a | 33.40a | 20.26a | 18.26$^{f}$ |
| | 2015 | 39.20a | 13.60ab | 14.00ab | 12.20b | 12.80b | 7.41 |
| B (mg dm$^{-3}$) | 2014 | 0.16a | 0.13a | 0.14a | 0.15a | 0.14a | 0.02 |
| | 2015 | 0.17a | 0.12b | 0.11b | 0.09b | 0.12ab | 0.02 |
| Cu (mg dm$^{-3}$) | 2014 | 2.34a | 2.26a | 2.22a | 2.34a | 2.20a | 0.18 |
| | 2015 | 3.08a | 2.74b | 2.62b | 2.64b | 2.64b | 0.15 |
| Fe (mg dm$^{-3}$) | 2014 | 16.60a | 15.60a | 15.80a | 16.00a | 16.00a | 2.95 |
| | 2015 | 28.80a | 22.60ab | 18.80b | 18.80b | 22.80ab | 4.16 |
| Mn (mg dm$^{-3}$) | 2014 | 5.94a | 7.12a | 5.96a | 7.44a | 5.74a | 1.82 |
| | 2015 | 11.18a | 10.16a | 8.78a | 9.22a | 10.30a | 1.30 |
| Zn (mg dm$^{-3}$) | 2014 | 0.14a | 0.16a | 0.18a | 0.28a | 0.24a | 0.01$^{f}$ |
| | 2015 | 1.84a | 0.28b | 0.40b | 0.16b | 1.30a | 0.11$^{f}$ |

Means followed by common letters in the line do not differ according to Tukey's test at 5 % probability level. $^{f}$Data corrected by the equation $(x+0.5)^{0.5}$. Actual means presented with letters by Tukey's test as a function of the statistics with corrected data. S. D.= standard deviation.

Table 3. Descriptive analysis of chemical properties in different soil layer

| Variables | Years | | | | | |
|---|---|---|---|---|---|---|
| | 2014 | | | 2015 | | |
| | Layer (m) | | | Layer (m) | | |
| | 0.00-0.10 | 0.10-0.20 | S. D. | 0.10-0.20 | 0.00-0.10 | S. D. |
| P (mg $dm^{-3}$) | 4.56a | 1.68b | $0.06^f$ | 6.84a | 4.12b | 0.32 |
| O.M. (g $dm^{-3}$) | 20.76a | 16.76b | 0.30 | 22.12a | 17.72b | 0.29 |
| E (Mg $ha^{-1}$) | 17.71a | 13.43b | 0.24 | 18.88a | 14.18b | 0.18 |
| pH ($CaCl_2$) | 5.36a | 4.69b | 0.07 | 5.23a | 4.75b | 0.05 |
| K ($mmol_c$ $dm^{-3}$) | 0.91a | 0.58b | 0.03 | 1.33a | 0.83b | $0.08^f$ |
| Ca ($mmol_c$ $dm^{-3}$) | 10.20a | 2.84b | $0.08^f$ | 12.20a | 6.00b | 0.50 |
| Mg ($mmol_c$ $dm^{-3}$) | 12.16a | 3.84b | 0.43 | 13.64a | 6.60b | 0.38 |
| H+Al ($mmol_c$ $dm^{-3}$) | 25.76b | 30.84a | 0.82 | 27.24b | 30.28a | 0.77 |
| Al ($mmol_c$ $dm^{-3}$) | 1.16b | 3.88a | $0.10^f$ | 1.12a | 2.72a | $0.30^f$ |
| SB ($mmol_c$ $dm^{-3}$) | 23.27a | 7.26b | 0.89 | 27.23a | 13.43b | 0.87 |
| CEC (mmolc $dm^{-3}$) | 49.03a | 38.10b | 0.77 | 54.20a | 43.71b | 0.83 |
| BS (%) | 46.33a | 19.28b | 1.68 | 50.20a | 30.69b | 1.33 |
| m (%) | 8.24b | 33.69a | $0.39^f$ | 4.92b | 18.36a | $1.92^f$ |
| B (mg $dm^{-3}$) | 0.12a | 0.12a | 0.004 | 0.12a | 0.12a | 0.01 |
| Cu (mg $dm^{-3}$) | 2.30a | 2.27a | 0.03 | 2.78a | 2.74a | 0.04 |
| Fe (mg $dm^{-3}$) | 18.24a | 16.00b | 0.54 | 25.92a | 22.36b | 0.91 |
| Mn (mg $dm^{-3}$) | 8.63a | 6.44b | 0.31 | 13.37a | 9.93b | 0.37 |
| Zn (mg $dm^{-3}$) | 0.52a | 0.20b | 0.02 | 0.97a | 0.80b | $0.08^f$ |

Means followed by common letters in the line do not differ according to Tukey's test at 5 % probability level. $^f$Data corrected by the equation $(x+0.5)^{0.5}$. Actual means presented with letters by Tukey's test as a function of the statistics with corrected data. S. D.= standard deviation.

The carbon sequestration potential in the Savanna region of Brazil had already been demonstrated by Carvalho *et al*. (2009), with several indications that the carbon accumulation rate can be highly increased through the use of a CLI system. The increased OM levels and improved physical quality of the soil with the introduction of pastures in agricultural areas with adequate fertility levels indicate that CLI has the potential to reduce the environmental impact of productive activities by decreasing greenhouse gas emissions and consequently increasing the production stability of annual crops and improving the use of water and nutrients (Franchini et al., 2010).

## CONCLUSIONS

The cation exchange capacity and base saturation of the treatments with sorghum in a monocrop or intercropped with Palisadegrass were higher, and the aluminum content and m% were lower than the treatments in which the grass was grown alone.

The different crop-livestock integration strategies increased the soil fertility and total carbon stock, especially in the 0.00-0.10 m layer, improving the chemical attributes of the soil in a short period, irrespective of the cultivation system.

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