Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 124 No. 2 (2023) 149–158

https://doi.org/10.17170/kobra-202311028941 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Newly implemented crop-livestock-forest systems increase available water and aeration in soils of the Brazilian Savannah

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Abstract

There is a growing demand for cropping systems that guarantee food production by improving the use efficiency of natural resources such as soil and water. The crop-livestock-forest (CLF) system is a form of sustainable intensification in which biodiversity and yields are increased on the same area. In this study, the physical-hydric properties of a Ferralsol and Cambisol in Central Brazil within the Savannah biome (*Cerrado*) were investigated 2 and 1 year after implementation of CLF systems. Soil samples were collected at seven soil depths up to 1 metre deep in CLF systems, within and between rows of trees, in a native forest (NF) and in a non-cultivated pasture, which depth was used as a reference (P-REF) for comparing soil quality with CLF establishment. Statistical analysis of soil water retention capacity considered two soil layers, 0.0–0.3 and 0.3–1.0 m, using clay and gravel contents as covariates in a mixed model. Main differences were noted within 0.0–0.3 m soil layer. In the Ferralsol, the available water was 0.2–0.3 mm higher in the CLF than in the P-REF, mainly due to an improvement in Theta R and microporosity. The Cambisol, in turn, showed in CLF and in NF a higher aeration capacity by up to 0.3 $m^3\ m^{-3}$ than in P-REF, as indicated by the Theta S and macroporosity values. The S index values indicated that CLF can improve soil physical quality of light textured soils such as Cambisol in the short term compared to P-REF. This improvement in soil quality is key to sustaining food production under tropical conditions.

Keywords: soil water retention capacity, pasture, Eucalyptus trees, integration

1 Introduction

The current global food system does not provide food security for all humans on Earth, and it is feared that it will not do so in the future in a way that reconciled environmental and social wellbeing with agricultural development (Maggio *et al.*, 2019). There is a significant and growing recognition of the need to transform food systems in order to reduce the negative impact on the environment. As a consequence, the agricultural sector has increased efforts on how to become more 'sustainable' (Benton & Harwatt, 2022). Sustainable means that agriculture development must be regulated by social and natural restrictions. Integrated systems have been proposed as an agricultural model for the recovery of degraded soils, and for the preservation of natural resources such as soil and water (Barcellos *et al.*, 2011). The crop-livestock-forest (CLF) system is characterised by the simultaneous and proximate presence of different agricultural species, components of livestock, and forestry activities. Adopting integrated systems as a proposal to make better use of the same area and timespan for intensifying production by the introduction of more diversity, including agricultural, forestry and livestock components, seems to be a feasible option (Romano, 2010).

The CLF system can offer many advantages over non-integrated, less biodiverse systems. One example is the improved use of nutrients and water through soil structuring and organic matter accumulation (Silva *et al.*, 2014). Moreover, it increases the productive efficiency of meat and milk (Carvalho *et al.*, 2019) which, among other benefits,

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Published online: 21 November 2023 – Received: 30 August 2022 – Accepted: 29 October 2023

reduces the need to open new areas, and increases farmer income (Alvarenga *et al.*, 2012).

The CLF system contains different plant species associated with the presence of animals, thus differing from monocultures concerning soil attributes (Alves *et al.*, 2017). The presence of different root systems, including forages, alters the dynamics of soil exploration by plants, increasing the ability of the cropping system to access nutrients and water in deeper soil layers (Zago *et al.*, 2020).

In Central Brazil, the conventional model for soil management consisted of successive heavy disc-harrowing as a soil tillage prior to an annual and solo crop cultivation, without rotation with other crops or forages. Consequently, the surface layer breaks down and soil capacity to retain water and organic matter is reduced (Jakab *et al.*, 2019). This is especially serious for Ferralsols in Central Brazil, which are highly weathered soils with a mean total carbon content of 1.7 g kg^{-1} within the 0.0–0.2 m soil layer (Anghinoni *et al.* 2021; Schaefer *et al.*, 2023). In this context, management practices that can link agricultural productivity to increased soil use efficiency has taken place in Brazil. Public policies (Brasil, 2012; Brasil, 2021) has driven the expansion of systems that integrates agricultural components and practices which increase the resilience of agricultural systems to reduce their vulnerability to the potential consequences of global warming, favouring the adaptation of crops to dry spells or heat stress (Akinnagbe & Irohibe, 2014; Anghinoni *et al.*, 2021). The term "resilience" refers to the responsiveness of the medium (plants and soils) to a disturbing agent or a harmful condition, minimizing the impact of such a situation and adapting to it. The term "adaptation", in turn, refers to all adjustments that need to be made in an agricultural system to better respond to actual or anticipated changes resulting from climate change (González-Sánchez *et al.*, 2022). Therefore, the present study assessed the short-term impact of CLF systems on physical-hydric properties of typical soils in Central West region of Brazil, where 47 % of country wide crop production is located (IBGE, 2023).

2 Materials and methods

2.1 Description and history of the area

According to the Brazilian Soil Classification System (Santos *et al.*, 2018), the soils under study are a typical Rhodic Ferralsol and a dystrophic Haplic Cambisol in Central Brazil, within the Savannah biome. The experiments were conducted in the municipalities of Morrinhos and Iporá in the state of Goiás, where 9.2 % of Brazil's crop production is harvested, the fourth largest in Brazil (IBGE, 2023). The climate is classified as Aw according to the Köppen-Geiger climate classification system (Kottek *et al.*, 2006).

On the Ferralsol in Morrinhos, the crop-livestock-forest (CLF) system was established in January 2018 and consisted of eucalyptus trees (clone AEC 2034 - *Eucalyptus camaldulensis* Dehnh. × *Eucalyptus grandis* W. Hill ex Maiden × *Eucalyptus urophylla* S.T. Blake) arranged with 10-metres spacing between rows and 4-metres spacing between trees in the row. On the Cambisol in Iporá, the CLF system was established in October 2018 and consisted also of eucalyptus trees (clone I144 - *Eucalyptus urophylla* × *Eucalyptus grandis*) arranged with 10-metres spacing between rows and 2-metres spacing between trees within the rows. On both areas, trees were planted in an east-west orientation. Between rows of trees, crops, such as soybean and corn, and forages such as *Urochloa* sp. grass were cultivated since implementation of the CLF system. Dairy cows grazed the forage as electric fences protected the trees. A non-cultivated forage grass of the genus *Urochloa* (syn. *Brachiaria*), on which beef-cattle have grazed for more than 30 years, served as reference area (P-REF) for both soil types. The native forest (NF) was represented by an area with vegetation typical of the Brazilian Savannah. The NF was located in a nearby area to the other treatments for each soil type.

At the moment of tree planting the soil was fertilised with 16.5 g of N, 34 g of P, and 24 g of K_2O per tree. As top-dressing, 1.7 g of B were applied per tree. The soil pH was adjusted to 5.5–6.0 with application of 2,500 kg ha^{-1} of dolomitic limestone. Mineral fertilisation and liming were necessary due to low chemical fertility level of a Ferralsol and Cambisol for agronomic cultivation. These soils are generally acid-dystrophic soil types in the Brazilian Savannah (Battle-Bayer *et al.*, 2010). Fertilisation, especially with boron, is necessary to prevent the dieback disease in eucalyptus trees under Brazilian Savannah conditions (Reis *et al.*, 2017).

In Brazil, *Eucalyptus* is the most abundant tree species in forest plantations, covering approximately 7.5 million hectares (IBÁ, 2022). Due to its rapid growth and adaptation to Brazilian ecosystems, it is now also the most commonly used tree species as a forest component in integrated cropping systems. After 20 years of public policies to promote forest plantations in marginal lands, the tendency to use lands less suitable for agriculture continues for economic reasons due to the exponential demand for wood and fibre (Ferraz *et al.*, 2019). Eucalyptus plantations are usually associated with high water consumption (Reichert *et al.*, 2017). To balance wood production with water ecosystem services, natural hydrological resilience should be measured (Ferraz *et al.*, 2019).

2.2 Description and history of the area

Soil sampling was carried out between November and December 2019, 2 years after planting eucalyptus trees in the CLF on Ferralsol, and 1 year after implementation of CLF on Cambisol. Disturbed and undisturbed (volumetric rings) soil samples were collected at seven soil depths: 0.0–0.1 m; 0.1–0.2 m; 0.2–0.3 m; 0.3–0.4; 0.4–0.6; 0.6–0.8; and 0.8–1.0 m. Sampling was carried out within rows of trees (CLF-WR) and between rows of trees (CLF-BR), five metres away from the rows of trees (Fig. 1). Two trenches 1-metre deep were opened for each treatment (CLF-WR, CLF-BR, NF and P-REF), totalizing four soil profiles (repetitions) within each treatment, summing up 112 soil samples for each soil type.

Fig. 1: *One metre deep profile of a Cambisol (left) and positions (▲) of trenches in a Ferralsol (right) for soil sampling within and between tree rows in a crop-livestock-forest system, Central West Brazil, Goiás State, Savannah biome, December 2019.*

Soil samples were air-dried, passed through a 2mm sieve and an aliquot of the sample was used for particle-size distribution analysis according to Teixeira *et al.* (2017), shown in Table 1. The soil organic matter was determined by wet combustion according to Silva *et al.* (1998).

Undisturbed soil samples collected with volumetric rings (stainless steel cylinders measuring 5 cm height and 5 cm diametre) were used to evaluate bulk density (BD), porosity (Teixeira *et al.*, 2017), soil aeration capacity (SAC) (Reynolds *et al.*, 2002), and derivation of soil water retention curves (SWRCs) via centrifuge method given by Freitas Júnior & Silva (1984). The SWRCs were obtained using the mathematical model proposed by van Genuchten (1980).

Soil samples in volumetric rings were saturated with water for 12 h and analysed in a Kokusan H-1400 pF® centrifuge. Four samples were analysed at a time, for 30 minutes, at seven speed levels: 600, 700, 800, 1300, 1800, 2400 and 9100 rpm (equivalent to 0, 33.00, 44.92, 58.67, 154.93, 297.03 and 528.05 g). The volume of water removed from the soil samples corresponds to seven matrix potentials: −6, −8, −10, −33, −60, −100, and −1500 kPa. Bulk density was determined as the ratio between the dry soil mass contained in the ring and the ring volume. This value was used to calculate volumetric soil moisture in each sample (cm^3 cm^{-3}). The saturated soil sample corresponds to the potential at 0 kPa before centrifugation. The ratio between observed volumetric soil moisture and matrix potential resulted in water retention curves for each treatment (van Genuchten, 1980), as in Eq. (1).

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1 + (\alpha\psi)^n}\right]^m \qquad (1)$$

Where: $\theta(\psi)$ is the observed volumetric soil moisture (cm^3 cm^{-3}) at a given matrix potential ψ (kPa); θ_r is residual moisture or Theta R (moisture contained in the soil under $\psi \geq -1500$ kPa); θ_s is saturated moisture or Theta S (moisture contained in the soil under 0 kPa); and m, α , and n are shape parameters of the soil water retention curves. Field capacity (FC) consisted of soil moisture retained at a tension of −8 kPa and at −6 kPa, with permanent wilting point (PWP) at a tension of −1500 kPa and available water capacity defined as (AWC = FC − PWP).

The S index is used to evaluate soil physical quality. It is defined as the slope of the SWRCs at its inflection point. This variable was determined according to Dexter (2004). Andrade & Stone (2009) established adjusted S index for soils of the Brazilian Savannah. The threshold value of $S = 0.045$ divides soils of good physical-hydric quality from soils with a tendency to become degraded. Values of $S \leq 0.025$ indicate physically degraded soils.

2.3 Statistical Analysis

Statistical analysis was performed using mixed models that allow considering random effects such as texture (Table 1) and repeated measurements (soil profiles and depths). To analyse fixed effects (treatments), gravel content and clay content were considered as covariates (random effect). For Ferralsol, data was divided in two groups according to clay content: (1) below 50 %; (2) equal to or above 50 %. For Cambisol, data was divided according to gravel content: (1) equal to or above 50 %; (2) below 50 %. Covariates for each of the seven depths was included as random effect in the analysis for two soil layers separately: 0.0–0.3 m (0.0–0.1, 0.1–0.2, 0.2–0.3 m) and 0.3–1.0 m (0.3–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0 m). Therefore, soil depths (n = 3 or 4) and soil profiles (n = 4) were taken as repeated measurements for each soil layer (0.0–0.3 and 0.3–1.0 m), and covariance parameters (clay or gravel content within each soil sample; n = 1 or 2) were considered in the mixed model to reduce error related to spatial variability and/or possible

Table 1: *Particle-size analysis of a Ferralsol and a Cambisol at 0.0–0.3 m and 0.3–1.0 m soil layers under crop-livestock-forest (CLF) systems within (WR) and between (BR) tree rows, native forest (NF), and reference pasture (P-REF) located in Goiás State, Central West Brazil, within the Savannah biome.*

Treatment	*Clay*	*Silt* ($g\,kg^{-1}$)	*Sand*	*Gravel ratio*	*Soil texture*
Ferralsol 0.0–0.3 m					
CLF-WR	469.4 (31.9)	169.6 (25.0)	361.0 (34.3)	na	Clay
CLF-BR	486.8 (31.9)	184.6 (25.0)*	328.6 (34.3)	na	Clay
NF	486.0 (32.1)	134.1 (25.1)	379.9 (34.6)	na	Clay
P-REF	485.2 (31.9)	158.0 (25.0)	356.9 (34.3)	na	Clay
Ferralsol 0.3–1.0 m					
CLF-WR	494.9 (16.0)**	145.3 (18.2) *	359.8 (20.9)**	na	Clay
CLF-BR	507.5 (16.4)**	165.8 (18.6)**	326.6 (21.4)	na	Clay
NF	531.1 (16.7)**	142.8 (19.0)*	326.2 (21.8)	na	Clay
P-REF	556.2 (16.5)	122.4 (18.8)	321.4 (21.6)	na	Clay
Cambisol 0.0–0.3 m					
CLF-WR	201.8 (33.4)**	151.1 (24.7)	647.0 (43.5)**	0.55	Sandy clay loam
CLF-BR	165.5 (33.8)**	147.8 (25.0)	686.7 (44.1)**	0.58	Sandy loam
NF	203.8 (33.1) **	179.4 (24.5)**	616.8 (43.2)**	0.51	Sandy clay loam
P-REF	380.1 (33.1)	140.8 (24.5)	479.1 (43.2)	0.37	Sandy clay
Cambisol 0.3–1.0 m					
CLF-WR	423.4 (47.3)	219.4 (26.5)*	357.3 (49.6)	0.54	Clay
CLF-BR	434.0 (47.4)	185.0 (26.6)	381.1 (49.7)	0.56	Clay
NF	326.6 (47.5)	268.8 (26.7)**	404.7 (49.9)	0.55	Clay loam
P-REF	451.4 (47.8)	184.9 (26.8)	363.8 (50.2)	0.33	Clay

Gravel ratio is the proportional amount of gravel in the Cambisol; na: not applicable. Significant differences between means given by the Dunnett test using P-REF as a reference. Asterisks indicate the nominal value of significance (p-value): $^{**}p \leq 0.05$; $^{*}p \leq 0.15$, within each soil type and soil layer, separately. Standard error of means ($n = 4$) is presented between parentheses.

different texture among soil samples. In this way, the standard error of means (n = 4) is reduced due to additional covariance parameter estimates, apart of residuals given by repeated measurements and can be specific for each mean. The Dunnett test was applied to analyse significant differences between P-REF and the other treatments. The analyses considered the treatments: reference pasture (P-REF), native forest (NF), and CLF system within (CLF-WR) and between (CLF-BR) tree rows for each soil type separately. As consequence of the large experimental areas, we adopted p-value ≤ 0.15 as our threshold to safeguard against high type II error. Analyses were performed using the linear mixed model procedure (Proc MIXED) of the SAS/STAT®statistical software (SAS Institute Inc. 2008).

3 Results

3.1 Soil water retention curve parameters

In the surface layer (0.0–0.3 m) of Ferralsol, P-REF and NF differed significantly for almost all parameters of the SWRCs, except for Theta R (Table 2). Theta R was significantly higher in CLF than in P-REF, both within and between tree rows. On the contrary, Theta S was significantly lower in CLF-BR than in P-REF. Theta S was significantly higher in NF than in P-REF. In the 0.3–1.0 m layer, curve shape parameters (*m* and *n*) were significantly lower in CLF-BR than in P-REF. In turn, Theta R and Theta S were significantly higher in CLF-WR and CLF-BR than in P-REF.

Theta S was equal in magnitude for CLF and NF. Parameter Alpha was significantly higher in NF than in P-REF. In the 0.0–0.3 m layer of Cambisol, retention curve shape parameters *m* and *n*, Theta R and Theta S differed significantly between CLF and P-REF. Theta R and Theta S values in CLF were equivalent to those in NF. Parameter Alpha was significantly higher in NF than in P-REF. In the 0.3–1.0 m layer of Cambisol, Theta S and Theta R were statistically lower in NF than in P-REF. Theta S was lower in NF and CLF-WR.

In the Ferralsol, in the CLF at the 0.0–0.3 m layer, the lowest values of Theta R and highest values of Theta S associate with the lowest MIP and highest MAP values, respectively (Table 3).

Table 2: *Parameters of soil water retention curves in the 0.0–0.3 and 0.3–1.0 m layers of a Ferralsol and Cambisol, at 2 and 1 year after implementation of the crop-livestock-forest (CLF) systems respectively, within (WR) and between (BR) tree rows, and under native forest (NF) and reference pasture (P-REF) located in Goiás State, Central West Brazil, within the Savannah biome.*

Treatment	*Alpha (kPa)*	*m*	*n*	*Theta R ($kg\,kg^{-1}$)*	*Theta S ($kg\,kg^{-1}$)*
Ferralsol 0.0–0.3 m					
CLF-WR	0.53 (*1.5*)	0.31 (*0.02*)	1.47 (*0.04*)	0.21 (*0.005*)**	0.43 (*0.03*)
CLF-BR	0.41 (*1.5*)	0.31 (*0.02*)	1.45 (*0.04*)	0.21 (*0.005*)**	0.41 (*0.03*) *
NF	7.92 (*1.5*)**	0.28 (*0.02*)**	1.39 (*0.04*)**	0.20 (*0.005*)	0.51 (*0.03*)**
P-REF	1.33 (*1.5*)	0.31 (*0.02*)	1.45 (*0.04*)	0.20(*0.005*)	0.44 (*0.03*)
Ferralsol 0.3–1.0 m					
CLF-WR	1.63 (*0.7*)	0.34 (*0.02*)	1.51 (*0.04*)	0.21 (*0.004*)**	0.53 (*0.04*)**
CLF-BR	1.80 *(0.8)*	0.32 (*0.02*)**	1.47 (*0.04*)**	0.22 (*0.004*)**	0.54 (*0.04*)**
NF	2.54 (*0.7*)**	0.33 (*0.02*)	1.51 (*0.04*)	0.19 (*0.004*)	0.50 (*0.04*)*
P-REF	1.21 (*0.7*)	0.34 (*0.02*)	1.52 (*0.04*)	0.19 (*0.004*)	0.46 (*0.04*)
Cambisol 0.0–0.3 m					
CLF-WR	24.99 (*13.8)*	0.31 (*0.03*)**	1.45 (*0.05*)**	0.08 (*0.01*)**	0.36 (*0.03*)**
CLF-BR	13.78 *(14.0)*	0.30 (*0.03*)*	1.44 (*0.05*)*	0.09 (*0.01*)*	0.34 (*0.03*)*
NF	46.75 *(13.7)***	0.26 (*0.03*)	1.35 (*0.05*)	0.09 (*0.01*)*	0.38 (*0.03*)**
P-REF	13.18 (13.7)	0.27 (*0.03*)	1.36 (0.05)	0.12 (0.01)	0.30 (*0.03*)
Cambisol 0.3–1.0 m					
CLF-WR	14.03 *(6.6)*	0.28 (*0.02*)	1.39 *(0.04)*	0.15 *(0.02)*	0.33 *(0.03)**
CLF-BR	10.05 *(6.6)*	0.28 *(0.02)*	1.39 *(0.04)*	0.14 *(0.02)*	0.33 (*0.03*)
NF	9.01 *(6.6)*	0.26 *(0.02)*	1.35 *(0.04)*	0.12 *(0.02)**	0.29 *(0.03)***
P-REF	9.44 *(6.4)*	0.27 *(0.02)*	1.38 *(0.04)*	0.15 *(0.02)*	0.36 *(0.03)*

Theta R is the moisture contained in soil under -1500 kPa; Theta S is the moisture contained in soil under 0 kPa; *m*, *alpha*, and *n* are shape parameters of soil water retention curves. Significant differences between means given by the Dunnett test using P-REF as a reference. Standard error of means (n = 4) given between parentheses. Asterisks indicate the nominal value of significance (p-value):** $p \leq 0.05$; * $p \leq 0.15$, within each soil type and soil layer separately.

3.2 *Physical-hydric properties*

An ideal soil for plant development has a macroporosity of $0.10\,m^3\,m^{-3}$ (Pagliai *et al.*, 2003). In turn, total porosity should be $0.50\,m^3\,m^{-3}$ of total soil volume, with microporosity ranging between 0.25 and $0.33\,m^3\,m^{-3}$. Main significant effects were observed within the 0.0–0.3 m soil layer (Table 3). As for the porosity of Ferralsol, in the surface layer 0.0–0.3 m, the CLF-BR treatment showed lower total porosity and higher bulk density, consequently higher volume of micropores (MIP) and lower volume of macropores (MAP) than P-REF. Total porosity and S Index were equivalent between NF and CLF-BR. Notwithstanding, SAC was significantly lower in CLF than in P-REF in the Ferralsol (Table 3). On the other hand, in the subsurface layer (0.3–1.0 m) of Ferralsol, TP increased significantly, and BD decreased in CLF treatments (CLF-WR and CLF-BR) in relation to the reference pasture (P-REF).

Regarding the available water capacity in the surface layer (0.0–0.3 m), the CLF system showed higher values of AWC6 and AWC8 than the reference pasture (P-REF). On the other hand, in the Cambisol, which is sandier than the Ferralsol, at the 0.0–0.3 m layer, only the CLF-BR showed higher values of AWC6 in relation to P-REF.

In Cambisol, significant differences occurred between CLF and P-REF only in the 0.0–0.3 m layer, with lower MIP values and higher MAP values in relation to P-REF. The CLF-WR accounted for higher TP and lower BD values.

Macroporosity is proportional to soil aeration capacity. In Ferralsol, the lower volume of MAP decreased SAC of the CLF in the 0.0–0.3 m layer. On the other hand, in Cambisol, the greater volume of MAP in CLF than in P-REF increased SAC of the CLF in the 0.0–0.3 m layer. The S index in Ferralsol (Table 3), at the 0.0–0.3 m layer, was significantly lower in the CLF-BR (0.042) than in P-REF (0.051). Values of S index below 0.045 indicates a tendency of soil degradation (Andrade & Stone, 2009). However, at deeper soil layer (0.3–1.0 m), S index of CLF (0.074–0.076) was significantly higher than in P-REF (0.064). On the other hand, in the Cambisol at the 0.0–0.3 m layer, S index in the CLF system (0.053-0.059) was significantly higher than in the P-

Table 3: *Soil bulk density (BD), total porosity (TP), S index, microporosity (MIP), macroporosity (MAP), soil aeration capacity (SAC), available water capacity at −8 kPa (AWC8) and at −6 kPa (AWC6) in 0.0–0.3 and 0.3–1.0 m layers of a Ferralsol and Cambisol at 2 and 1 year after implementation of the crop-livestock-forest (CLF) systems respectively, within (WR) and between (BR) tree rows, native forest (NF) and reference pasture (P-REF) in Goiás State, Central West region of Brazil, within the Savannah biome.*

Treatment	*BD* ($g\,cm^{-3}$)	*TP* ($m^3\,m^{-3}$)	*S Index*	*MIP* ($m^3\,m^{-3}$)	*MAP* ($m^3\,m^{-3}$)	*SAC* ($m^3\,m^{-3}$)	*AWC8* ($mm\,cm^{-1}$)	*AWC6* ($mm\,cm^{-1}$)
Ferralsol 0.0–0.3 m								
CLF-WR	1.25	0.53	0.05	0.41**	0.11**	0.24**	1.27**	1.43**
	(0.04)	(0.02)	((0.01)	(0.02)	(0.03)	(0.04)	(0.11)	(0.12)
CLF-BR	1.28*	0.52*	0.04**	0.43**	0.09**	0.20**	1.30**	1.45**
	(0.04)	(0.02)	(0.01)	(0.02)	(0.03)	(0.04)	(0.11)	(0.12)
NF	1.14**	0.57**	0.06*	0.32**	0.26**	0.46**	0.70**	0.80**
	(0.04)	(0.02)	(0.01)	(0.02)	(0.03)	(0.04)	(0.11)	(0.12)
P-REF	1.23	0.54	0.05	0.38	0.16	0.32	1.05	1.20
	(0.04)	(0.02)	(0.01)	(0.02)	(0.03)	(0.04)	(0.11)	(0.12)
Ferralsol 0.3–1.0 m								
CLF-WR	1.11**	0.58**	0.08*	0.36	0.22	0.41	1.01	1.17
	(0.05)	(0.02)	(0.01)	(0.02)	(0.04)	(0.05)	(0.09)	(0.10)
CLF-BR	1.09**	0.59**	0.07*	0.36	0.23*	0.41	1.00	1.15
	(0.05)	(0.02)	(0.01)	(0.02)	(0.04)	(0.05)	(0.09)	(0.11)
NF	1.14**	0.57**	0.07	0.31**	0.26**	0.47**	0.77**	0.89**
	(0.05)	(0.02)	(0.01)	(0.02)	(0.04)	(0.05)	(0.09)	(0.11)
P-REF	1.21	0.54	0.07	0.36	0.19	0.37	0.99	1.15
	(0.05)	(0.02)	(0.01)	(0.02)	(0.04)	(0.05)	(0.09)	(0.11)
Cambisol 0.0–0.3 m								
CLF-WR	1.37**	0.48**	0.06**	0.16**	0.32**	0.68**	0.44	0.51
	(0.07)	(0.03)	(0.01)	(0.02)	(0.03)	(0.06)	(0.07)	(0.08)
CLF-BR	1.41	0.47	0.05**	0.19**	0.28**	0.61**	0.54	0.62*
	(0.07)	(0.03)	(0.01)	(0.02)	(0.04)	(0.06)	(0.07)	(0.08)
NF	1.33**	0.50**	0.05**	0.19 **	0.31**	0.63**	0.52	0.58
	(0.07)	(0.03)	(0.01)	(0.02)	(0.03)	(0.06)	(0.07)	(0.08)
P-REF	1.48	0.44	0.03	0.24	0.20	0.47	0.46	0.52
	(0.07)	(0.03)	(0.01)	(0.02)	(0.03)	(0.06)	(0.07)	(0.08)
Cambisol 0.3–1.0 m								
CLF-WR	1.43	0.46	0.04	0.27	0.19	0.43	0.50	0.56
	(0.06)	(0.02)	(0.01)	(0.03)	(0.04)	(0.07)	(0.09)	(0.10)
CLF-BR	1.42	0.47	0.04	0.26	0.21	0.46	0.50	0.57
	(0.06)	(0.02)	(0.01)	(0.03)	(0.04)	(0.07)	(0.09)	(0.10)
NF	1.50**	0.43**	0.03**	0.26	0.17	0.41	0.62	0.69
	(0.06)	(0.02)	(0.01)	(0.03)	(0.04)	(0.07)	(0.09)	(0.10)
P-REF	1.37	0.48	0.04	0.27	0.21	0.44	0.57	0.64
	(0.06)	(0.02)	(0.01)	(0.03)	(0.04)	(0.07)	(0.09)	(0.10)

Significant differences between means followed the Dunnett test using P-REF as a reference. Asterisks indicate the nominal value of significance (p-value): $^{**}p \leq 0.05$; $^{*}p \leq 0.15$, within each soil type and soil layer, separately. Standard error of means (n = 4) given between parentheses.

REF (0.033), and equivalent to that observed in NF (0.053). In the 0.3–1.0 m layer, CLF did not differ from P-REF, and values for S index was all the minimum threshold of 0.045 (Andrade & Stone, 2009).

The soil organic matter content (SOC) was lower in the CLF system than in the pasture-REF at 0.0–0.3 m layer in Ferralsol. On the contrary, in Cambisol, the SOC was higher in the CLF system than in the P-REF (Table 4).

Table 4: *Soil organic matter content ($g\,kg^{-1}$) in the 0.0–0.3 and 0.3–1.0 m layers of a Ferralsol and Cambisol under two crop-livestock-forest (CLF) systems, at 2 and 1 year after implementation of the CLF respectively, within (WR) and between (BR) rows of trees, native forest (NF) and reference pasture (P-REF) located in Goiás State, Central West region of Brazil, within the Savannah biome.*

	Soil organic matter content ($g\,kg^{-1}$)	
Treatment	*0.0–0.3 m*	*0.3–1.0 m*
Ferralsol		
CLF-WR	30.4 (*3.2*)*	20.2 (*2.3*)*
CLF-BR	32.7 (*3.2*)	19.6 (*2.3*)*
NF	33.5 (*3.2*)	20.5 (*2.4*)*
P-REF	34.8 (*3.2*)	22.6 (*2.4*)
Cambisol		
CLF-WR	16.6 (*3.8*)	6.0 (*2.0*)*
CLF-BR	20.6 (*3.8*)*	6.0 (*2.0*)*
NF	28.4 (*3.8*)**	7.4 (*2.0*)
P-REF	15.1 (*3.8*)	8.2 (*2.0*)

Significant differences between means followed the Dunnett test using P-REF as a reference. Asterisks indicate the nominal value of significance (p-value): $^{**}p \leq 0.05$; $^{*}p \leq 0.15$, within each soil type and soil layer, separately. Standard error of means (n = 4) given between parentheses.

4 Discussion

4.1 Soil water retention curve parameters

The higher values of Theta R in CLF on Ferralsol regarding to P-REF may be due to its higher microporosity (Table 2), as at low soil water potentials, available surface area is more determinant for soil water retention than available pore space (Berg *et al.*, 1997). On the other hand, the lowest and highest values of Theta S in the 0.0–0.3 and 0.3–1.0 layers, in the CLF system on Ferralsol, were due to the lowest and highest macroporosity values in these layers, respectively (Table 3). The amount of water that can be retained at high potentials depends primarily on the available pore space (Berg *et al.*, 1997) and is influenced both by total porosity (TP) and by the distribution of larger pores (Machado *et al.*, 2008).

The higher values of retention curve shape parameters *m* and *n* in the 0.0–0.3 m layer of CLF on Cambisol in relation to P-REF may be due to the more uniform distribution of macropores. High values of *n* correspond to a well-expressed sigmoidal curve due to the uniform distribution of macropores (Berg *et al.*, 1997). The magnitude of the soil water retention curve parameters, especially Alpha, Theta R, and Theta S, shows the difference between the two soil types and explains why a Cambisol has a lower water retention capacity than a Ferralsol (Table 3).

4.2 Physical-hydric properties

The lower TP and higher BD in the Ferralsol surface layer for CLF-BR treatment regarding to P-REF may be due to the impact of machine traffic on this treatment at the moment of CLF implementation and afterwards, with activities such as fertilisations and harvest of crops and forage for silage, as the treatment of the CLF-WR did not present the same result for TP and BD.

Lower BD values usually indicate a good volume of soil macropores, reduced resistance to root penetration, faster diffusion of nutrients and oxygen, and a higher mineralization rate of soil organic matter (Stone & Moreira, 2000). Total porosity is inversely proportional to bulk density (Ferreira, 2010), which is commonly used as an indicator of compaction.

Differently from the Ferralsol, the eucalyptus trees contributed to better soil porosity in the Cambisol. After one year of implementation of a CLF system, the surface layer showed lower MIP values and higher MAP values in relation to P- REF (Table 3). Rocha *et al.* (2015) concluded that the influence of eucalyptus trees, through the contribution of litter and root system, was of outstanding importance for improving soil physical condition, increasing porosity and reducing bulk density.

The higher values of AWC6 and AWC8 in CLF than in the reference pasture in the surface layer of Ferrasol were due to the greater volume of micropores, which are responsible for the retention and storage of soil water. Moreover, a higher Theta R also contributes for increase AWC in the CLF system. On the other hand, the higher values of AWC6 showed by CLF-BR in relation to P-REF in the sandier Cambisol were most likely due to the higher organic matter content (Table 4). Minasny & Mcbratney (2018) found that the increase in AWC with increasing organic matter is greater in sandy soil, while the effect in clayey soil is almost negligible. A greater effect of organic matter occurs in the presence of large pores, possibly due to the formation of macroaggregates. This effect diminishes with the reduction of pore size.

SAC refers to the number of pores responsible for the exchange of oxygen and carbon dioxide between the atmosphere and the soil (Ferreira, 2010), and it is directly proportional to macroporosity. In this sense, as in Cambisol the volume of MAP in surface layer was higher in CLF than in P-REF, and the contrary occurred in Ferrasol, SAC increased with the implantation of CLF system on the Cambisol and decreased on the Ferrasol. Higher SAC means higher capacity to meet the respiratory demand of soil microorganisms.

This soil biological machinery correlates closely with physical and chemical components, which together influence the productivity and sustainability of soils, as well as their ecological functions and environmental services (Mendes *et al.*, 2018).

The lower S index in CLF-BR than in P-REF in Ferralsol, at the 0.0–0.3 m layer, reinforces the effect of the mechanisation that took place between the rows in the CLF system. On the other hand, the higher values of S index and soil organic matter content in the CLF system than in the P-REF showed that the implementation of the CLF system can already improve soil quality one year after implementation in Cambisol, ensuring forage and crop production.

In the Cambisol, the effect of the tree root system may have been more pronounced, favouring an increase in organic matter and aggregation of the soil, thus increasing porosity and consequently reducing bulk density (Loss *et al.*, 2012). The overall role of CLF systems in recovering soil degradation of non-cultivated permanent pastures is clear. The implementation of these systems is also important for adapting to the changes already taking place in the savannah biome in Brazil (Rodrigues *et al.*, 2022). The cultivation of trees is essential for the thermal well-being of animals and humans in tropical regions. Eliminating deforestation and restoring deforested areas and degraded soils can regionally lead to a reduction of the side effects exacerbated by global warming, such as increases in minimum temperatures and evapotranspiration.

5 Conclusion

The implementation of the CLF system had different effects on the two soils studies. Greater effects occurred in the 0.0–0.3 m layer. In Ferralsol, CLF positively affected available water capacity and in Cambisol on the soil aeration capacity. The short-term effects of CLF establishment were more evident in Cambisol. These results are an important guide for monitoring the impact that the CLF system will have over time. They serve for management decisions, as these systems are considered key to sustaining food production under Brazilian savannah conditions.

Acknowledgements

This research was funded by The Brazilian Agricultural Research Corporation (Embrapa) via INTEGRACarbono, project number 20.18.03.043.00.00. This publication is based upon work supported by the Sustainable Rural Project - Cerrado in partnership with the Inter-American Development Bank (IDB), the U.K. Government, the Brazilian Institute for Development and Sustainability (IABS), and the ICLF Network Association. L.L.F. received a fellowship from FAPEG via CAPES grant no. 201810267001504-DOCFIX. B.E.M. received a productivity fellowship from CNPq grant no. 307807/2022-3.

Conflict of interest

The authors declare that they have no conflict of interest.

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