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Predicting soil CO_2 emissions and sinks due to soil management factors of *Brachiaria decumbens* pastures using Tier 2 IPCC Methodology

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ABSTRACT

Soil carbon sequestration refers to the process of transferring carbon dioxide (CO_2) from the atmosphere into the soil. The objective of this research was to do a simulation of how soil management factors in pastures can contribute to mitigate climate change by reducing soil CO_2-eq emissions due to increases of soil organic carbon.In livestock systems of Cumaral (Meta), Colombia, IPCC Tier 2 methodology was used to compare changes in soils C stocks under (a) two pasture types: *Brachiaria decumbens* grass pastures (B1) and *Brachiaria decumbens* grass pastures associated with *Pueraria phaseloides* legume (B2); (b) four increasing doses of $CaCO_3$: 0, 1.1, 2.2, 3.3 tons ha^{-1}; (c) three sources of N, P, K fertilizers: 100 kg ha^{-1} Urea, 200 kg ha^{-1} Triple Superphosphate and 100 kg ha^{-1} Potassium Chloride. The statistical design was a randomized complete block in factorial arrangement 2 x 4 x 3. Tukey test indicated that the inclusion of kudzú in *B. decumbens* pasture (B2), 2.2 and 3.3 tons $CaCO_3$ ha^{-1} in both pastures, and the fertilization of B1 with Urea and B2 with Triple Superphosphate presented a greater benefit in soil C accumulation and CO_2-eq emissions neutralization. Adittional cluster analysis showed that B2 liming with higher lime doses regardless of the type of fertilizer used presented major soil C stored grouped in Cluster 1. We concluded that these soil management factors should be feasible to implement in pastures, that can help offset the negative effects of global climate change on livestock systems at tropical zones.

Keywords: Carbon stocks, climate change, fertilizers, simulation.

Predicción de emisiones y sumideros de CO_2 del suelo debido a factores de manejo del suelo de *Brachiaria decumbens* usando Tier 2 metodología IPCC

RESUMEN

El secuestro de carbono en el suelo se refiere al proceso de transferencia de dióxido de carbono (CO_2) de la atmósfera al suelo. El objetivo de esta investigación fue hacer una

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simulación de cómo los factores de manejo del suelo en pasturas, pueden contribuir a mitigar el cambio climático al reducir las emisiones de CO_2-eq del suelo debido a los aumentos de acumulación de carbono orgánico en el suelo. En sistemas ganaderos de Cumaral (Meta), Colombia, se utilizó la métodología Tier 2 del Panel Intergubernamental sobre Cambio Climático (IPCC) para comparar los cambios en las existencias de C del suelo en (a) dos tipos de pasturas: pasturas de pasto *Brachiaria decumbens* (B1) y pasturas del pasto *Brachiaria decumbens* asociadas con leguminosa de *Pueraria phaseloides* (B2); cuatro dosis crecientes de $CaCO_3$: 0, 1.1, 2.2, 3.3 tons ha^{-1}; y (c) tres fuentes de fertiliantes N, P, K: 100 kg ha^{-1} Urea, 200 kg ha^{-1} Superfosfato triple y 100 kg ha^{-1} Cloruro de potasio. El diseño estadístico fue un bloques completos al azar en arreglo factorial 2 x 4 x 3. El test de Tukey indicó que la inclusión de la leguminosa en la pastura (B2), la aplicación de 2.2 y 3.3 tons $CaCO_3$ ha^{-1} en ambas pasturas y la fertilización de B1 con Urea y de B2 con Superfosfato triple presentaron un mayor beneficio en la acumulación de C del suelo y la neutralización de las emisiones de CO_2-eq. El análisis de cluster adicional mostró que B2 encalada con más altas dosis de cal indistintamente del tipo de fertilizante usado presentaron mayor almacenamiento de C del suelo agrupados en el Cluster 1. Nosotros concluimos que estos factores de manejo de suelos deberían ser factibles de implementar en pasturas, lo que puede ayudar a compensar los efectos negativos del cambio climático global en los sistemas ganaderos de zonas tropicales.
Palabras clave: Stocks de C, cambio climático, fertilizantes, simulación.

INTRODUCTION

Carbon sequestration is represented by an increase in the stocks of carbon in any reservoir other than the atmosphere (IPCC 2006). Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. The soil is considered the main temporary reservoir ecosystem of C (Lal 2014). Globally, soil systems contain up to three or more C than above-ground biomass (560 GT) (Alexander *et al.* 2015).

Technical potential for soil organic carbon (SOC) sequestration at global (Olsen 2013) and US (Swan *et al*. 2015; Sperow 2016) scales, generally support these earlier estimates of a significant soil C sink potential, on the order of hundreds of teragrams (1 Tg equals 1 million metric tonnes) per year in the United States and roughly an order of magnitude higher globally. However, there are very few reports of mitigation practices associated to absorption potential of soil CO_2 emissions in pastures in Colombia (Naranjo *et al.* 2012; Parra and Mora-Delgado 2017; Parra *et al.* 2019), and specifically in the area of influence (Silva and Orozco 2018).

Soil management factors of land use FLU (extensive pasture), soil management factor FMG (degraded pasture) and input by crop residues FI (low level) were influential factors on losses of soil C rates associated with emissions of soil CO_2-eq to the atmosphere in tropical zone of Ariari zone of Orinoquia, Colombia (Silva and Orozco 2018). This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of soil organic matter (SOM) (IPCC 2014), accounting for about 75% of total soil C stored and plays a major role in determining atmospheric concentrations of CO_2-eq and climate change (Chambers *et* *al.* 2016). Factor land use (FLU), currently accounting for about 25% of global GHG emissions (IPCC 2006), must be part of an effective climate change mitigation strategy for agricultural systems of Meta state. In tropical zones, improved grazing management (appropriate pastures, use of lime and fertilizers) optimizes productivity, and offers GHG mitigation and adaptation benefits (Thornton and Herrero 2010). *Brachiaria* grasses are the most widely used forages for livestock in the tropics. *Brachiaria* pastures releases biological nitrification inhibitors (BNIs) from its roots, which reduce GHG emissions by inhibiting nitrification in the soil (Moreta *et al.* 2014). However, any change in pastures land use may significantly alter related source or sink characteristics for atmospheric soil CO_2-eq and other GHGs (Naranjo *et al.* 2012), the incorporation of legumes in the pastures can increase the soil C reserves (Lal 2014; Guan *et al.* 2016). In general, increased soil C accumulation in pastures is associated with a land use factor (FLU), related the type of land use (i.e. extensive pastures, intensive pasture, silvopastoral systems), an input factor (FI) which is related to the input of C in soil for pasture residues, and a soil managent factor (FMG) related to the input applied (i.e. improved pasture, degraded pasture, no degraded pasture) (IPCC 2006). According to Mosquera *et al.* (2012) comparing soil C stocks at 1 m equivalent under *B. decumbens* and *B. decumbens* associated with legumes showed 114.2 and 121.6 tons C ha^{-1} in flat topography and 102.0 and 153.4 tons C ha^{-1} in the sloping areas respectively, these differences were obtained in (less than) 15 years, indicating the advantages of the legume in pasture. Also, positive effects on SOC by consortion of *Crotalaria* legume with corn crop was reported by Corrêa *et al.* (2014).

Hence, soil organic carbon (SOC) accumulation largely depends on type of legume cover on pasture, due to that grass and legume species differ in root depth and spatial distribution (Guan *et al.* 2016). The synthesis by Chambers *et al.* (2016) suggests that with proper management of grazing and pasture can actively sequester soil C for 20 years (lifetime approximate benefits range from 0.02 to 0.44 tons C ha^{-1} yr^{-1}).

Since then, rates of SOC sequestration through adoption of best management practices have been assessed for diverse land uses and eco-regions, such as the inclusion of cover crops in pastures (Poeplau and Don 2013; Lal 2015), for conversion of extensive pasture for improved pasture (Naranjo *et al.* 2012; Parra *et al.* 2019). Accumulation of SOC in improved pastures also can occur following changes in soil management practices as lime and fertilizer aplication, that either increase the production of residue remaining on the field or decrease the losses of soil organic carbon in the form of carbon dioxide (Lal 2015). When low fertility soils pastures receive fertilizer and/or lime, forage productivity and SOC levels generally increase, which probably led to more roots, forage residues and animal feces to supply the particulate and total organic C fractions (Bennett *et al.* 2014; Paradelo *et al.* 2015). Consequently, according to Paradelo *et al.* (2015) reviewed the literature found that, on balance, liming increased soil C content mostly because it increased crop yields and therefore residue returns. Also, Poeplau and Don (2013) found that lime applied at 5 tons ha^{-1} was still improving aggregate stability, vegetation cover, total C and N and soil respiration 12 years after application. There is a need to understand the interactions between pasture type, liming and N, P, K fertilizers sources to achieve higher SOC and reduced soil CO_2-eq emissions in productive tropical grasslands. These practices are suggested also to optimize the availability of good quality grass biomass in relation to animal requirements, leading to improved productivity (Parra and Mora-Delgado 2017).

Gibbons *et al*. (2014) looked at the trade-off between lime applications and greenhouse gas (GHG) emissions on livestock farms. Lime increases soil pH, improves pastures growth, and decreases extractable Al^{3+} possibly generating optimal soil conditions for a greater soil C accumulation (Goulding 2016). The objective of this research was evaluate the effect of two types of *Brachiaria decumbens* pasture, alone and in association with legume of kudzu *P. phaseloides*, four doses of lime and three fertilizer sources N, P, K in the simulations of soil C stocks over the next 20 years and CO_2-eq emissions applying the IPCC Tier 2 methodology, in order to define soil practices management that contribute to a greater extent to mitigate soil CO_2 emissions.

MATERIALS AND METHODS

Study site

The experiment was conducted in livestock zone of Cumaral, Meta state, located at 452 meters above sea level on the eastern Cordillera of Colombia (4º16’10”N, 73º29’11”W). Grasslands are the largest ecosystems in the world with an estimated area of 52.2 million km^2, corresponding to around 40% of the total land in the world, while pasture areas in Colombia are estimated around 33.9% of the country total area with 28,245,262 animal heads. Meta contributes 7.38% of the country’s bovine production and Cumaral with 58,453 animal heads at 2020 (ICA 2020). In the area predominates extensive pastures of dual-purpose livestock. In the area the main problem of livestock production is pasture degradation due to the reduced pasture and animal management. The clay soil is on alluvial terraces at the site was classified as Ultisol (Soil Survey Staff 2006). The mean annual temperature is 25.5ºC, the annually average rainfall is 3856 mm, 70% of the precipitation occurs between April and June. Relative humidade between 75-90% depending of season types.

Statistical design

The statistical design of this study was a randomized complete block design in factorial arrangement 2 x 4 x 3, factor A refers to two pasture types already established previously where: B1 = *Brachiaria decumbens* grass of 10 years of established, B2 = *Brachiaria decumbens* grass associated with kudzu *P. phaseloides* legume of 5 years of established; factor B refers to different lime doses respect to the recommended lime dose according to soil analysis accounting by 3.3 tons $CaCO_3$ ha^{-1} (Castro and Gómez 2010).

$$\textit{Tons } CaCO_3/ha = 1.8 \times (Al - (RAS\ (Al + Ca + Mg))/100) \quad (1)$$

Where *1.8* is a constant, *RAS* it is the maximum percentage of aluminum that tolerates *Brachiaria* grasses 35%, *Al* is aluminum concentration (3.1 cmol kg^{-1}), was determined by using potassium chloride 1 N extraction and quantification by volumetric colorimetric, *Ca+Mg* are soil bases (2.2 and 1.3 cmol kg^{-1}), that were determined by ammonium acetate extraction 1 N (pH 7), following the standardized methods and procedures and recommended by the Instituto Geográfico Agustín Codazzi (2016). Description of soil properties in initial soil analysis showed extremely acid pH (4.5), measured with a potentiometer method, for which a water:soil solution (1:1) was prepared (IGAC 2016).

Lime doses ($CaCO_3$) treatments were L0 = no lime, L1 = 1/3 of the recommended lime dose (1.1 tons ha^{-1}), L2 = 2/3 of the recommended lime dose (2.2 tons ha^{-1}), L3 = 3/3 of the recommended lime dose (3.3 tons ha^{-1}); factor C refers to doses of N, P, K fertilizers sources, corresponding to F1 = 100 kg ha^{-1} Urea, F2 = 200 kg ha^{-1} triple superphosphate (TSP), F3 = 100 kg ha^{-1} potassium chloride (PCl). For a total of 24 experimental treatments and 3 replicates for a total of 72 experimental units.

Treatment management

The lime and fertilizer doses were applied to each experimental unit with an area of 4 x 5 m, 20 m^2, the experiment was conducted from February 2017 to February 2018, the lime and fertilizer doses were applied after the first cut (the pasture is cut every three months and there are four cuts in an one year), and were not reapplied (a single application) during the experiment, the application of products was done randomly on each experimental unit in Abril during rainy season, first the lime was applied and then the fertilizers because the applied doses are recommended per year, the treatments were evaluated for one time at the end of the fourth cut. The renewal of the legume *P. phaseloides* in the pasture is made every two years.

Initial soil C stock determination

Three soil samples were taken in each experimental unit at a depth of 30 cm with a hole, and they were mixed to obtain a composite sample, for a total of 72 soil samples, the samples were taken at the end of the fourth cut in each experimental unit, 9 months after starting treatments, which were prepared in Analytical Soils Services Laboratory at Unillanos University, Villavicencio, Colombia.

Soil organic carbon (SOC) was determined by the Walkley-Black volumetric colorimetric, following the standardized methods and procedures recommended by the Instituto Geográfico Agustín Codazzi (2016). The samples for soil bulk density were dried at 100°C until obtaining a constant weight, for determination of their mass by the paraffin-shaped method. The initial soil C stocks of each experimental units were calculated using the following equation 2 (IPCC 2006). Quality control was assured by using duplicates. Reagent blank and several certified reference materials were used to check the accuracy and precision of the analytical data:

$$\textit{Initial soil C stock (tons } ha^{-1}\textit{)} = 10 \times (C \times bd \times d) \quad (2).$$

Where *C* is the amount of carbon in tons ha^{-1}, *bd* is the bulk density in tons m^{3-1}, and *d* is the sampling at 30 cm depth. Values of bulk density in the field was uniform and ranged of 1.2 to 1.24 tons m^{3-1} between the experimental units.

Predicting Soil Greenhouse Gas Emissions

Final soil C stocks over the next 20 years were determined (IPCC 2006), equation 3:

$$\textit{Final Soil C stock (tons C } ha^{-1}\textit{)} = \textit{Initial Soil C stock * IPCC default} \quad (3)$$

Where *IPCC default* were factors related to soil management practices: land use (FLU), tillage practices (FMG) and residue inputs (FI) for a time-period of 20 years (Table 1). Simulation of gains and/or losses ratio of soil C by soil management factors effects were estimated by using specific Tier 2 methodology proposed by IPCC (2006), equation 4:

Gains and/or losses soil C rates tons C ha^{-1} yr^{-1}=Initial Soil C stock–Final Soil C stock/T (4)

Which *T* is time dependence on a projection of twenty years old for default values that represents soil C stocks changes by the influence of soil management factors in grasslands at 0.30 m depth (IPCC 2006). In addition to the intensity of management adopted (for instance, high, medium and low inputs) those factors take into account also climate and soil type in the specific region (tropical zone). The rates served to project soil CO_2-eq

TABLE 1. IPCC default values for estimating changes of soil C stocks (projection in 20 years old at 0.30 m detph) in pastures.

Factor	Level	Climate regime	IPCC default	Definition	Treatments used
Land use (FLU)	Permanent grassland	All	1.0	All permanent grassland is assigned a land-use factor of 1.	All
Management (FMG)	Improved grassland	Tropical	1.17	Represents grassland which is sustainably managedwith moderate grazing pressure and that receive at least one improvement (e.g., fertilization, species improvement, irrigation).	All
Input (applied only to improved grassland) (FI)	Medium	All	1.0	Applies to improved grassland where no additional management inputs have been used.	B1-L0-F1, F2, F3 B2-L0-F1, F2, F3
Input (applied only to improved grassland) (FI)	High	All	1.11	Applies to improved grassland where one or more additional management inputs/improvements have been used (beyond that is required to be classified as improved grassland)	B1 and B2-L1, L2, L3-F1, F2, F3

Adapted of IPCC (2006).

B1 = *Brachiaria decumbens* grass, B2 = *Brachiaria decumbens* grass associated with kudzu *P. phaseloides* legume. L0 = no lime, L1 = 1/3 of the recommended $CaCO_3$ dose (1.1 tons ha^{-1}), L2 = 2/3 of the recommended $CaCO_3$ dose (2.2 tons ha^{-1}), L3 = 3/3 of the recommended $CaCO_3$ dose (3.3 tons ha^{-1}). F1 = 100 kg ha^{-1} Urea, F2 = 200 kg ha^{-1} triple superphosphate (TSP), F3 = 100 kg ha^{-1} potassium chloride (PCl).

emissions and/or sinks to the atmosphere. A conversion factor of C to CO_2 of 3.67 was used (IPCC 2006).

Statistical analyses

The initial, and final soil C stocks, soil CO_2-eq emissions data obtained at 0.30 m soil depth were analysed by ANOVA using a factorial design:

$$Yijkl = \mu + Bi + Lj + Fk + Bl + BLij + BFik + LFjk + BLFijk + \varepsilon ijk \quad (7).$$

Where *Yijk* is the dependent variable, μ is the variable mean, *Bi* is the pasture type (PT) effect i, *Lj* is the lime doses (LD) effect j, *Fk* is the N, P, K fertilizer sources (FS) effect k, *Bl* is the block l, *BLij* is the pasture type–lime doses interaction (PT × LD), *BFik* is the pasture type–N, P, K fertilizer souces interaction (PT × FS), *LFik* is the lime dose–N, P, K fertilizer sources interaction (LD × FS), *BLFijk* is the type pasture-N,P,K fertilizer source-lime doses–block interaction (PT x FS x LD), and *εijk* is the error. The Tukey test was used for subsequent comparisons ($p < 0.05$) if the ANOVA was significant at 95 and 99% probability. Then, for the triple effects a single variable (soil CO_2-eq emissions) was included in the cluster model by multivariate analysis according to euclidean distances. All statistical analysis were conducted in Info Stat versión 8.

RESULTS

Variance analysis

Table 2 shows that pasture type, lime doses, pasture*lime doses, pasture*fertilizers and triple interaction have significant impacts on the soil initial C stocks, soil final C stocks, and soil CO_2-eq emissions, when the significant level is 0.05 ($p < 0.05$). While the interaction lime doses*fertilizer

TABLE 2. Multi-factors variance analysis for changes in soil C stocks, and soil CO_2 emissions and sinks

Source	Degree of Freedoom	Initial soil C Stocks		Final soil C Stocks		Soil CO_2-eq emissions and/or sinks	
		MS	F-ratio	MS	F-ratio	MS	F-ratio
Pasture type	1	1220.31	6.16*	1,650.42	7.46*	580.98	6.11*
Lime doses	3	598.10	3.02*	669.14	2.52*	300.01	3.15*
Fertilizers	2	1,112.45	5.61**	1,640.93	7.42**	537.22	5.65**
Pasture*lime doses	3	630.32	3.18*	716.68	3.24*	290.15	3.05*
Pasture*fertilizers	2	679.15	3.42*	750.66	3.40*	329.87	3.47*
Lime dose*fertilizer	6	290.15	1.46ns	382.66	1.73ns	135.05	1.42ns
Pasture*lime doses*fertilizers	6	532.10	2.68*	557.58	2.52*	265.01	2.78*
Error	25	198.01		221.06		95.01	
Total	71						

MS=Mean Square, F-ratio=MS/error and compared at 95%, 99% probability, table F Fischer is not significant, when the significant level is 0.01 and 0.05. However, fertilizer is highly significant, when the significant level is 0.01 ($p < 0.01$).

Effect of pasture type on predicting soil CO_2 emissions and sinks

Simulation of soil CO_2 sinks was highly dependent on pasture type, the initial and final soil stocks C sinks simulation was increased with B2, where B1 allows to store less soil C that B2, ranged between 72–159 tons C ha^{-1} over the next 20 years ($p < 0.05$) (Table 3). Both pastures type were positively associated with soil CO_2 emissions mitigation due that they act as soil C sinks (Table 3). B1 showed an increase of 2.05 times the content of initial soil C stock after 20 years, while in B2 the increase was 2.12 times, with difference between them ($p < 0.05$). The B1 and B2 pastures both predicts gains of soil C rates of 1.94 and 4.42 tons C ha^{-1} yr^{-1} respectively.

Effect of lime doses on predicting soil CO_2 emissions and sinks

The higher soil C stocks contents, were detected in the higher lime doses treatments, compared to lower in the control (L0) and L1 ($p < 0.05$). Liming with 3.3 and 2.2 t $CaCO_3$ ha^{-1} stored more C and acts as higher soil CO_2 sinks accounting for -16 and -17 tons CO_2-eq ha^{-1} yr^{-1} over the next 20 years respectively, with no difference between them ($p > 0.05$), since the simulation showed that soil CO_2-eq is not absorbed with L0, due to that non losses and/or gains of soil C are generated because IPCC methodology report "Applies to improved grassland where no additional management inputs have been

TABLE 3. Effects of pasture type, lime doses and fertilizer sources on predicting soil CO_2 emissions and sinks (changes over the next 20 years).

Simple factors	Initial soil C stocks tons C ha^{-1}	Final soil C stocks tons C ha^{-1}	Total soil CO_2-eq sinks tons CO_2-eq ha^{-1} yr^{-1}
		Pasture type	
B1	35a* ± 5.0	72a ± 13.4	-7a ± 2.3
B2	75b ± 23	159b ± 33.4	-16b ± 3.3
		Lime doses	
L0	36a*± 9.5	36a ± 7.4	——
L1	48b ± 13.2	116b ± 35.4	-14a ± 2.3
L2	69c ± 28.2	158c ± 43.4	-17b ± 2.3
L3	67c ± 21.2	152c ± 38.4	-16b ± 2.1
		Fertilizers soucers	
F1	59b*± 19.5	120b ± 27.4	-11.75b ± 2.5
F2	69b ± 23.2	148b ± 35.4	-15.21b ± 3.3
F3	38a ± 18.2	78a ± 13.4	-7.7a ± 2.3

* For each variable analyzed values on the same column (factors) with different letters differ significantly ($p < 0.05$), Tukey's test. B1 = *Brachiaria decumbens* grass, B2 = *Brachiaria decumbens* grass associated with kudzu *P. phaseloides* legume. L0 = no lime, L1 = 1.1 tons $CaCO_3$ ha^{-1}, L2 = 2.2 tons $CaCO_3$ ha^{-1}, L3 = 3.3 $CaCO_3$ tons ha^{-1}. F1 = 100 kg ha^{-1} Urea, F2 = 200 kg ha^{-1} triple superphosphate (TSP), F3 = 100 kg ha^{-1} potassium chloride (PCl).

used", and therefore the default value is 1 (IPCC 2006). L1 generated soil C gains of 3.57 tons C $ha^{-1}yr^{-1}$ and neutralized soil CO_2 emissions of -14 tons CO_2-eq ha^{-1} yr^{-1}, being equal to L0 ($p > 0.05$). For instance our calculation showed that the addition of highest lime doses resulted in a net annual soil C gains of 4.7 and 4.5 tons C ha^{-1} yr^{-1} for L2 and L3 respectively.

Effect of fertilizers sources on predicting soil CO_2 emissions and sinks

The fertilization with Triple superphosphate (F2) increased soil C stocks by 70 t C ha^{-1} and with Urea (F1) by 42 t C ha^{-1} ($p > 0.05$), when compared to the fertilization with Potassium chloride (F3) in a projection over the next 20 years ($p < 0.05$) resulting both in significant higher soil CO_2-eq neutralization of -15.21 and -11.75 tons CO_{2-}eq ha^{-1} yr^{-1} respectively (Table 3). Soil CO_2-eq sinks did not differ significantly between F1 and F2, accouting for gains of soil C rates of 3.21 and 4.15 tons C $ha^{-1}yr^{-1}$ respectively. The fertilization with F3 resulted in lower soil CO_2-eq mitigation account with -7.7 tons CO_2-eq ha^{-1} yr^{-1} (Table 3).

Effect of pasture type and lime doses and pasture type and fertilizers interaction on predicting soil CO_2 emissions and sinks

Both soil liming with L2 and L3 increased soil C stocks in B1 and B2, no significant difference in soil C stocks among the two treatments was found ($p > 0.05$) (Table 4). In the pastures B1 and B2, in the first 0–30 cm soil detph in the treatment control L0 had less initial C storage and was different of the others ($p < 0.05$) (Table 4). The pasture B2 including liming practice of 2.2 and 3.3 tons $CaCO_3$ ha^{-1}

TABLE 4. Effect of pasture type and lime doses interaction and pasture type and fertilizer sources interaction on predicting soil CO_2 emissions and sinks (changes over the next 20 years).

Sources	Initial soil C stocks tons C ha^{-1}		Final soil C stocks tons C ha^{-1}		Total soil CO_2-eq sinks tons CO_2-eq ha^{-1} yr-1	
	B1	**B2**	**B1**	**B2**	**B1**	**B2**
			Lime doses			
L0	27*a	44a	27a	44a	—-	—-
L1	30a	67b	69b	163b	-8a	-18a
L2	42b	92c	95c	222c	-10b	-25b
L3	42b	97c	95c	209c	-10b	-22b
			Fertilizer sources			
F1	44*c	73b	88c	152b	-8c	-12b
F2	34b	104c	70b	227c	-7b	-24c
F3	28a	47a	57a	99a	-6a	-10a

* For each variable analyzed values on the same column (factors) with different letters differ significantly ($p < 0.05$), Tukey's test. B1 = *B. decumbens* grass, B2 = *B. decumbens* grass associated with kudzu *P. phaseloides* legume. L0 = no lime, L1 = 1.1 tons $CaCO_3$ ha^{-1}, L2 = 2.2 tons $CaCO_3$ ha^{-1}, L3 = 3.3 $CaCO_3$ tons ha^{-1}. F1 = 100 kg ha^{-1} Urea, F2 = 200 kg ha^{-1} triple superphosphate (TSP), F3 = 100 kg ha^{-1} potassium chloride (PCl).

account for neutralization of -25 and -22 tons CO_2-eq ha^{-1} yr^{-1} respectively. Which indicates that mitigation of soil CO_2-eq emission in B2 could be achieved by increasing lime doses application rate to a reasonable L2 level.

Effect of pasture type and fertilizers sources on predicting soil CO_2 emissions and sinks

The fertilization with 200 kg ha^{-1} of Triple superphosphate (F2) in B2 increased final soil C stocks stored in a projection over the next 20 years by 75 and 128 tons C ha^{-1}, when compared to the fertilizartion with 100 kg ha^{-1} of Urea and K, respectively, that were higher that in B1. F2 significantly increased soil CO_2-eq sinks by 2.0 and 2.4 times higher rates that F1 and F3 respectively, accounting for -24 tons CO_2 eq $ha^{-1}yr^{-1}$ ($p < 0.05$) (Table 4). The fertilization with Urea in B1 increased final soil C stocks in a projection of 20 years, when compared to the fertilizarion with P and K fertilizer sources, showing difference with the other fertilizers sources used ($p < 0.05$). In B1 and B2 the fertilization with K showed lower increases in neutralization of soil CO_2 emission.

Effect of pasture type, lime doses and fertilizers sources on predicting soil CO_2 sinks

Our results in dendogram of Figure 1. systemically illustrated the effect of pasture type, lime doses and N, P, K fertilizers sources on predicting soil CO_2-eq sinks.

The cluster analysis showed that two large groups were formed. Cluster 1 form the major sinks of soil CO_2-eq. B2 and higher lime doses were distinctly separated from B1 and non-lime and medium lime doses that form cluster 2, in both the fertilization with F1, F2 and/or F3 did not show the obvious patterns under different lime doses levels possibly du to that lime treatments increased the utilization of the fertilizers on soil CO_2-eq sinks.

DISCUSSION

Because the advanced soil CO_2 emissions simulation depends on the factor

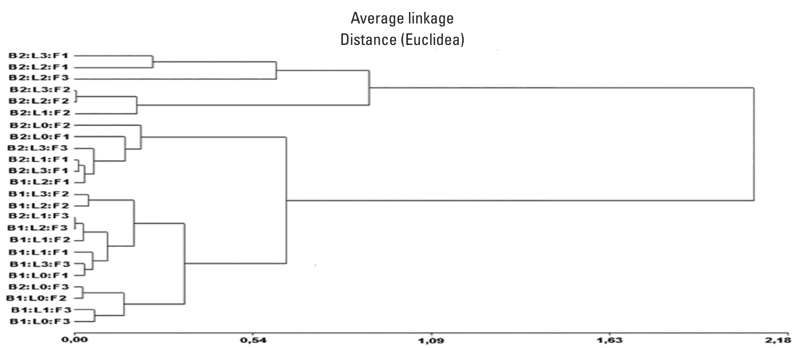

FIGURE 1. Hierarchical clustering analysis based on the Euclidean dissimilarity index. Dendrogram represents soil CO_2-eq sinks similarity between the pasture type, lime doses and fertilizer sources interactions. B1 = *B. decumbens* grass, B2 = *B. decumbens* grass associated with kudzu *P. phaseloides* legume. L0 = no lime, L1 = 1.1 tons $CaCO_3$ ha^{-1}, L2 = 2.2 tons $CaCO_3$ ha^{-1}, L3 = 3.3 $CaCO_3$ tons ha^{-1}. F1 = 100 kg ha^{-1} Urea, F2 = 200 kg ha^{-1} triple superphosphate (TSP), F3 = 100 kg ha^{-1} potassium chloride (PCl).

evaluated, as initial soil C contents and soil bulk density, is a variable that did not vary, with ranges between 1.2 to 1.24 tons m^{3-1} for clay soils, which are considered not to be soil physical limiting (IGAC 2016), and they are not indicating any degree of soil compaction in the pastures evaluated. Naranjo *et al.* (2012) reported 1.06 tons CO_2 eq ha^{-1} yr^{-1} in a degraded pasture with soil compaction and overgrazing, where these pastures are generally managed under extensive grazing systems, with variable animal per hectare (stocking rates 0.85 UGG=450 kg of weight) in relation to the availability of biomass 7.0 tons DM ha^{-1} $year^{-1}$. Fisher *et al.* (2007), making an analysis in different types of pastures, reported that losses due to degradation and non management can represent 1.5 tons CO_2-eq ha^{-1} $year^{-1}$. Despite the huge potential for mitigation of the soil CO_2-eq emissions, especially in B2, as confirmed also by Guan *et al.* (2016), the legumes in pastures can be beneficial effects for SOC sequestration. It is important to point that soil C accumulation could be lost rapidly depending of the soil management decision taken on those sites. The use of nitrogen-fixing legumes as cover pastures can incorporate more than 200 kg N ha^{-1} (Guan *et al.* 2016). In general, more productive grass varieties practices are known to increase C input to the soil and thus soil organic carbón SOC (Olsen 2013; Sperow 2016). A plausible adoption rate of 30% of improved deep-rooted legumes associated to *Brachiaria pastures* at Cerrados of Brazil represented a mitigation potential of soil emission of -29.8 tons CO_2-eq yr^{-1} to the atmosphere (Thornton and Herrero 2010). Value than was higher that those simulated in this study account by -7 tons CO_2-eq yr^{-1} in B1, and -16 tons CO_2-eq yr^{-1} in B2. Agricultural systems combine legume forages with grasses, improving animal nutrition and generating co-benefits like improved soil fertility and increased soil and biomass C accumulation (Parra *et al.* 2019). However, belowground C-inputs from exudation and root sloughing from C4 grasses are high in *Brachiaria* pastures, forming the base for soil organic matter-buildup in these systems (Anderson-Teixeira *et al.* 2016). In other research, Raji and Ogunwole (2006) showed that *B. decumbens* sequestered about 20 tons C ha^{-1} in 35 years (1.8 tons C ha^{-1} yr^{-1}) lower when compared to the simulations of this study accounting 1.94 and 4.42 tons C ha^{-1} yr^{-1} in B1 and B2, over the next 20 years. Pastures of *Brachiaria brisantha*, *B. humidicola* and *Panicum maximum* inject substantial amounts of C into the soil which compensate or frequently even over-compensate for initial SOM-losses caused by deforestation (Guan *et al.* 2016). However, this holds true only for well-managed pastures, preferably also containing a legume component (Poeplau and Don 2013). According to Chambers *et al.* (2016), over the lifetime of the cropland soil health conservation practices, it can be expected that NRCS conservation practices sequester approximately 0.07 to 0.96 tons C ha^{-1} y^{-1}. It could be verified that the fertilization of pasture, calagem use (Paradelo *et al.* 2015), the use of productive species, conversion of permanent pasture for improved pasture (Parra *et al.* 2019), the presence of legumes in pasture, increases soil C accumulation (Guan *et al.* 2016) and decrease GHG emissions (Naranjo *et al.* 2012). This study confirms that well-managed B2 on livestock system in the tropics can neutralizer soil CO_2 emissions and accumulate soil carbon. Our results of greater effectiveness of the higher doses of limes on soil CO_2 emission simulation also coincided with Paradelo *et al.* (2015), that concluded that liming might be an effective mitigation strategy against climate change. Soil acidity at tropical zones is ameliorated by applying lime or other acid-neutralizing materials (Castro and Gómez 2010). 'Liming' also reduces N_2O emissions, but this is more than offset by CO_2 emissions from the lime as it neutralizes acidity (Goulding 2016). However, this has to be balanced against the emissions of soil CO_2 when lime neutralizes acidity in soils, which must be reported in national greenhouse gas balance inventories (IPCC 2006), since in this study soil C sinks for lime are only considered regarding the gains of soil C. The greater effectiveness of lime is related to increases soil pH (Castro and Gómez 2010), improvement of the pH of the rhizosphere, higher microbial activity and generation of stable organic matter.

Our simulation showed that the fertilization with 200 kg ha^{-1} of Superphosphate triple (F2) generated 14.49 and 44.92% more soil C stored that with 100 kg ha^{-1} of Urea (F1) and Potassium chloride (F3). Possibly in acid soils such as those studied, *Brachiaria decumbens* pastures has a better ability to sequester soil C with the application of N and P fertilizers because soils tropical are soil NP deficient. On undegraded pastures (productive), the input of N is the essential element for the increased of pastures productivity (Silva *et al.* 2018), soil organic matter SOM by animal manure (Richardson *et al.* 2011). On other hand, adequate levels of soil P are important for root production in grass and clover pastures. Phosphorus applications favor legumes, therefore, they can be used to support legume growth in a grass/legume pasture (Richardson *et al.* 2011). High soil carbon contributions have been reported from input from plant roots in grassland sites for fertilizer application (Tiemann *et al.* 2009), pasture growth and nutrient uptake result in some localized acidification around plant roots through the exudation of acids from the roots. However, according to Goulding (2016), excluding the particular case of legumes, the contribution of this to soil acidification is small <10% when compared with N and S fertilizer inputs, but it has an important influence on the bioavailability of plant nutrients in the rhizosphere, increasing pastures productivity and soil C stocks (Poeplau and Don 2013).

In double interaction, the implementation of kudzu on *B. decumbens* pasture (B2) including liming practice with the higher doses of lime application tend to store more soil C that in a alone *B. decumbens* pasture B1. The literature is rich with examples where soil conservation practices can be used to mitigate GHG emissions and adapt to climate change (Gibbons *et al.* 2014; Lal 2014), the increase in soil C stocks is subject to greater amounts of crop and pasture residues returned to the soil including minimal soil disturbance (Raji and Ogunwole 2006), reasons that could support the behavior obtained. Legume of lower C/N ratio increases mineralization process, improving soil fertility and increasing pasture aerial and root biomass, with increases in soil organic matter, possibly due to that the greater biological activity in limed soils, despite increasing soil respiration rates (Poeplau and Don 2013), led to plant C inputs being processed and incorporated into resistant soil organic-mineral pools more effectively (Paradelo *et al.* 2015). Greater biological activity in limed soils and legumes, despite increasing soil respiration rates, led to plant C inputs being processed and incorporated into resistant soil organic-mineral pools more effectively (Poeplau and Don 2013). Liming in pastures and legume might be an effective mitigation strategy against climate change (Gibbons *et al.* 2014). Fertilizers provided the essential elements of N, P, and K for pasture growth, which improved the shoot, root, and total biomass, a best response of B1 to the fertilization with Urea and B2 to the fertilization with Triple Superphosphate on soil C sinks, would be indicating that tropical pastures on nutrient-poor soils respond positively to the fertilization with N and P fertilizers, regardless of the type of pasture. For example, the fertilization with N and cover cropping can increase soil organic C and total N by increasing the amount of plant residues returned to the soil (Sainju *et al.* 2008). This situation can also to corroborate the result indistinctly of the fertilization with N, P, K fertilizer sources on higher mitigation of soil CO_2-eq with B2 and the higher lime doses. Our study of both cluster analysis identified showed that soil C sinks are determined mainly by pasture type and lime doses that possibly influence fertilizers used. Plants contribute to the formation of stable aggregates (SOM) protected from degradation in soil through fine roots and mycorrhizal associations, root litter contributes about one third of total litter inputs in grassland soils and half in forest soils where rhizodeposition represents about 11% of the C assimilated by plants or 27% of that allocated to roots (Freschet *et al.* 2013). On the other hand, the effect of liming and fertilization on soil C stock varies with the nature of the fertiliser, as well as with the climate and other site-specific factors (Goulding 2016). The presence of legumes in a pasture, reduces the amount of N fertilizer needed to support forage production. Pastures vary in their tolerance to acidity, mainly associated with legumes (Chambers *et al.* 2016); but also biological nitrification inhibition (BNI) in *Brachiaria* pastures is a novel strategy to improve eco-efficiency of crop-livestock systems and to mitigate climate change (Moreta *et al.* 2014). Lime can improve the efficiency of fertilizer use in nutrient-poor tropical soils according to edafic and climatic conditions (Castro and Gómez 2010). Positive response of lime was observed on soil C stocks (Paradelo *et al.* 2015). The fertilization with N and lime has been essential for the increase in SOC content, considered N as a limiting factor for the growth of pastures, reducing soil CO_2 emissions (Lal 2014), however, they can increase N_2O emissions (Naranjo *et al.* 2012). Unlike of Rigueiro-Rodríguez *et al.* (2011) in silvopastoral systems with *Pinus radiata* in which the combination of lime and high doses of sewage sludge (480 kg N total ha^{-1}) reduced the SOM, could come from the increment of the SOM mineralization rate as a result of the inputs of Ca to the soil caused by both practices, which could therefore reduce the soil capacity to sequester carbon. We also verified in triple interaction of dendogram that both pastures showed little response to the fertilization with Potassium chloride (F3). Possibly, the effect of fertilizer with K is not as evident in improving microbial activity, as it is with N and P fertilizers. The grassland SOM mainly derived from roots, senescent leaves and stems of the vegetations, where soil microorganisms exert a dominant influence on the net soil C balance by controlling soil organic matter (SOM) decomposition and plant nutrient availability (Conant *et al.* 2001). However, in pastures of livestock systems of Cumaral optimizing the lime doses with the verifiquied in this study, the use of fertilizers is made more efficient, favoring possibly other physical-chemical and biological processes in the soils and pastures. Grassland management including fertilization was crucial to the grassland recovery from overgrazing due to higher C stored (Chen *et al.* 2011). Soil management strategies identified can be potentially useful for decrease soil CO_2 emission, in order to guarantee soil CO_2 fixation in livestock systems at tropical zones.

CONCLUSIONS

The implementation of soil management factors as to introduce kudzú on pasture of *B. decumbens* (B2), the fertilization of pastures with Urea and Triple superphosphate, and liming practice applying 2.2 and 3.3 tons $CaCO_3$ ha^{-1}, exhibited major effect on higher soil C stocks rates and soil CO_2 mitigation. Both pasture types with higher lime doses responded better to increases in soil C and mitigation of CO_2-eq emisión that with L0 and L1. The fertilization of B1 with Urea and of B2 with Triple superphosphate stored more soil C which minimize soil CO_2 emissions to the atmosphere. According to cluster analysis, over all factors included in the current simulation the major influential factor on mitigation of soil CO_2 emissions is B2 with higher lime doses, indistinctly of N, P, K fertilizer sources grouped in cluster 1.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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