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Soil carbon stock and humification in pastures under different levels of intensification in Brazil

Aline Segnini[1], Alfredo Augusto Pereira Xavier[1], Pedro Luis Otaviani-Junior[1], Patrícia Perondi Anchão Oliveira[2], André de Faria Pedroso[2], Maria Fernanda Ferreira Menegucci Praes[3], Paulo Henrique Mazza Rodrigues[3], Débora Marcondes Bastos Pereira Milori[1]*

[1]Embrapa Instrumentação, R. XV de Novembro, 1452 – 13560-970 – São Carlos, SP – Brasil.
[2]Embrapa Pecuária Sudeste, Rod. Washington Luiz, km 234, s/n –13560-970 – São Carlos, SP – Brasil.
[3]Universidade de São Paulo/FMVZ – Depto. de Nutrição e Produção Animal, Av. Duque de Caxias Norte, 225 – 13635-900 – Pirassununga, SP – Brasil.
*Corresponding author <debora.milori@embrapa.br>

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ABSTRACT: Intensive management of tropical pastures has shown potential for greenhouse gas (GHG) mitigation due to high forage production and C accumulation in the soil. This study aimed to evaluate different pasture management options in relation to their effect on soil C stocks and soil organic matter (SOM) humification. Pastures in four beef cattle production systems were assessed: intensive and irrigated pasture with high stocking rate (IHS); dryland pasture with high stocking rate (DHS); dryland pasture with moderate stocking rate (DMS); degraded pasture (DP). The soil under the native forest was also evaluated and soil carbon stocks from the 0-100 and 0-30 cm layers were assessed. Carbon stocks (0-100 cm) ranged from 99.88 to 142.33 Mg ha^{-1} in DP and DMS, respectively and were, respectively, 14 % and 24 % higher compared to the soil under the forest and indicate the capacity of adequately managed tropical pastures to mitigate GHG emissions from livestock production. Humification indexes indicated the presence of more labile C in pastures with greater C accumulation (DHS and DMS), mainly in the upper soil layers, indicating recent C accumulation resulting from correct management. However, more labile C can be easily lost to the atmosphere as CO_2, depending on pasture management. Low C stocks associated with high humification indexes are characteristics of DP in which significant amounts of SOM are lost. It is necessary to develop technologies to improve C sequestration in IHS and results indicate the importance of quantifying C stocks in association with C stability.
Keywords: Atlantic Forest biome, Brazilian livestock systems, Laser-Induced Fluorescence Spectroscopy, humification index, organic matter

Introduction

The Brazilian government has committed to implementing policies to reduce GHG emissions in the livestock-raising sector by 2020 (Nepstad et al., 2009). Intensive management of tropical grasses has shown GHG mitigation potential as a consequence of the high productivity of these pastures when fertilized, which results in soil carbon (C) accumulation (Oliveira et al., 2007a; Ontl and Schulte, 2012; Bustamante et al., 2012; Ruviaro et al., 2014). Moreover, adequate physiological management of tropical grasses (Conant et al., 2001) and maintenance of soil fertility are agronomic practices that are essential to restore and intensify degraded pastures (Oliveira et al., 2003; Oliveira et al., 2005; Santos and Corrêa, 2005; Oliveira et al., 2008).

Determination of C content is imperative to any evaluation of the impact of pasture management on soils. According to Braz et al. (2013), well-managed pastures can increase soil C stocks while soils under poorly managed or degraded pastures may lose C compared to soils under the original vegetation. Studies of C spatial variability at a depth of 1 m have shown deep C incorporation in pastures under adequate management (Fisher et al., 1994; Boddey et al., 2010). Grass species with abundant root systems during pasture recovery and intensification processes appear to be the reason for this behavior (Oliveira et al., 2007b).

Irrigation is another factor which must be evaluated in relation to soil C dynamics. The soil type, crop and soil preparation method are among the factors that may modify the irrigation effect on soil C stocks (Bayer et al., 2006). The increase in soil water content caused by irrigation provides favorable conditions for microbial activity, intensifying microbial organic matter (OM) decomposition and carbon mineralization (Andrén et al., 1992). Although the responses of crops to water supplementation are well known, information on the effects of irrigation on soil organic matter (SOM) and C stocks in tropical warm areas is scarce.

The potential of pastures to retain C involving OM stability is an important aspect in the identification of GHG mitigation alternatives for the cattle-raising sector in Brazil. However, few studies have evaluated the mitigation potential of pastures by increasing C sequestration in livestock production systems in the Atlantic Forest biome (Boddey et al., 2006; Assad et al., 2013).

The principal aim of this study was to evaluate the effects of degradation, recovery and intensification of pastures of beef cattle production systems on soil C stocks and SOM humification in the Atlantic Forest biome. In order to evaluate the potential for C sequestration in deeper layers in the soil a comparative study of C stocks in the 0-30 and 0-100 cm soil layers was conducted.

Materials and Methods

Study area and soil sampling

The study was carried out in São Carlos, in the state of Sao Paulo, Brazil (22°1′ S and 47°53′ W, 853 m above sea level). The experimental period was from 1996 to 2011. The prevailing climate is Cwa, according to the Koeppen classification, with a mean annual temperature of 20 °C and an average cumulative annual rainfall of around 1,360 mm.

Soil samples were collected in pastures and from the original vegetation (Atlantic Forest - "seasonal semi-deciduous forest") in a transition zone with two soil types: Hapludox soils (Red Latosol and Yellow Latosol, both Oxisols according to the FAO classification system). Pastures, with two replicates per system (blocks), were subject to four beef cattle production systems, described as follows: intensively managed and irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with a high stocking rate (IHS); intensively managed dryland *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate (DHS); dryland pasture with a mix of *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) and *Urochloa* (*Brachiaria*) *brizantha* (Hochst ex A. Rich) Stapf (cv. Marandu) grasses, with moderate stocking rate (DMS); degraded *Urochloa* (*Brachiaria*) *decumbens* pasture under extensive management (DP). The tropical pasture (*Panicum* sp.) in IHS was overseeded with oats (*Avena bysantina* Koch, cv. São Carlos) and ryegrass (*Lolium multiflorum* Lam., cv. BRS Ponteio) in the autumn. The intensively managed pastures (established in 2002) were divided into 12 paddocks (0.14 to 0.15 ha each) which were grazed for three days, under a rotational grazing system with 36 days of rest. Each DMS pasture (established in 1996) was divided into six paddocks (0.55 ha each) which were grazed for six days also under a rotational system (30 days rest). The degraded pastures (two paddocks of 1.7 ha) were kept under continuous grazing. Pastures were managed under variable stocking rate ("put and take") and stocking rates were adjusted accordingly to the visually estimated forage availability in each paddock. All pastures (except DP) were limed and fertilized with superphosphate and potassium chloride to achieve 20 mg dm^{-3} of P and 4 % K in CTC - soil cation exchange capacity -, according to Oliveira et al. (2008). Annual top-dressing nitrogen fertilization was applied at the rate of 600 kg N ha^{-1} in IHS, 400 kg N ha^{-1} in DHS and 200 kg N ha^{-1} in DMS. Doses were divided into five applications during the rainy season in DHS and DMS and eight applications, four during the wet and four during the dry season in IHS. The degraded pasture was not fertilized nor limed. Other relevant soil and management parameters are described in Table 1. The native forest soil was sampled so as to represent original soil conditions in the experimental areas. The IHS and DHS systems were implemented in 2002 and DP and DMS in 1996. Samples were collected in 2011 (Table 1).

Soil samples were collected at the following depths: 0-5, 5-10, 10-20, 20-30, 30-40, 40-60, 60-80 and 80-100 cm, with six field replicates (three replicates per block). In each replicate, two sub-samples were collected on two sides of the trench, for each depth interval, using an aluminum ring of known volume, for subsequent evaluation of dry soil weight (at 110 °C) and determination of soil bulk density using the mean of two sub-samples.

Soil sample preparation and carbon stocks determination

Soil samples were air-dried at approximately 25 °C (until reaching constant mass), gently crushed using a mortar and pestle and passed through a 9-mesh sieve (particle size smaller than 2 mm). Sub-samples were finely ground so as to be able to pass through a 100-mesh sieve (particle size smaller than 0.150 mm) for all analyses. Total C analysis was performed, in duplicate, on approximately 10 mg of soil using a CHN elemental analyzer. Soil C stocks are usually estimated using the soil bulk density at each depth interval and the corresponding C content (Veldkamp, 1994). Subsequently, C stock data were corrected for soil compaction, according to the equation proposed by Sisti et al. (2004), using data from the soil under the natural vegetation as the reference. The calculation of the equivalent soil mass was carried out for the 0-30 and 0-100 cm layers according to Ellert and Bettany (1995), also using the native forest soil as the reference.

Table 1 – Management and soil characteristics of pastures under different levels of intensification in four beef cattle grazing systems and the native vegetation.

Characteristic	IHS	DHS	DMS	DP	FO
Stocking rate (AU ha^{-1}*)	5.9	4.9	3.4	1.1	-
Management time (years)	9	9	15	15	-
Sand (g kg^{-1})	676	434	322	768	568
Silt (g kg^{-1})	74	131	145	70	83
Clay (g kg^{-1})	251	434	533	162	349
Soil texture class**	Sandy clay loam	Sandy clay	Clay	Sandy Loam	Sandy Clay loam

*Animal-unit per hectare in the rainy season; IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) pasture under extensive management; FO = native vegetation ("seasonal semi-deciduous forest"). **Soil texture class according to Textural soil triangle.

Humification of Soil Organic Matter

The analysis of SOM humification by Laser-Induced Fluorescence Spectroscopy (LIFS) is important because it complements soil C stock data. The LIFS technique measures recalcitrant C, that can be a sensitive indicator of changes caused by land use and soil management (Milori et al., 2011; Segnini et al., 2013; Martins et al., 2015; Bordonal et al., 2017).

Homogenized soil samples (particle size smaller than 0.15 mm) were pelletized (1 cm × 2 mm pellets of approximately 0.5 g) and submitted to 8 tons of pressure before SOM humification analyses by LIFS. Samples were excited by a continuous wave (cw) laser, at a wavelength of 405 nm radiation, emitted by diode laser equipment (lab-assembled instrument) with a power source of approximately 200 mW. Experimental procedures were conducted according to Segnini et al. (2010). The measurement range was from 475 nm to 800 nm, the integration time 500 ms, and the average and boxcar five and four, respectively, for all evaluations. Five spectra were obtained for each sample and the results presented here correspond to the means of five measurements and field replicates. The ratio of the area under the fluorescence emission bands and total organic C content (g kg^{-1}) were defined as the SOM humification index (H_{LIFS}) (Milori et al., 2006).

Statistical analysis

Data were analyzed by the mixed procedure of SAS (Statistical Analysis System, version 9.2), after verifying the residue normality by the Shapiro-Wilk test (PROC UNIVARIATE). When normality was not obtained, logarithmic or square root transformation of data was necessary.

The model included the effects of five treatments, eight soil sampling depths and the interaction between treatments and depth. The choice of the matrix that best fit the data was based on the lower corrected Akaike information criteria value (AICC) (Wang and Goonewardene, 2004). The effects of treatment were analyzed by Tukey test ($p \leq 0.05$).

Results and Discussion

Soil bulk density and SOM

Soil layers ($p \leq 0.05$) and pasture systems ($p \leq 0.01$) affected soil bulk densities. Soils in DHS and DMS presented bulk densities similar to the soil in the forest (Table 2). In IHS, higher soil compaction (Table 2) may have occurred due to the combination of two factors, frequent irrigation and possibly intense animal trampling. According to Silva et al. (2003), soil compression is greater in soils with high water content. In the DP system, with greater soil exposure and no irrigation, there was also increased compaction and higher bulk density (Table 2). In general, soil bulk density depends on the soil structure, water amount, soil texture, SOM, management, land use, soil compaction and cover vegetation type (Ramos et al., 2015). Generally, soils under native vegetation present lower densities, because, for the most part, there is no compaction of the nondisturbed soil (Table 2). However, in this trial, soil bulk density in the forest was no different to the soils under the DHS and DMS systems. Pore size distribution and resistance to root penetration are among those physical properties that are altered by soil compaction.

According to Ramos et al. (2015), soil bulk density has a significant effect on root growth, but this depends on other factors such as water content in the soil. Despite the statistical difference observed, the variation in soil bulk density among the various soil profiles in this experiment was small (Table 2) and may be explained by root system growth in grassland systems (Silva et al., 2003). The presence of *Panicum maximum* and *Brachiaria decumbens*, which have abundant root systems, may have influenced soil structure in the pastures evaluated. Liming and fertilization also had an impact, causing an increase in forage and root yields, mostly in the second year after the recovery of the *Brachiaria decumbens* degraded pastures has been initiated (Oliveira et al., 2003).

Soil C content results indicate there was an interaction ($p \leq 0.05$) between production system and soil depth. Higher soil C values were obtained in the surface layers, in all pasture systems and the forest, and C content decreased in the lower layers under all systems (Table 2, Figure 1). Superficial layers receive a continuous input of fresh material from vegetation and animals and this trend is commonly observed in most Brazilian soils, especially Oxisols (Sá et al., 2015). Similar results are observed in forests, mainly due to the deposition of decayed material from roots and vegetative aerial parts in the upper layers of the soil.

Table 2 – Soil bulk density (BD), carbon (C) content and organic matter (SOM) humification index (H_{LIFS}) of pastures in four beef cattle grazing systems and the native vegetation.

Item*	Treatments (systems)					Depths (cm)								
	IHS	DHS	DMS	DP	FO	0-5	5-10	10-20	20-30	30-40	40-60	60-80	80-100	SEM
BD (Mg m^{-3})	1.36^{a}	1.13^{b}	1.09^{b}	1.36^{a}	1.17^{b}	1.21^{bc}	1.25^{ab}	1.26^{a}	1.23^{bc}	1.22^{bc}	1.21^{bc}	1.19^{c}	1.20^{bc}	0.0098
C (%, m m^{-1})	1.09^{b}	1.37^{a}	1.50^{a}	0.95^{b}	1.24^{ab}	2.04^{a}	1.71^{b}	1.40^{c}	1.19^{d}	1.03^{e}	0.90^{f}	0.81^{g}	0.73^{h}	0.035
H_{LIFS} (a.u.) × 10^3	80.38^{b}	30.54^{c}	26.25^{c}	107.1^{a}	58.78^{b}	29.15^{g}	37.03^{f}	45.60^{e}	52.08^{d}	62.58^{c}	78.12^{b}	87.54^{a}	92.76^{a}	3.3172

*BD = Bulk density; C = soil carbon content; H_{LIFS} = soil organic matter humification index; IHS = Intensively managed irrigated *Panicum maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Panicum maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Urochloa* (*Brachiaria*) *decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) pasture under extensive management; FO = native vegetation ("seasonal semi-deciduous forest"); SEM = standard error of the means; Treat * Depth = Interaction pasture systems *vs* soil depth; $^{a\text{-}h}$ = means followed by different letters within a line are different ($p \leq 0.05$) by the Tukey test.

In soil layers above a depth of 10 cm, soil C contents were higher in the dryland systems (DHS and DMS) compared to IHS and DP. Despite irrigation, soil C content in the 0-5 cm layer was lower in IHS compared to the forest. In layers between the depths of 10 and 30 cm, soil C content was higher in DHS and DMS than in the forest, IHS and DP (Table 3, Figure 1). The soils in DHS and DMS, in addition to benefiting from good management, presented high clay content (Table 1). Consequently, they were able to accumulate considerable quantities of C, well above the quantities detected under the native vegetation. These results corroborate findings by Fisher et al. (1994), who compared soils in well-managed pastures and savannas in South America. The authors showed the importance of tropical grasses in sequestering C in deeper soil layers.

Between the depths of 40 and 60 cm, soil C content was higher in DMS, intermediate in IHS, DHS and the forest and lower in DP. In the other evaluated soil layers (60-100 cm), C content was similar for all systems (Table 3, Figure 1). These aspects indicate that pastures, after some years of management, show great potential for removing CO_2 from the atmosphere and enriching the soil with SOM, as indicated by Corazza et al. (1999).

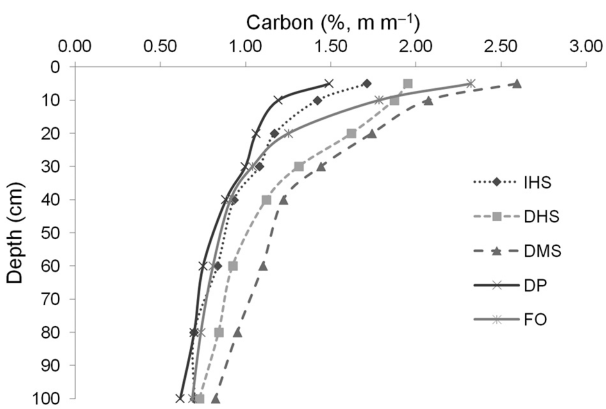

Figure 1 – Carbon content in the different layers of soil in the grazing systems and the native vegetation. IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Brachiaria decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) pasture under extensive management; FO = native vegetation ("seasonal semi-deciduous forest").

Soil C stocks

Carbon stocks were corrected to an equal mass of soil at a depth of 100 cm under the native vegetation, in which C stock was 114.72 Mg ha^{-1}. The C stocks for the first 30 cm layers were corrected to an equal mass of soil at a depth of 30 cm under the native vegetation in which C stock was 49.55 Mg ha^{-1} (Table 5).

On average, soils in DHS and DMS had the largest C stocks, compared with the other pasture systems and the native forest (Table 4). C stock content results indicate there was an interaction ($p \leq 0.05$) between production system and soil depth (Table 4). Values of C stocks found in the 30 cm layer were 64 % higher in DMS compared to the DP system and the other systems presented intermediary values (Table 5).

Considering all the layers (0-100 cm), C stock values ranged from 99.88 Mg ha^{-1} (in the degraded system) to 142.33 Mg ha^{-1} (in DMS), with higher values in DMS compared to DP, IHS and the forest and intermediate values in the DHS system (Table 5). In this trial, irrigation did not result in an increase in C stocks in the IHS system compared to the forest and the DMS system (Table 5).

According to De Bona et al. (2006), irrigation can increase soil C input but at times it is not enough to

Table 3 – Carbon (C) content in the different layers of soil in the grazing systems and the native vegetation.

Depths	Treatments				
	IHS	DHS	DMS	DP	FO
cm	%, m m^{-1}				
0-5	1.71^{bc}	1.95^{b}	2.59^{a}	1.49^{c}	2.32^{a}
5-10	1.42^{b}	1.87^{a}	2.07^{a}	1.19^{b}	1.78^{ab}
10-20	1.17^{b}	1.62^{a}	1.74^{a}	1.06^{b}	1.25^{b}
20-30	1.08^{b}	1.31^{ab}	1.44^{a}	0.99^{b}	1.04^{b}
30-40	0.93	1.12	1.22	0.88	0.91
40-60	0.83^{ab}	0.92^{ab}	1.10^{a}	0.74^{b}	0.81^{ab}
60-80	0.70	0.84	0.95	0.70	0.74
80-100	0.70	0.73	0.82	0.62	0.69

IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Brachiaria decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) pasture under extensive management; FO = native vegetation ("seasonal semi-deciduous forest"); $^{a-c}$ = means followed by different letters within a line are different ($p \leq 0.05$) by the Tukey test.

Table 4 – Soil Carbon Stocks in the four beef cattle grazing systems and the native vegetation in two layers of soil (0-30 and 0-100 cm).

Item	Treatments					Depths (cm)		
	IHS	DHS	DMS	DP	FO	0-30	0-100	SEM
Carbon Stocks (Mg ha^{-1})	76.66^{b}	94.87^{a}	103.08^{a}	68.85^{b}	82.88^{b}	50.68	119.85	5.08

IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Brachiaria decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf (cv. Basilisk) pasture under extensive management; FO = native vegetation ("seasonal semi-deciduous forest"); SEM = standard error of the means; Treat * Depth = Interaction pasture systems *vs* soil depth; $^{a-b}$ = means followed by different letters within a line are different ($p \leq 0.05$) by the Tukey test.

increase C stocks. Soil management may modify the irrigation effect on soil C stocks (Bayer et al., 2006). According to Andrén et al. (1992) an increase in soil water content caused by irrigation provides favorable conditions for microbial activity which intensify microbial organic matter (OM) decomposition and carbon mineralization. These factors may have contributed to the lower C stocks detected in IHS.

In this study the various pasture systems with *Brachiaria* and *Panicum* presented soil C stocks similar or superior to stocks in the soil under the native forest. In the same context Braz et al. (2013) pointed out the potential of well-managed *Brachiaria* pastures for accumulating more soil C than degraded pastures.

The magnitude of C stocks found in this work (up to 142.33 Mg ha^{-1}) was comparable to other results found in the literature, considering evaluations of grasslands in which samples were taken at the same soil profile depth (100 cm). Most of these evaluations had savanna as the natural vegetation. Fisher et al. (1994) found approximately 200 Mg ha^{-1} of C in the Colombian savannas, and above 200 Mg ha^{-1} when *Brachiaria humidicola* was introduced. Corazza et al. (1999) found 150 Mg C ha^{-1} in *Brachiaria decumbens* pasture in the Brazilian savanna while Silva et al. (2004) found around 100 and 113 Mg C ha^{-1} in a degraded pasture with native grass and a *Panicum maximum* pasture, respectively. Fisher et al. (2007) reported C stocks in the order of 165 and 138 Mg ha^{-1} for productive and degraded pastures, respectively, in soils with 80 % clay.

It is expected that the significant changes in C stocks occur in the 0-30 cm layer, as a result of agricultural management and changes in land use. The IPCC (Intergovernmental Panel on Climate Change) recommends that C stocks be evaluated in deep soil layers (down to 1 m) when studying the ecosystem or effects of soil management on tropical pastures in which grasses present deep root systems (Batjes, 2010). According to Boddey et al. (2010), in most studies on soil C, stock assessments were made in the surface soil layers.

The interesting aspect of the results of this trial were the different contributions of different soil layers to total C stock. Considering all pasture systems and the forest, C stocks calculated for the 0-30 and 30-100 cm layers represented, respectively, an average of 42 % and 58 % of the C stocks obtained for the 0-100 cm layers (Table 4 and 5). This emphasizes the sampling of deep soil layers, especially when studding pastures established with grasses possessing abundant root systems such as *Brachiaria*. Under productive pastures, considerable quantities of C can be stored as deep as 100 cm (Silva et al., 2004; Fisher et al., 2007). According to Schmidt et al. (2011), deeper soil layers also contribute to more than half of the global soil C stocks. This study shows the contribution of the root system of *Brachiaria* to increasing C stocks. But according to Fisher et al. (2007), total C stocks can decline over time, mainly if the area is not well managed or fertilized.

Table 5 – Carbon stocks in two layers of soil in the grazing systems and the native vegetation.

Depths	Treatments				
	IHS	DHS	DMS	DP	FO
cm	Mg ha^{-1}				
0-30	44.59^{ab}	53.79^{ab}	63.7^{a}	38.94^{b}	49.55^{ab}
0-100	109.86^{b}	129.63^{ab}	142.33^{a}	99.88^{b}	114.72^{b}

IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Brachiaria decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf extensive management; FO = native vegetation ("seasonal semi-deciduous forest"); $^{a-b}$ = means followed by different letters within a line are different ($p \leq 0.05$) by the Tukey test.

Soil organic matter humification

Lower H_{LIFS} were obtained for the surface layers of all evaluated soils (Table 2). The H_{LIFS} was higher for the soil under the degraded pasture, lower in DHS and DMS and intermediate in soils under the Forest and IHS, with statistical differences in interaction ($p \leq 0.01$) levels varying accordingly to the layer depth (Table 2 and 6; Figure 2). The H_{LIFS} of DHS and DMS were lower compared to the other pastures and were similar to the native forest index for the surface layers (Table 6). In the deep layers, differences between H_{LIFS} were greater with lower values in DHS and DMS compared to IHS, DP and the forest (Table 6; Figure 2).

The lower H_{LIFS} obtained for the top soil layers in the pastures can be associated with the occurrence of labile C derived from a continuous supply of fresh ma-

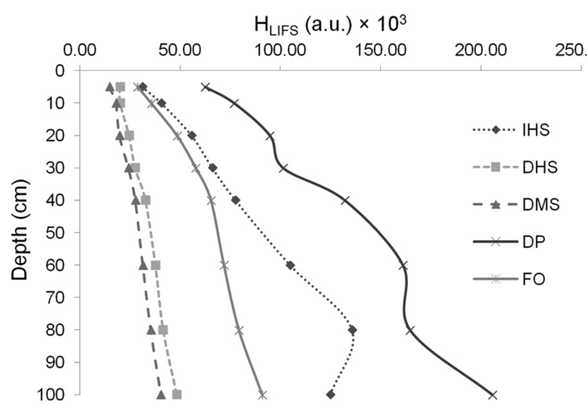

Figure 2 – Humification index H_{LIFS} in the different layers of soil in the grazing systems and the native vegetation. IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Brachiaria decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf extensive management; FO = native vegetation ("seasonal semi-deciduous forest").

Table 6 – Humification index H_{LIFS} in the different layers of soil in the grazing systems and the native vegetation.

Depths	Treatments				
	IHS	DHS	DMS	DP	FO
cm	a.u. × 10^3				
0-5	31.07[ab]	20.01[b]	14.80[b]	62.52[a]	28.80[ab]
5-10	40.55[ab]	20.15[b]	18.07[b]	76.945[a]	35.60[b]
10-20	55.67[b]	24.53[b]	19.83[b]	94.76[a]	48.45[b]
20-30	66.10[ab]	27.56[c]	24.27[c]	101.34[a]	57.83[b]
30-40	77.58[b]	32.69[c]	27.71[c]	132.11[a]	65.37[bc]
40-60	104.74[b]	37.66[d]	31.46[d]	161.02[a]	71.86[cd]
60-80	135.64[a]	41.52b[c]	35.412[c]	164.58[a]	79.30[b]
80-100	124.82[b]	48.34[c]	40.50[c]	205.63[a]	90.97[b]

IHS = Intensively managed irrigated *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DHS = Intensively managed dry land *Megathyrsus* (*Panicum*) *maximum* Jacques (cv. Tanzânia) pasture with high stocking rate; DMS = Dryland *Brachiaria decumbens* pasture with moderate stocking rate; DP = Degraded *Urochloa* (*Brachiaria*) *decumbens* Stapf extensive management; FO = native vegetation ("seasonal semi-deciduous forest"); [a-d] = means followed by different letters within a line are different ($p \leq 0.05$) by the Tukey test.

terial from the cover vegetation and animals. In deeper layers there is an increase in H_{LIFS} due to the presence of more recalcitrant C provided by unsaturated organic compounds containing double bonds and condensed rings. Greater humification increases soil resistance against microbial decomposition and, consequently, enhances SOM stability (Segnini et al., 2010). The aromatic structures present in rigid molecules of humified SOM are considered to be more recalcitrant or stable in terms of biological decomposition than structures derived from polysaccharides and proteinaceous moieties (Bayer et al., 2006). Results presented here are in agreement with previous studies by Milori et al. (2006, 2011) and Tivet et al. (2013). Considering the humification in DP, it is important to emphasize that the lower levels of C and the high humification index obtained may indicate that at the degradation stage the rigid and condensed aromatic structures presented in SOM are predominant since there is no effective microbial activity to metabolize additional material. Morover, there is no labile C input into the system, already degraded.

The analyses of SOM humification complements soil C stock data because the LIFS technique measures recalcitrant C which can be a sensitive indicator of variances, caused by changes in land use and soil management, in terms of mitigation of CO_2 emissions (Milori et al., 2011). The "vulnerability" of C was checked in this kind of assessment. Considering the results of this study, it is possible to infer that the DHS and DMS systems that had the highest C stock values are susceptible to CO_2 losses if management is not appropriate which is mainly due to the high lability of C in their soils particularly in the surface layers. In studies of soil quality C stock levels *per se* are not always a sensitive indicator of variances caused by changes in land use and soil management, the C labile fraction being more affected and more sensitive compared to recalcitrant C fractions.

According to Ontl and Schulte (2012), effects of land management on soil organic C levels, especially the impacts of management in agricultural settings, is the subject of much of the current research. According to these authors, the main changes in soil C take a relatively long time to occur making punctual and short period measurements of changes in C stocks less than meaningful.

Conclusions

The results from this study indicate the capacity of tropical pastures to mitigate GHG emissions in livestock production systems, when under intensive management. In this case, soils under tropical pastures may act as long-term C sinks and most of the C is stored below 30 cm deep soil layers.

Carbon stock and humification indexes are useful tools for diagnosing degradation in pastures. Low C stocks associated with high humification indexes are characteristics of degraded pastures in which significant amounts of organic matter have been lost. Pasture systems with high soil C stocks and low humification indexes are fragile and susceptible to CO_2 losses to the atmosphere if management is not correct due to the high lability of soil C.

It is necessary to develop technologies to improve C sequestration in irrigated pastures. Definition of a balance between water supply and mineralization of organic matter will avoid excessive mineralization and preserve any increase in the soil C stock.

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Authors' Contributions

Conceptualization: Segnini, A., Xavier, A.A.P., Oliveira, P.P.A., Pedroso, A.F., Milori, D.M.B.P. Data acquisition: Segnini, A., Xavier, A.A.P., Otaviani-Junior, P.L., Oliveira, P.P.A., Pedroso, A.F. Data Analysis: Segnini, A., Xavier, A.A.P., Otaviani-Junior, P.L., Oliveira, P.P.A., Pedroso, A.F., Praes, M.F.F.M., Rodrigues, P.H.M., Milori, D.M.B.P. Design of methodology: Segnini, A., Xavier, A.A.P., Otaviani-Junior, P.L., Oliveira, P.P.A., Pedroso, A.F., Praes, M.F.F.M., Rodrigues, P.H.M., Milori, D.M.B.P. Writing and Editing: Segnini, A., Xavier, A.A.P., Oliveira, P.P.A., Pedroso, A.F., Praes, M.F.F.M., Rodrigues, P.H.M., Milori, D.M.B.P.

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