University of São Paulo
"Luiz de Queiroz" College of Agriculture

Intensification and diversification of degraded pasture areas in Brazil: potential of soil C accumulation and mitigation of the climate changes

Júnior Melo Damian

Thesis presented to obtain the degree of Doctor in Science. Area: Soil and Plant Nutrition

Piracicaba
2021

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **CARLOS EDUARDO PELLEGRINO CERRI**

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For all scientists and farmers, who wake up early and sleep late,
working for a better future for everyone.

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“Morri, mas ressuscitei das cinzas da minha fé,
o sangue de São Sepé me fez santo e eu me fiz rei,
gaúcho me transformei num barbaresco improviso,
e alí no chão impreciso de parceria com o vento,
sou hoje um prolongamento do chão sagrado onde piso.”

Jayme Caetano Braun (Missioneiro)

“Science can tell us what exists; but to compare the worths, both of what exists and of what does not exist, we must consult not science, but…our heart.”

William James (The Will to Believe)

“Imagination is more important than knowledge. Knowledge is limited; imagination encircles the world.”

Albert Einstein (Attributed)

CONTENTS

ABSTRACT

Intensification and diversification of degraded pasture areas in Brazil: potential of soil C accumulation and mitigation of the climate changes

Pasture improvements in Brazil, where pastures occupy ~167 million ha, have great potential for soil carbon (C) accumulation and to mitigate of greenhouse gases (GHG), such as the carbon dioxide (CO_2). However, soil degradation on current pasture areas (> 50% are degraded) is an issue to be solved through sustainable management. The aim of our current field study was to quantify soil C stocks and to elucidate the processes, involved in the soil C accumulation in areas subjected to different intensive and diversified systems of pasture management in Brazil. Treatments included fertilized pasture (FP), integrated crop-livestock (ICL) and integrated livestock-forest (ILF), compared to the extensive form (conventional management system) under contrasting climatic conditions (tropical humid, tropical mesic and subtropical). To meet this goals, there were avaluaded i) the soil C stocks changes and the soil organic matter (SOM) quality; ii) the relationships between the soil C and N stocks with the different phosphorus (P) fractions; iii) the soil chemical and biochemical properties and, the soil bacterial community structure to assess the controlling factors on soil C accumulation and, iv) the use mathematical modeling to predict the soil C changes and GHG emissions. In general, the adoption of more intensive and diversified systems of pasture management in areas previously used with extensive management systems increased the soil C stocks and the soil C lability. Likewise, there was an improvement in the soil chemical properties related to soil fertility, especially in soil P. The increase in the labile P contents was directly proportional to the increase of the more labile SOM fractions. Furthermore, the conversion of conventional management system to more intensive and diversified pasture management systems, besides changing the soil chemical and biochemical properties and the soil bacterial community structure, also modified the mechanisms that control the soil C accumulation. According to the structural equation modeling, the improvement in the soil chemical properties was the factor that most influenced in soil C accumulation. In addition, through long-term predictions performed with the DayCent model, it was found that while extensively managed pastures were a GHG source to the atmosphere, systems of pasture management, such as FP, ICL and ILF were GHG sinks. Thus, for the conditions tested in this study the DayCent model proved to be an a efficient and cost-effective tool to predict soil C pool changes and to monitor GHG emissions. Finally, it is believed that the results found in this thesis can assist national initiatives aimed at restoring degraded pasture areas (e.g., “ABC Plan”), as well as fits the scope of the Brazil’s NDC (Nationally Determined Contribution) for mitigating GHG emissions (reduce emissions 37% by 2025 and 43% by 2030) through the increase of the soil C stocks and, adopting sustainable pasture management systems.

Keywords: Sustainability; Integrated agricultural systems; SOM; P fractions; Soil bacterial community structure; CO_2 emissions; Modeling

RESUMO

Intensificação e diversificação de áreas de pastagens degradadas no Brasil: potencial de acúmulo de C no solo e mitigação das mudanças climáticas

Melhorar a qualidade das pastagens no Brasil, onde as mesmas ocupam ~167 milhões de ha, têm grande potencial para acúmulo de carbono (C) no solo e para mitigar gases de efeito estufa (GEE), como é o caso do dióxido de carbono (CO_2). No entanto, a degradação do solo nas áreas de pastagens atuais (> 50% estão degradadas) é um problema a ser resolvido por meio de sistemas sustentáveis de manejo de pastagens. O objetivo do presente estudo de campo foi quantificar os estoques de C do solo e elucidar os processos envolvidos no acúmulo de C no solo em áreas submetidas a diferentes sistemas intensivos e diversificados de manejo de pastagens no Brasil. Os tratamentos incluíram pastagem fertilizada (PF), integração lavoura-pecuária (ILP) e integração pecuária-floresta (IPF), em comparação à forma extensiva (sistema de manejo convencional) sob condições climáticas contrastantes (tropical úmido, tropical mesic e subtropical). Para atender a esses objetivos, foram avaliados i) as mudanças nos estoques de C do solo e na qualidade da matéria orgânica do solo (MOS); ii) as relações entre os estoques de C e N do solo com as diferentes frações do fósforo (P) do solo; iii) as propriedades químicas e bioquímicas do solo e a estrutura da comunidade bacteriana do solo, visando avaliar os fatores de controle do acúmulo de C no solo e, iv) o uso de modelagem matemática para prever as mudanças do C do solo e as emissões de GEE. Em geral, a adoção de sistemas mais intensivos e diversificados de manejo de pastagens em áreas anteriormente utilizadas com sistemas de manejo extensivos, aumentou os estoques a a labilidade do C do solo. Da mesma forma, houve uma melhoria nas propriedades químicas do solo relacionadas à fertilidade, principalmente no P do solo. O aumento do conteúdo de P lábil foi diretamente proporcional ao aumento das frações mais lábeis da SOM. Além disso, a conversão de sistemas de manejo convencionais para sistemas de manejo de pastagens mais intensivos e diversificados, além de alterar as propriedades químicas e bioquímicas do solo e a estrutura da comunidade bacteriana do solo, também modificou os mecanismos de controle do acúmulo de C no solo. De acordo com a modelagem de equações estruturais, a melhoria nas propriedades químicas do solo foi o fator que mais influenciou no acúmulo de C no solo. Além disso, por meio das predições a longo prazo realizadas com o modelo DayCent, verificou-se que enquanto pastagens extensivamente manejadas foram uma fonte de GEE para a atmosfera, sistemas de manejo de pastagens como FP, ICL e ILF foram sumidouros de GEE. Assim, para as condições testadas neste estudo, o modelo DayCent provou ser uma ferramenta eficiente e econômica para prever mudanças nos reservatórios de C do solo e monitorar as emissões de GEE. Por fim, acredita-se que os resultados encontrados nesta tese podem auxiliar as iniciativas nacionais voltadas para a restauração de áreas de pastagens degradadas (ex: "Plano ABC"), bem como se enquadram no escopo do NDC (Contribuição Nacionalmente Determinada) do Brasil para mitigação de emissões de GEE (reduzir as emissões em 37% até 2025 e 43% até 2030) através do aumento dos estoques de C no solo e da adoção de sistemas sustentáveis de manejo de pastagens.

Palavras-chave: Sustentabilidade; Sistemas agrícolas integrados; MOS; Frações do P, Estrutura da comunidade bacteriana do solo; Emissões de CO_2; Modelagem

1. GENERAL INTRODUCTION

Globally, pastures areas correspond to two-thirds (3.2 billion hectares) of the total agricultural land (4.8 billion hectares) (FAO, 2020). However, according to FAO (Food and Agriculture Organization) while the area with cropland increased by 5% (on average by > 0.2% yr^{-1}), the land used for pastures showed a decreased of 2% (on average by < 0.1% yr^{-1}) during 1990–2018. In this scenario, for the same period the highest reductions were observed in Oceania (< 26%), Asia (< 3%), Europe (< 3%) and Africa (< 3%). The only exception was in North America (> 2%) and South America (> 1%), where there were increased in the pasture areas. More specifically in South America, Brazil is the main represent accounting with ~167 million ha of pastures (MapBiomas, 2020).

The pastures areas corresponded to 66% of the total area occupied by the Brazilian agriculture sector in 2019 (Figure 1a). For the 1985-2019 period (Figures 1c and 1d), the pastures areas increased 1.27 million ha yr^{-1} while the agriculture area incresed 1.15 million ha yr^{-1}. However, according to estimates made by LAPIG (Laboratório de Processamento de Imagens e Geoprocessamento) approximately 56% of the total pastures areas in Brazil has some degree of degradation (Figure 1b). Due to the great importance of this theme, in recent years there has been an increase in environmental and market pressures for Brazil to seek to identify and also propose new alternatives for the recovery of pastures (Kehoe et al., 2019). For Sattler et al. (2017), the main cause of pasture degradation is a combination of inappropriate land use (land use for which it is environmentally unsuitable) and inappropriate land management practices (land use in ways that could be sustainable if managed properly, but practical necessary are not adopted). According to Dias-Filho (2014), despite the concern with the high incidence of degraded pasture areas there is great potential for increasing the productivity of national livestock by simply recovering these unproductive areas.

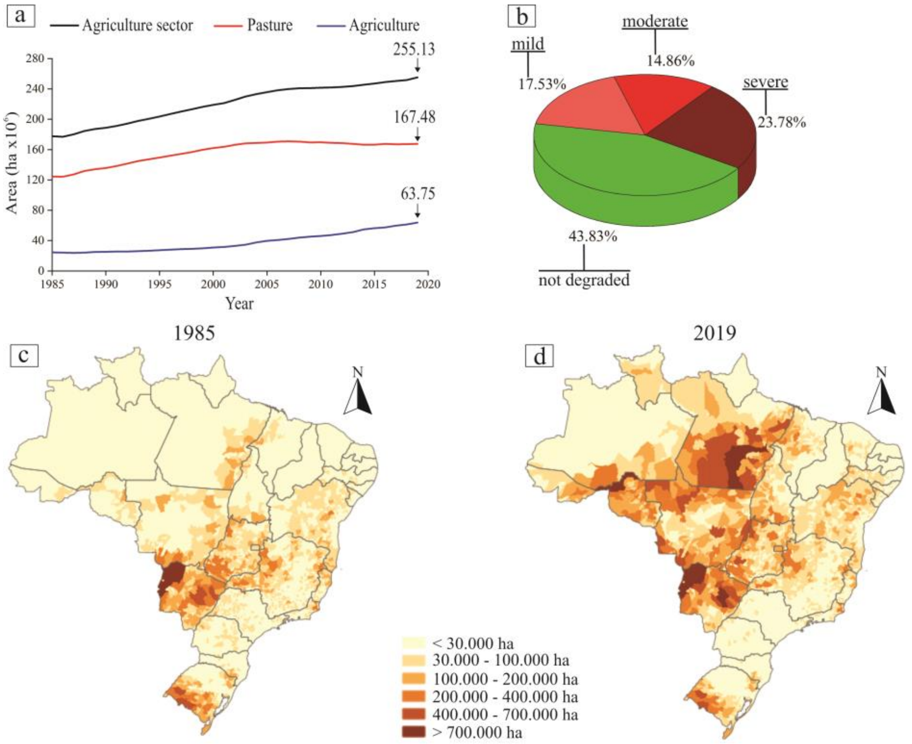

Figure 1. Analyses of the pasture areas in Brazil (a), degree of degradation (b) and evolution during 1985 (c) and 2019 (b). Source: LAPIG (https://pastagem.org/atlas/map), MapBiomas (https://mapbiomas.org/en) and IBGE (https://www.ibge.gov.br/).

In general, the main regions of Brazil with the greatest proportions of degraded pastures are found in the Midwest and Northeast (Figure 2a). These areas are located in agricultural frontier regions, and the stigma of non-demanding activity in inputs and technology has resulted in an increase in degraded pasture areas (Dias-Filho, 2014). Nevertheless, as previously discussed there is a great potential for increasing the productivity (UA/ha) of Brazilian pastures. Indeed, estimates made by LAPIG indicate that there is a wide possibility of increasing pasture productivity throughout Brazil (Figure 1b). Aware of this possibility, the Brazilian government together with research institutions seek to propose new initiatives for the sustainable management of pastures. An important evolution in public policy initiatives in Brazil was the creation of the ABC Plan (National Plan for Low Carbon Emission in Agriculture) in 2010. Among the goals of the ABC plan is the recovery of 15 million hectares of degraded pastures through the adoption of more intensive and diversified systems of pasture management, such as fertilized pasture (FP), integrated crop-livestock (ICL), integrated livestock-forest (ILF). Additionally to the socioeconomic benefits (e.g., increase in annual income and job opportunities) of adopting these management systems, the ABC plan aims to reduce approximately 1168-1259 million t CO_2eq of the estimated greenhouse gas (GHG) emissions for 2020-year (3236 million t CO_2eq). Thereby, it is widely known that the carbon (C) sequestration in the soil is one of the most effective strategies for curbing the carbon dioxide (CO_2) emissions to the atmosphere (Paustian et al. 2016; Minasny et al. 2017; Cotrufo et al. 2019; Shi et al. 2020).

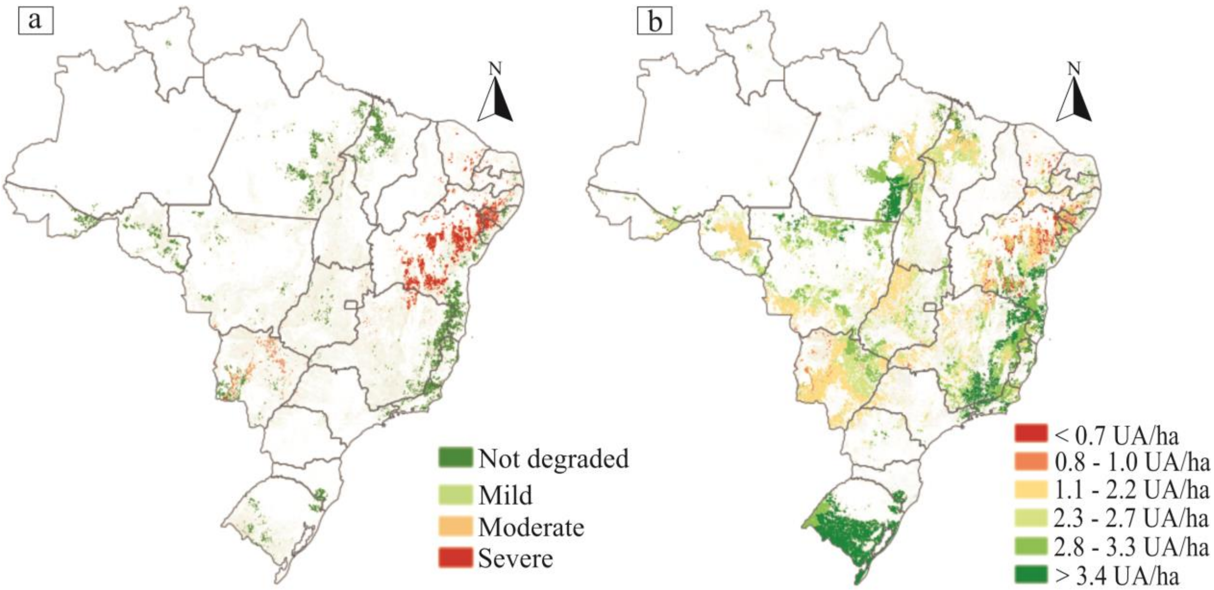

Figure 2. Spatialization of the degree of degradation (a) and the potential for intensification of pastures (b) in Brazil. Source: LAPIG (https://pastagem.org/atlas/map).

The soil plays as the main carbon (C) sink (2500 Pg C), being the largest soil C pool among the terrestrial ecosystems (approximately 4 times of the C compartment of vegetation and 3.3 times the C of the atmosphere) (Lal, 2004). In this sence, pastures have great potential for CO_2 sequestration since estimates show that globally C accumulation in pastures can be 50% higher than it is in forests (FAO, 2007). However, inadequate pasture management can reduce the potential for C sequestration and mitigate the CO_2 emissions. Thus, the adoption of more intensive and diversified systems of pasture management can be an efficient alternative to avoid soil C losses, ensuring the sustainability of the livestock system.

Despite the eminent potential for carbon accumulation and sequestration with the adoption of more intensive and diversified systems of pasture management, few studies have been carried out in Brazil seeking to evaluate the processes and dynamics of the soil C accumulation of these management systems. The conversion of extensive system of pasture management to more intensive and diversified systems of pasture management still need more studies, including: i) assess the changes in the stocks of soil C in the soil and in different soil organic matter (SOM) fractions; ii) evaluate the relationship between the total soil C and N, SOM fractions with phosphorus (P) fractions; iii) the changes and the relationship between the soil C pools, soil chemical and biochemical properties and the soil microorganisms (e.g., bacteria and fungi) and, iiii) calibrate mathematical models for long-term predictions of soil C pool changes and to monitor GHG emissions. In this context, the present doctoral thesis sought to raise answers to these questions as well as to outline future perspectives on this topic in Brazil.

1.1. General hypothesis

Due to the large potential in total area for improvement and intensification of the pastures in Brazil, the hypothesis of this thesis is that the adoption of more intensive and diversified systems of pasture management [fertilized pasture (FP), integrated crop-livestock (ICL), integrated livestock-forest (ILF)] in areas previously used with extensive management systems, promotes increases in the flow of C inputs in the soil and favoring the soil C accumulation.

1.2. General objective

The main objective of this study was to quantify soil C stocks and to elucidate the processes (SOM quality, interactions with the soil chemical and biochemical properties, mathematical modeling), involved in the soil C accumulation with the pastureland intensification and diversification in different climatic conditions (tropical humid, tropical mesic and subtropical) in Brazil.

1.3. Thesis structure

To meet the hypothesis and objective proposed, this thesis will be organized in four chapters. The first chapter will address the changes in the soil C stocks and the quality of SOM with the conversion from extensively managed pastures to more intensive and diversified systems of pasture management. In the second chapter, the relationship between the soil C and N stocks with the different P fractions will be analyzed, since phosphorus is a limiting nutrient in tropical soils and few studies have been carried out with this theme. The third chapter seeks to evaluate the relationship between soil C pools, soil chemical and biochemical properties with the soil bacterial community structure, and to assess the controlling factors on soil C accumulation under different pasture management systems. Finally, the fourth chapter aims to use the DayCent model to predict the soil C changes and GHG emissions due to the pastureland intensification and diversification in Brazil.

References

Cotrufo, F., Ranalli, M.G., Haddix, M.L., Six, J., Lugato, E., 2019. Soil carbon storage informed by particulate and mineral-associated organic matter. Nat. Geosci. 12:989–994.

Dias Filho, M.B., 2014. Diagnosis of pastures in Brazil (in portuguese). Embrapa. Brasil, Brasília. pp. 1–36.

FAO, 2020. Land Statistics: Global, Regional and Country Trends, 1961-2018. URL: http://www.fao.org/economic/ess/environment/data/land-use-and-land-cover/en/. Acessed 16 Dec 2020.

FAO, 2007. State of the world's forests 2007. URL: http://www.fao.org/3/a0773e/a0773e00.htm. Acessed 9 Dec 2020.

Kehoe, L., Reis, T., Virah-Sawmy, M., Balmford, A., Kuemmerle, T., 604 signatories., 2019. Science 364, 341–342.

LAPIG, 2020. Atlas of Brazilian Pastures (in portuguese). URL: https://www.lapig.iesa.ufg.br/lapig/index.php/produtos/atlas-digital-das-pastagens-brasileiras. Acessed 11 Dec 2020.

MapBiomas, 2020. Brazilian annual land use and land cover mapping project. URL: https://mapbiomas.org/en. Acessed 14 Dec 2020.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Chen, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savian, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.C., Vagen, T.G., Wesemael, B.V., Winowieckit, L., 2017. Soil carbon 4 per mille. Geoderma 292:59-86.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532:49–57.

Sattler, D., Seliger, R., Nehren, U., Torres, F.N., da Silva, A.S., Raedig, C., Hissa, H.R., Heinrich, J., 2017. Pasture degradation in South East Brazil: status, drivers and options for sustainable land use under climate change. In: Filho, W.L., Freitas, L.E.(Eds.), Climate Change Adaptation in Latin America. Springer, Cham, pp. 3-17.

Shi, H., Li, X., Liu, X., Wang, S., Liu, X., Zhang, H., Tang, D., Li, T., 2020. Global protected areas boost the carbon sequestration capacity: Evidences from econometric causal analysis. Sci. Total Environ. 715:1–10.

2. CHANGES IN SOIL CARBON INDUCED BY THE INTENSIFICATION AND DIVERSIFICATION OF PASTURELAND IN BRAZIL*

Abstract

The extensive system of pasture management in Brazil can reduce soil C stocks and increase CO_2 emissions to the atmosphere. However, the adoption of sustainable management systems can change these conditions and enact modern practices of natural resource management as defined by the concept of ecosystem services. A field study was therefore carried out to assess the effects of adopting more intensive and diversified systems of pasture management on the quality and stocks of soil C. Treatments included fertilized pasture (FP), integrated crop-livestock (ICL), and integrated livestock-forest (ILF) and were compared to conventional management systems (CSs) under different soil and climate conditions (tropical humid, tropical mesic and subtropical). C stocks of in the soil and in different SOM fractions were determined in the top one-metre layer. Adopting ICL systems under the conditions of a tropical humid and subtropical climate afforded increases in soil C stocks of 0.75 Mg ha^{-1} yr^{-1} and 0. 0.15 Mg ha^{-1} yr^{-1}, respectively, relative to the CS. Similarly, the conversion of a CS to FP (tropical humid climate) and ILF (tropical mesic climate) led to increases in soil C stocks of 2 and 0.55 Mg ha^{-1} yr^{-1}, respectively. The adoption of more intensive and diversified systems of pasture management also increased C lability and management indices under all climate conditions. These results can be serve as a scientific basis for government initiatives focused on recovering degraded pastures in Brazil through the use of more sustainable management systems.

Keywords: Ecosystem services; Fertilized pasture; Integrated crop-livestock; Integrated livestock-forest; CMI.

2.1. Introduction

Given the need to produce food to support growth in the world population, anthropic activities end up changing natural ecosystems (Gang et al., 2014; Galán-Acedo et al., 2019). However, the indiscriminate intensification of land management can have negative consequences for regulating and supporting services, especially due to soil degradation (Gounand et al., 2018). For Lal (2014). In addition to the on-site effects of soil erosion (e.g., degrading soil quality and reducing agronomic/biomass productivity), off-site impacts include an increase in greenhouse gas (GHG) emissions to the atmosphere. Accordingly, ecosystem services are a principal focus of contemporary conservation strategies that, among other targets, apply measures aimed at reducing GHG emissions such as CO_2 (Millennium ecosystem assessment, 2005).

Pastures have great potential for CO_2 sequestration since estimates show that globally, C accumulation in pastures can be 50% higher than it is in forests (FAO, 2007); as such, C accumulation in pastures also exceeds its accumulation in agricultural areas (Li et al., 2017). Pastureland corresponds to approximately 40% of the total land area worldwide (Wang and Fang, 2009). Between 1970 and 2005, pastureland grew by approximately 4% globally, and this growth influenced the demand for food, including that for meat and milk (Sattari et al., 2016). In Brazil, most of the land has been allocated to pasture, covering approximately 159 million hectares (IBGE, 2017) and representing approximately 16% of the equivalent land area of Europe.

However, soil degradation in pastureland in Brazil makes it difficult to provide ecosystem services. Estimates show that 50% to 70% of all pastureland is degraded and/or in some stage of degradation, resulting in low

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grass yields; on average, the grass grown in these areas supports one animal unit per hectare (Dias Filho, 2014). In addition, it is estimated that livestock activity is responsible for 44% of GHG emissions generated by the land use sector in Brazil (SEEG 2016). To change these conditions, the Brazilian government created the 'ABC Program', which, among other initiatives, aims to restore areas degraded as a result of extensive grazing. Fertilization and the use of pasture in integrated systems [e.g., integrated crop-livestock (ICL) and integrated livestock-forest (ILF) systems] are among the management improvements recommended by the ABC Program to meet this need. Overall, these strategies aim at reducing areas of degraded pasture (Gil et al., 2016), increasing economic revenue (Thornton and Herrero, 2015), reducing net CO_2 emissions (Cohn et al., 2014) and improving soil quality, especially the amount of soil organic matter (SOM) (Assmann et al., 2015).

The greatest input of C and N to the soil occurs through the cycling of the shoot and root biomass of different plant species and through animal waste, which has been made possible by more intensive and diversified systems of pasture management. These factors can play a key role in increasing soil C stocks (Rasse et al., 2005; Cardinael et al., 2015a; Upson et al., 2016); however, it is necessary to identify how these management systems influence soil C stocks at deeper layers and how changes in attempts to recover soil can affect SOM dynamics. According to Ghimire et al. (2019), pasture systems sequester more C than agricultural soils, but C is so sensitive to such disturbances that accrued C is easily lost when pastures are cultivated. However, sustainable management systems that contribute to belowground C inputs and reduce soil disturbance can accumulate C.

For Sato et al. (2019), more intensive and diversified systems of pasture management may present a positive C balance, making it possible to recommend this cultivation system for sustainable intensification as an alternative to mitigate GHG emissions. However, Sarto et al. (2020) reported that despite the importance of these management systems for C sequestration, qualitative and quantitative data on soil C stocks in tropical regions are still lacking. Based on these issues, the hypothesis of the present study is based on the assumption that the intensification and diversification of extensively managed pastureland (conventional management system) can increase soil labile carbon as well as the rate of soil carbon stocks in different carbon pools (SOM fractions). As such, the aim of the present study was to assess the quality (lability index and carbon management index) and accumulation (stocks) of soil C submitted to more intensive and diversified systems of pasture management under different soil and climate conditions in Brazil.

2.2. Materials and Methods

2.2.1. Description of the study sites

Study sites were selected to assess the effects of integrated production systems on C dynamics in the soil under contrasting soil and climatic conditions in Brazil (Fig. 1a). The first site is located in Nova Guarita, Mato Grosso, midwestern Brazil (Lat.: 10° 9' 10.41"S; Long.: 55° 31' 49.53"W) at 380 m elevation. The prevailing soil at this site is classified as an Oxisol (USDA, 2014), and the local climate is classified as Aw (Köppen), tropical hot and humid with a mean annual temperature of 25.9°C and a mean annual rainfall level of 2,628 mm. The second site is located in Nova Odessa, São Paulo, southeastern Brazil (Lat.: 22° 75' 12"S; Long.: 47° 27' 81"W) at 550 m elevation. The prevailing soil in this region is also classified as Oxisol (USDA, 2014), and the local climate is classified as Cwa (Köppen), tropical rainy with dry winter with a mean annual temperature of 20.2°C and a mean annual rainfall level of 1,262 mm. The third site is located in Eldorado do Sul, Rio Grande do Sul, southern Brazil (Lat.: 30° 05' 22"S; Long.: 51° 39' 08"W) at 46 m elevation. The prevailing soil in this region is classified as Ultisol (USDA, 2014), and the local climate is classified as Cfa (Köppen), subtropical with a mean annual temperature of 19.3°C and a mean annual rainfall level of 1,398 mm. More details about the climatic conditions in Mato Grosso (tropical humid), São Paulo (tropical mesic) and Rio Grande do Sul (subtropical) can be found in Fig. 1b.

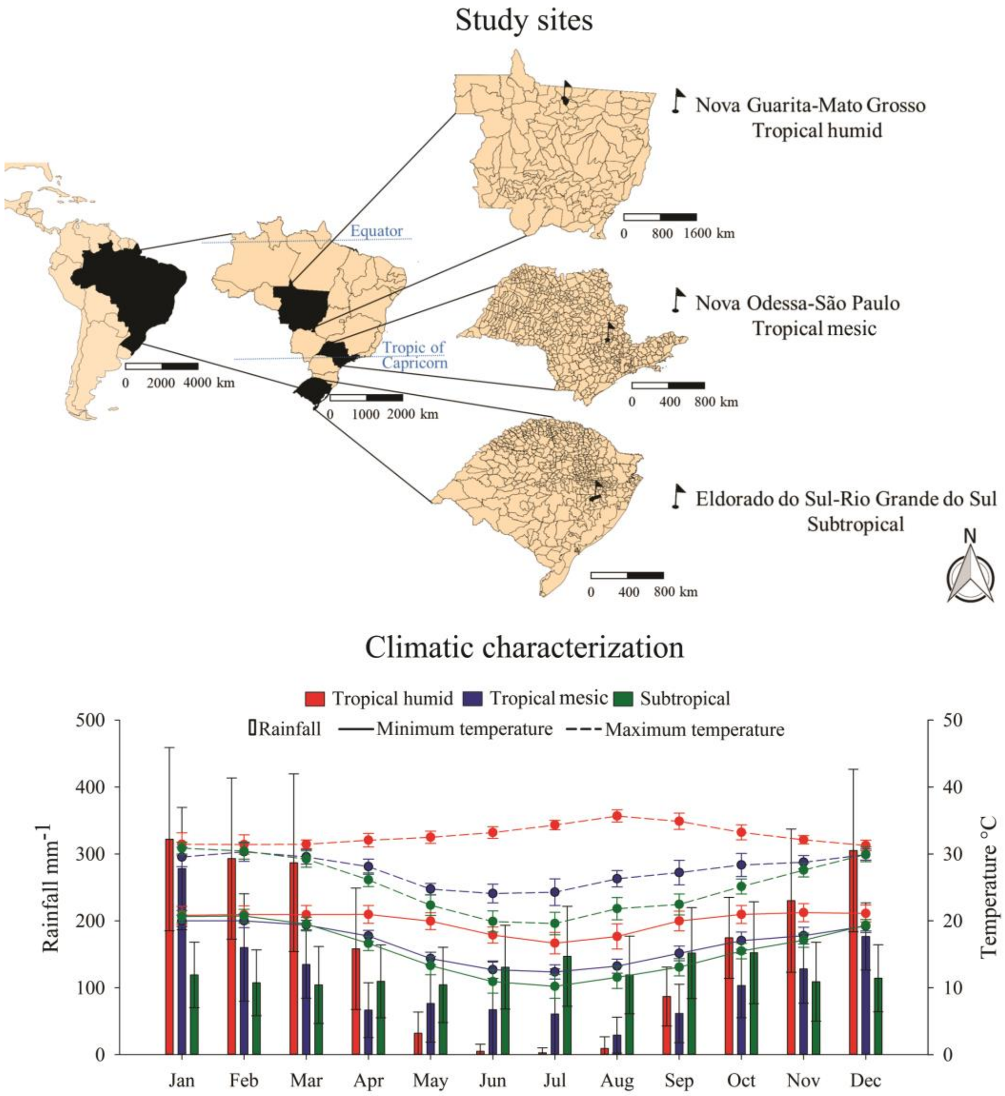


Figure 1. Geographic location and the climatic characterization in the study sites during the 38-year period. Bars represent the standard deviation of the mean values (n = 38). INMET (2019).

2.2.2. Systems of pasture management and soil sampling

To assess the benefits of more intensive and diversified systems of pasture management, at each site, pastures under a variety of management regimes were identified and compared to pastures under conventional systems of pasture management (extensive), which is mainly characterized by a lack of control over grazing pressure and no fertilization. Typically, pastures under conventional management in Brazil have stocking rates of below 0.8 animal units per hectare (AU·ha^{-1}) (IBGE, 2017). Specifically, the following systems of pasture management were compared:

i) Tropical humid treatments include the conventional system (CS), fertilized pasture (FP), ICL with maize/soybeans and ICL with rice/soybean. The site is located in the Amazonian biome, and since 2004, its native vegetation has been removed for pasture implementation under conventional management systems. In the CS (equivalent edaphoclimatic conditions), in 2012 and 2015, ICL systems and FP were implemented, respectively, as the current land use.

ii) Tropical mesic treatments include the conventional system (CS), ILF with rotational grazing and ILF with no grazing. The site is located in the Atlantic Forest biome, where native vegetation was removed to implement the CS in 1995. In the CS (equivalent edaphoclimatic conditions), ILF systems were implemented in 2015 as the current land use.

iii) Subtropical treatments include the conventional system (CS); ICL with no grazing, ICL with rotational stocking and moderate-intensity grazing, ICL with continuous stocking and moderate-intensity grazing, ICL with rotational stocking and low-intensity grazing and ICL with continuous stocking and low-intensity grazing. The CS is located in the Pampa biome, and in 2003, it was chosen for the installation of a long-term experiment focused on ICL. Forage supplies were defined as those presenting 2.5 (moderate grazing intensity) and 5 times (low grazing intensity) more daily consumption of dry matter based on NRC (1985) data by lambs or lactating ewes. The resulting forage supplies reached 10 kg (moderate grazing intensity) and 20 kg (low grazing intensity) of forage dry mass per 100 kg ha^{-1} animal live weight.

More details about the management systems adopted at these sites, the applied fertilization and soil texture features can be found in Table 1.

Table 1. Description of the study areas.

Climatic condition	Tropical humid			Tropical mesic			Subtropical		
Description	*Brachiaria ruziziensis* Germ. & C.M. Evrard was used for pasture in CS, FP and ICL. CS: In this management system is characterized by grazing all year. The stocking rate is ~0.5 $AU\cdot ha^{-1}$. FP: In this management system is characterized by grazing all year. The stocking rate is ~1.2 $AU\cdot ha^{-1}$. ICL: In this management system, the cultivation period is divided by the crop (october to march) and pasture (may to september) phase. The stocking rate is ~1.8 $AU\cdot ha^{-1}$.			*Brachiaria brizantha* cv. Marandu was used as pasture in CS and ILF. Two rows of African mahogany trees (*Kaya ivorensis* A. Chev.) spaced 15x5m away from each other were used in ILF. CS: In this management system is characterized by grazing all year. The stocking rate is ~0.7 $AU\cdot ha^{-1}$. ILF: In the management system with integrated livestock-forest with rotational grazing, the grazing phase is between may and january. The stocking rate is ~2.9 $AU\cdot ha^{-1}$.			*Lolium multiflorum* Lam. was used for pasture in ICL. The prevailing grass speciein the CS (Pampa) was *Paspalum notatum* Flügge. CS: In this management system is characterized by grazing all year. The stocking rate is ~0.6$AU\cdot ha^{-1}$. ICL: In this management system, the cultivation period is divided by the crop (november to may) and pasture (july to october) phase. The stocking rate is ~2.1 $AU\cdot ha^{-1}$.		
Crop nutritional management	15 kg ha^{-1} of N and 60 kg ha^{-1} of P_2O on a yearly basis.			-			18 kg ha^{-1} of N and 40 kg ha^{-1} of P_2O and 40 kg ha^{-1} of K_2O on a yearly basis.		
Pasture nutritional management	15 kg ha^{-1} of N; 80 kg ha^{-1} of P_2O and 40 kg ha^{-1} of K_2O on a yearly basis. Application of 2000 kg ha^{-1} of limestone at the time of system deployment.			100 kg ha^{-1} of N on a yearly basis.			150 kg ha^{-1} of N and 60 kg ha^{-1} of P_2O and 60 kg ha^{-1} of K_2O on a yearly basis. Application of 1000 kg ha^{-1} of limestone at the time of system deployment.		
	Oxisol[1]			Oxisol[2]			Ultisol[3]		
Layers (cm)	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)
0-10	620±21.23	67±4.24	313±8.49	561±13.44	175±7.78	264±8.49	630±7.78	220±15.56	150±8.49
10-20	610±56.57	88±7.07	302±12.02	569±0.71	176±14.14	254±11.31	625±12.03	203±2.83	170±6.36
20-40	480±21.23	67±4.24	453±20.51	520±15.56	149±7.74	331±7.07	552±11.31	221±7.07	227±6.36
40-60	412±14.85	32±2.82	556±10.61	508±25.46	143±33.23	329±16.97	525±4.95	195±8.49	280±5.66
60-80	333±72.83	47±2.83	580±81.32	493±30.41	180±9.46	327±5.66	415±7.07	201±4.24	384±19.80
80-100	385±3.53	29±2.12	585±28.25	492±46.67	179±17.68	329±4.58	350±9.90	185±4.95	464±24.75

CS, conventional system; FP, fertilized pasture; ICL, integrated crop-livestock and ILF, integrated livestock-forest .1Oxisol formed from tertiary sediments - the clay fraction is predominantly formed by kaolinite and Al oxide (gibbsite) (Campos, et al., 2011); 2Oxisol formed from basalt rocks - the clay fraction is predominantly formed by kaolinite, Fe oxides (goethite, hematite and magnetite/maghemite), Al oxide (gibbsite) (Cherubin et al., 2016); 3Ultisols formed by granite rocks - the clay fraction is predominantly formed by kaolinite and Fe oxides (hematite and goethite) (Bayer et al., 2011).

Soil sampling was carried out in August and October 2017 at sites with tropical humid and subtropical climates, respectively, and in January 2018 at sites with tropical mesic climates. Samples from the three assessed sites under each management system were collected in cross-sections with nine sampling areas (repetitions) spaced 50 m apart. The soil samples were collected at depths of 0–10, 10–20, 20–30, 30–40, 40-50, 50–60, 60-70, 70–80, 80-90 and 90-100 cm with a Dutch auger. In addition, a trench was opened to collect undeformed samples with a Kopeck ring in each assessment location at the same depths listed above. This procedure was adopted to determine bulk density (BD), which was subsequently used to calculate C and N stocks. BD values for each site under different climatic conditions can be found in Supplementary Table S1. After collection, all soil samples were air dried, ground and sieved to 2 mm for the other assessments.

The chemical attributes of soil samples from each management system and location were determined based on the method described by Raij et al. (2001). The results can be found in Supplementary Tables S2 (tropical humid), S3 (tropical mesic) and S4 (subtropical).

2.2.3. Carbon and nitrogen stocks

Soil C and N stocks (Mg ha^{-1}) were calculated by multiplying the total C and N (g kg^{-1}) by BD (g cm^{-3}) and depth (cm). However, different management systems can change BD; eventually, the soil mass that represents a certain soil depth can also vary. Thus, C and N stock comparisons for each treatment must be performed with equal soil masses by adjusting the soil depth based on a reference site (Ellert and Bettany, 1995). It is necessary to find a new depth for each site to represent the same soil mass at all study sites to correct the soil mass. The mass representing the same soil mass is also used to accurately determine the soil C and N stocks (Eq. 1).

$$\text{Equivalent depth} = (BD_{CS}/BD_{ID}) \times RD \tag{1}$$

where the equivalent depth is the new depth found in a specific site (cm), BD_{CS} is the BD of each CS in each location (in g cm^{-3}), BD_{ID} is the BD of each more intensive and diversified system of pasture management in each location (g cm^{-3}), and RD is the reference depth (cm).

The conversion factors (CFs) for conversion from a CS to more intensive and diversified systems of pasture management (FP, ICL and ILF) were calculated considering changes in soil C stocks with the CS used as a reference as described in Eq. (2).

$$CF = CM / CS \tag{2}$$

where CF = the conversion factor; CM = soil C stocks of each more intensive and diversified systems of pasture management (Mg ha^{-1}); and CS = soil C stocks of the CS (Mg ha^{-1}).

The rate of soil carbon change associated with both more intensive and diversified systems of pasture management was calculated based on the difference in C stocks measured between the current and previous systems of pasture management as described in Eq. (3).

$$\Delta C = (Cc - Cp) / T \tag{3}$$

where ΔC = the rate of soil carbon change (Mg ha^{-1} yr^{-1}); Cc = soil C stocks of the current system of pasture management (Mg ha^{-1}); Cp = soil C stocks of the previous system of pasture management (Mg ha^{-1}); and T = time passed since pasture management conversion (years).

2.2.4. Physical fractionation of SOM and the carbon management index

The soil was physically fractionated using the granulometric method. We used sieved (2 mm - TFSA) air-dried soil samples; the procedure required the use of soil samples from layers 0-10, 40-50 and 90-100 cm. These layers were selected based on our previous analysis of the results of soil C and N stocks. In addition, other studies show that these layers show differences related to the relative amount and type of plant C input and differences with respect to the impacts of pastureland intensification that allow an adequate assessment of management practice impacts on SOM dynamics (Mello et al., 2014; Oliveira et al., 2017a; Wade et al., 2019).

Fractionation required the use of 20 g of soil samples that were weighed and transferred to 100 mL glass pots, to which 70 mL of distilled water was added. The samples were subjected to ultrasound treatment (model VC505) for 15 min at 70% (500 W) of the maximum power of the device. This procedure provided approximately 130 J mL^{-1} of energy to the samples (Sonics Vibra Cell) (Cambardella and Elliott, 1992; Christensen, 1992). After sonication, samples were sieved through a set of 75 and 53 μm sieves. The fractions remaining on the 75 μm sieve were separated employing the densimetric method using distilled water at organomineral-F1 (coarse sand) and organic-F2 (coarse light) (75-2000 μm). Fractions that passed through the 75 μm sieve were separated through a 53 μm sieve. This sieving (53-75 μm) separated the organomineral- F3 fraction (fine sand). The fraction passing through the sieve (< 53 μm) was labelled the organomineral-F4 fraction (silt+clay) (Feller and Beare, 1997). This identification of different fractions allowed us to determine C and N concentrations (%) per dry combustion in an elementary analyser (Nelson and Sommers 1996) for each SOM fraction.

The total C and N contents (g kg^{-1}) in the SOM fractions were calculated by multiplying the C and N concentrations in each fraction by their corresponding mass. Finally, soil C and N stocks (Mg ha^{-1}) for each SOM fraction were calculated by multiplying the total C and N contents by BD and depth. Although the fractionation of the SOM method used in this study showed a good recovery rate (average recovery of 95%), we emphasize that differences between the values of C and N stocks in the soil and the different SOM fractions are acceptable. Other factors, such as characteristics inherent to the soil type in view of its segregation according to the soil granulometry and mode of soil management adopted, can increase or reduce these differences.

2.2.5. Carbon management index

The SOM fractionation results allowed for the calculation of the C management index (CMI) originally proposed by Blair et al. (1995) with adaptations made by Diekow et al. (2005). The CMI was determined using Eq. (4):

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100 \tag{4}$$

where the CPI (carbon pool index) = the total soil organic C of each more intensive and diversified system of pasture management (Mg ha^{-1})/the total organic C of each conventional system (Mg ha^{-1}); LI (lability index) = the soil C lability of each more intensive and diversified system of pasture management/the soil C lability of the conventional system; lability = labile C (Mg ha^{-1})/non labile C (Mg ha^{-1}); labile C = the total organic C in the light coarse fraction (Mg ha^{-1}); and nonlabile C = the total soil organic C – labile C.

2.2.6. Data Analysis

The analysis of variance (ANOVA) was used to test the differences in stocks of C and N in the soil and in the different SOM fractions, and in the soil C management indices of each climatic condition (tropical humid, tropical mesic and subtropical). The Tukey test was used to compare the means of the different systems of pasture management (CS, FP, ICL and ILF). The principal component analysis (PCA) analysis was also performed to investigate the relationship between stocks of C and N in the soil and in the different SOM fractions for each climate condition. All analyses were conducted using Statistical Analysis System – SAS v.9.3 software (SAS Inc., Cary, USA). Significant differences were evaluated at the 0.05 level.

2.3. Results

2.3.1. Stocks of C and N in the soil and in the different SOM fractions

The adoption of more intensive and diversified systems of pasture management resulted in an increase in stocks of C and N in the soil and in the different SOM fractions. In general, for each pasture management system, there was a reduction in soil C and N stocks with depth (Table 2). However, when comparing the layers (0–10, 10–20, 20–30, 30–40, 40-50, 50–60, 60-70, 70–80, 80-90 and 90-100 cm), the more intensive and diversified systems of pasture management showed greater soil C and N stocks than the CS. This effect can especially be seen in the 0-10, 20-30, 40-50 and 90-100 cm layers. The greater responses of the soil C and N stocks in these layers justify the assessment approach applied in this study to the 0-10 (Table 2), 0-30, 0-50 and 0-100 cm layers (Table 3); international initiatives also recommend examining these layers to inventory soil C and N stocks (IPCC, FAO and '4 per 1000' initiative).

Table 2. Soil C and N stocks (Mg ha^{-1}) in different systems of pasture management under tropical humid, tropical mesic and subtropical climate conditions.

Climatic condition	Management systems	Soil layers									
		0-10 cm	10-20 cm	20-30 cm	30-40 cm	40-50 cm	50-60 cm	60-70 cm	70-80 cm	80-90 cm	90-100 cm
						C stocks					
Tropical humid	CS	15.80±3.67b	11.14±3.52c	7.79±3.25c	6.95±2.12c	7.44±1.62b	7.72±1.98b	7.29±1.64b	6.53±1.50b	5.89±1.34b	0.98±0.15b
	FP	32.96±4.61a	28.69±1.63a	23.97±2.85a	19.88±1.09a	15.81±6.48a	15.40±1.96a	12.60±1.23a	10.26±1.20a	8.80±1.02a	1.58±0.19a
	ICL$_{MS}$	22.64±4.38b	20.18±6.50b	15.27±3.22b	11.99±2.33b	10.64±2.64b	8.84±1.99b	7.84±1.24b	7.29±0.90b	6.44±0.82b	1.74±1.39a
	ICL$_{RS}$	15.79±7.40b	14.57±5.71c	9.97±1.98c	9.66±4.14b	9.58±4.34b	6.87±2.40b	5.67±1.98b	3.91±2.04c	3.90±2.44b	0.67±0.41b
Topical mesic	CS	20.65±8.94a	27.76±9.71a	23.17±7.71a	16.30±1.59b	13.78±1.31b	11.43±1.41b	9.33±1.60b	9.69±1.71b	8.18±1.30b	7.63±1.27b
	ILF$_{RG}$	21.51±6.57a	32.02±11.09a	22.55±3.97a	17.50±1.70b	14.57±1.20b	12.03±0.94b	10.93±1.34a	10.59±1.72b	8.50±1.76b	8.56±1.33b
	ILF$_{NG}$	19.87±5.29a	33.75±5.33a	22.84±3.12a	19.74±1.96a	16.94±1.93a	14.53±1.78a	12.41±1.54a	12.60±1.58a	12.38±3.49a	10.82±1.50a
Subtropical	CS	16.43±3.76b	11.21±2.21a	11.62±2.02a	11.92±3.02a	11.82±1.77a	11.77±1.54a	11.78±2.05a	12.51±1.56a	10.27±2.15a	9.52±1.13a
	ICL$_{NG}$	11.09±3.12b	11.48±3.85a	9.16±2.56a	9.17±2.14a	8.52±2.41b	8.68±3.05b	9.35±2.24b	7.63±2.81b	6.42±1.75a	3.22±1.26b
	ICL$_{RM}$	16.54±4.47a	11.32±2.75a	10.80±1.37a	10.25±0.87a	8.70±0.40b	9.01±0.58b	9.14±1.58b	8.05±1.79b	6.82±1.98a	5.41±1.29b
	ICL$_{CM}$	19.53±2.31a	10.42±2.31a	10.56±2.94a	9.06±2.86a	9.27±0.32b	8.98±2.93b	7.99±0.64b	7.15±1.61b	4.76±2.18a	3.57±3.86b
	ICL$_{RL}$	16.59±4.51b	8.99±4.55a	10.55±4.92a	9.56±4.66a	10.17±1.56a	9.87±5.11b	7.78±0.77b	6.36±1.02b	5.28±1.33a	4.67±1.85b
	ICL$_{CL}$	16.74±1.18b	8.75±1.18a	9.98±3.91a	9.89±6.17a	7.87±1.80b	9.76±5.35b	7.60±1.80b	7.20±3.10b	6.21±3.55a	3.88±3.60b
						N stocks					
Tropical humid	CS	1.30±0.21b	1.10±0.32b	0.69±0.32c	0.69±0.16b	0.70±0.25b	0.74±0.21b	0.76±0.23b	0.59±0.18b	0.66±0.19a	0.12±0.03a
	FP	2.80±0.32a	2.57±0.12a	2.16±0.21a	1.69±0.22a	1.28±0.54a	1.27±0.18a	0.95±0.37a	0.90±0.23a	0.70±0.22a	0.13±0.04a
	ICL$_{MS}$	1.55±0.26b	1.43±0.57b	1.02±0.20b	0.79±0.25b	0.70±0.29b	0.57±0.27b	0.53±0.29b	0.51±0.17b	0.43±0.14b	0.12±0.11a
	ICL$_{RS}$	0.98±0.63b	0.80±0.35c	0.51±0.25c	0.60±0.24b	0.57±0.43b	0.58±0.32b	0.35±0.15b	0.24±0.16c	0.36±0.16b	0.05±0.14a
Topical mesic	CS	1.53±0.76a	1.94±0.77a	1.55±0.62a	1.04±0.22a	0.84±0.27a	0.68±0.18a	0.54±0.21a	0.64±0.21a	0.46±0.18a	0.47±0.19b
	ILF$_{RG}$	1.57±0.51a	2.30±0.76a	1.69±0.35a	1.32±0.33a	1.08±0.28a	0.88±0.21a	0.76±0.28a	0.75±0.24a	0.64±0.26a	0.61±0.17a
	ILF$_{NG}$	1.11±0.35a	1.87±0.47a	1.23±0.36b	1.11±0.18a	0.85±0.22a	0.74±0.15a	0.59±0.17a	0.55±0.12a	0.54±0.25a	0.42±0.19b
Subtropical	CS	1.39±0.40b	1.21±0.35a	1.27±0.22b	1.17±0.45a	0.83±0.27b	1.24±0.18a	1.09±0.65a	1.23±0.74a	1.18±0.52a	1.02±0.71a
	ICL$_{NG}$	1.38±0.35b	1.39±0.57a	1.15±0.43a	1.09±0.33a	0.75±0.62b	1.07±0.68a	1.08±0.52a	7.47±0.43	1.13±0.37a	0.66±0.49a
	ICL$_{RM}$	1.67±0.51a	1.09±0.34a	0.99±0.25a	0.97±0.05a	0.86±0.15a	0.81±0.08b	0.95±0.23a	0.92±0.22b	0.91±0.28a	0.76±0.16a
	ICL$_{CM}$	1.94±0.25a	1.04±0.25a	1.02±0.21a	0.94±0.21a	0.97±0.11a	0.92±0.17b	1.04±0.29a	1.01±0.11a	0.64±0.11a	0.55±0.47a
	ICL$_{RL}$	1.64±0.45a	0.96±0.44a	1.08±0.57a	0.99±0.68a	0.94±0.12a	1.07±0.77a	0.91±0.05a	0.88±0.13b	0.97±0.12a	0.72±0.11a
	ICL$_{CL}$	1.63±0.20a	1.02±0.20a	1.05±0.19a	1.02±0.34a	0.82±0.16b	1.23±0.45a	0.96±0.23a	0.93±0.10b	0.87±0.09a	0.67±0.08a

Unless indicated otherwise, data are the mean±s.e.m. (n = 9). Different lower-case letters mean significant differences in the same soil layers at the different treatments ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.

Table 3. Soil C and N stocks (Mg ha^{-1}) in different systems of pasture management for four soil layers (0-10, 0-30, 0-50 and 0-100 cm) under tropical humid, tropical mesic and subtropical climate conditions.

Climatic condition	Management systems	C stocks	N stocks	C stocks	N stocks	C stocks	N stocks
		0-30 cm		0-50 cm		0-100 cm	
Tropical humid	CS	34.74±9.21b	3.07±0.83b	49.14±11.06c	4.45±0.97b	77.54±15.52c	7.32±1.56b
	FP	85.62±7.70a	7.53±0.55a	121.31±10.97a	10.50±0.91a	169.96±14.01a	14.45±1.38a
	ICL$_{MS}$	58.08±12.07b	3.99±0.87b	80.72±16.25b	5.49±1.24b	112.87±20.09b	7.65±1.88b
	ICL$_{RS}$	40.34±11.83b	2.30±0.99c	59.58±19.28c	3.47±1.46c	80.60±25.73c	5.06±1.48c
Topical mesic	CS	71.59±13.07a	5.03±1.23b	101.66±14.72a	6.91±1.17b	147.94±18.73b	9.70±1.52b
	ILF$_{RG}$	76.08±9.80a	5.59±0.84a	108.15±11.64a	7.97±1.29a	158.76±14.75a	11.61±2.18a
	ILF$_{NG}$	76.46±8.49a	4.21±0.89b	113.14±10.79a	6.18±1.21b	175.87±16.46a	9.02±1.79b
Subtropical	CS	39.26±6.15a	3.87±0.95a	63.01±8.07a	5.88±1.54a	118.84±11.26a	11.64±1.11b
	ICL$_{NG}$	31.73±5.16a	3.92±0.79a	49.41±7.54a	5.76±1.47a	84.72±9.99b	17.19±0.85a
	ICL$_{RM}$	38.66±8.15a	3.76±1.05a	57.62±8.65a	5.59±1.15a	96.05±13.39a	9.96±1.85b
	ICL$_{CM}$	40.53±2.86a	4.01±0.21a	58.86±2.93a	5.89±0.18a	91.32±7.57b	10.04±0.91b
	ICL$_{RL}$	36.13±4.66a	3.67±0.69a	55.86±5.11a	5.60±0.77a	89.82±7.12b	10.16±0.78b
	ICL$_{CL}$	35.47±6.17a	3.71±0.34a	54.75±5.34a	5.73±0.45a	86.32±12.36b	9.82±0.86b

Unless indicated otherwise, data are the mean±s.e.m. (n = 9). Different lower-case letters mean significant differences in the same soil layers at the different treatments (p < 0.05). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.

Under a tropical humid climate, the adoption of FP gave an increase in soil C and N stocks in the 0-10, 0-30, 0-50 and 0-100 cm layers relative to the CS (Table 2 and Table 3), especially in the 0-100 cm layer, where increases were valued at 92 Mg ha^{-1} (>119%) and 7 Mg ha^{-1} (>97%), respectively. The conversion of the CS to FP also increased the C and N of the F4 SOM fraction (Tables 4 and 5) in each layer under evaluation (0-10, 40-50 and 90-100 cm), particularly in the 0-100 cm layer, where the increments were 74 Mg ha^{-1} (>92%) and 7 Mg ha^{-1} (>108%), respectively. The F4 fraction also showed the greatest relative contributions between the SOM fractions of FP (Fig. 2a). For FP, C and N stocks in this fraction represented 91% and 98%, respectively, while for the CS, the values were 76% and 91%, respectively.

Table 4. C stocks in different SOM fractions (Mg ha^{-1}) subjected to different systems of pasture management under each climatic condition.

Layers	Tropical humid					Tropical mesic					Subtropical				
		F1	F2	F3	F4		F1	F2	F3	F4		F1	F2	F3	F4
0-10 cm	CS	0.87±0.15a	1.35±0.14a	0.18±0.02a	10.87±0.30b	CS	0.37±0.04a	2.54±0.93a	0.15±0.08b	19.19±4.98b	CS	0.69±0.15b	1.06±0.66b	0.67±0.05a	12.00±0.81b
	FP	0.77±0.04a	0.87±0.02a	0.17±0.04a	22.50±0.42a	ILF$_{RG}$	0.44±0.07a	2.60±1.14a	0.30±0.05a	23.59±3.73a	ICL$_{NG}$	1.29±0.22a	2.24±0.25a	0.44±0.12a	11.64±1.05b
	ICL$_{MS}$	0.93±0.12a	1.15±0.07a	0.13±0.01a	15.44±0.85b	ILF$_{NG}$	0.43±0.06a	2.24±0.81a	0.23±0.16a	20.55±2.65b	ICL$_{RM}$	1.16±0.06a	1.57±0.66a	0.61±0.07a	12.56±1.11b
	ICL$_{RS}$	0.66±0.05a	3.32±0.96a	0.32±0.05a	11.81±0.75b						ICL$_{CM}$	1.44±0.21a	2.41±0.42a	0.83±0.14a	15.77±0.87a
											ICL$_{RL}$	1.04±0.11a	2.06±0.63a	0.65±0.18a	13.77±1.43b
											ICL$_{CL}$	1.20±0.13a	1.70±0.57a	0.80±0.18a	13.50±0.67b
40-50 cm															
	CS	0.50±0.06a	0.90±0.29b	0.07±0.02a	7.27±0.55b	CS	0.40±0.01a	0.93±0.20a	0.05±0.01a	14.02±0.96a	CS	0.18±0.03b	0.06±0.03b	0.18±0.01a	5.56±0.42b
	FP	0.26±0.02b	0.14±0.02b	0.05±0.01a	11.82±0.09a	ILF$_{RG}$	0.30±0.01a	0.74±0.19a	0.16±0.19a	12.82±0.92a	ICL$_{NG}$	0.36±0.04b	0.09±0.03b	0.17±0.05a	11.22±0.31a
	ICL$_{MS}$	0.55±0.03a	0.23±0.05b	0.03±0.01a	6.16±0.03b	ILF$_{NG}$	0.34±0.02a	0.50±0.08a	0.06±0.02a	15.74±2.08a	ICL$_{RM}$	0.44±0.06a	0.19±0.03a	0.16±0.07a	7.83±0.51a
	ICL$_{RS}$	0.60±0.08a	2.70±0.24a	0.16±0.01a	8.80±0.17b						ICL$_{CM}$	0.49±0.08a	0.09±0.11b	0.06±0.02a	8.44±0.32a
											ICL$_{RL}$	0.39±0.03a	0.10±0.03b	0.13±0.01a	9.61±0.27a
											ICL$_{CL}$	0.47±0.07a	0.13±0.06b	0.18±0.05a	9.87±0.62a
90-100 cm															
	CS	0.09±0.01a	0.14±0.02b	0.01±0.00a	0.84±0.04b	CS	0.39±0.19a	0.44±0.13a	0.04±0.01a	7.66±1.30a	CS	0.29±0.03a	0.01±0.01b	0.35±0.04a	6.16±1.35a
	FP	0.66±0.11a	0.37±0.07b	0.10±0.15a	5.94±0.10a	ILF$_{RG}$	0.27±0.07a	0.81±0.31a	0.06±0.01a	7.14±0.50a	ICL$_{NG}$	0.19±0.02a	0.02±0.02b	0.20±0.02a	3.91±1.06b
	ICL$_{MS}$	0.81±0.14a	0.16±0.05b	0.09±0.01a	4.56±0.14a	ILF$_{NG}$	0.32±0.04a	0.37±0.11a	0.07±0.00a	11.02±1.55a	ICL$_{RM}$	0.20±0.02a	0.03±0.03a	0.29±0.13a	4.58±0.75a
	ICL$_{RS}$	0.72±0.19a	1.11±0.08a	0.12±0.01a	4.69±0.16a						ICL$_{CM}$	0.18±0.01a	0.05±0.02a	0.15±0.01a	5.17±1.36a
											ICL$_{RL}$	0.21±0.02a	0.02±0.01b	0.22±0.02a	3.94±0.89b
											ICL$_{CL}$	0.16±0.01a	0.02±0.01b	0.19±0.03a	2.89±0.15b
0-100 cm															
	CS	6.31±0.88a	9.90±2.25b	1.20±0.32a	80.68±6.36b	CS	3.89±0.04a	14.89±2.73a	1.35±0.23a	154.53±16.71a	CS	5.24±0.17b	4.68±0.57b	3.41±0.33a	78.69±2.75b
	FP	5.07±0.31a	4.55±1.30b	1.02±0.08a	155.05±2.95a	ILF$_{RG}$	3.53±0.15a	13.71±2.47a	1.76±0.84a	165.64±7.76a	ICL$_{NG}$	6.74±039a	9.42±0.36a	2.92±0.26a	96.47±8.04a
	ICL$_{MS}$	7.25±0.47a	1.37±0.08b	0.28±0.04a	101.38±14.20b	ILF$_{NG}$	3.74±0.08a	13.04±0.81a	1.58±0.18a	171.90±5.30a	ICL$_{RM}$	6.99±0.56a	8.14±1.20a	3.30±0.39a	94.44±7.54a
	ICL$_{RS}$	6.34±0.30a	30.54±2.45a	2.16±1.34a	95.93±17.25b						ICL$_{CM}$	8.75±1.08a	10.35±0.99a	3.62±0.33a	105.06±3.61a
											ICL$_{RL}$	6.09±0.41a	8.39±1.03a	3.67±0.81a	109.25±6.45a
											ICL$_{CL}$	7.47±0.96a	8.02±1.86a	4.75±1.15a	107.52±3.23a

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). Different lower-case letters mean significant differences in the same soil layers at the different treatments ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.F1, organomineral fraction (75-2000 μm); F2, organic fraction (75-2000 μm); F3, organomineral fraction (53-75 μm); F4, organomineral fraction (<53 μm).

Table 5. N stocks in different SOM fractions (Mg ha^{-1}) subjected to different systems of pasture management under each climatic condition.

Layers	Tropical humid					Tropical mesic					Subtropical				
0-10 cm		F1	F2	F3	F4		F1	F2	F3	F4		F1	F2	F3	F4
	CS	0.00±0.00a*	0.04±0.01b	0.01±0.00a	0.95±0.05b	CS	0.00±0.00a*	0.09±0.05a	0.01±0.01b	1.09±0.45b	CS	0.28±0.01b	0.05±0.04b	0.05±0.00b	0.94±0.08b
	FP	0.00±0.00a	0.03±0.01b	0.00±0.00a	2.02±0.05a	ILF_{RG}	0.00±0.00a	0.07± 0.03a	0.02±0.04a	1.92±0.32a	ICL_{NG}	0.19±0.01b	0.10±0.01a	0.11±0.02a	2.50±0.11a
	ICL_{MS}	0.00±0.00a	0.05±0.00b	0.00±0.00a	1.18±0.06b	ILF_{NG}	0.00±0.00a	0.07± 0.05a	0.01±0.01b	1.39±0.21a	ICL_{RM}	0.34±0.02a	0.12±0.05a	0.06±0.01b	1.21±0.16b
	ICL_{RS}	0.00±0.00a	0.13±0.05a	0.01±0.00a	0.98±0.04b						ICL_{CM}	0.40±0.01a	0.18±0.03a	0.07±0.01b	1.31±0.09b
											ICL_{RL}	0.34±0.03a	0.16±0.05a	0.06±0.01b	1.26±0.14b
											ICL_{CL}	0.35±0.01a	0.11±0.04a	0.08±0.01b	1.27±0.08b
40-50 cm															
	CS	0.00±0.00a*	0.02±0.00b	0.00±0.00a*	0.50±0.02b	CS	0.00±0.00a*	0.01±0.01a	0.00±0.00a*	0.82±0.14a	CS	0.14±0.04b	0.00±0.00a	0.05±0.00a	1.02±0.04a
	FP	0.00±0.00a	0.01±0.00b	0.00±0.00a	1.05±0.05a	ILF_{RG}	0.00±0.00a	0.01±0.00a	0.00±0.00a	1.02±0.27a	ICL_{NG}	0.25±0.01a	0.00±0.00a	0.03±0.01a	0.98±0.05a
	ICL_{MS}	0.00±0.00a	0.02±0.00b	0.00±0.00a	0.52±0.04b	ILF_{NG}	0.00±0.00a	0.02±0.00a	0.00±0.00a	1.05±0.18a	ICL_{RM}	0.26±0.03a	0.00±0.00a	0.03±0.01a	0.85±0.08a
	ICL_{RS}	0.00±0.00a	0.07±0.01a	0.00±0.00a	0.78±0.05b						ICL_{CM}	0.28±0.02a	0.01±0.00a	0.02±0.02a	0.99±0.06a
											ICL_{RL}	0.23±0.02a	0.00±0.00a	0.03±0.00a	1.02±0.09a
											ICL_{CL}	0.22±0.03a	0.00±0.00a	0.03±0.01a	1.03±0.09a
90-100 cm															
	CS	0.00±0.00a*	0.00±0.00b	0.00±0.00a*	0.06±0.01b	CS	0.00±0.00a*	0.01±0.00a	0.00±0.00b	0.41±0.15a	CS	0.14±0.01a	0.00±0.00a*	0.07±0.01a	0.87±0.02a
	FP	0.00±0.00a	0.03±0.00b	0.00±0.00a	0.56±0.05a	ILF_{RG}	0.00±0.00a	0.03±0.02a	0.00±0.01a	0.44±0.16a	ICL_{NG}	0.16±0.02a	0.00±0.00a	0.06±0.02a	0.76±0.01a
	ICL_{MS}	0.00±0.00a	0.00±0.00b	0.00±0.00a	0.42±0.04a	ILF_{NG}	0.00±0.00a	0.01±0.00a	0.01±0.02a	0.59±0.14a	ICL_{RM}	0.14±0.01a	0.00±0.00a	0.08±0.03a	0.91±0.05a
	ICL_{RS}	0.00±0.00a	0.07±0.01a	0.00±0.00a	0.48±0.03a						ICL_{CM}	0.17±0.03a	0.00±0.00a	0.04±0.00a	0.94±0.05a
											ICL_{RL}	0.17±0.02a	0.00±0.00a	0.08±0.01a	0.88±0.11a
											ICL_{CL}	0.15±0.01a	0.00±0.00a	0.06±0.01a	0.92±0.04a
0-100 cm															
	CS	0.00±0.00a*	0.25±0.06b	0.05±0.03a	6.55±0.79b	CS	0.00±0.00a*	0.48±0.13a	0.01±0.01b	9.70±1.21a	CS	1.87±0.09b	0.31±0.08b	0.45±0.06a	9.51±0.12b
	FP	0.00±0.00a	0.14±0.03b	0.03±0.01a	13.65±0.46a	ILF_{RG}	0.00±0.00a	0.35±0.02a	0.02±0.02b	13.26±1.04a	ICL_{NG}	2.09±0.05a	0.60±0.04a	0.83±0.11a	15.49±1.32a
	ICL_{MS}	0.00±0.00a	0.23±0.01b	0.02±0.01a	7.33±0.98b	ILF_{NG}	0.00±0.00a	0.36±0.08a	0.09±0.01a	11.43±0.58a	ICL_{RM}	2.77±0.18a	0.59±0.23a	0.44±0.08a	10.52±1.19b
	ICL_{RS}	0.00±0.00a	1.20±0.19a	0.10±0.06a	8.16±0.82b						ICL_{CM}	3.20±0.12a	0.74±0.08a	0.42±0.04a	10.93±0.61b
											ICL_{RL}	2.74±0.12a	0.62±0.22a	0.49±0.08a	11.16±0.33b
											ICL_{CL}	2.62±0.54a	0.54±0.17a	0.56±0.09a	11.29±0.65b

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). Different lower-case letters mean significant differences in the same soil layers at the different treatments ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL_{MS}, integrated crop-livestock with maize/soybeans; ICL_{RS}, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF_{RG}, integrated livestock-forest with rotational grazing; ILF_{NG}, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL_{NG}, integrated crop-livestock with no grazing; ICL_{RM}, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL_{CM}, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL_{RL}, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL_{CL}, integrated crop-livestock with continuous stocking and low-intensity grazing.F1, organomineral fraction (75-2000 μm); F2, organic fraction (75-2000 μm); F3, organomineral fraction (53-75 μm); F4, organomineral fraction (<53 μm).*Below detection limit.

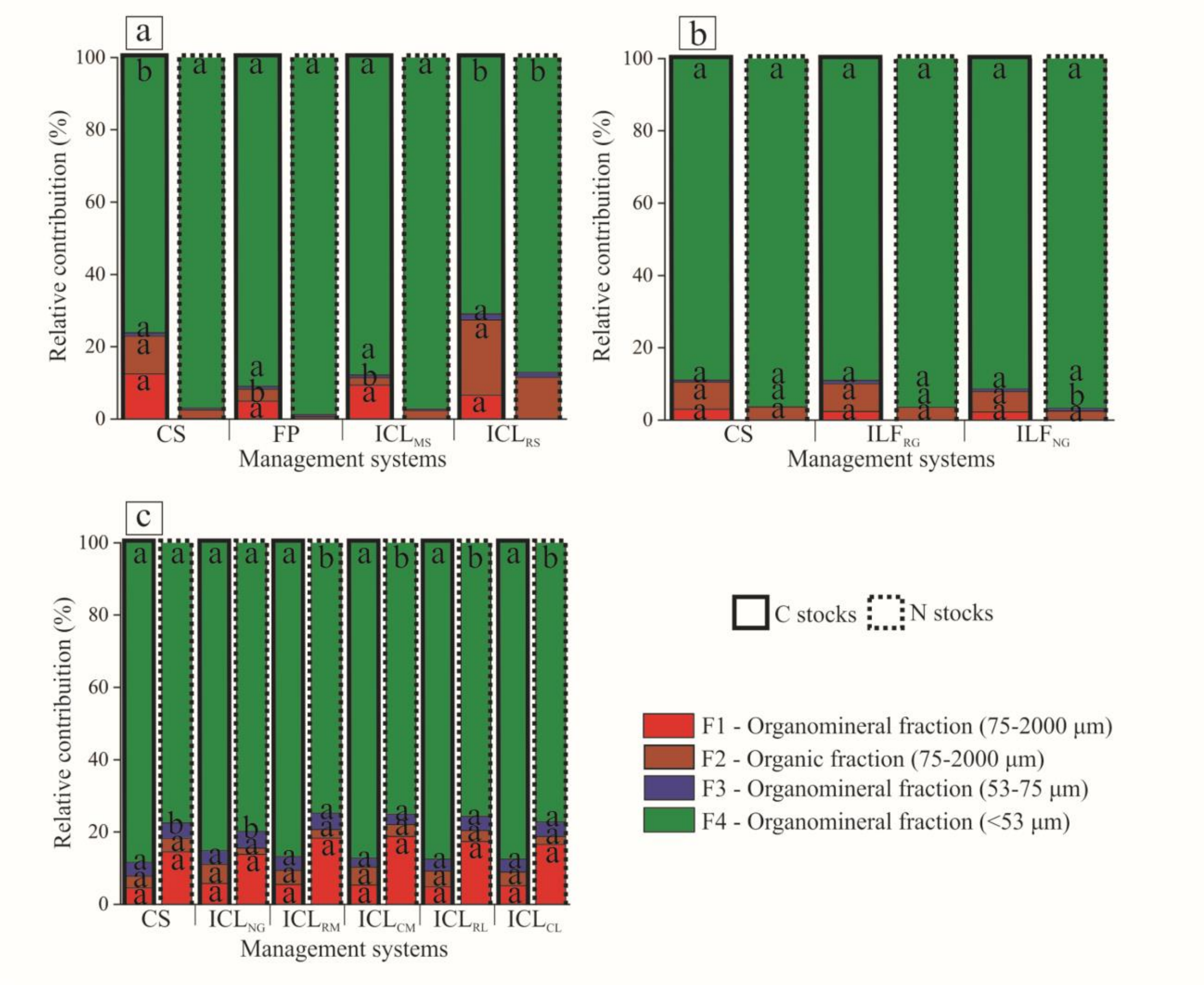


Figure 2. Relative contributions of different SOM fractions subjected to different systems of pasture management in the 0-100 cm layer under tropical humid (a), tropical mesic (b) and subtropical (c) climate conditions. Different lower-case letters mean significant differences in the same SOM fractions at the different treatments ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.

The conversion of the CS to ICL under a tropical humid and subtropical climate also afforded increases in stocks of C and N in the soil and in the different SOM fractions. ICL with maize/soybeans under the tropical humid climate showed the greatest increments relative to the CS, where the increase in the 0-100 cm layer reached 35 Mg ha^{-1} (>46%). Under the subtropical climate, the greatest effects were found in the 0-10 cm layer, where ICL with continuous stocking and moderate-intensity grazing presented the largest increase in soil C and N stocks relative to the CS of 3 Mg ha^{-1} (>19%) and 0.55 Mg ha^{-1} (>40%), respectively. For the SOM fractions, the greatest effects of the conversion of the CS to the ICL management systems under the tropical humid and subtropical climates were found for C and N of the F2 fraction (Tables 4 and 5). For the tropical humid and subtropical climates, respectively, the ICL with rice/soybeans and ICL with continuous stocking and moderate-intensity grazing showed average increases in C and N stocks of the F2 fraction of 13 Mg ha^{-1} (>165%) and 0.68 Mg ha^{-1} (>259%) in the 0-100 cm layer, respectively. The greater effects of these management systems on C and N of the F2 fraction can also be seen from the larger relative contributions of this fraction relative to the CS (Fig. 2a and 2c). On average, for ICL with rice/soybeans and ICL with continuous stocking and moderate-intensity grazing, the C and N stocks of the F2 fraction represented 13% and 8%, respectively, while for the CS, these values were 7% and 3%, respectively.

Under the tropical mesic climate with the adoption of the ILF management systems, the greatest effects on the stocks of soil C and N were found in the 0-100 cm layer (Table 3). For this layer, ILF with rotational grazing especially stands out, with this management system showing increases of 12 Mg ha^{-1} (>8%) and 2 Mg ha^{-1} (>20%), respectively, relative to the CS. ILF with rotational grazing also displayed the greatest increases in C and N in the SOM fractions, particularly in the 0-10 cm layer (Tables 4 and 5). The increases in this layer occurred in the F3 and F4 fractions, where the respective values were 15 Mg ha^{-1} (>100%) and 4 Mg ha^{-1} (>23%) for C and 0.01 Mg ha^{-1} (>100%) and 0.83 Mg ha^{-1} (>76%) for N. The relative contributions of these fractions (F3 and F4) to the C and N stocks under ILF with rotational grazing were 0.89% and 89% for C and 0.65% and 97% for N, respectively (Supplementary Fig. S1d). For the CS, these values were 0.54% and 81% for C and 0.04% and 85% for N, respectively.

2.3.2. Principal component analysis of stocks of C and N in the soil and in the different SOM fractions

From a principal component analysis (PCA), it was possible to determine the relationship between stocks of C and N in the soil and in the different SOM fractions for each climate condition. The PCA also helped us understand the mechanisms of C and N accumulation affecting different soil pools with the conversion of the CS to more intensive and diversified systems of pasture management. For FP under the tropical humid climate, as seen in the 0-100 cm layer (Fig. 3a and 3b) and the 0-10, 40-50 and 90-100 cm layers (Supplementary Figs. S2a-S2c), there was a close relationship between this management system and soil C and N and the C and N of the F4 SOM fraction.

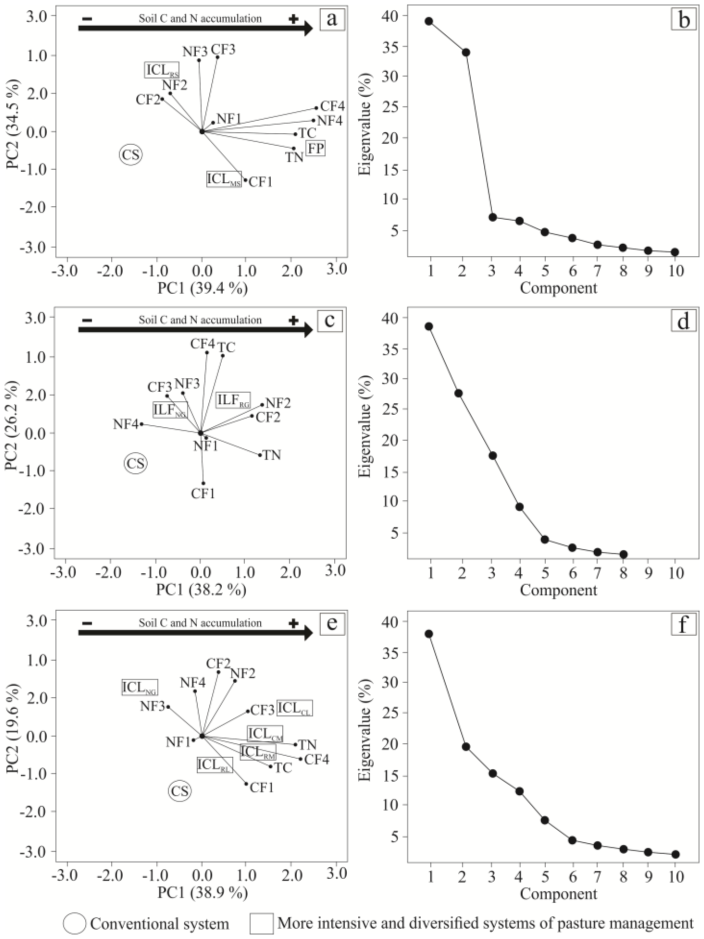


Figure 3. Principal component analysis (PCA) applied to the different systems of pasture management in the 0-100 cm layer under tropical humid (a and b), tropical mesic (c and d) and subtropical (e and f) climate conditions. Tropical humid: CS, conventional system; FP, fertilized pasture; ICL_{MS}, integrated crop-livestock with maize/soybeans; ICL_{RS}, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF_{RG}, integrated livestock-forest with rotational grazing; ILF_{NG}, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL_{NG}, integrated crop-livestock with no grazing; ICL_{RM}, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL_{CM}, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL_{RL}, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL_{CL}, integrated crop-livestock with continuous stocking and low-intensity grazing. TC, total soil C; TN, total soil N; CF1, C of the F1 fraction of SOM; NF1, N of the F1 fraction of SOM; CF2, C of the F2 fraction of SOM; NF2, N of the F2 fraction of SOM; CF3, C of the F3 fraction of SOM; NF3, N of the F3 fraction of SOM; CF4, C of the F4 fraction of SOM; NF4, N of the F4 fraction of SOM.

Under tropical humid and subtropical conditions, the ICL management systems were closely related, mainly due to C and N in the soil and in the F2, F3 and F4 SOM fractions (Fig. 3a and 3e). For the tropical humid climate, ICL with rice/soybeans established a particular relationship with C and N of the F2 fraction in the 0-100 cm layer (Fig. 3a and 3b) and in the 0-10, 40-50 and 90-100 cm layers (Supplementary Figs. S2a-S2c). However, for ICL with maize/soybeans, a relationship was only found with C of the F1 fraction in the 0-100 cm and 0-10 cm layers. For the subtropical climate, an important relationship was found between ICL with rotational stocking and moderate-intensity grazing and ICL with continuous stocking and moderate-intensity grazing and soil C and N and with C from the F3 and F4 fractions in the 0-100 cm layer (Fig. 3e and 3f) and in the 0-10 and 90-100 cm layers (Supplementary Figs. S2g and S2i).

For the ILF management systems under tropical mesic conditions, the relationship between ILF with rotational grazing and C and N of the F2 fraction in the 0-100 cm layer (Fig. 3c and 3d) and in the 0-10, 40-50 and 90-100 cm layers (Supplementary Figs. S2d-S2f) is noteworthy. A relationship was found between ILF with no grazing and C and N of the F3 fraction in the 0-100 cm layer and in the 0-10, 40-50 and 90-100 cm layers.

2.3.3. Soil-carbon management indices

In general, the C lability (LI), pool (CPI) and management (CMI) indices under more intensive and diversified systems of pasture management were higher than those found under the CS and were sensitive to changes in the management system under the different climate conditions. For these indices (LI, CPI and CMI), FP presented superior values to those of the CS for almost all of the layers under evaluation (Supplementary Figs. S3a-S3c and S4a-S4c). In the 0-100 cm layer, the indices were 250% (Fig. 4a), 94% (Fig. 4b) and 86% (Fig. 4c) higher than those of the CS, respectively.

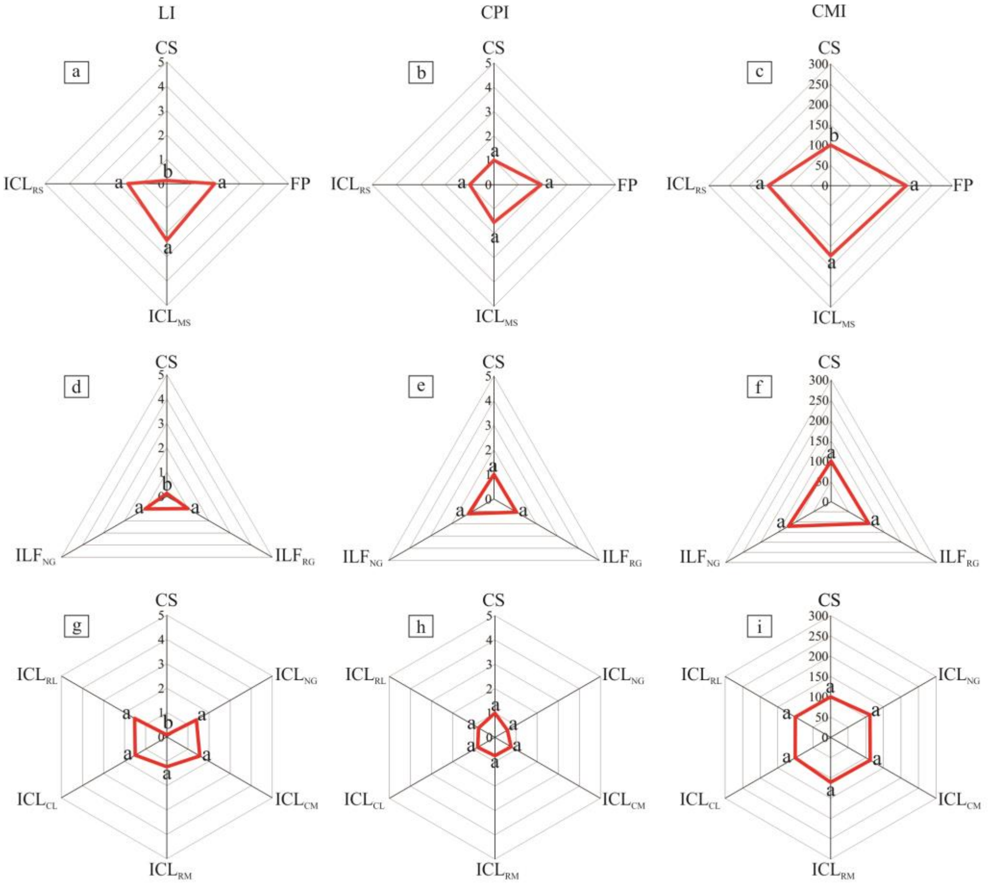


Figure 4. Carbon lability (LI), pool (CPI) and management (CMI) indices in different systems of pasture management in the 0-100 cm layer under tropical humid (a, b and c), tropical mesic (d, e and f) and subtropical (g, h and i) climate conditions. Different lower-case letters mean significant differences in the same soil C management indices at the different treatments ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL_{MS}, integrated crop-livestock with maize/soybeans; ICL_{RS}, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF_{RG}, integrated livestock-forest with rotational grazing; ILF_{NG}, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL_{NG}, integrated crop-livestock with no grazing; ICL_{RM}, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL_{CM}, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL_{RL}, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL_{CL}, integrated crop-livestock with continuous stocking and low-intensity grazing.

LI, CPI and CMI were also higher than CS for the ICL management systems under tropical humid and subtropical climate conditions. Under the tropical humid climate, ICL with maize/soybeans gave the best results for these management indices, particularly in the 0-100 cm layer. Under this management system, the results for LI, CPI and CMI were 396% (Fig. 4a), 54% (Fig. 4b) and 73% (Fig. 4c) higher, respectively, than those of the CS. For the subtropical climate, the CPI was no higher under the ICL management systems than under the CS in the 40-50 (Supplementary Fig. S3h), 90-100 (Supplementary Fig. S3i) and 0-100 cm (Fig. 4h) layers. However, IL and CMI showed higher indices than those of the CS. ICL with continuous stocking and moderate-intensity grazing showed the highest indices for the 0-100 cm layer, with respective values 156% (Fig. 4g) and 13% (Fig. 4i) greater than those under of the CS.

The ILF management systems under the tropical mesic climate also showed higher values for LI, CPI and CMI than the CS for each layer under evaluation (Supplementary Figs. S3d-S3f and S4d-S4f). The values of these indices in the 0-100 cm layer were similar under ILF with rotational grazing and ILF with no grazing. The average values were 96% (Fig. 4d), 14% (Fig. 4e) and 15% (Fig. 4f) higher than those under the CS, respectively.

2.3.4. Conversion factors and rates of change in soil carbon stock

The effect of converting the CS into more intensive and diversified systems of pasture management generally had a positive effect on the rate of soil carbon change and the conversion factor under the different climate conditions. The conversion of the CS to FP contributed to an increase in the rate of soil carbon change and in the conversion factor in all layers (0-10, 0-30, 0-50 and 0-100 cm) with an average increases for the 0-100 cm layer recorded at 2 Mg ha^{-1} yr^{-1} (Fig. 5a) and 1.45 (Fig. 5b), respectively.

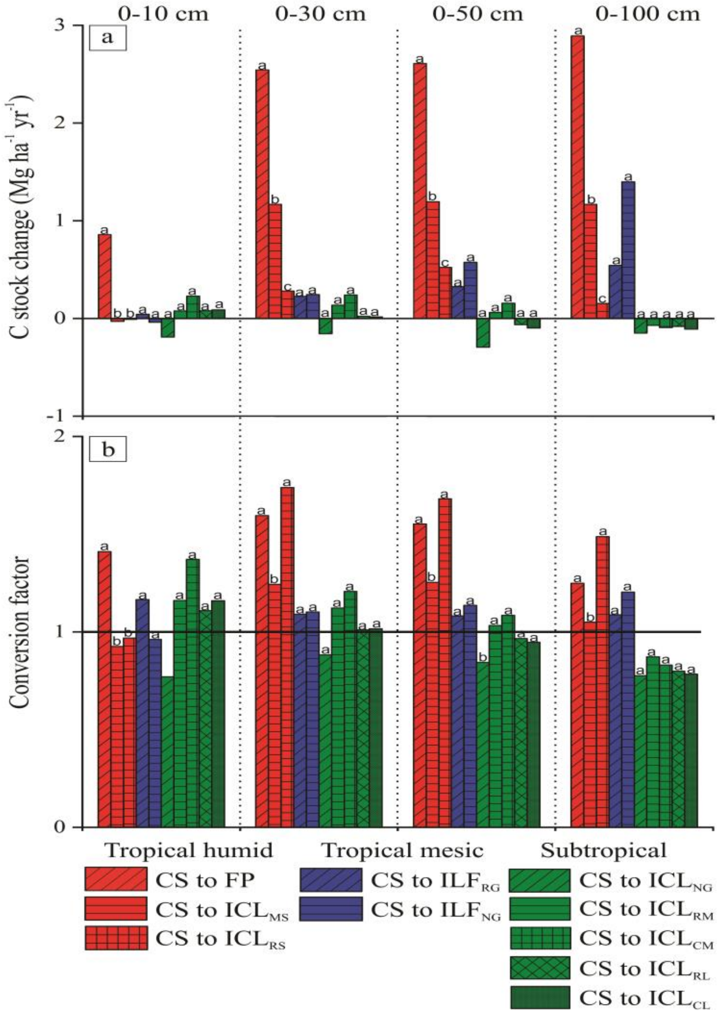


Figure 5. Rate of soil carbon change (a) and conversion factor (b) associated with the conversion from conventional system to more intensive and diversified systems of pasture management for four soil layers (0-10,0-30, 0-50 and 0-100 cm) under the different climatic conditions (tropical humid, tropical mesic and subtropical). The baseline is the soil C stocks in CS. Different lower-case letters mean significant differences in the same soil layers at the different treatments ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{\text{MS}}$, integrated crop-livestock with maize/soybeans; ICL$_{\text{RS}}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{\text{RG}}$, integrated livestock-forest with rotational grazing; ILF$_{\text{NG}}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{\text{NG}}$, integrated crop-livestock with no grazing; ICL$_{\text{RM}}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{\text{CM}}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{\text{RL}}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{\text{CL}}$, integrated crop-livestock with continuous stocking and low-intensity grazing.

There was also an increase in the rate of soil carbon change and in the conversion factor for almost all of the layers under evaluation when converting the CS to the ICL management systems under a tropical humid and subtropical climate. Under the tropical humid climate, in converting the CS to ICL with rice/soybeans and to ICL with maize/soybeans, the greatest effects on the rate of soil carbon change and on the conversion factor were seen in the 0-30, 0-50 and 0-100 cm layers, where for the 0-100 cm layer, these management systems presented average increases of 0.75 Mg ha^{-1} yr^{-1} (Fig. 5a) and 1.41 (Fig. 5b), respectively. In converting the CS to the ICL management systems under a subtropical climate, the greatest effects on the rate of soil carbon change and on the conversion factor were seen in the 0-10, 0-30 and 0-50 cm layers. However, when the 0-100 cm layer is considered, ICL with rotational stocking and moderate-intensity grazing and ICL with continuous stocking and moderate-intensity grazing stand out with respective average increases of 0.15 Mg ha^{-1} yr^{-1} (Fig. 5a) and 1.16 (Fig. 5b), respectively.

There was an increase in the rate of soil carbon change and in the conversion factor when converting the CS to the ILF management systems under a tropical mesic climate, especially in the 0-30, 0-50 and 0-100 cm layers. For the 0-100 cm layer, the conversion of the CS to ILF with rotational grazing and ILF with no grazing showed average increases of 0.55 Mg ha^{-1} yr^{-1} (Fig. 5a) and 1.12 (Fig. 5b), respectively.

2.4. Discussion

2.4.1. Effect of adopting more intensive and diversified systems of pasture management on C and N stocks in the soil and in different SOM fractions

In general, soil C and N stocks decreased significantly with depth under each system of pasture management (Table 2). For Ngaba et al. (2020), this effect is due to the topsoil being more biologically active and to the greater contributions of roots relative to the subsoil. The same authors report that understanding the effect of depth on soil C and N stocks is important, as it influences mechanisms of soil sequestration. Indeed, in this study, the greatest effects of the more intensive and diversified systems of pasture management on soil C and N stocks relative to the CS were found in the 0-10, 20-30, 40-50 and 90-100 cm layers. Segnini et al. (2019) found similar results for these layers when evaluating the intensification of pastureland in relation to a CS. According to Mello et al. (2014), the evaluation of soil C balance in the 0-30 cm, 0-50 cm and 0-100 cm layers is suitable to provide more complete information on the effects of land use change in Brazil. To assess the efficiency of pasture management systems for storing C and N, it is therefore recommended that evaluations be carried out to a depth of at least 1 m. For these and other reasons (see Sections 2.4 and 3.1), the 0-10, 0-30, 0-50 and 0-100 cm layers were considered in the present study in evaluating differences in C and N stocks resulting from the adoption of more intensive and diversified systems of pasture management.

The adoption of FP, relative to the adoption of a CS, under tropical humid conditions increased soil C and N stocks in the 0-10, 0-30, 0-50 and 0-100 cm layers (Tables 2 and 3). This result shows that applying mineral fertilizers is an important alternative means of increasing the soil C and N stocks of pastures under a CS in such conditions. Mineral fertilizers mainly provide nutrients such as N, P, and Ca through the application of limestone; in weathered soils, such as the soils found under these climate conditions, these nutrients are naturally deficient (Damian et al., 2020). Improving soil fertility affords greater inputs of C and N via plant biomass due to improvements in the productive environment of the soil under pasture (Chan et al., 2010) and to an increase in root biomass (C and N uptake by roots) (Coonan et al., 2019). In addition, Chen et al. (2018) found that the application of N reduces the activity of lignin-modifying enzymes, increasing recalcitrant soil C that acts to protect the most stable C from degradation. The observed increased accumulation of C and N in the soil under FP can be explained by increases in the stocks (Tables 4 and 5) and relative contributions (Fig. 2a) of C and N in the F4 SOM fraction within each layer of soil. The F4 fraction is related to the greater stability of C and N due to mineral-SOM interactions occurring in the soil microaggregates (Li et al., 2017; Roscoe et al., 2001).

For the ICL management systems under tropical humid and subtropical conditions, the adoption of these management systems was efficient in increasing soil C and N stocks, especially under ICL with maize/soybeans (tropical humid) and ICL with continuous stocking and moderate-intensity grazing (subtropical) (Table 3). This result corroborates the results of other studies showing that ICL management systems, due to the presence of various crops together with an animal component, increase the amount and quality of biomass above and below ground, contributing to increases in soil C and N stocks (Assmann et al., 2015; Carvalho et al., 2010; Salton et al., 2014). This effect can be seen from the increase (Tables 4 and 5) and relative contributions (Figs. 2a and 2c) of C and N stocks in the F2 SOM fraction under ICL with rice/soybeans (tropical humid) and ICL with continuous stocking and moderate-intensity grazing (subtropical), since this fraction includes the least-transformed plant residue in the soil. For ICL with rice/soybeans, the effect can be attributed to the greater resilience of SOM, which is a result of planting rice and soybeans in succession (Brar et al., 2013). For ICL with continuous stocking and moderate-intensity grazing, the results show that this management system improves the efficiency of animal contributions, favouring the SOM fractions responsible for supplying energy to soil microorganisms (F2) and for C and N cycling in the soil (Matsuoka et al., 2003; Brandani et al., 2017).

Under the conditions of a tropical mesic climate, the ILF management systems also showed positive results, such as an increase in C and N in the soil and in the different SOM fractions. ILF with rotational grazing had the highest stocks of soil C and N in the 0-100 cm layer (Table 3). This can be attributed to the tree-like component, which, despite the short period since planting, contributed to an increase in C and N stocks, mainly due to the capture of more resources, such as solar radiation and water (Upson et al., 2016). Another important factor is the animal component, where the input of urine and manure results in the continuous recycling of C and N over time (Liu et al., 2011). ILF with rotational grazing also showed the largest increase (Tables 4 and 5) and relative contributions (Supplementary Fig. S1d) of C and N stocks in the F3 and F4 SOM fractions of the 0-10 cm layer. These results show that the combination of animal waste and tree litter favours an increase in the soil C fractions in the intermediate recalcitrant phase (F3) and in the more recalcitrant fractions (F4) (Fontaine et al., 2007).

Among the main effects of changes in soil C occurring with the adoption of management systems with FP, ICL and ILF, we highlight the potential for a reduction in the decomposition of SOM. For Reay et al. (2008), the reduction of microbial decomposition is a key process in increasing soil C stocks. In this sense, Carvalho et al. (2010) reinforced the high capacity of more intensive and diversified systems of pasture management to accumulate C in deeper soil layers through the accretion and deposition of degradation-resistant organic material. However, further large-scale studies should be carried out to understand the biochemical processes involved in the long-term stability of soil C under these management systems.

In general terms, it should be noted that the data show that the more weathered soils are (tropical humid > tropical mesic > subtropical), the greater the stocks of C and N in the various SOM fractions will be and the greater relative contributions of C and N in the silt- and clay-related fractions will become (e.g., F3 and F4). This reaffirms the need for studies conducted under different climate conditions and with different soil classes to establish more intensive and diversified systems of pasture management, particularly due to the great heterogeneity of the soil and climate in Brazil. The results also confirm the assertions of Lehmann and Kleber (2015), who emphasize the importance of further study on the interactions of SOM with minerals in the soil to understand their dynamics in different ecosystems.

Recently, Lavallee et al. (2020) proposed a conceptual method based on mineral-SOM interactions [particulate organic matter (POM) and mineral-associated organic matter (MAOM)] to understand the formation, persistence, and functions of SOM. The authors found that according to the microbial efficiency-matrix stabilization hypothesis, lower-quality plant inputs should favour the formation of POM, while higher-quality plant inputs should result in greater MAOM formation. In the present case, as the POM (the F1 and F2 fractions in this study) is controlled by microbial and enzymatic inhibition, it has less persistence in the soil than the MAOM (the F3 and F4 fractions in this study); MAOM persistence is controlled by interactions with the soil mineral matrix. Despite not being evaluated in this study, the higher quality and greater quantity of animal and plant inputs resulting from the adoption of more intensive and diversified systems of pasture management modify the mechanisms that regulate the stocks and persistence of soil C.

2.4.2. Relating stocks of C and N in the soil to the different SOM fractions for systems of pasture management under different climatic conditions

From the relationship between stocks of C and N in the soil and the different SOM fractions obtained from the PCA under the various systems of pasture management, no relationship could be found for these attributes in the CS for any of the climate conditions under evaluation (tropical humid, tropical mesic or subtropical) (Fig. 3a, 3c and 3e). Accordingly, it can be concluded that in a CS, dynamic processes of SOM and of C and N accumulation in the various compartments are relatively slow. Furthermore, a CS is highly dependent on inputs of C and N from the biomass of the grass used (de Moraes Sá et al., 2018).

For the more intensive and diversified systems of pasture management such as FP (tropical humid), ICL (tropical humid and subtropical) and ILF (tropical mesic), the results of the PCA corroborate those shown in Section 4.1. In this case, the adoption of these management systems increases stocks of C and N in the soil and in the different SOM fractions in relative to the CS. The intensification and diversification of areas of pasture under the CS through fertilization and the correction of soil acidity (liming), in addition to the greater diversity of plants with different root systems, favour greater C and N cycling and accumulation in the soil (Tracy and Zhang, 2008; Chávez et al., 2011; Tivet et al., 2013). These properties are confirmed by the stronger relationship found between the more intensive and diversified systems of pasture management and the C and N of the SOM fractions influenced by continuous inputs of plant biomass (F1 and F2 fractions). Lin et al. (2020), in evaluating the period of pasture rotation, found the percentage increase in coarse fractions (F1 and F2 fractions) to be three times that of finer fractions (F3 and F4 fractions) from pasture years 1 to 5.

2.4.3. Soil C management indices under more intensive and diversified systems of pasture management

The indicators of C management, i.e., the lability (LI), pool (CPI) and management (CMI) indices, were sensitive in showing changes in systems of pasture management under the different climate conditions (Fig. 4; Supplementary Fig. S3 and S4). This corroborates the results of Oliveira et al. (2017), who report that the methodology used to calculate the indicators of C management through the physical fractionation of SOM described by Diekow et al. (2005) is the most effective in describing management changes in tropical and subtropical regions. In addition, it should be noted that among these indices, the CMI in particular allows gains or losses in soil quality to be assessed in terms of the increase in C that occurs with a change in management systems.

For FP under the tropical humid climate, for each index under evaluation (LI, CPI and CMI), this management system was superior to the CS, where the average increase was 140% (Fig. 4a-4c). The increase in these indices observed relative to the CS suggests that the increase in grass biomass (Brachiaria) above and below ground is the result of mineral fertilization. LI and CMI in particular are highly dependent on the continuous input of C via plant biomass (Rumpel & Kögel-Knabner, 2011). It should also be noted that the addition of nutrients such as N may heavily influence the physiological pathways of C. In this case, soluble forms of C may also be related to increases in LI and CMI under FP relative to those under a CS (Duval et al., 2016).

The ICL management systems under a tropical humid and subtropical climate showed the greatest increases in LI and CMI relative to the CS. These increases were 145% (Fig. 4a and 4 g) and 43% (Fig. 4c and 4i), respectively, in the 0-100 cm layer. Among the ICL management systems evaluated under the tropical humid climate, ICL with maize/soybeans showed the greatest increases in LI and CMI. According to Loss et al. (2013), a mixture of soybeans+maize+grass (brachiaria)+animal waste slows SOM decomposition. This process increases the amount and resilience of the labile SOM fractions (F1 and F2), which are the fractions with the most influence on LI and CMI. Under the subtropical climate, ICL with continuous stocking and moderate-intensity grazing showed the greatest increases in LI and CMI. Assmann et al. (2014) and Silva et al. (2014), in studies of different grazing intensities under a subtropical climate, found higher respective values of 43% and 22% for LI and of 60% and 27% for CMI under moderate grazing intensities relative to intensive grazing. In addition, the system of continuous animal management adopted in the area may have contributed to the increase in these indices, particularly due to higher inputs of animal waste. Animal waste is associated with enzymes (e.g., β-glucosidase, proteases and alkaline phosphatase) directly or indirectly responsible for SOM dynamics and with the accumulation of C in labile form in the soil (Alef et al., 1995; Nunan et al., 2006).

Under the tropical mesic climate, despite the short period since implementation, the ILF management systems contributed significantly to increases in LI, CPI and CMI relative to the CS (Fig. 4d-4f). These results corroborate studies that indicate that such effects are mainly due to ILF increasing the annual addition of C (Barreto et al., 2014; Ramesh et al., 2015). Moreover, these management systems modify the quality of SOM (e.g., the C/N ratio and lignin, cellulose, hemicellulose, protein and carbohydrate content) and, consequently, the activity of soil microorganisms and rates of SOM decomposition (Matos et al. 2020). Sharrow and Ismail (2004) also highlight the importance of the animal component and of litter added to the soil under ILF. The authors report that under this management system, 45 kg ha^{-1} of N is deposited by animal urine and approximately 95 kg ha^{-1} of is deposited C by litter, favouring the rapid conversion of organic residue into labile C fractions and recalcitrant forms of C in the soil. Furthermore, Leite et al. (2014), from studies of different ILF management systems, found respective values for LI, CPI and CMI of 0.79, 1.26 and 108. These results are similar to those given in this work, presenting average values for ILF with no grazing and ILF with rotational grazing of 1.02 (Fig. 4d), 1.14 (Fig. 4e) and 114 (Fig. 4f), respectively.

2.4.4. Temporal assessment of C stocks with the adoption of more intensive and diversified systems of pasture management

Converting the CS to FP under a tropical humid climate gave average increases of 2 Mg ha^{-1} yr^{-1} (Fig. 5a) and 45% (Fig. 5b) in the rate of soil carbon change and conversion factor, respectively, within the 0-100 cm layer. Braz et al. (2013), in studies on management intensification in areas of degraded pasture in Brazil, found increases in the rate of soil carbon change of 0.25 to 2.95 Mg ha^{-1} yr^{-1}. The authors note that this large variation must be mainly due to differences in soil texture; for this study, clay content was the highest among the three study areas (on average, 59% higher). In this case, it should be noted that soil texture is an important parameter for evaluating increases in the rate of soil carbon change in areas of pasture (Carvalho et al., 2010).

In the conversion of the CS to the ICL management systems under the conditions of a tropical humid and subtropical climate, increases were seen in the rate of soil carbon change and the conversion factor. In the 0-100 cm layer, the average increases were 0.75 and 0.15 Mg ha^{-1} yr^{-1} (Fig. 5a) and 41% and 16% (Fig. 5b), respectively. Despite mainly ICL with rice/soybeans and ICL with maize/soybeans under the tropical humid climate and ICL with rotational stocking and moderate-intensity grazing and ICL with continuous stocking and moderate-intensity grazing under the subtropical climate showing an increase in the rate of soil carbon change and the conversion factor, the ICL management systems under the tropical humid climate had higher values for these parameters than under the subtropical climate. This result may be associated with higher clay content levels found under a tropical humid climate, which are 67% greater than those found under a subtropical climate. In addition, the time necessary for establishment and adaptability to soil, climate and grassy conditions found in the Pampa biome (Paspalum notatum Flügge) favours greater soil C stocks with more stability relative to the ICL management systems (Franzluebbers et al., 2014; Vargas et al., 2015). The results found by Salton et al. (2014) under a tropical humid climate and by Cecagno et al. (2018) under a subtropical climate corroborate those of this study. These authors found values for the rate of soil carbon change of 0.44 and 0.23 Mg ha^{-1} yr^{-1}, respectively.

Under the conditions of a tropical mesic climate, the conversion of the CS to the ILF systems increased the rate of soil carbon change and the conversion factor. On average, for ILF with rotational grazing and ILF with no grazing in the 0-100 cm layer, these increases were 0.55 Mg ha^{-1} yr^{-1} (Fig. 5a) and 12% (Fig. 5b), respectively. Despite the short period since implantation, the observed rates of soil carbon change are consistent with estimates for converting a CS to ILF, which range from approximately 0.10 to 4 Mg ha^{-1} yr^{-1} (Batjes, 2004; Thangata and Hildebrand, 2012). Chatterjee et al. (2018), in evaluating the contribution of ILF systems to increases in the rate of soil carbon change, concluded that this management system increases rates of C stock by an average of 26% under tropical conditions relative to pasture alone. Furthermore, the authors agree with the results found in this study, especially regarding the benefits of animal and forest components in increasing the C stock in areas of pasture.

Although the results found under the different climate conditions show that more intensive and diversified systems of pasture management are efficient in accumulating soil C, a constant monitoring of soil C stocks is recommended. For Toru and Kibret Raul (2019), it is essential to monitor soil C stocks, as each management system has either a positive or negative impact on the carbon balance. Prediction models (e.g., Century and DayCent) can be used for this purpose, and conducted studies in Brazil have already shown satisfactory results for monitoring soil C stocks due to changes in management systems (Cerri et al., 2003; Oliveira et al., 2017b).

Several studies have found an increase in C stocks with the intensification and diversification of pastureland, but there are still uncertainties surrounding the rate of soil C change over time (Paustian et al., 2016, Olson et al., 2017). In this respect, the temporal dynamics of SOM and C and N cycling must be properly recognized for a more comprehensive analysis. For Stanley et al. (2018), the rate of soil C sequestration is directly linked to land potential and the productivity of both pasture and cattle and to the quality of the management system. For these authors, evaluations that take into account the spatial and temporal scales are essential for more accurately estimating the effects of management systems on C sequestration rates. Similarly, the Intergovernmental Panel on Climate Change (IPCC) assumes that C stocks only stabilise to a new steady state 20 years after all changes in management are made (IPCC 2006). Therefore, using the rate of soil carbon change found in this study would be significant only for the specific period of data collection (2003-2018).

With this study, we contribute information that can expand the adoption of more sustainable management systems in pastures in Brazil. According to Silva et al. (2017), the improved management of degraded pastures has a potential role in SOC sequestration, potentially reducing the emissions intensity of stocking and finishing systems. On the other hand, Batista et al. (2019) reported that the restoration of pastures on a large scale may not be sufficient to increase soil C stocks and reduce GHG emissions and thus that Brazil should seek more diversified strategies for pasture intensification. In this case, the systems of pasture management evaluated in this study (FP, ICL and ILF) show great potential as sustainable production alternatives and as soil C sinks.

2.5. Conclusions

The adoption of more intensive and diversified systems of pasture management has led to significant changes in C and N stocks under different soil and climate conditions. Overall, the adoption of ICL systems, compared to an CS, was found to increase the rate of soil carbon change by 0.75 Mg ha^{-1} yr^{-1} under a tropical humid climate and by

0.15 Mg ha^{-1} yr^{-1} under a subtropical climate. Likewise, for ILF systems under a tropical mesic climate and for FP under a tropical humid climate, the rates of increase in soil carbon stocks were 0.55 and 2 Mg ha^{-1} yr^{-1}, respectively. Management systems under ICL, FP and ILF provide greater inputs of plant biomass, and this effect generated an increase in C stock mainly in the F1 (organomineral-75-2000 μm) and F2 (organic-75-2000 μm) fractions of SOM with a consequent increase in soil lability and carbon management indices. In addition, for the purpose of SOM monitoring with the replacement of areas of conventional pasture by more intensive and diversified systems of pasture management, measurements taking into account only superficial soil layers may increase bias in results. It is therefore necessary to evaluate the soil C balance at a depth of at least 1 m when changing a pasture management system.

The results of the present study offer basic information for decision-making surrounding public policies and programmes of the federal government aimed at reducing greenhouse gases in the atmosphere and soil degradation (e.g., Brazil's NDC and ABC programme). Moreover, as Brazil has signed the Paris Agreement, it must reduce its greenhouse gas emissions by 37% by 2025 and by 43% by 2030. According to our results and considering the studied areas of conventional pasture under tropical humid (Mato Grosso = 1.60 Mha), tropical mesic (São Paulo = 0.10 Mha) and subtropical (Rio Grande do Sul = 0.09 Mha) climates in Brazil (IBGE, 2017), we project soil sequestration levels of 118, 99 and 2 Tg CO_2 from the adoption of the FP, ICL and ILF management systems, respectively. Together, these values make up 51% of total emissions from the Brazilian agricultural sector (429 Tg CO_2) registered in 2015 (BRASIL, 2017). However, we emphasize that these results are restricted to the specific period of data collection (2003-2018). Other studies should be carried out to help improve these estimates, especially taking into account greenhouse gas emissions (e.g., CH_4 and N_2O) resulting from the intensification and diversification of pasture areas in Brazil. Thus, the information described in the present study can help governmental institutions made investments to mitigate such emissions, particularly through projects focused on implementing integrated production systems in areas of conventional pasture based on different soil and climate conditions.

References

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G. de A., Kunrath, T.R., Bayer, C., Carvalho, P.C. de F., Franzluebbers, A.J., 2015. Carbon and nitrogen cycling in an integrated soybean-beef cattle production system under different grazing intensities. Pesq. agropec. bras. 50, 967–978.

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G.A., Cecagno, D., Carlos, F.S., Carvalho, P.C.F., 2014. Soil carbon and nitrogen stocks and fractions in a long-term integrated crop–livestock system under no-tillage in southern Brazil. Agr. Ecosyst. Environ. 190, 52-59.

Alef, K., Nannipieri, P., Trazar-Cepeda, C., 1995. Phosphatase activ- ity. In Methods in Applied Soil Microbiology and Biochemistry. Eds. Alef, K., Nannipieri, P. pp 335-344. Academic Press, London.

Barreto, P.A.B., Gama-Rodrigues, E.F., Gama-Rodrigues, A.C., Fontes, A.G., Polidoro, J.C., 2011. Distribution of oxidizable organic C fractions in soils under cacao agroforestry systems in Southern Bahia, Brazil. Agroforest Syst. 81, 213–220.

Batjes, N.H., 2004. Estimation of soil carbon gains upon improved management within croplands and grasslands of Africa. Environ. Dev. Sustain. 6, 133–143.

Batista, E., Soares-Filho, B., Barbosa, F., Merry, F., Davis, J., van der Hoff, R., Rajão, R.G., 2019. Large-scale pasture restoration may not be the best option to reduce greenhouse gas emissions in Brazil. Environ. Res. Lett. 14, 1-12.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pillon, C.N., Sangoi, L., 2001. Changes in Soil Organic Matter Fractions under Subtropical No-Till Cropping Systems. Soil Sci. Soc. Am. J. 65, 1473–1478.

Blair, G.J., Lefroy, R.D.B., Lisle, L., 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust. J. Agric. Res. 46, 1459–1466.

BRASIL., 2017. Estimativas anuais de emissões de gases de efeito estufa no Brasil. 4º edição. Available from: https://sirene.mctic.gov.br/portal/opencms/publicacao/index.html (Accessed September 2019).

Brar, B.S., Singh, K., Dheri, G.S., Balwinder-Kumar, 2013. Carbon sequestration and soil carbon pools in a rice-wheat cropping system: Effect of long-term use of inorganic fertilizers and organic manure. Soil Tillage Res. 128, 30–36.

Braz, S.P., Urquiaga, S., Alves, B.J.R., Jantalia, C.P., Guimarães, A.P., dos Santos, C.A., dos Santos, S.C., Machado Pinheiro, É.F., Boddey, R.M., 2013. Soil Carbon Stocks under Productive and Degraded Pastures in the Brazilian Cerrado. Soil Sci. Soc. Am. J. 77, 914.

Brandani, C.B., Abbruzzini, T.F., Conant, R.T., Cerri, C.E.P., 2017. Soil organic and organomineral fractions as indicators of the effects of land management in conventional and organic sugar cane systems. Soil Research 55, 145–161.

Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri, C.C., 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Tillage Res. 110, 175–186.

Cambardella, C.A., Elliott, E.T., 1992. Particulate Soil Organic-Matter Changes across a Grassland Cultivation Sequence. Soil Sci. Soc. Am. J. 56, 777.

Campos, M.C.C., Ribeiro, M.R., Júnior, V.S.S., Filho, M.R.R., Souza, R.V.C.C., Almeida, M.C., 2011. Características mineralógicas de latossolos e argissolos na região sul do Amazonas. Rev. Acad., Ciênc. Agrár. Ambient. 9, 11-18.

Cardinael, R., Chevallier, T., Barthès, B.G., Saby, N.P.A., Parent, T., Dupraz, C., Bernoux, M., Chenu, C., 2015a. Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon - A case study in a Mediterranean context. Geoderma 259–260, 288–299.

Cecagno, D., Gomes, M.V., Costa, S.E.V.G.A., Martins, A.P., Denardin, L.G.O., Bayer, C., Anghinoni, Carvalho, P.C.F., 2018. Soil organic carbon in an integrated crop-livestock system under different grazing intensities. Rev. Bras. Cienc. Agrar. 13, 1-7.

Cerri, C.E.P., Coleman, K., Jenkinson, D.S., Bernoux, M., Victoria, R., Cerri, C.C, 2003. Modeling Soil Carbon from Forest and Pasture Ecosystems of Amazon, Brazil. Soil Sci. Soc. Am. J. 67, 1879–1887.

Chan, K.Y., Oates, A., Li, G.D., Conyers, M.K., Prangnell, R.J., Poile, G., Liu, D.L., Barchia, I.M., 2010. Soil carbon stocks under different pastures and pasture management in the higher rainfall areas of south-eastern Australia. Aust. J. Soil Res. 48, 7–15.

Christensen, B.T., 1992. Physical Fractionation of Soil and Organic Matter in Primary Particle Size and Density Separates. In: Stewart, B.A. (Ed), Advances in Soil Science, Springer, New York, pp. 1–90.

Chávez, L.F., Escobar, L.F., Anghinoni, I., de Faccio Carvalho, P.C., Meurer, E.J., 2011. Diversidade metabólica e atividade microbiana no solo em sistema de integração lavoura-pecuária sob intensidades de pastejo. Pesqui. Agropecu. Bras. 46, 1254–1261.

Chatterjee, N., Nair, P.K.R., Chakraborty, S., Nair, V.D., 2018. Changes in soil carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis. Agr. Ecosyst. Environ. 266, 55–67.

Cherubin, M.R., Franco, A.L.C., Cerri, C.E.P., Karlen, D.L., Pavinato, P.S., Rodrigues, M., Davies, C.A., Cerri, C.C., 2016. Phosphorus pools responses to land-use change for sugarcane expansion in weathered Brazilian soils. Geoderma 265, 27–38.

Chen, J., Luo, Y., Groenigen, K.J., Hungate, B.A., Cao, J., Zhou, X., Wang, R., 2018. A keystone microbial enzyme for nitrogen control of soil carbon storage. Sci. Adv. 4, 1-6.

Cohn, A.S., Mosnier, A., Havlik, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., Obersteiner, M., 2014. Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. PNAS 111, 7236–7241.

Coonan, E.C., Richardson, A.E., Kirkby, C.A., Kirkegaard, J.A., Amidy, M.R., Simpson, R.J., Strong, C.L., 2019. Soil carbon sequestration to depth in response to long-term phosphorus fertilization of grazed pasture. Geoderma 338, 226-235.

de Moraes Sá, J. C., Gonçalves, D.R.P., Ferreira, L.A., Mishra, U., Inagaki, T.M., Furlan, F.J.F., Moro, R.S., Floriani, N., Briedis, C., de Oliveira Ferreira, A., 2018. Soil carbon fractions and biological activity based indices can be used to study the impact of land management and ecological successions. Ecol. Indic. 84:96–105.

Damian, J.M., Firmano, R.F., Cherubin, M.R., Pavinato, P.S., Soares, T.M., Paustian, K., Cerri, C.E.P., 2020. Changes in soil phosphorus pool induced by pastureland intensificationand diversification in Brazil. Sci. Total Environ. 703, 1-12.

Dias Filho, M.B., 2014. Diagnóstico das pastagens no Brasil. Documentos, Embrapa, Brasília, pp. 1-36.

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P., Kögel-Knabner, I., 2005. Carbon and nitrogen stocks in physical fractions of a subtropical Acrisol as influenced by long-term no-till cropping systems and N fertilisation. Plant and Soil 268, 319–328.

Duval, M.E., Galantini, J.A., Capurro, J.E., Martinez, J.M., 2016. Winter cover crops in soybean monoculture: Effects on soil organic carbon and its fractions. Soil Tillage Res. 161, 95-105.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

FAO. Food and Agricultural Organization of the United Nations. State of the world's forests 2007. Rome-Italy, 2007.

Feller, C., Beare, M.H., 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79, 69–116.

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., Rumpel, C., 2007. Stability of organic carbon in deep soil depths controlled by fresh carbon supply. Nature 450, 277–280.

Franzluebbers, A.J., Sawchik, J., Taboada, M.A., 2014. Agronomic and environmental impacts of pasture–crop rotations in temperate North and South America. Agr. Ecosyst. Environ. 190, 18–26.

Gang, C., Zhou, W., Chen, Y., Wang, Z., Sun, Z., Li, J., Qi, J., Odeh, I., 2014. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. Environ. Earth Sci. 72, 4273–4282.

Galán-Acedo, C., Arroyo-Rodríguez, V., Andresen, E., Arasa-Gisbert, R., 2019. Ecological traits of the world's primates. Sci. Data 6, 1-5.

Gil, J., Garrett, R., Berger, T., 2016. The wide-scale adoption of integrated crop-livestock systems in Mato Grosso, Brazil: Evidence from the household and regional levels. Land Use Policy Submitted 557–568.

Gounand, I., Little, C.J., Harvey, E., Altermatt, F., 2018. Beyond local functioning: carbon subsidies connecting ecosystems worldwide. Nat. Commun. 9, 1–9.

Ghimire, R., Bista, P., Machado, S., 2019. Long-term management effects and temperature sensitivity of soil organic carbon in grassland and agricultural soils. 9, 1–10.

IBGE, 2017. Instituto Brasileiro de Geografia e Estatística. Censo Agropecuário 2017. IBGE, Rio de Janeiro, Rio de Janeiro.

IPCC, 2006. Agriculture, forestry and other land use. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Hayama.

Lal, R., 2014. Soil conservation and ecosystem services. Int. Soil Water Conserv. Res. 3, 36-47.

Lavallee, J.M., Soong, J.L., Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob. Change Biol. 26, 261–273.

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature 528, 60–68.

Leite, L.F.C., Iwata, B.F., Araújo, A.S.F., 2014. Soil organic matter pools in a tropical savanna under agroforestry system in northeastern Brazil. Revista Árvore 38, 711-723.

Li, C., Fultz, L.M., Moore-Kucera, J., Acosta-Martínez, V., Horita, J., Strauss, R., Zak, J., Calderón, F., Weindorf, D., 2017. Soil carbon sequestration potential in semi-arid grasslands in the Conservation Reserve Program. Geoderma 294, 80–90.

Lin, D., McCulley, R.L., Nelson, J.A., Jacobsen, K.L., Zhang, D., 2020. Time in pasture rotation alters soil microbial community composition and function and increases carbon sequestration potential in a temperate agroecosystem. Sci. Total Environ. 698, 1-9.

Liu, D.L., Chan, K.Y., Conyers, M.K., Li, G., Poile, G.J., 2011. Simulation of soil organic carbon dynamics under different pasture managements using the RothC carbon model. Geoderma 165, 69–77.

Loss, A., Pereira, M.G., Perin, A., Beutler, S.J., Anjos, L.H.C., 2013. Oxidizable carbon and humic substances in rotation systems with brachiaria/livestock and pearl millet/no livestock in the Brazilian Cerrado. Span. J. Agric. Res. 11, 217-231.

Matos, P.S., Fonte, S.J., Lima, S.S., Pereira, M.G., Kelly, C., Damian, J.M., Fontes, M.A., Chaer, G.M., Brasil, F.C., Zonta, E., 2020. Linkages among soil properties and litter quality in agroforestry systems of southeastern Brazil. Sustainability 12, 1-22.

Matsuoka, M., Mendes, I.C., Loureiro, M.F., 2003. Biomassa microbiana e atividade enzimática em solos sob vegetação nativa e sistemas agrícolas anuais e perenes na região de Primavera do Leste (MT). Rev. Bras. Cienc. Solo. 27, 425–433.

Mello, F.C., Cerri, C.E.P., Davies, C.A., Holbrook, N.M., Paustian, K., Maia, S.M.F., Galdos, M.V., Bernoux, M., Cerri, C.C., 2014. Payback time for soil carbon and sugar-cane ethanol. Nat. Clim. Change. 4, 605–609.Millennium ecosystem assessment., 2005. The Millennium Ecosystem Assessment assessed the consequences of ecosystem change for human well-being. Available from: https://www.millenniumassessment.org/en/index.html (Accessed September 2019).

Ngaba, M.J.Y., Ma. Q., Hu, L., 2020. Variability of soil carbon and nitrogen stocks after conversion of natural forest to plantations in Eastern China. PeerJ 8, e8377.

NRC - National Research Council, 1985. Nutrient Requirements of Sheep, 6 ed. National Academic of Science, Washington, pp. 99.

Nunan, N., Singh, B.K., Reid, E., Ord, B., Papert, A., Squires, J., Prosser, J.I., Wheatley, R.E., McNicol, J.W., Millard, P., 2006. Sheep-urineinduced changes in soil microbial community structure. FEMS Microbiol Ecol. 56, 310–320.

Oliveira, D.M., Paustian, K., Cotrufo, M.F., Fiallos, A.R., Cerqueira, A.G., Cerri, C.E.P., 2017a. Assessing labile organic carbon in soils undergoing land use change in Brazil: A comparison of approaches. Ecological Indicators 72, 411–419.

Oliveira, D.M., Williams, S., Cerri, C.E.P., Paustian, K., 2017b. Predicting soil C changes over sugarcane expansion in Brazil using the DayCent model. Glob. Change Biol. Bioenergy 9, 1436–1446.

Olson, K.R., Al-Kaisi, M., Lal, R., Morton, L.W., 2017. Soil ecosystem services and in-tensified cropping systems. J. Soil Water Conserv. 72, 64A–69.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57.

Raij, B., Andrade, J.C., Cantarella, H., Quaggio, J.A., 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico de Campinas, Campinas. pp. 285.

Rasse, D.P., Rumpel, C., Dignac, M.F., 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant and Soil 269, 341–356.

Ramesh, T., Manjaiah, K.M., Mohopatra, K.P., Rajasekar, K., Ngachan, S.V., 2015. Assessment of soil organic carbon stocks and fractions under different agroforestry systems in subtropical hill agroecosystems of north-east India. Agroforest Syst. 89, 677-690.

Roscoe, R., Buurman, P., Velthorst, E.J., Vasconcellos, C. a, 2001. Soil organic matter dynamics in density and particle size fractions as revealed by the C-13/C-12 isotopic ratio in a Cerrado's oxisol. Geoderma 104, 185–202.

Rumpel, C., Kögel-Knabner, I., 2011. Deep soil organic matter—a key but poorly understood component of terrestrial C cycle. Plant Soil 338, 143-158.

Reay, D.S., Dentener, F., Smith, P., Grace, J., Feely, R.A., 2008. Global nitrogen deposition and carbon sinks. Nat. Geosci. 1, 430-437.

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M., 2014. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agr. Ecosyst. Environ. 190, 70–79.

Sattari, S.Z., Bouwman, A.F., Martinez Rodríguez, R., Beusen, A.H.W., Van Ittersum, M.K., 2016. Negative global phosphorus budgets challenge sustainable intensification of grasslands. Nat. Commun. 7, 1-12.

Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S., Hamm, M.W., 2018. Impacts of soil carbon sequestration on life cycle greenhouse gas emissionsin Midwestern USA beeffinishing systems. Agric. Syst. 162, 249-258.

Sato, J.H., Figueiredo, C.C., Marchão, R.L., Oliveira, A.D., Vilela, L., Delvico, F.M., Alves, B.J.R., Carvalho, A.M., 2019. Understanding the relations between soil organic matter fractions and N2O emissions in a long-term integrated crop–livestock system. Eur. J. Soil Sci. 3, 1–14.

Sarto, M.V.M., Borges, W.L.B., Sarto, J.R.W., Rice, C.W., Rosolem C.A., 2020. Deep soil carbon stock, origin, and root interaction in a tropical integrated crop–livestock system. Agroforest Syst. 4, 1–13.

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., 2019. Soil carbon stock and humification in pastures under different levels of intensification in Brazil. Sci. Agric. 76, 33-40.

SEEG, 2016. Sistema de Estimativa de Emissão de Gases de Efeito Estufa; São Paulo, Brazil.

Sharrow, S.H., Ismail, S., 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agroforest Syst. 60, 123-130.

Silva, F.D., Amado, T.J.C., Ferreira, A.O., Assmann, J.M., Anghinoni, I., Carvalho, P.C.F., 2014. Soil carbon indices as affected by 10 years of integrated crop–livestock production with different pasture grazing intensities in Southern Brazil. Agr. Ecosyst. Environ. 190, 60-69.

Silva, R.O., Barioni, L.G., Hall, J.A.J., Moretti, A.C., Veloso, R.F., Alexander, P., Crespolini, M., Moran, D., 2017. Sustainable intensification of Brazilian livestock production throughoptimized pasture restoration. Agric. Syst. 153, 201-211.

Tivet, F., De Moraes Sá, J.C., Lal, R., Borszowskei, P.R., Briedis, C., dos Santos, J.B., Sá, M.F.M., da Cruz Hartman, D., Eurich, G., Farias, A., Bouzinac, S., Séguy, L., 2013. Soil organic carbon fraction losses upon continuous plow-based tillage and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. Geoderma 209–210, 214–225.

Toru, T., Kibret, K., 2019. Carbon stock under major land use/land cover types of Hades sub-watershed, eastern Ethiopia. Carbon Balance Manag. 14, 2-14.

Thangata, P.H., Hildebrand, P.E., 2012. Carbon stock and sequestration potential of agroforestry systems in smallholder agroecosystems of sub-Saharan Africa: Mechanisms for 'reducing emissions from deforestation and forest degradation' (REDD+). Agr. Ecosyst. Environ. 158, 172–183.

Thornton, P.K., Herrero, M., 2015. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. Nat. Clim. Change 5, 830–836.

Tracy, B.F., Zhang, Y., 2008. Soil compaction, corn yield response, and soil nutrient pool dynamics within an integrated crop-livestock system in Illinois. Crop Science 48, 1211–1218.

Upson, M.A., Burgess, P.J., Morison, J.I.L., 2016. Soil carbon changes after establishing woodland and agroforestry trees in a grazed pasture. Geoderma 283, 10–20.

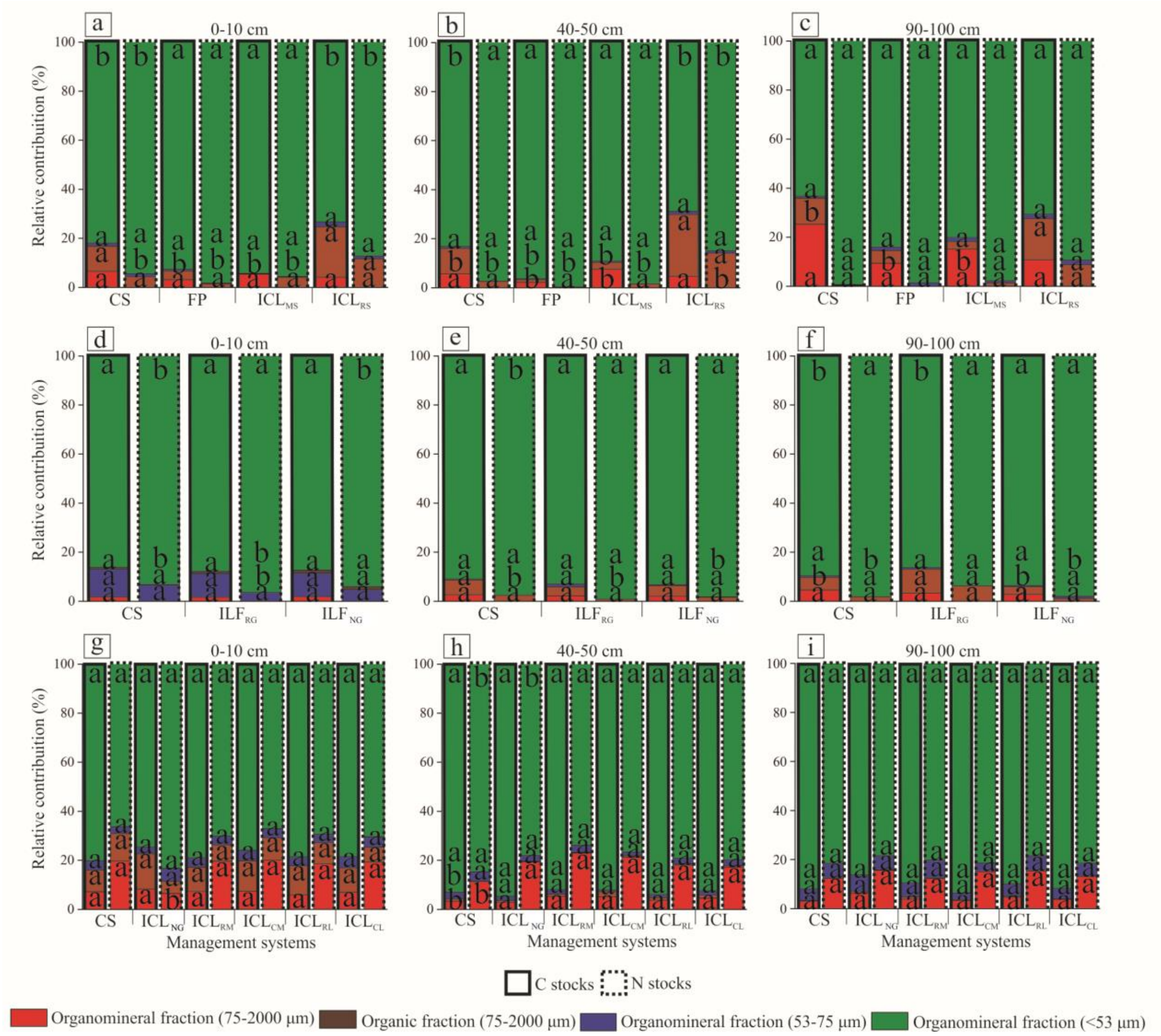
USDA, 2014. Keys to Soil Taxonomy, USDA—Natural Resources Conservation Service; Washington, USA.

Vargas, R.S., Bataiolli, R., da Costa, P.B., Lisboa, B., Passaglia, L.M.P., Beneduzi, A., Vargas, L.K., 2015. Microbial quality of soil from the Pampa biome in response to different grazing pressures. Genetics and Molecular Biology 38, 205–212.

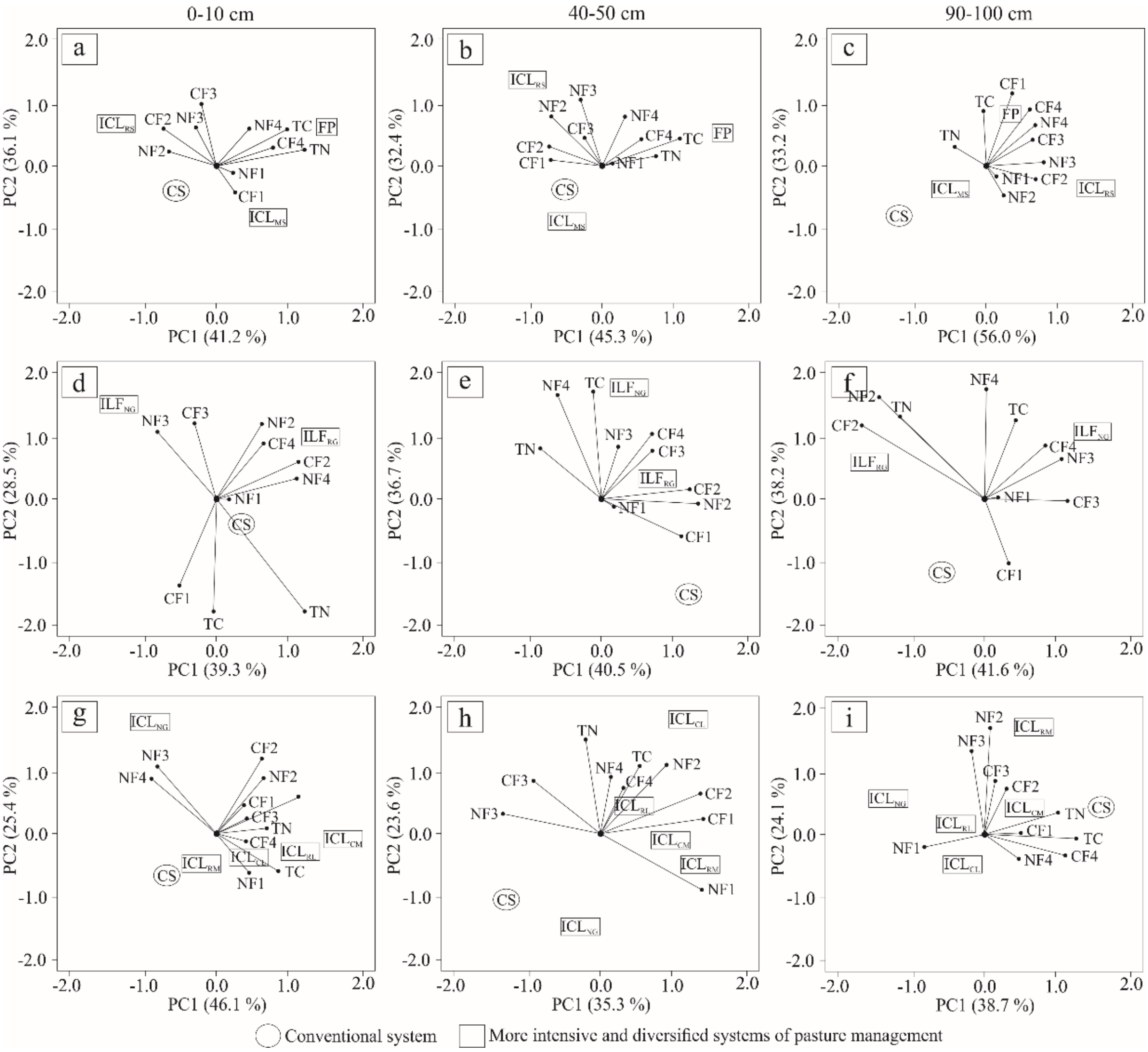
Wang, W., Fang, J., 2009. Soil respiration and human effects on global grasslands. Glob. Planet. Change 67, 20–28.

Wade, A.M., Richter, D.D., Medjibe, V.P., Bacon, A.R., Heine, P.R., White, L.J.T., Poulsen, J.R., 2019., 2019. Estimates and determinants of stocks of deep soil carbon in Gabon, Central Africa. Geoderma 341, 236-248.

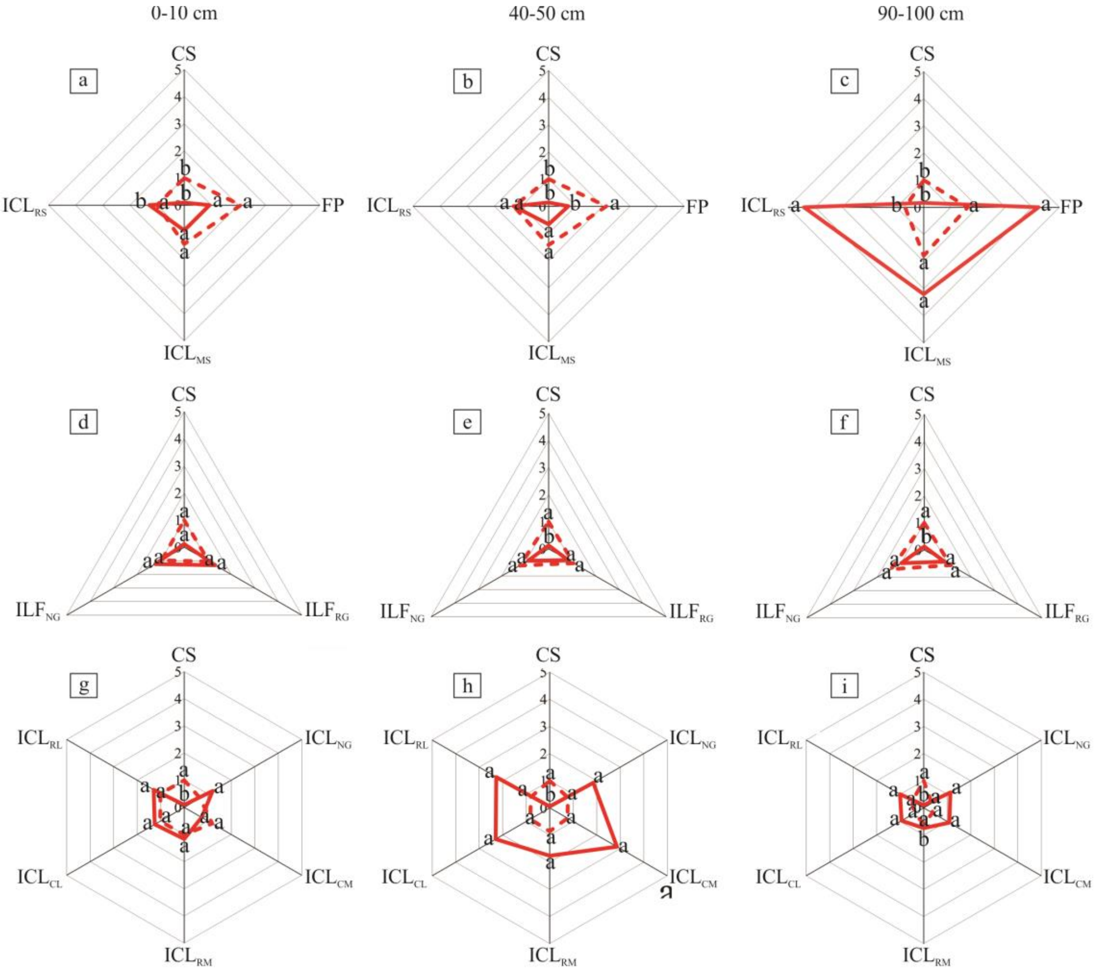
Supplementary material



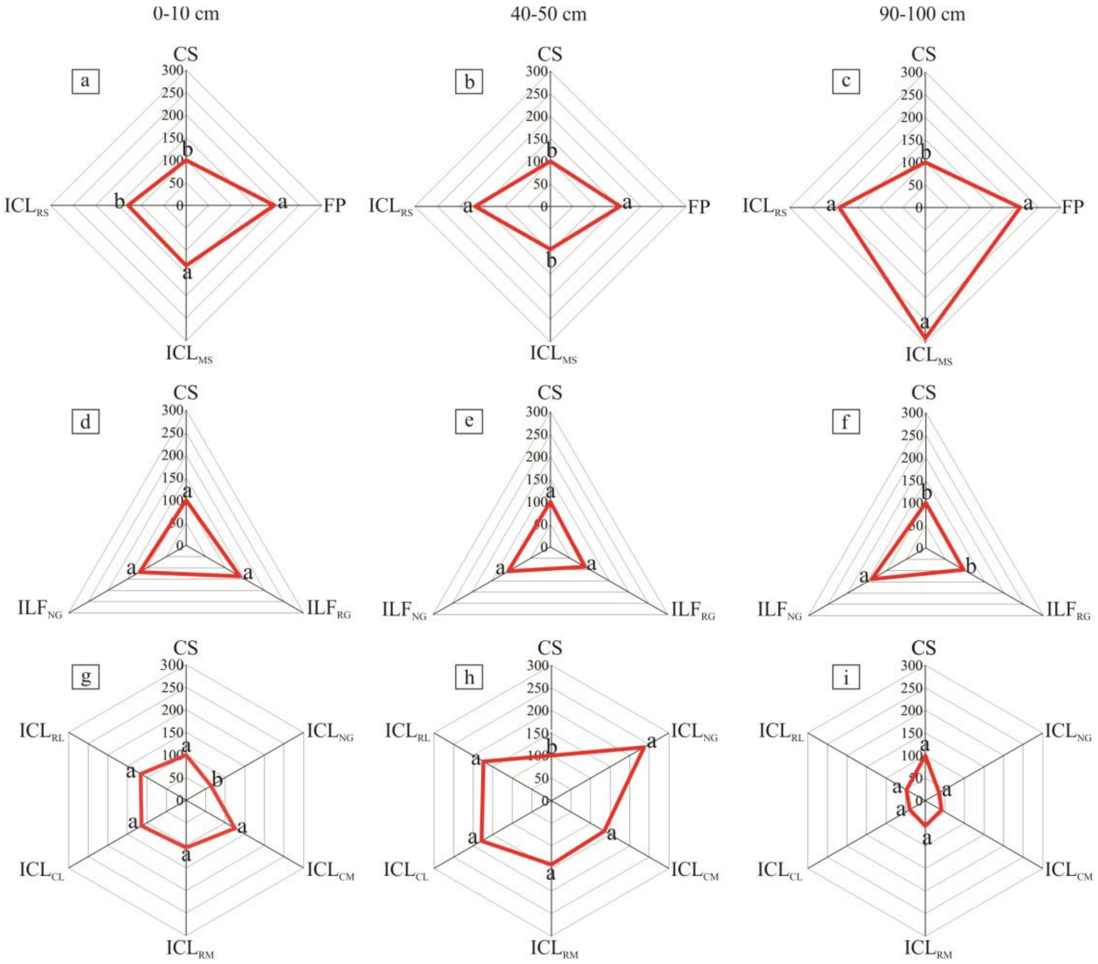
Supplementary Figure S1. Relative contributions of different SOM fractions subjected to systems of pasture management for three soil layers (0-10, 40-50 and 90-100 cm) under tropical humid (a, b and c), tropical mesic (d, e and f) and subtropical (g, h and i) climate conditions. Mean values followed by the same letter did not statistically differ in the Tukey's test at 5% probability ($p \leq 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL_{MS}, integrated crop-livestock with maize/soybeans; ICL_{RS}, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF_{RG}, integrated livestock-forest with rotational grazing; ILF_{NG}, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL_{NG}, integrated crop-livestock with no grazing; ICL_{RM}, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL_{CM}, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL_{RL}, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL_{CL}, integrated crop-livestock with continuous stocking and low-intensity grazing.



Supplementary Figure S2. Principal component analysis (PCA) applied to the different systems of pasture management for three soil layers (0-10, 40-50 and 90-100 cm) under tropical humid (a, b and c), tropical mesic (d, e and f) and subtropical (g, h and i) climate conditions. Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing. TC, total soil C; TN, total soil N; CF1, C of the F1 fraction of SOM; NF1, N of the F1fraction of SOM; CF2, C of the F2fraction of SOM; NF2, N of the F2 fraction of SOM; CF3, C of the F3 fraction of SOM; NF3, N of the F3 fraction of SOM; CF4, C of the F4 fraction of SOM; NF4, N of the F4 fraction of SOM.



Supplementary Figure S3. Carbon lability (straight red line) and pool (red dotted line) indices in different systems of pasture management for three soil layers (0-10, 40-50 and 90-100 cm) under tropical humid (a, b and c), tropical mesic (d, e and f) and subtropical (g, h and i) climate conditions. Mean values followed by the same letter did not statistically differ in the Tukey's test at 5% probability ($p \leq 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.



Supplementary Figure S4. Carbon management index in different systems of pasture management for three soil layers (0-10, 40-50 and 90-100 cm) under tropical humid (a, b and c), tropical mesic (d, e and f) and subtropical (g, h and i) climate conditions. Mean values followed by the same letter did not statistically differ in the Tukey's test at 5% probability ($p \leq 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.

Supplementary Table S1. Soil bulk density (g cm^{-3}) in different systems of pasture management under tropical humid, tropical mesic and subtropical climate conditions.

Layers	Tropical humid		Tropical mesic		Subtropical	
0-10 cm	CS	1.33±0.10	CS	1.03±0.23	CS	1.60±0.12
	FP	1.18±0.06	ILF$_{RG}$	1.30±0.08	ICL$_{NG}$	1.39±0.09
	ICL$_{MS}$	1.34±0.11	ILF$_{NG}$	1.18±0.22	ICL$_{RM}$	1.51±0.14
	ICL$_{RS}$	1.38±0.14			ICL$_{CM}$	1.50±0.19
					ICL$_{RL}$	1.65±0.11
					ICL$_{CL}$	1.47±0.12
10-20 cm	CS	1.46±0.09	CS	1.55±0.14	CS	1.60±0.18
	FP	1.27±0.27	ILF$_{RG}$	1.64±0.07	ICL$_{NG}$	1.53±0.08
	ICL$_{MS}$	1.31±0.14	ILF$_{NG}$	1.52±0.04	ICL$_{RM}$	1.58±0.13
	ICL$_{RS}$	1.76±0.27			ICL$_{CM}$	1.56±0.21
					ICL$_{RL}$	1.66±0.09
					ICL$_{CL}$	1.59±0.11
20-30 cm	CS	1.49±0.07	CS	1.66±0.01	CS	1.63±0.08
	FP	1.08±0.10	ILF$_{RG}$	1.76±0.04	ICL$_{NG}$	1.74±0.07
	ICL$_{MS}$	1.35±0.17	ILF$_{NG}$	1.56±0.14	ICL$_{RM}$	1.69±0.12
	ICL$_{RS}$	1.68±0.21			ICL$_{CM}$	1.65±0.07
					ICL$_{RL}$	1.64±0.06
					ICL$_{CL}$	1.65±0.10
30-40 cm	CS	1.51±0.16	CS	1.73±0.07	CS	1.65±0.09
	FP	1.07±0.13	ILF$_{RG}$	1.71±0.03	ICL$_{NG}$	1.69±0.11
	ICL$_{MS}$	1.28±0.12	ILF$_{NG}$	1.48±0.21	ICL$_{RM}$	1.59±0.07
	ICL$_{RS}$	1.60±0.11			ICL$_{CM}$	1.69±0.09
					ICL$_{RL}$	1.67±0.06
					ICL$_{CL}$	1.64±0.06
40-50 cm	CS	1.52±0.15	CS	1.72±0.02	CS	1.62±0.05
	FP	1.10±0.11	ILF$_{RG}$	1.60±0.08	ICL$_{NG}$	1.66±0.10
	ICL$_{MS}$	1.21±0.16	ILF$_{NG}$	1.56±0.04	ICL$_{RM}$	1.58±0.12
	ICL$_{RS}$	1.56±0.09			ICL$_{CM}$	1.61±0.05
					ICL$_{RL}$	1.64±0.06
					ICL$_{CL}$	1.67±0.16
50-60 cm	CS	1.44±0.11	CS	1.63±0.01	CS	1.55±0.14
	FP	1.04±0.17	ILF$_{RG}$	1.62±0.10	ICL$_{NG}$	1.56±0.11
	ICL$_{MS}$	1.27±0.24	ILF$_{NG}$	1.62±0.06	ICL$_{RM}$	1.49±0.15
	ICL$_{RS}$	1.43±0.16			ICL$_{CM}$	1.48±0.10
					ICL$_{RL}$	1.66±0.17
					ICL$_{CL}$	1.62±0.06
60-70 cm	CS	1.42±0.17	CS	1.53±0.19	CS	1.41±0.10
	FP	1.03±0.29	ILF$_{RG}$	1.62±0.08	ICL$_{NG}$	1.43±0.09
	ICL$_{MS}$	1.26±0.12	ILF$_{NG}$	1.38±0.13	ICL$_{RM}$	1.41±0.10
	ICL$_{RS}$	1.65±0.19			ICL$_{CM}$	1.33±0.04
					ICL$_{RL}$	1.43±0.12
					ICL$_{CL}$	1.53±0.03
70-80 cm	CS	1.41±0.15	CS	1.66±0.09	CS	1.43±0.13
	FP	1.06±0.21	ILF$_{RG}$	1.54±0.05	ICL$_{NG}$	1.42±0.19
	ICL$_{MS}$	1.25±0.24	ILF$_{NG}$	1.50±0.17	ICL$_{RM}$	1.45±0.12
	ICL$_{RS}$	1.60±0.18			ICL$_{CM}$	1.41±0.11
					ICL$_{RL}$	1.50±0.07
					ICL$_{CL}$	1.42±0.10
80-90 cm	CS	1.37±0.14	CS	1.62±0.09	CS	1.47±0.08
	FP	1.05±0.21	ILF$_{RG}$	1.57±0.04	ICL$_{NG}$	1.48±0.19
	ICL$_{MS}$	1.13±0.26	ILF$_{NG}$	1.41±0.07	ICL$_{RM}$	1.45±0.08
	ICL$_{RS}$	1.46±0.09			ICL$_{CM}$	1.53±0.10
					ICL$_{RL}$	1.46±0.11
					ICL$_{CL}$	1.54±0.10
90-100 cm	CS	0.26±0.46	CS	1.57±0.13	CS	1.46±0.09
	FP	1.10±0.22	ILF$_{RG}$	1.54±0.06	ICL$_{NG}$	1.45±0.10
	ICL$_{MS}$	1.24±0.18	ILF$_{NG}$	1.58±0.11	ICL$_{RM}$	1.52±0.15
	ICL$_{RS}$	1.49±0.19			ICL$_{CM}$	1.54±0.14
					ICL$_{RL}$	1.55±0.08
					ICL$_{CL}$	1.61±0.08

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). Tropical humid: CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. Tropical mesic: CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. Subtropical: CS, conventional system; ICL$_{NG}$, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing.

Supplementary Table S2. Characterization of soil chemical attributes for different systems of pasture management under tropical humid climate.

Layers	Manangemant systems	pH $CaCl_2$	P	K	Ca	Mg	Al	H+Al	SB	CEC_{pH7}	BS	AS
0-10 cm		index	mg dm^{-3}	mmol$_c$ dm^{-3}							%	
	CS	4.33± 0.21	3.70± 0.26	2.37± 0.50	6.01± 0.79	1.99± 0.13	0.19± 0.07	20.10± 1.72	10.73± 0.79	32.43± 3.32	31.18± 0.75	0.00± 0.00
	FP	4.70± 0.43	5.83± 0.15	2.13± 0.35	15.41± 1.41	3.92± 0.63	0.91± 0.08	33.10± 4.36	22.47± 1.28	59.60± 2.76	40.06± 3.54	5.23± 0.99
	ICL$_{MS}$	4.66± 0.42	8.84± 0.18	1.61± 0.53	12.11± 0.85	1.79± 1.14	0.23± 0.23	20.03± 1.75	17.77± 1.04	38.70± 0.72	47.63± 4.03	0.00± 0.00
	ICL$_{RS}$	5.20± 0.10	19.73± 0.55	4.63± 1.60	14.27± 1.17	9.48± 0.73	0.70± 0.40	19.43± 2.28	27.38± 1.56	50.49± 0.79	60.72± 4.16	3.50± 0.69
10-20 cm												
	CS	4.50± 0.03	3.04± 0.23	1.50± 0.07	6.18± 0.68	1.84± 0.27	0.51± 0.14	17.27± 1.18	9.86± 0.69	27.69± 0.82	33.56± 1.88	5.34± 0.87
	FP	4.85± 0.13	5.88± 0.16	1.78± 0.15	14.46± 1.51	3.59± 0.46	0.92± 0.07	32.87± 2.74	20.15± 1.32	55.34± 1.56	37.59± 2.28	5.22± 1.02
	ICL$_{MS}$	4.75± 0.10	6.42± 0.07	1.49± 0.03	9.49± 0.13	2.56± 0.79	0.14± 0.11	17.73± 2.18	16.11± 1.90	33.77± 1.18	44.28± 3.34	0.00± 0.00
	ICL$_{RS}$	5.00± 0.12	13.28± 0.34	3.00± 0.66	10.40± 0.56	6.77± 0.23	0.70± 0.33	18.43± 2.22	20.79± 0.92	41.74± 1.36	49.00± 2.60	5.84± 0.84
20-40 cm												
	CS	4.33± 0.15	2.38± 0.35	0.64± 0.36	6.34± 0.61	1.69± 0.42	0.82± 0.22	14.43± 0.70	8.98± 0.60	22.94± 1.95	35.93± 3.27	10.67± 1.74
	FP	5.00± 0.20	3.93± 0.22	1.43± 0.59	13.51± 1.61	3.27± 0.37	0.93± 0.10	32.63± 2.07	17.82± 1.60	51.07± 0.39	35.11± 1.06	5.21± 1.04
	ICL$_{MS}$	4.83± 0.30	4.00± 0.10	1.37± 0.57	6.86± 1.11	3.34± 0.54	0.05± 0.02	15.41± 2.68	14.45± 2.84	28.84± 1.64	40.95± 2.69	0.00± 0.00
	ICL$_{RS}$	4.80± 0.10	6.83± 0.16	1.26± 0.61	6.52± 0.41	4.06± 0.57	0.70± 0.28	17.45± 2.28	14.25± 2.47	32.98± 1.97	37.26± 2.14	8.18± 1.06
40-60 cm												
	CS	4.33± 0.45	3.12± 0.26	0.62± 0.36	5.92± 0.64	1.71± 0.40	0.02± 0.01	15.72± 2.15	9.58± 0.87	25.91± 1.67	34.35± 2.88	0.00± 0.00
	FP	4.64± 0.25	3.31± 0.15	0.64± 0.34	10.72± 1.69	4.19± 0.34	0.82± 0.22	26.83± 3.75	14.25± 1.82	46.45± 1.60	33.25± 1.10	6.20± 1.96
	ICL$_{MS}$	4.8± 0.10	2.54± 0.35	1.95± 0.65	5.40± 1.95	1.86± 0.33	0.02± 0.01	13.02± 1.82	9.53± 1.40	21.36± 1.93	39.09± 3.54	0.00± 0.00
	ICL$_{RS}$	4.75± 0.21	1.46± 0.21	0.58± 0.29	5.00± 0.68	1.77± 0.45	0.01± 0.01	14.15± 1.89	7.46± 1.17	22.57± 1.05	29.93± 1.84	0.00± 0.00
60-80 cm												
	CS	4.42± 0.21	2.30± 0.20	0.29± 0.18	5.49± 0.84	1.62± 0.51	0.83± 0.17	13.98± 1.88	8.09± 0.63	23.51± 0.97	34.26± 4.41	11.58± 1.83
	FP	4.77± 0.15	2.27± 0.15	0.74± 0.20	6.02± 0.22	3.08± 0.54	0.93± 0.08	21.58± 3.09	9.94± 1.22	35.63± 1.03	32.42± 6.31	10.26± 2.08
	ICL$_{MS}$	4.80± 0.30	2.30± 0.20	1.20± 0.32	3.41± 1.03	1.12± 0.67	0.02± 0.01	12.05± 0.98	6.30± 1.70	16.38± 1.09	29.42± 3.05	0.00± 0.00
	ICL$_{RS}$	5.30± 0.10	1.30± 0.22	0.58± 0.35	5.04± 0.94	2.28± 0.36	0.01± 0.00	11.81± 2.84	7.66± 1.52	21.88± 2.02	34.42± 1.35	0.00± 0.00
80-100 cm												
	CS	5.17± 0.15	2.50± 0.10	0.37± 0.25	5.57± 0.63	0.79± 0.25	0.02± 0.01	14.46± 1.57	8.79± 1.38	23.67± 2.77	35.14± 1.00	0.00± 0.00
	FP	4.90± 0.20	2.60± 0.15	0.81± 0.12	5.96± 0.59	1.68± 0.32	0.90± 0.11	20.61± 1.23	8.61± 4.71	28.91± 1.50	20.37± 1.20	14.56± 3.73
	ICL$_{MS}$	4.80± 0.16	2.76± 0.05	0.96± 0.22	4.95± 1.00	2.04± 0.09	0.01± 0.01	13.50± 2.24	9.92± 1.54	28.73± 3.66	38.63± 3.26	0.00± 0.00
	ICL$_{RS}$	5.07± 0.18	1.74± 0.21	0.43± 0.33	5.12± 0.36	0.69± 0.42	0.01± 0.01	11.39± 1.59	11.03± 1.14	15.52± 3.52	23.75± 1.68	0.00± 0.00

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). CS, conventional system; FP, fertilized pasture; ICL$_{MS}$, integrated crop-livestock with maize/soybeans; ICL$_{RS}$, integrated crop-livestock with rice/soybeans. pH $CaCl_2$: potential de hydrogen in solution of $CaCl_2$ 0.01 mol L^{-1} (1:2.5)—active acidity; H +Al: potential acidity; SB: sum of bases; CECpH$_7$: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation.

Supplementary Table S3. Characterization of soil chemical attributes for different systems of pasture management under tropical mesic climate.

Layers	Manangemant systems	pH CaCl$_2$	P	K	Ca	Mg	Al	H+Al	SB	CEC$_{pH7}$	BS	AS
0-10 cm		index	mg dm^{-3}				mmol$_c$ dm^{-3}				%	
	CS	4.73± 0.21	2.97± 0.15	1.60± 0.10	5.94± 0.40	5.78± 0.45	2.39± 0.72	31.30± 1.82	11.90± 1.58	41.85± 2.59	29.79± 1.24	12.29± 0.84
	ILF$_{RG}$	5.27± 0.15	10.42± 0.81	1.47± 0.15	26.97± 1.73	11.11± 1.01	1.49± 0.21	25.35± 1.06	33.71± 3.99	67.38± 7.05	66.68± 5.11	0.44± 0.76
	ILF$_{NG}$	5.10± 0.20	5.35± 0.79	1.25± 0.18	8.88± 0.87	5.94± 0.67	2.06± 0.24	34.22± 4.32	13.65± 2.59	52.06± 2.31	34.18± 2.16	9.87± 1.44
10-20 cm												
	CS	4.70± 0.17	2.98± 0.18	1.41± 0.10	4.98± 0.20	4.97± 0.09	2.60± 0.11	29.20± 1.30	10.15± 1.30	38.88± 1.99	26.44± 1.37	16.74± 1.86
	ILF$_{RG}$	4.98± 0.10	6.60± 0.48	1.15± 0.08	20.51± 1.28	9.55± 0.83	1.64± 0.22	25.39± 0.99	27.21± 2.91	59.48± 4.00	56.90± 3.77	3.93± 0.40
	ILF$_{NG}$	4.80± 0.28	3.84± 0.37	1.05± 0.04	6.45± 0.70	4.50± 0.79	4.93± 0.15	34.82± 1.71	9.66± 2.02	47.96± 1.97	26.01± 1.32	26.46± 4.56
20-40 cm												
	CS	4.67± 0.15	3.00± 0.50	1.25± 0.15	4.00± 0.80	4.18± 0.60	2.82± 0.54	27.10± 4.08	8.40± 1.10	35.91± 1.39	23.08± 1.68	21.19± 2.89
	ILF$_{RG}$	4.70± 0.26	2.78± 0.39	0.82± 0.12	14.05± 0.83	7.99± 1.01	1.79± 0.25	25.44± 2.68	20.71± 1.98	51.59± 0.97	47.12± 2.69	7.41± 0.52
	ILF$_{NG}$	4.50± 0.36	2.33± 0.15	0.86± 0.09	4.02± 0.53	3.05± 0.93	7.81± 0.53	35.41± 2.74	5.67± 1.87	43.86± 1.62	17.84± 1.60	43.05± 7.75
40-60 cm												
	CS	4.07± 0.25	2.83± 0.15	1.38± 0.16	3.05± 0.58	2.08± 0.87	6.97± 1.70	32.98± 1.50	5.49± 0.81	39.35± 1.08	16.30± 1.82	43.77± 7.61
	ILF$_{RG}$	5.13± 0.35	2.77± 0.13	0.85± 0.14	13.41± 0.80	10.66± 1.45	0.74± 0.43	17.75± 2.06	21.18± 1.86	42.02± 0.79	55.82± 4.50	3.37± 0.72
	ILF$_{NG}$	5.26± 0.31	2.58± 0.35	0.86± 0.12	2.09± 0.77	0.95± 0.08	10.32± 0.88	28.72± 2.83	2.70± 0.79	34.48± 2.00	11.42± 3.70	65.17± 8.76
60-80 cm												
	CS	4.20± 0.36	2.30± 0.10	0.55± 0.13	2.08± 0.88	0.81± 0.17	6.30± 1.23	30.75± 2.01	2.65± 0.75	34.22± 1.78	10.96± 3.29	46.71± 14.36
	ILF$_{RG}$	5.27± 0.31	2.90± 0.20	0.86± 0.05	5.02± 0.78	3.53± 0.48	5.40± 0.74	25.10± 3.21	6.36± 1.77	38.00± 1.58	27.43± 4.04	28.19± 8.75
	ILF$_{NG}$	4.44± 0.21	2.55± 0.25	0.69± 0.07	0.55± 0.13	0.90± 0.13	11.18± 1.06	45.77± 4.63	1.86± 0.53	47.07± 5.09	5.36± 0.84	68.59± 12.71
80-100 cm												
	CS	4.36± 0.14	2.97± 0.15	0.56± 0.05	3.96± 0.40	0.74± 0.25	5.82± 0.54	25.07± 3.54	4.61± 0.95	30.31± 0.88	18.15± 1.98	46.10± 8.46
	ILF$_{RG}$	4.65± 0.15	2.90± 0.10	0.93± 0.04	4.00± 0.20	2.09± 0.20	5.79± 1.58	22.99± 1.86	5.30± 0.96	32.38± 1.00	26.31± 5.59	37.79± 9.74
	ILF$_{NG}$	4.77± 0.17	2.41± 0.35	0.63± 0.12	0.67± 0.17	1.06± 0.12	9.12± 0.67	33.43± 3.99	1.05± 0.22	38.25± 1.00	2.85± 0.49	75.70± 10.51

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). CS, conventional system; ILF$_{RG}$, integrated livestock-forest with rotational grazing; ILF$_{NG}$, integrated livestock-forest with no grazing. pH CaCl$_2$: potential de hydrogen in solution of CaCl$_2$ 0.01 mol L^{-1} (1:2.5)—active acidity; H +Al: potential acidity; SB: sum of bases; CECpH$_7$: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation.

Supplementary Table S4. Characterization of soil chemical attributes for different systems of pasture management under subtropical climate.

Deph	Manangemant systems	pH $CaCl_2$	P	K	Ca	Mg	Al	H+Al	SB	CEC$_{pH7}$	BS	AS
0-10 cm		index	mg dm^{-3}	mmol$_c$ dm^{-3}							%	
	CS	4.50± 0.30	6.00± 0.50	2.13± 0.15	5.80± 0.53	4.95± 0.28	3.84± 0.47	52.73± 4.78	12.11± 1.29	63.88± 2.43	18.57± 2.54	20.88± 1.82
	ICL$_{NG}$	3.65± 0.05	79.74± 3.71	2.08± 0.03	10.15± 0.87	5.65± 0.45	11.27± 1.06	73.20± 2.68	15.87± 2.13	89.02± 1.38	21.50± 1.30	34.38± 7.83
	ICL$_{RM}$	3.52± 0.34	84.08± 3.27	2.33± 0.12	11.48± 1.08	6.08± 0.57	12.61± 1.23	80.33± 5.49	17.84± 2.90	100.36± 1.04	23.41± 2.85	32.77± 7.24
	ICL$_{CM}$	3.66± 0.15	102.71± 8.27	2.08± 0.03	8.12± 0.57	4.12± 0.89	13.53± 1.14	63.29± 5.05	12.70± 1.58	84.47± 2.46	17.03± 1.25	44.74± 8.42
	ICL$_{RL}$	3.76± 0.23	92.09± 3.50	2.05± 0.04	12.02± 1.55	6.27± 1.17	12.67± 1.25	71.51± 4.00	17.96± 2.32	82.28± 0.93	26.52± 1.86	36.42± 9.14
	ICL$_{CL}$	3.65± 0.22	80.11± 5.50	1.83± 0.54	8.19± 0.76	4.42± 0.85	16.38± 1.33	79.50± 2.60	12.90± 1.59	91.16± 8.88	16.09± 1.92	44.01± 6.38
10-20 cm												
	CS	4.57± 0.19	14.74± 5.50	2.06± 0.07	5.32± 0.55	4.03± 0.39	4.67± 0.87	46.72± 4.57	10.49± 1.40	58.84± 1.86	18.06± 1.24	32.18± 5.71
	ICL$_{NG}$	3.62± 0.16	51.63± 2.88	1.98± 0.02	10.25± 0.12	4.64± 0.48	11.55± 0.82	52.13± 3.33	15.78± 1.71	71.17± 0.20	28.98± 2.56	29.92± 6.98
	ICL$_{RM}$	3.67± 0.24	53.82± 1.42	2.14± 0.08	12.37± 1.50	6.31± 0.21	12.71± 0.68	49.64± 3.45	18.42± 2.38	70.94± 8.88	36.41± 0.80	30.77± 8.02
	ICL$_{CM}$	3.69± 0.09	62.54± 5.18	1.95± 0.03	9.75± 1.32	4.87± 0.86	14.38± 1.31	38.83± 3.46	14.43± 1.80	60.45± 1.29	37.18± 2.32	44.39± 7.61
	ICL$_{RL}$	3.86± 0.12	60.28± 1.17	2.05± 0.00	13.27± 0.40	6.97± 0.37	11.97± 0.62	41.13± 2.29	19.55± 2.43	60.21± 0.92	46.87± 1.77	31.87± 9.24
	ICL$_{CL}$	3.77± 0.15	49.05± 3.57	1.84± 0.23	9.06± 1.15	5.13± 0.11	15.12± 0.41	49.66± 2.35	14.21± 1.82	65.85± 4.20	29.71± 2.25	41.46± 6.83
20-40 cm												
	CS	4.64± 0.14	23.48± 2.41	1.98± 0.03	4.84± 0.58	3.11± 0.55	5.49± 1.30	40.70± 4.38	8.87± 1.60	53.81± 2.33	17.55± 1.96	43.49± 10.28
	ICL$_{NG}$	3.59± 0.34	23.52± 2.14	1.88± 0.06	10.34± 1.01	3.63± 0.93	11.83± 1.40	31.06± 4.89	15.70± 1.29	53.33± 0.98	36.46± 4.17	25.46± 6.24
	ICL$_{RM}$	3.82± 0.13	23.55± 2.81	1.94± 0.05	13.26± 1.99	6.54± 0.85	12.81± 0.90	18.95± 1.43	19.00± 1.96	41.51± 1.92	49.41± 2.27	28.78± 9.32
	ICL$_{CM}$	3.73± 0.15	22.37± 2.10	1.82± 0.03	11.38± 2.08	5.63± 0.84	15.23± 1.70	14.38± 2.18	16.16± 2.13	36.43± 0.91	57.33± 4.21	44.03± 6.79
	ICL$_{RL}$	3.97± 0.32	28.46± 1.17	2.05± 0.04	14.52± 2.07	7.68± 0.73	11.28± 1.60	10.75± 1.16	21.14± 2.75	38.13± 1.92	67.21± 4.01	27.32± 9.37
	ICL$_{CL}$	3.90± 0.10	17.99± 2.09	1.86± 0.10	9.93± 1.57	5.84± 0.89	13.85± 1.45	19.82± 2.23	15.52± 1.13	40.54± 0.84	43.33± 2.66	38.90± 7.28
40-60 cm												
	CS	4.57± 0.15	5.63± 2.85	0.21± 0.03	4.87± 0.57	1.79± 0.25	21.82± 2.04	66.09± 5.02	7.38± 0.80	77.95± 1.74	11.40± 0.93	65.55± 7.31
	ICL$_{NG}$	3.80± 0.13	16.21± 2.15	1.10± 0.02	9.27± 1.03	3.16± 1.12	10.43± 0.84	57.21± 5.50	11.17± 2.09	68.01± 2.38	19.83± 1.46	37.57± 7.05
	ICL$_{RM}$	3.69± 0.20	16.55± 2.01	0.95± 0.09	10.22± 1.48	4.24± 0.62	11.49± 1.08	53.89± 2.59	13.09± 1.64	63.48± 1.84	24.78± 1.51	34.93± 5.64
	ICL$_{CM}$	3.45± 0.25	17.75± 2.71	1.24± 0.05	10.99± 1.36	4.74± 0.85	12.27± 1.04	48.57± 2.83	14.78± 2.26	58.03± 1.83	30.96± 2.21	26.07± 6.20
	ICL$_{RL}$	4.14± 0.14	17.32± 2.52	1.05± 0.04	8.05± 1.68	2.52± 0.43	12.23± 1.13	42.44± 3.49	10.77± 1.09	49.53± 5.16	24.69± 3.01	27.95± 7.41
	ICL$_{CL}$	3.60± 0.16	18.88± 1.97	0.93± 0.09	7.63± 1.19	2.72± 0.81	9.97± 1.11	29.98± 2.34	9.07± 1.93	39.03± 1.39	31.54± 3.60	25.11± 9.44
60-80 cm												
	CS	4.21± 0.11	2.57± 0.42	0.79± 0.16	3.42± 1.11	1.44± 0.45	21.63± 1.57	28.88± 2.02	5.44± 0.66	43.33± 1.04	13.47± 1.71	65.54± 5.85
	ICL$_{NG}$	3.25± 0.15	10.31± 1.53	0.90± 0.03	2.63± 0.63	2.37± 0.53	9.46± 0.90	17.47± 0.74	4.07± 1.33	37.19± 1.32	15.13± 1.19	30.17± 8.88
	ICL$_{RM}$	3.63± 0.12	15.46± 3.56	0.84± 0.08	4.21± 0.89	2.77± 0.37	8.53± 2.52	18.49± 0.73	7.29± 1.51	37.80± 1.95	20.29± 1.08	35.96± 4.08
	ICL$_{CM}$	3.51± 0.20	11.54± 1.17	0.95± 0.05	4.51± 1.79	2.58± 0.59	7.83± 0.84	18.67± 0.70	7.38± 0.29	35.04± 3.21	26.79± 4.02	34.99± 7.27
	ICL$_{RL}$	3.28± 0.20	13.09± 2.93	0.72± 0.12	3.24± 0.60	1.38± 0.50	7.18± 1.41	15.78± 1.18	5.40± 0.57	39.89± 2.21	15.92± 4.75	42.30± 9.29
	ICL$_{CL}$	4.71± 0.18	14.55± 3.73	0.62± 0.09	4.63± 1.02	1.63± 0.38	6.52± 1.00	21.07± 1.66	6.54± 0.56	37.93± 1.55	17.87± 1.50	36.13± 11.74
80-100 cm												
	CS	4.57± 0.31	2.34± 0.35	0.86± 0.04	3.30± 0.73	3.73± 0.24	22.32± 1.86	75.11± 11.55	7.55± 0.90	91.95± 3.45	8.29± 1.87	63.40± 11.12
	ICL$_{NG}$	4.27± 0.38	5.02± 0.39	0.71± 0.07	2.74± 0.47	1.54± 0.47	13.08± 2.08	29.28± 5.53	4.87± 0.69	38.16± 2.67	12.54± 0.69	49.71± 16.43
	ICL$_{RM}$	4.39± 0.18	4.53± 0.53	0.73± 0.04	2.25± 0.30	1.59± 0.53	12.12± 1.93	43.65± 8.19	5.27± 0.45	58.68± 1.51	8.64± 3.12	50.55± 13.06
	ICL$_{CM}$	3.57± 0.33	4.48± 0.78	0.67± 0.08	2.53± 0.53	1.41± 0.43	12.18± 0.95	67.63± 10.18	5.47± 0.42	85.24± 1.39	6.44± 2.24	40.52± 33.63
	ICL$_{RL}$	3.92± 0.13	2.24± 0.36	0.54± 0.05	1.37± 0.57	1.44± 0.36	10.74± 1.40	21.87± 1.34	3.04± 0.58	28.06± 1.56	13.14± 1.80	58.08± 17.46
	ICL$_{CL}$	4.27± 0.20	2.10± 0.21	0.44± 0.06	1.44± 0.53	1.19± 0.16	11.52± 2.24	21.55± 2.74	2.94± 0.33	28.89± 1.48	9.41± 1.83	51.93± 13.02

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). CS, conventional system; ICLNG, integrated crop-livestock with no grazing; ICL$_{RM}$, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICL$_{CM}$, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICL$_{RL}$, integrated crop-livestock with rotational stocking and low-intensity grazing; ICL$_{CL}$, integrated crop-livestock with continuous stocking and low-intensity grazing. pH $CaCl_2$: potential de hydrogen in solution of $CaCl_2$ 0.01 mol L^{-1} (1:2.5)—active acidity; H +Al: potential acidity; SB: sum of bases; CECpH$_7$: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation.

3. CHANGES IN SOIL PHOSPHORUS POOL INDUCED BY PASTURELAND INTENSIFICATION AND DIVERSIFICATION IN BRAZIL[*]

Abstract

The adoption of more intensive and diversified pasture systems is a promising alternative to improve sustainability of grazing lands in Brazil. Phosphorus (P) is one of the main determinants of ecosystem function in these management systems; therefore, we assessed the effects of adopting more intensive and diversified pasture management systems on soil P dynamics in a set of field experiments. Treatments included fertilized pasture (FP), integrated crop-livestock (ICL), integrated livestock-forest (ILF), compared to conventional management systems (CS) under contrasting climatic conditions (tropical humid, tropical mesic and subtropical). P fractions and total P were determined by soil layer to 1 m depth. Size and distribution of P stocks were related to soil organic matter (SOM) fractions and to clay type and content. Based on the results, P biological fraction represented 9% of P in the soil, on average, in CS under the three assessed climatic conditions. Management systems with FP and the ones with ICL and ILF mainly influenced labile (0.01, 0.02 and 0.03 Mg ha^{-1} yr^{-1}, respectively), moderately labile (0.03, 0.01 and 0.07 Mg ha^{-1} yr^{-1}, respectively) and total soil P fractions (0.21, 0.08 and 0.20 Mg ha^{-1} yr^{-1}, respectively). Clay content and pH were the soil properties mostly related to P fractions; besides, P fractions presented close relationship with these fractions and with total soil C and N, as well as with different SOM fractions. These results can be the scientific basis for governmental initiatives focused on recovering degraded pasture sites in Brazil. The establishment of management practices that favor efficient P use are essential to improve the sustainability of production systems.

Keywords: Ecosystem services, Integrated crop-livestock, Integrated livestock-forest, P fractions, SOM fractions.

3.1. Introduction

Globally pastures cover approximately 3 billion ha corresponding to 67% of agricultural land and accounting for 30% of beef produced on the planet (FAO, 2003; Ramankutty et al., 2008). Pasture accounts for largest land use in Brazil of approximately 159 million ha (IBGE, 2017) accounting for ~19% of Brazil's land area, equal to about 16% of the land surface of Europe. It is estimated that from 50% to 70% of the total pasture area in Brazil suffers some degree of degradation, with forage yields of 34-36% of their real potential (Dias Filho, 2014; Strassburg et al., 2014).

In 2012, the Brazilian government launched the "ABC Plan", due to the large extent of pasture degradation and global pressures for more sustainable production (Chaudhary et al., 2018). This plan aims to finance management improvements to restore degraded extensively grazed lands with soil amendments (e.g., lime, gypsum and fertilization) and by adopting more intensively managed and diversified systems, such as fertilized pasture (FP), integrated crop-livestock systems (ICL) and integrated crop-forest (ILF). The adoption of integrated systems leads to greater diversity of products (grain, beef, timber) and thus opportunity for higher incomes to producers (Michalk et al., 2019; Cortner et al., 2019). Several studies point out that integrated systems can better mitigate greenhouse gas emissions compared to extensively grazed low-input pastures (Torres et al., 2017; Ghahramania and Bowranb, 2018), while enhancing soil chemical, physical and biological features (Liebig et al., 2017; Costa et al., 2018), mainly due to increased nutrient cycling and nutrient availability (Portilho et al., 2018; Jose et al., 2019).

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Phosphorus (P) is one of the nutrients most limiting to plant growth in many soils in tropical and subtropical environments, mainly because of the high adsorption of phosphate ions by aluminum (Al) and iron (Fe) oxides and hydroxides, which are abundant in these highly weathered soils (Novais et al., 2007). Brazil is important for global food security due to its large land base, but has a high dependence on inorganic P fertilizers for crop production due to high consumption and P adsorption (Withers et al., 2018). P adsorption to colloidal minerals in these soils is almost irreversible and reduces P availability to plants (Pavinato et al., 2009; Boitt et al., 2018). However, the adoption of more intensive and diversified pasture management systems can both increase P inputs to soil and potentially change soil P dynamics so as to increase availability to plants. In addition, integrated systems can increase SOM content through increase crop residue and manure inputs and greater organic matter input below-ground (Sulc and Franzluebbers., 2014; Salton et al., 2014). Together, these effects can change not only the P content in the soil, but also its availability to plants due to several mechanisms such as (i) higher production of organic acids (citrate) that increases P availability (Bayon et al., 2006); (ii) higher organic P content in the soil – which is lesser susceptible to strong adsorption in functional groups of Fe and Al oxides and hydroxides than inorganic P (Pavinato et al., 2017); and (iii) higher P content near the soil surface due to turnover in the root system of grass species (Merlin et al., 2015). All these changes depend on soil type, climatic conditions and management system.

In studies conducted in Brazil, Cherubin et al. (2016) and Franco et al. (2015) reported that the distribution on P among different pools in soil can be useful indicators for evaluating changes in land-use change on soil quality. In this context, the hypothesis in the current study is that intensification and diversification of extensively managed pastures (conventional management system) would result in soil P-pool modifications, mainly in the labile P fractions. The FP, ICL and ILF systems were assessed to test this hypothesis in three climate zones: tropical humid (Midwest), tropical mesic (Southeast), and subtropical (South), in Brazil.

3.2. Materials and Methods

3.2.1. Study site descriptions

Three sites were selected to assess the effects of integrated production systems on P dynamics in the soil under contrasting soil and climatic conditions in Brazil (Figure 1a). The first site was located in Nova Guarita, Mato Grosso, Midwest Brazil (Lat.: 10° 9' 10.41"S; Long.: 55° 31' 49.53"W) at 380m elevation. The prevailing soil in this site was classified as Oxisol (USDA, 2014) and the climate was classified as Aw (Köppen), tropical hot and humid, with mean annual temperature 25.9°C and mean annual rainfall of 2,628mm. The second site was located in Nova Odessa, São Paulo, South-eastern Brazil (Lat.: 22° 75' 12"S; Long.: 47° 27' 81"W) at 550m elevation. The prevailing soil in this region was also classified as Oxisol (USDA, 2014) and the climate was Cwa (Köppen), tropical rainy with dry winter, with mean annual temperature 20.2°C and mean annual rainfall of 1,262mm. The third site was located in Eldorado do Sul, Rio Grande do Sul, Southern Brazil (Lat.: 30° 05' 22"S; Long.: 51° 39' 08"W) at 46m elevation. The prevailing soil in this region was classified as Ultisol (USDA, 2014) and climate was classified as Cfa (Köppen), subtropical with mean annual temperature 19.3°C and mean annual rainfall of 1,398mm. More details about the climatic conditions in Mato Grosso (Tropical humid), São Paulo (tropical mesic) and Rio Grande do Sul (Subtropical) states can be found in Figure 1b.

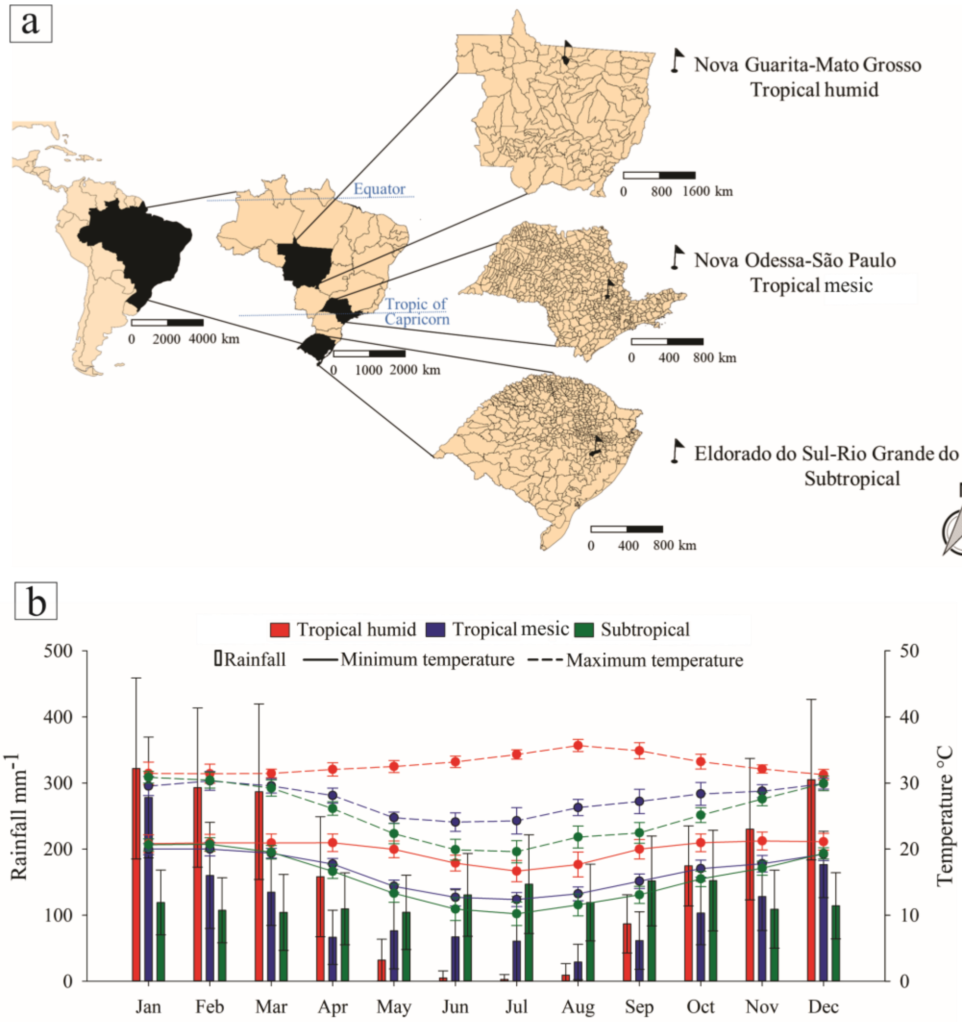


Figure 1. Geographic location (a) and mean annual rainfall, and maximum and minimum temperature in the study sites during the 38-year period (b). Bars represent the standard deviation of the mean values (n = 38). INMET (2019).

3.2.2. Systems of pasture management and soil sampling

Soil samples were collected in conventional (extensive) pasture management systems in each region. These conventional sites lacked control over grazing pressure and received no fertilization. In each region, contrasting improved management systems, with more intensive and diversified management regimes were selected, as described below:

i) Tropical humid - treatments included: 1) conventional system (CS); 2) fertilized pasture (FP) and 3) integrated crop-livestock (ICL). This site is located in the Amazonian biome and, back in 2004, its native vegetation was removed for pasture implementation under conventional management systems. In 2012 and 2015, parts of the area were converted to integrated crop-livestock and fertilized pasture systems, respectively.

ii) Tropical mesic - treatments included: 1) conventional system (CS) and 2) integrated livestock-forest (ILF). This site is located in the Atlantic Forest biome, where native vegetation was removed for the implementation of a conventional management system in 1995, parts of which were converted to an integrated livestock-forest system in 2015.

iii) Subtropical - treatments included: 1) conventional system (CS) and 2) integrated crop-livestock (ICL). This site is located in the Pampa biome, where parts of this biome were converted in 2003 to a long-term experiment with an integrated crop-livestock system.

More details about the management adopted in these sites, the applied fertilization and soil texture featuring can be found in Table 1.

Table 1. Study site descriptions.

Climatic condition	Tropical humid			Tropical mesic			Subtropical		
Description	*Brachiaria ruziziensis* Germ. & C.M. Evrard was used for pasture in management systems with CS*, FP and ICL. The management system with ICL presented history of soy/maize crops and rice/soy succession crops.			*Brachiaria brizantha* cv. Marandu was used as pasture in management systems with CS* and ILF. Two rows of African mahogany trees (*Kaya ivorensis* A. Chev.) spaced 15x5m away from each other were used in the management system with ILF.			Experiment with ICL cultivated with soy/maize succession crops in summer and with *Lolium multiflorum* Lam. in winter. The prevailing grass species in the system with CS* was *Paspalum notatum* Flügge.		
Crop nutritional management	15 kg ha^{-1} of N and 60 kg ha^{-1} of P_2O on a yearly basis.			-			18 kg ha^{-1} of N and 40 kg ha^{-1} of P_2O and 40 kg ha^{-1} of K_2O on an yearly basis.		
Pasture nutritional management	15 kg ha^{-1} of N; 80 kg ha^{-1} of P_2O and 40 kg ha^{-1} of K_2O on a yearly basis. Application of 2000 kg ha^{-1} of limestone at the time of system deployment.			100 kg ha^{-1} of N on a yearly basis.			150 kg ha^{-1} of N and 60 kg ha^{-1} of P_2O and 60 kg ha^{-1} of K_2O on a yearly basis. Application of 1000 kg ha^{-1} of limestone at the time of system deployment.		
	Oxisol[1]			Oxisol[2]			Ultisol[3]		
Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
0-10	620±21.23	67±4.24	313±8.49	561±13.44	175±7.78	264±8.49	630±7.78	220±15.56	150±8.49
10-20	610±56.57	88±7.07	302±12.02	569±0.71	176±14.14	254±11.31	625±12.03	203±2.83	170±6.36
20-40	480±21.23	67±4.24	453±20.51	520±15.56	149±7.74	331±7.07	552±11.31	221±7.07	227±6.36
40-60	412±14.85	32±2.82	556±10.61	508±25.46	143±33.23	329±16.97	525±4.95	195±8.49	280±5.66
60-80	333±72.83	47±2.83	580±81.32	493±30.41	180±9.46	327±5.66	415±7.07	201±4.24	384±19.80
80-100	385±3.53	29±2.12	585±28.25	492±46.67	179±17.68	329±4.58	350±9.90	185±4.95	464±24.75

CS, conventional system; FP, fertilized pasture; ICL, integrated crop-livestock and ILF, integrated livestock-forest .[1] Oxisol formed from tertiary sediments - the clay fraction is predominantly formed by kaolinite and Al oxide (gibbsite) (Campos et al., 2011); [2] Oxisol formed from basalt rocks - the clay fraction is predominantly formed by kaolinite, Fe oxides (goethite, hematite and magnetite/maghemite), Al oxide (gibbsite) (Cherubin et al., 2016); [3] Ultisols formed by granite rocks - the clay fraction is predominantly formed by kaolinite and Fe oxides (hematite and goethite) (Bayer et al., 2011).* No soil correction (e.g. lime, gypsum and fertilization).

Soil samples were taken in August and October 2017 at the tropical humid and subtropical sites, respectively, and in January 2018 at the tropical mesic site. Samples at each site, under each management system, were collected along transects with three sampling spots (repetitions) placed 50m away from each other. Samples were removed at depths of 0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm with a Dutch auger. Adjacently, a trench was opened to collect intact core samples with a Kopeck ring, for each depth, with three reps per treatment, to determine bulk density (BD) (Supplementary Table S1). All soil samples were air dried, ground and sieved (2mm) for subsequent analyses.

The chemical attributes of soil samples (i.e., N, P, K and pH etc.) from each management system and region were determined based on the methods described by Raij et al. (2001). Results can be found in Supplementary Table S2 (Tropical humid), S3 (tropical mesic) and S4 (Subtropical).

3.2.3. Fractionation and acid phosphatase analysis

Phosphorus (P) fractions in soil samples were determined by measuring the inorganic (Pi) and organic P (Po) as described by Hedley et al. (1982) and subsequently modified by Condron et al. (1985). This technique uses sequential chemical extractants on the same sample to progressively extract P fractions, from the most labile to the most stable pools. In total, 10 mL of extractant was added to 0.5 g soil in 15 mL centrifuge tubes (1:20 soil: solution ratio) at each step; the tubes were shaken end-over-end (vertical shaker, 60 rpm) for 16 h at 25 ℃. Extractants were used in the following order: anion exchange membrane (Piresin fraction), 0.5 M sodium bicarbonate ($NaHCO_3$) (fractions Pi_{bic} and Po_{bic}), 0.1 M sodium hydroxide (NaOH) (fractions Pi_{hyd01} and Pohyd01), 1.0 M hydrochloric acid (HCl) (fractions PiHCl) and 0.5 M NaOH (fractions Pihyd05 and Po_{hyd05}). The remaining soil was dried at 40 ºC and digested in H_2SO_4 + H_2O_2 for residual P ($P_{residual}$) determination. Phosphorus (P) concentrations were determined through the method by Murphy and Riley (1962). Total P in the alkaline extracts was determined through digestion in ammonium persulphate + H_2SO_4 and autoclaved at 121°C and 103 KPa for 2h. Inorganic P fractions (Pi) in alkaline extracts ($NaHCO_3$ and NaOH) were determined through the method by Dick and Tabatabai (1977). Then organic P (Po) was estimated as the difference between total P and Pi in the alkaline fractions.

P fractions were grouped based on relative P availability to plants, i.e., labile P (Pi_{resin} + Pi_{bic} + Po_{bic}), moderately labile P (Pi_{hyd01} + Po_{hyd01} + Pi_{HCl}) and non-labile P (Pi_{hyd05} + Po_{hyd05} + $P_{residual}$). Another way to group P fractions was proposed by Cross and Schlesinger (1995), who recommend grouping biological P pools, including all organic fractions (Po_{bic} + Po_{hyd01} + Po_{hyd05}), and the geochemical P, including all inorganic fractions and residual P (Pi_{resin} + Pi_{bic} + Pi_{HCl} + Pi_{hyd01} + Pi_{hyd05} + $P_{residual}$).

In addition to mass concentration of P fractions in the soil (mg kg^{-1}), we calculated P stocks for each pool - to 1m depth (Mg ha^{-1}) - by multiplying P concentration by bulk density and layer thickness for each field sample. Phosphorus (P) stocks in more intensive and diversified pasture management systems were adjusted on a mass equivalent basis (Ellert and Bettany 1995) relative to the conventional management system, to provide an unbiased assessment of the effect of changes in pasture management system at each site (Lee et al., 2009). Average annual P stock change rates were calculated by subtracting stocks in the conventional system at each location from stocks in the more intensive/diversified pasture systems and dividing by years since conversion.

Acid phosphatase enzyme activity was measured in samples collected at layer 0-10cm, based on the method described by Tabatabai (1994). One gram of soil was added to a solution of 5 mM p-nitrophenyl phosphate in 50 mM sodium acetate buffer (pH 4.8) at 55°C, to measure the amount of p-nitrophenol released. The reaction was stopped after 15 minutes by adding 1 ml of 0.1 M NaOH. The amount of *p*-nitrophenol released was measured in a spectrophotometer at 410nm. The unit of phosphatase activity was defined as 1nmol of *p*-nitrophenol formed per minute.

3.2.4. Total soil C and N in SOM fractions

Total soil C and N (TC and TN) were measured on dry soil samples that were ground and sieved in 100 mesh (0.149 mm) (Supplementary Figures. S1a and S1b). SOM was physically fractionated through the granulometric method modified by Christensen (1992), who used air-dried soil samples sieved in 2mm mesh (TFSA). After the end of the process (sieving+ultrasound), soil samples (20 g) were divided into the following fractions: organomineral (F1) and organic fraction (F2) (75-2000 µm); organomineral fraction F3 (53-75 µm) and organomineral fraction F4 (< 53 µm). Soil C and N content was determined using an elemental analyzer (Leco CN-2000®, St. Joseph, MI, USA). Total

C and N contents in SOM fractions were calculated by multiplying C and N concentration in each fraction by its corresponding mass (Supplementary Figures. S1c and S1d).

3.2.5. Data analysis

The effect of pasture management system under different climatic conditions on P pools were tested through analysis of variance (ANOVA) (PROC GLM). The Tukey test ($p < 0.05$) was used to compare the means in case of significant effect of each pasture management system at different depths. The Person's correlation (PROC CORR) was based on differences among P fractions in the soil, chemical attributes and clay content. Finally, principal components analysis (PROC FACTOR) was used to assess the association between P fractions in the soil and SOM fractions. All statistical analyses were carried out in the SAS-Statistical Analysis System software v.9.3 (SAS Inc., Cary, USA).

3.3. Results

3.3.1. P contents in different fractions

The adoption of more intensive and diversified pasture management systems significantly changed the amount and distribution of P fractions in the soil in comparison to CS for climate zone and across most soils depths (Figure 2). The greatest differences were observed in the labile and moderately labile P fractions of organic (Po_bic and Po_hyd0.1) and inorganic P (P_resin, Pi_bic, Pi_hyd0.1 and Pi_HCl). They showed higher P contents in the organic fractions in conventional management systems (CS), whereas the highest P contents in the inorganic fractions were observed in the more intensive and diversified management systems (FP, ICL or ILF). It is important pointing out that, besides increased P fraction contents in the soil, the adoption of more intensive and diversified pasture management systems also allowed the increased acid phosphatase activity in the 0-10 cm layer (Figure 3a). This enzyme is strongly correlated to P fractions in the soil (ranging from $0.64 < r2 < 0.86$) (Figures 3b-d).

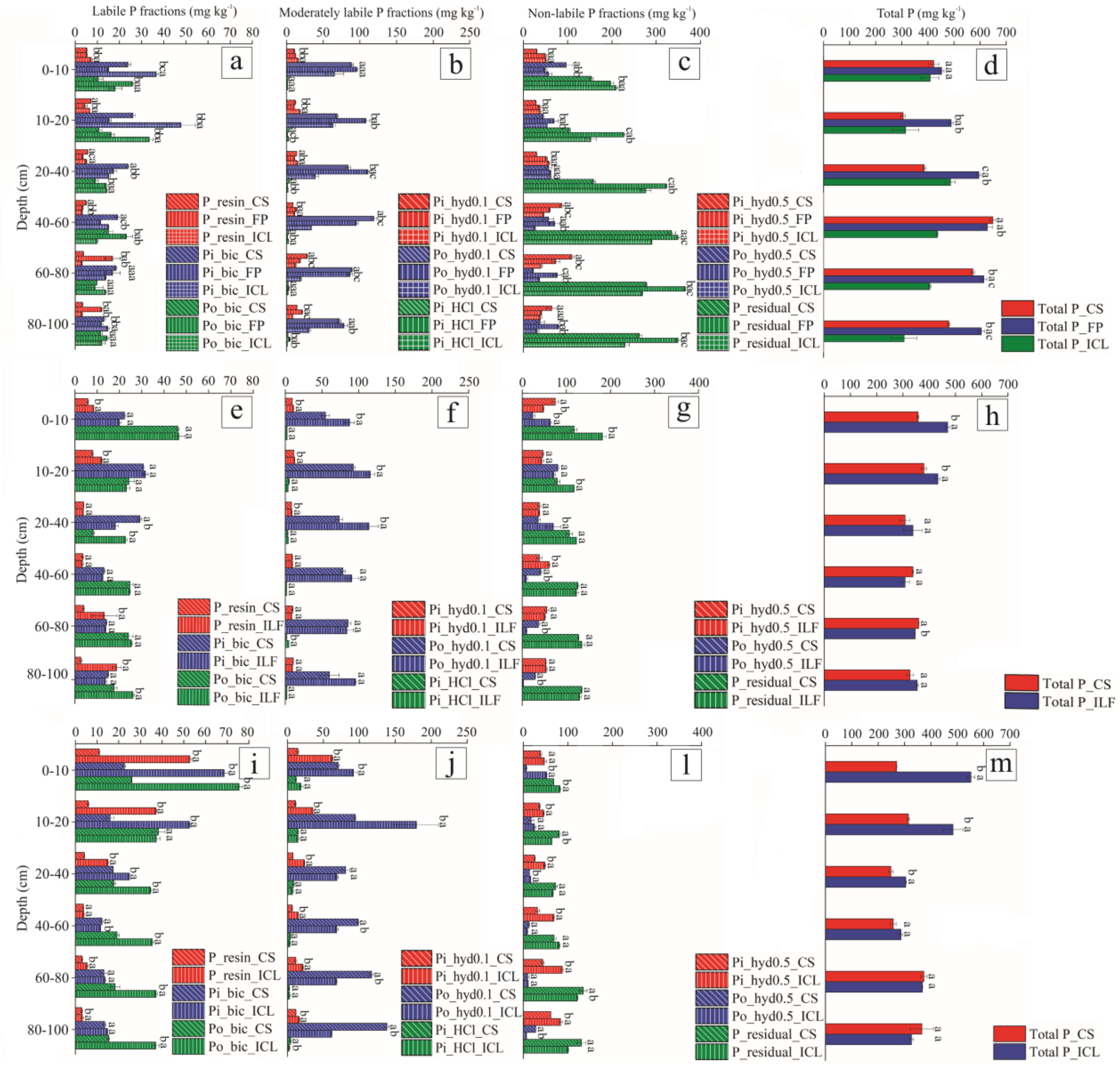


Figure 2. Phosphorus (P) contents in different fractions and in different soil layers in pasture management systems subjected to tropical humid (a, b, c and d), tropical mesic (e, f, g and h) and subtropical (i, j, l and m) climate conditions. Bars represent the standard deviation of mean values (n = 3). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

The conversion of CS into ICL at the tropical humid site increased labile P (Pi_bic and Po_bic) by 11 and 58% for the full soil depth (0-100 cm) (Figure 2). Moderately labile fractions showed Pi_hyd0.1 increase of 5% in these treatments. Increased non-labile fractions were only observed in P_residual (>22%) from CS to ICL. No increase in total P was observed in this conversion. The FP also led to increased labile P (P_resin and Po_bic) by 58 to 76% in layer 0-100 cm, in comparison to CS. There was increase in non-labile fractions (Po_hyd0.5 and P_residual) by 53 to 68% in comparison to CS. Finally, there was increase in total P after the conversion of CS into FP (>25%).

The conversion of CS into ILF under tropical mesic climate increased in the labile fractions (P_resin and Po_bic) by 38 to 154% in the 0-100 cm layer (Figure 2). We also observed an increase of 2 to 35% in all moderately labile fractions concerning (Pi_hyd0.1, Po_hyd0.1 and Pi_HCl) due ILF, in comparison to CS. Non-labile fractions only showed increase in P_residual (>21%). Total P increased due to this conversion (>25%).

Under subtropical climate, the conversion from CS to ICL led to increased labile fractions (P_resin, Pi_bic and Po_bic) by 81 to 107% for the full soil depth (0-100 cm) (Figure 2). Moderately labile fractions (Pi_hyd0.1 and Pi_HCl) also incresed by 2 to 165%. There was increase in non-labile fractions (Pi_hyd0.5 and Po_hyd0.5) by 64 to 110. This conversion of CS into ICL also recorded increased total P (>30%).

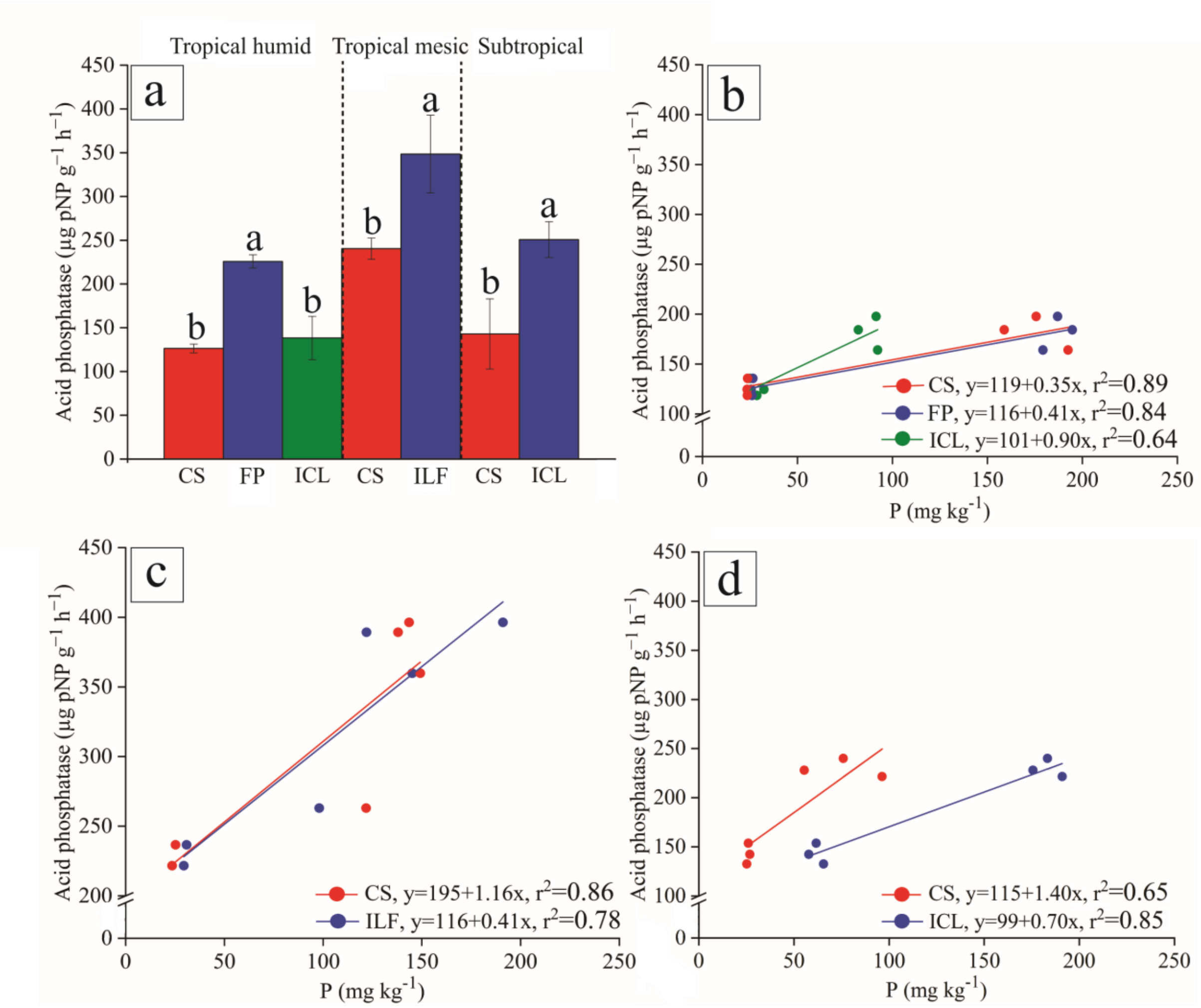


Figure 3. Acid phosphatase activity at layer 0-10 cm in the pasture management systems (a) and its association with P fractions under tropical humid (b), tropical mesic (c) and subtropical (d) climates. Bars represent the standard deviation of mean values (n = 3). Mean values followed by the same letter did not differ from each other by Tukey test (p <0.05). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

3.3.2. P stocks in different fractions

Regardless of the climate condition and assessed fraction, the lowest P stocks observed in CS (Figure 4) ranged from 0.59 to 5.16 Mg ha^{-1} in layer 0-100 cm. The FP significantly increased the P stocks, mainly in moderately labile and non-labile P fractions: 1.24 Mg ha^{-1} (>71%) and 6.35 Mg ha^{-1} (>123%), respectively, in comparison to CS (Figure 4a). Overall, the adoption of integrated systems induced P stock increase in all fractions in comparison to CS (Figure 4a-c). The adoption of ICL increased by 0.47 Mg ha^{-1} (>80%) and 1.67 Mg ha^{-1} (>205%) the labile fractions in soils subjected to tropical humid and subtropical climates, respectively. On the other hand, ILF increased by 0.76 Mg ha^{-1} (>88%) in the tropical mesic region.

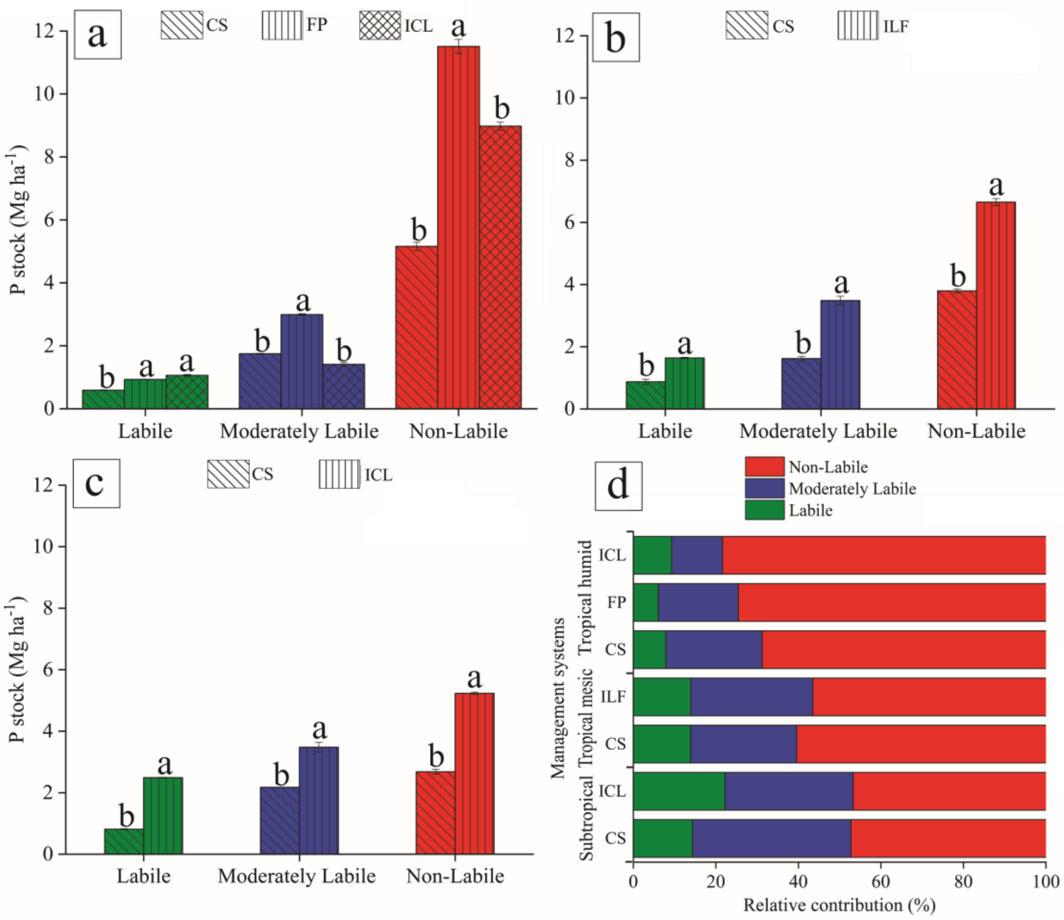


Figure 4. Labile, moderately labile and non-labile P stocks at layer 0-100 cm in different pasture management systems under tropical humid (a), tropical mesic (b) and subtropical (c) climate conditions, and the relative contribution of each fraction to Total P stock (d). Bars represent the standard deviation of the mean values (n = 3). Mean values followed by the same letter did not differ from each other by Tukey test ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

The labile fraction represented approximately 12%, 6% and 15% of the total P stock in CS, FP and in the means of integrated systems ICL and ILF, respectively (Figure 4d). Moderately labile fractions only presented increase under subtropical climate in ICL: 1.29 Mg ha^{-1} (>60%) in comparison to CS. On the other hand, ILF management increased by 1.86 Mg ha^{-1} (>115%) in comparison to CS under tropical mesic climate. Moderately labile fractions represented approximately 29%, 19% and 24% of the total P stock in CS, FP and integrated systems ICL and ILF, respectively (Figure 4d). Finally, significant increase was also observed in the non-labile fractions; increases ranged from 3.85 Mg ha^{-1} (>74%) to 6.35 Mg ha^{-1} (>123%) in integrated systems in comparison to CS. The non-labile fractions have prevailed in the soil and they represented approximately 58%, 74% and 60% of the total P stock in systems CS, FP and in integrated systems ICL and ILF, respectively. Overall, data have indicated that the more weathered the soils (tropical humid > tropical mesic > subtropical), the higher the rate of P stock in non-labile fractions (Figure 4d).

3.3.3. P stocks in biological and geochemical fractions

The most intensive and diversified pasture management systems had the greatest P stocks in the biological and geochemical P fractions in CS, under almost all climatic conditions (Figure 5). The FP system presented the highest P stocks in the biological and geochemical P fractions under tropical humid climate: increase by 2.17 Mg ha^{-1} (>87%) and 5.76 Mg ha^{-1} (>115%) in comparison to CS (Figure 5a). The adoption of the ICL system did not change the stocks of biological P; however, it increased the stocks of geochemical P by 3.89 Mg ha^{-1} (>77%) in comparison to CS (Figure 5a). According to the proportional contributions of P fractions, CS presented the greatest contribution to the biological fraction (33%), whereas ICL presented the lowest contribution (22%) to it (Figure 5d). The ICL system presented the highest contribution (78%) to the geochemical P fraction; whereas it represented the lowest contribution in CS (67%).

The adoption of integrated systems under tropical mesic and subtropical climate induced biological and geochemical P stock increase in comparison to CS (Figures 5b,c). Biological P increased by 2.29 (>89%) and 1.74 Mg ha^{-1} (>69%), and geochemical P by 3.19 (>85%) and 3.78 Mg ha^{-1} (>119%) in comparison to CS under these climates, respectively. Biological fractions (organic) represented 39%, 30% and 33% of the total P stock in the soil in CS, FL and integrated systems ICL and ILF, on average; whereas the geochemical fraction prevailed in these same systems: 61%, 70% and 66%, respectively (Figure 5d).

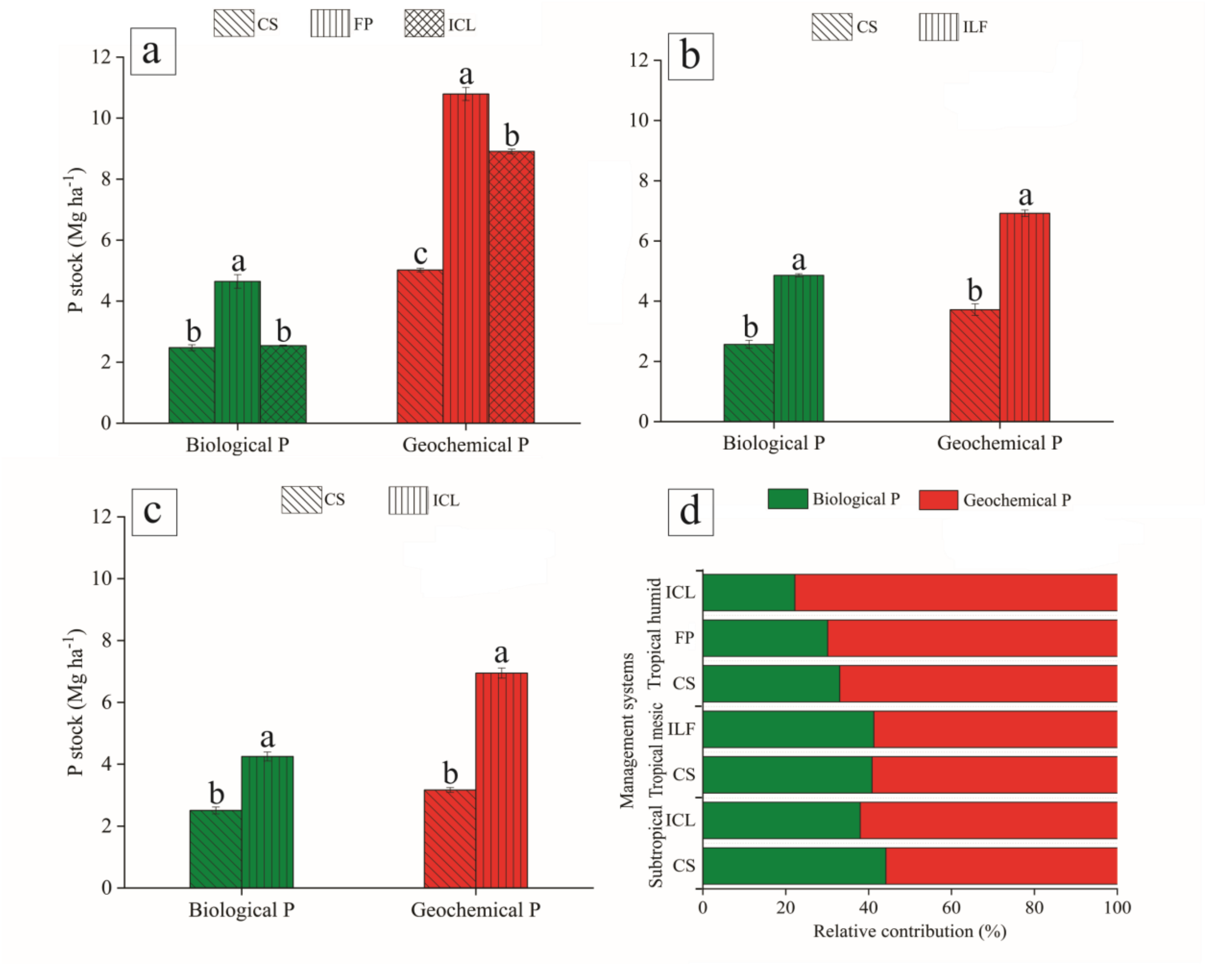


Figure 5. Biological and geochemical P stocks in layer 0-100 cm in different pasture management systems under tropical humid (a), tropical mesic (b) and subtropical (c) climates, and the relative contribution of each fraction to the total P stock (d). Bars represent the standard deviation of the mean values (n = 3). Mean values followed by the same letter did not differ from each other by Tukey test (p <0.05). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

3.3.4. Management-induced rates of change for P fractions

Overall, the annual P stock rate changes in different P fractions led to positive responses to CS conversion into more intensive and diversified pasture management systems (Figure 6). The greatest differences were observed under the tropical humid climate, in which CS conversion into FP increased labile, moderately labile and non-labile P fractions by 0.01, 0.03 and 0.17 Mg ha^{-1} yr^{-1} (Figure 6a), and biological, geochemical and total P fractions by 0.06, 0.16 and 0.21 Mg ha^{-1} yr^{-1}, respectively (Figure 6b). The adoption of ICL induced increase by 0.02 and 0.11 Mg ha^{-1} yr^{-1} in the labile and non-labile fractions (Figure 6a) and by 0.001, 0.10 and 0.09 Mg ha^{-1} yr^{-1} in the biological, geochemical and total P fractions, respectively (Figure 6b). However, a slight annual decrease (-0.01 Mg ha^{-1} yr^{-1}) was observed in the moderately-labile fractions in ICL in comparison to CS.

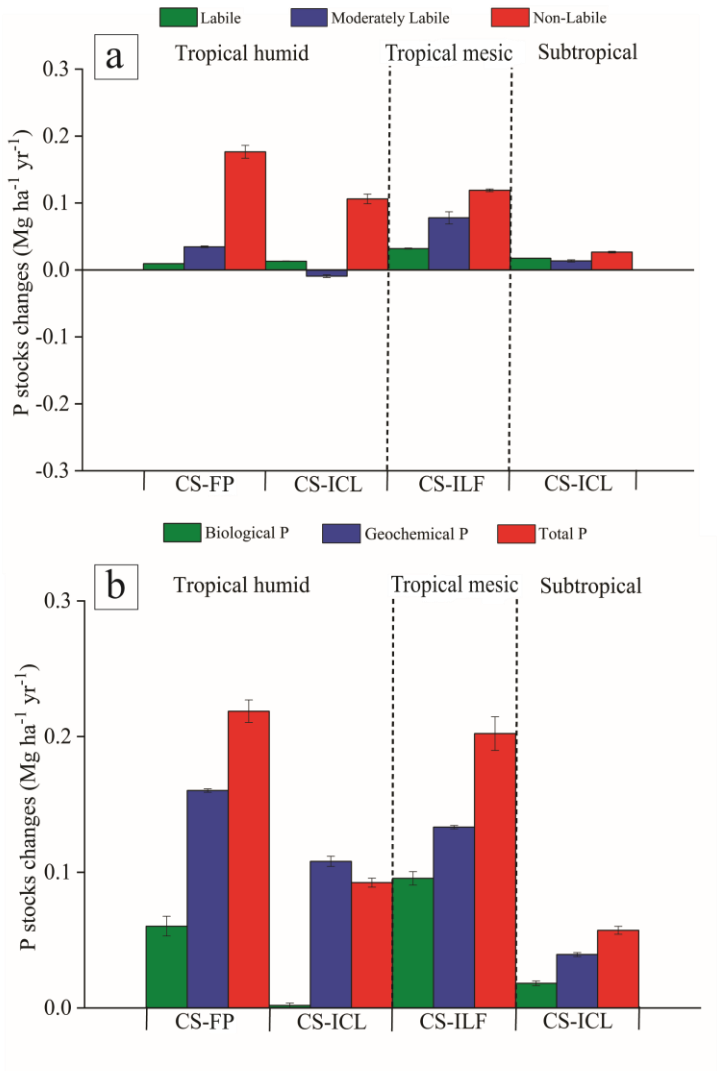


Figure 6. Annual rate of changes in the labile, moderately labile and non-labile P stocks (a) and in the biological, geochemical and total P stocks (b) in layer 0-100 cm, in comparison to the adoption of more intensive and diversified pasture management systems under each of the assessed climate conditions. Bars represent the standard deviation of the mean values (n = 3). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

The conversion of CS into ILF under tropical mesic climate also resulted in increased annual P rates in all fractions: 0.03, 0.08 and 0.11 Mg ha^{-1} yr^{-1} in the labile, moderately labile and non-labile fractions (Figure 6a) and 0.09, 0.13 and 0.20 Mg ha^{-1} yr^{-1} in biological, geochemical and total P fractions, respectively (Figure 6b). Similarly, one could also observe the positive effects of subtropical climate on the annual rates of P after ICL adoption. Different fractions presented similar values: mean increase by 0.03 Mg ha^{-1} yr^{-1} in comparison to CS.

3.3.5. Correlation between P fractions based on soil chemical attributes, clay content and association with SOM fractions

Within the pasture management systems tested, P fractions showed strong correlation to soil chemical attributes and to clay content (Table 2 and Supplementary Table S5). Overall, clay content and soil pH were the attributes presenting correlations to all assessed climatic conditions. It is important to highlighting the negative correlation of clay content to labile and biological P fractions (at r^2 ranging from -0.61 to -0.81) and the positive its correlations to moderately labile and non-labile, geochemical and total P fractions (at r^2 ranging from 0.45 to 0.76). The positive correlation of soil pH to the labile and moderately labile P fractions (at r^2 ranged from 0.44 to 0.58) stood out; whereas the positive correlation of soil chemical attributes concerning Ca, Mg, BS and CECpH7, mainly to labile and moderately labile P fractions, stood out (at r^2 ranging from 0.40 to 0.81) among the other soil chemical properties.

Table 2. Pearson's correlation coefficients between soil P pools and soil clay content, and chemical attributes.

Soil chemical attributes	Soil P pools					
	Lability			Origin		
	Labile	Mod. Labile	Non-Labile	Biological	Geochemical	Total
Clay	-0.81**	0.52*	0.45*	-0.62**	0.61**	0.76**
pH	0.44*	0.58*	0.32	0.21	0.11	0.26
K	0.21	0.05	-0.17	0.15	0.08	-0.13
Ca	0.51*	0.21	0.44*	0.05	-0.05	0.20
Mg	0.56*	-0.18	0.49*	0.43*	-0.08	0.15
BS	0.40*	0.53*	0.81*	0.18	0.46*	0.53*
CTCpH7	0.68**	0.10	0.56*	0.22	0.06	-0.17

* significant at 5% probability (p <0.05) and ** significant at 1% probability (p <0.01). Clay, clay content (g kg^{-1}); K, potassium (mmolc dm^{-3}); Ca, calcium (mmolc dm-3); Mg, magnesium (mmolc dm^{-3}); BS, base saturation (%) and CEC$_{pH7}$, potential cation exchange capacity (mmolc dm-3). Pearson's correlation was calculated by using the number of observations “n” = 72.

The P fractions showed strong association with total soil C and N and with SOM fractions (Figure 7 and Supplementary Figure S2). General results have represented 71% of the total data variation; therefore, the CS system has presented association between moderately labile and biological P fractions, and C and N in SOM fractions F1 and F2, respectively (Figure 7). The FP system presented association between non-labile and total P fractions, and C and N in SOM fraction F4. There was association of labile and geochemical P fractions with total soil C and N, as well as with C in SOM fractions F1 and F2. Finally, ILF did not lead to association with soil P fractions, but only to association between these fractions and C and N in SOM fraction F3.

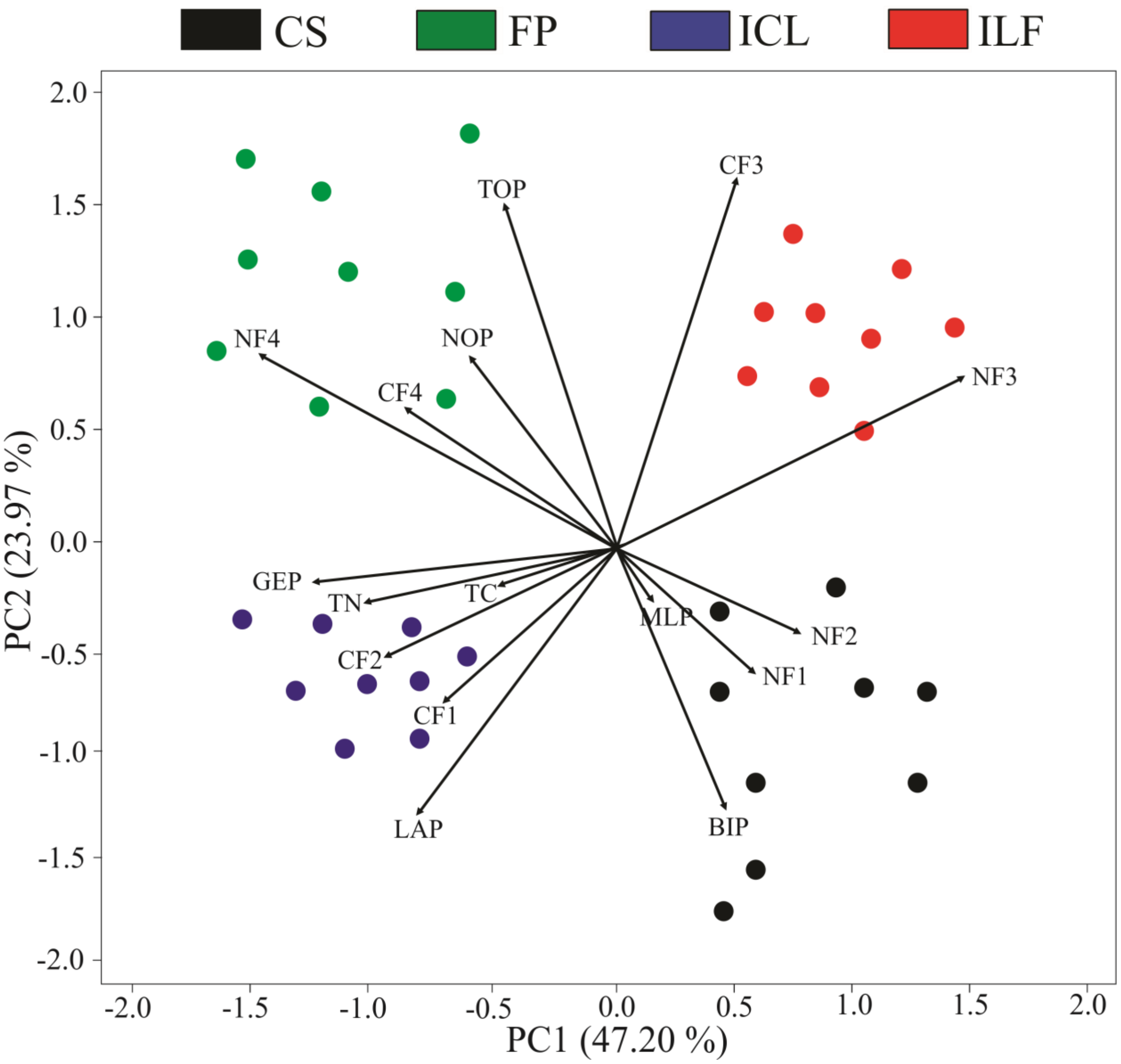


Figure 7. Principal component analysis between P fractions in the soil and C and N stock in the soil, and SOM fractions in pasture management systems under different climatic conditions in the soil layer 0-100 cm. LAP, labile P; MLP, moderately labile P; NOP, non-labile P; GEP, geochemical P; BIP, biological P; TOP, total P. TC, total soil C; TN, total soil N; CF1, total C in fraction F1; NF1, total N in fraction F1; CF2, total C in fraction F2; NF2, total N in fraction F2; CF3, total C in fraction F3; NF3, total N in fraction F3; CF4, total C in fraction F4; NF4, total N in fraction F4. Tropical humid: CS, conventional system; FP, fertilized pasture; ICL, integrated crop-livestock. Tropical mesic: CS, conventional system; ILF, integrated livestock-forest. Subtropical: CS, conventional system; ICL, integrated crop-livestock.

3.4. Discussion

3.4.1. P fractions under more intensive and diversified pasture management systems

The conversion of CS into FP led to increased organic fraction (Po_bic) and P_resin in the labile fraction (Figure 2a), as well as to organic (Po_hyd0.1 and Po_hyd0.5) and inorganic P in moderately labile (Figure 2b) and non-labile fractions (Figure 2c), respectively, as well as to increased total P (Figure 2d). Although this conversion (CS to

FP) also increased the inorganic P, it is important pointing out that the highest increase was observed in organic P. This finding corresponds to the greatest activity of acid phosphatase enzyme due to the highest content of organic P (Figures 3a and 3b), which met findings by Nesper et al. (2015), who highlight that well-managed pastures increase the organic P in the soil, mainly P from myo-inositol hexakisphosphate.

The greatest P stocks in moderately labile and non-labile P fractions were observed in FP (Figure 4a), as well as the greatest P stocks in the biological and geochemical P fractions (Figures 5a). The greatest P stocks in the most stable fractions (moderately labile, non-labile and geochemical P) in this management system can be explained by the "natural" process of P adsorption applied by fertilizer to the mineral colloids of weathered soils (Fe and Al oxides) and proven by the increased P contents under this management system (Supplementary Table S2). Higher P stocks in more stable fractions corroborate the findings by Conte et al. (2003), where they reported that pasture sites fertilized with phosphate can be prone to P immobilization in the soil.

The CS conversion into ICL under tropical humid and subtropical climate led to the greatest Pi_bic and Po_bic increase in labile P fractions (Figures 2a and 2e) and to Pi_hyd0.1 increase in moderately labile P fractions (Figures 2b and 2f). The main difference in this conversion under the two climates is observed under the subtropical climate condition, which showed P_resin and total P increase – this effect can be also attributed to implementation time. Cooler temperatures in subtropical climate regions allow slower mineralization of surface organic waste than the tropical humid climate, and this process can broaden the constant presence of carboxylic and phenolic groups with potential to block P adsorption sites in Fe and Al oxides (Gatiboni et al., 2015). Moreover, the used grass species (Lolium multiflorum Lam.) presented more significant P release into the soil due to the mineralization of crop waste in comparison to the grass species used under tropical humid climate (*Brachiaria spp*) (Semmartin et al., 2008; Almeida et al., 2018). Yet, the effect of subtropical climate (low temperatures) did not influence the activity of acid phosphatase (Figures 3a and 3d), and this finding is in compliance with studies that have reported that climate does not influence the activity of this enzyme (Turner et al., 2003; Xiao-Guang et al., 2011). The most important effect results from the quality of the management system. The shortest implementation time may explain the absence of total P increase in ICL under tropical humid climate, and this outcome corroborates the study by Deiss et al. (2016), who highlighted that management systems with ICL lead to greater P output through production components (beef and grains). The increase in total P response is slower than that found in systems with annual crops and/or pasture.

Management systems with ICL under tropical humid and subtropical climate have presented the greatest P stocks, mainly in the labile fraction (Figures 4a and 4c). It is noteworthy that this effect results from the greater and constant input of inorganic P through fertilization; however, one cannot neglect the importance of different crop types and animals in these sites, since they give more cycling to soil P through organic waste deposition and decomposition (Fernandes et al., 2002; Rotta et al., 2015). Besides, the animal component greatly influences P cycling, because animals have the ability to hydrolyse phytates into orthophosphates in their digestive system, and these orthophosphates will be available for plants and microorganisms (Humer and Zebeli, 2015). It is essential to point out that ICL under subtropical climate condition has presented the greatest P stock in the geochemical P fraction (Figures 5c). Costa et al. (2014) also found greater P stocks in this fraction at depth 0-20 cm when they assessed a management system with ICL under subtropical conditions. They suggested that the geochemical P rates in deeper layers could be higher, and this hypothesis was confirmed by the P evaluation carried out in deeper soil layers (100 cm) in the current study. The greatest geochemical P stock in the management system can also be related to the fact that, at the end of grazing, part of the vegetal materials under and on the ground remains in the site, and it contributes to the accumulation of a greater stock of geochemical P throughout the cultivation time. These inorganic reactions mostly regulate the P cycle in the soil (Floate and Torrance, 1970; Rheinheimer and Anghinoni, 2003).

The CS conversion into ILF under tropical mesic conditions increased the P contents in the labile fractions (P_resin and Po_bic) and in all moderately labile fractions (Pi_hyd0.1, Po_hyd0.1 and Pi_HCl) (Figures 2e and 2f). Management systems with ILF presented greater volume of fine roots (~1.85 mg cm^{-3}), and these roots accounted for the lowest root exudate rates - this process stimulates the microbial community in the soil (Upson and Burgess, 2013). The exudate/root combination can change the organic and inorganic forms of P in the soil, which are available for plants and increase the activity of enzyme acid phosphatase (Figures 3a and 3c), as well as allow greater interaction between roots and mycorrhizal fungi in the soil – these fungi are important for soil P cycling (Chen et al., 2004; Achat et al., 2012; Nash et al., 2014). The ILF system also showed increase in non-labile (P_residual) and total P fractions, and this outcome suggests that, despite the short implementation time, this management system is efficient to fulfil plants' P needs and to accumulate the excesses of P in non-labile forms in the soil.

The ILF system under tropical mesic climate presented the greatest P stocks, mainly in the labile, moderately labile (Figure 4b) and biological fractions (Figure 5b). The positive effect of ILF in comparison to CS on these fractions was assessed by Wang et al. (2017), who have explained that management systems based on perennial grass species increase P reabsorption efficiency and, consequently, exhaust P availability in the soil (labile and moderately labile fractions). This process slowly reduces microbial P biomass in the biological fraction. Yet, the initial ILF installation stage can benefit from the greatest P contents in the soil, since P from organic waste decomposition – which adds to the soil – is more significant than its absorption by trees, a fact that improves the quality of P in the labile fractions and increases the demands by microorganisms in the soil (Fan et al., 2015).

3.4.2. Time evaluation of P stocks in more intensive and diversified pasture management systems

The comparison between pasture systems under different climatic conditions to assess the rates of annual changes in P stocks in the soil showed that, overall, more intensive and diversified pasture management systems have more positive responses in comparison to CS (Figure 6). Regardless of the management system, higher rates of annual changes in P stocks were observed under tropical humid climate (0.15 Mg ha^{-1} yr^{-1}). This outcome accounts for 36% and 400% increase in P stocks under tropical mesic and subtropical climate conditions, which have recorded mean annual changes of 0.11 and 0.03 Mg ha^{-1} yr^{-1}, respectively. Roy et al. (2017) conducted a study with phosphate fertilization in a grain production site under tropical humid climate and found annual changes in P stocks by 0.014 Mg ha^{-1} yr^{-1} in the 0-20 cm layer. They have concluded that even after 30 years of intensive application of phosphate fertilizer, soil adsorption ability remained high – approximately ¾ of P applied to the soil remained unavailable for plants. This information reinforces the importance of assessing different climatic conditions and soil types when it comes to the implementation of more intensive and diversified pasture management systems, mainly because of the great soil and climate heterogeneity in Brazil.

Only the conventional management conversion into ICL, under tropical humid climate, recorded negative annual change rates: -0.08 Mg ha^{-1} yr^{-1} in the moderately labile fraction (Figure 6a). According to MacDonald et al. (2012), the labile and moderately labile P fractions are strongly influenced by the management system under tropical climate conditions, mainly in soil presenting low P content, such as the case of ICL under tropical humid climate in the current study - this efficiency will be mainly influenced by cultivation time. MacDonald et al. (2011) carried out a global study about P content in agricultural soils and found that only 34% (0.004 Mg ha^{-1} yr^{-1}) of the total P stocked in the soil (0.013 Mg ha^{-1} yr^{-1}) was in its labile form. Similar results were found in the present study: the mean of labile P proportion in the rates of annual changes in P stocks in the soil reached 33%, 37% and 42% among pasture management systems under tropical humid, tropical mesic and subtropical climate conditions, respectively.

3.4.3. Linking soil P pools to soil chemical and organic matter attributes in pasture management systems

The strong correlation to soil chemical attributes, mainly to clay content and pH (Table 2), stand out among the main effects leading to the greatest P accumulation in the soil given the adoption of more intensive and diversified pasture management systems (sections 4.1 and 4.2). The close relationship between P fractions in the soil and clay content can be explained by the prevalence of Fe and Al oxides and hydroxides in soil constitution, a fact that allows great adsorption of phosphates (Novais et al., 2007; Conte et al., 2003). On the other hand, correlations to pH result from greater P solubility due to P content increase (Gama-Rodrigues et al., 2014; Kruse et al., 2015), which results from more intensive and diversified management systems. Cherubin et al. (2016) performed a study about the dynamics of different P fractions in the soil in a site subjected to the conversion of native forest into pasture and sugarcane crops. They found negative correlations between clay content and biological and labile P fractions, and positive correlation of it to the geochemical P fractions, as well as positive correlation between pH and labile and biological P fractions. The correlations found by Cherubin et al. (2016), meet the results in the present study, and indicates that these P fractions (biological, labile and geochemical) account for the greatest variations in changes resulting from different management systems.

The P fractions have also presented close relationship with the SOM fractions, which shows that SOM is also an important is an important parameter for studies about the dynamics of P in tropical ecosystems (Figure 7). The relationship between P and SOM fractions is of great importance, as according to Hagyóa and Tóth (2018), P and SOM are the main attributes used in international inventories for soil quality assessment in croplands and grasslands. The CS assessed under the three climatic conditions showed similar correlation between moderately labile and biological P fractions and N in SOM fractions F1 and F2. The strong relationship of CS with labile and biological P fractions in addition to the SOM fractions points out the strong dependence of biomass production on the grassland site, because SOM fractions F1 and F2 were formed by less transformed vegetal waste, which holds the P from fungi that decompose such waste. The high dependence of the CS of biomass production on the grassland site, explains why organic P fractions (e.g., labile and biological fractions) are expected to undergo faster enzymatic hydrolysis (Salas et al., 2003; Von Lützow et al., 2007). However, the high dependence of the CS of biomass production on the grassland site can also highlight the high susceptibility of these systems to degradation, mainly because of excessive grazing, which compromises the recycling of nutrients by biomass, such as P.

The relationship between non-labile and total P fractions and C and N stocks in SOM fraction F4 in the FP system under tropical humid climate has shown that phosphate fertilizer application along with limestone may have had some effect on such relationship (Figure 7). Fonte et al. (2014) found higher organic P contents in well-managed pasture sites in comparison to the conventional management and this outcome suggests that this effect can be associated with differences in soil structure. In the case of the present study, Ca^{2+} increase resulting from limestone application (Supplementary Table S2) works as ionic bridge between SOM bond to clay particles (F4). This process improves soil aggregation and protects the organic forms of P (Briedis et al., 2012).

There was association between labile and geochemical P fractions and total soil C and N, and C in SOM fractions F1 and F2 in ICL under tropical humid and subtropical climate (Figure 7). The strong relationship between the P fractions (labile and geochemical) mainly with the total soil N, can be firstly attributed to the high demand for N by crops in the ICL system to increase biomass, as well as to the high dependence of organic P in systems poor in this nutrient, such as the case of the tropical humid climate condition (Ziadi et al., 2008). Furthermore, ICL is efficient to provide vegetal waste (F1 and F2) in order to fulfil microbial activity demands in the soil and, consequently, to improve the input of P available for plants (labile P). The association between labile P fractions and SOM fractions F1 and F2 may have resulted from the constant supply of animal and vegetal waste to microbial activity, since this process favors SOM mineralization, a fact that may have influenced C and N accumulation in the soil (Six et al., 2002), as well as C and N relationship with such P fraction.

There was not association between P fractions and ILF under tropical mesic climate conditions, but strong ILF correlation to C and N in SOM fraction F3 (Figure 7). The ILF system greatly influenced C in the SOM fractions, which had intermediate recalcitrance in the soil (F3). This SOM fraction can be working as gradual P release source in the soil, as well as occupying P absorption location in the soil and, consequently, increasing its availability (Fontaine et al., 2007; Rocha et al., 2015). The multifunctionality of this SOM fraction (F3), which acts as P source in the soil and occupies P absorption location in it, can account for the lack of influence of a given specific P fraction in the ILF system. Therefore, further studies must be carried out in order to better understand such association in soils subjected to this management system.

3.5. Conclusions

Pasture intensification and diversification in sites previously managed under extensive practices (CS) have changed the soil P fraction dynamics. The CS, without fertilization, presented the lowest P contents in the soil and the highest organic P proportions (39%). This outcome suggests that P availability to fulfil plants' nutritional demands depends on SOM turnovers (Organic P). Management systems with FP increase the P content in the soil; however, this P is mainly accumulated in moderately labile (0.03 Mg ha^{-1} yr^{-1}) and non-labile P fractions (0.17 Mg ha^{-1} yr^{-1}). Integrated systems (ICL and ILF) led to greater P content increase, mainly in labile (0.02 and 0.03 Mg ha^{-1} yr^{-1}, respectively), moderately labile (0.01 and 0.08 Mg ha^{-1} yr^{-1}, respectively) and total P fractions (0.06 and 0.20 Mg ha^{-1} yr^{-1}, respectively).

There was a close relationship between the P fractions with total soil C and N and with SOM fractions; overall, labile, moderately labile and biological P fractions were more closely correlated to SOM fractions F1 (organomineral) and F2 (organic fraction 75-2000 µm), and the non-labile and geochemical P fractions had greater correlation to SOM fractions F3 (53-75 µm) and F4 (< 53 µm). The results also indicate that the P dynamics in the soil in pasture sites is closely related to SOM dynamics. The labile and moderately labile P fractions are related to SOM organomineral (F1) and organic fractions (75-2000 µm), whereas the non-labile P fractions are related to SOM organomineral fractions F3 (53-75 µm) and F4 (< 53 µm).

The results found in this study may help efforts (e.g., Brazil´s NDC and ABC Program) focused on recovering degraded pasture sites in Brazil. The establishment of management practices that favor efficient P use are essential to improve the sustainability of production systems. In addition, the adoption of sustainable management systems can reduce the dependence on P fertilizers imports and also contribute to reducing the depletion of global P resources. Moreover, these results can also help mathematical models (such as Century and DayCent) whose aim lies on predicting P contents based on management system changes throughout time in tropical pasture sites.

References

Achat, D.L., Augusto, L., Bakker, M.R., Gallet-Budynek, A., Morel, C., 2012. Microbial processes controlling P availability in forest spodosols as affected by soil depth and soil properties. Soil Biol. Biochem. 44, 39-48.

Almeida, D.S., Penn, C.J., Rosolem, C.A., 2018. Assessment of phosphorus availability in soil cultivated with ruzigrass. Geoderma 312, 64-73.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pillon, C.N., Sangoi, L., 2001. Changes in Soil Organic Matter Fractions under Subtropical No-Till Cropping Systems. Soil Sci. Soc. Am. J. 65, 1473–1478.

Bayon, R.C.L., WeisskoFP, L., Martinoia, E., Jansa, J., Frossard, E., Keller, F., Gobat, J.M., 2006. Soil phosphorus uptake by continuously cropped Lupinus albus: a new microcosm design. Plant Soil 283, 309–321.

Boitt, G., Schmitt, D.R., Gatiboni, L.C., Wakelin, S.A., Black, A., Sacomori, W., Cassol, P.C., Condron, L.M., 2018. Fate of phosphorus applied to soil in pig slurry under cropping in southern Brazil. Geoderma 321, 164-172.

Briedis, C., Sá, J.C. de M., Caires, E.F., Navarro, J. de F., Inagaki, T.M., Boer, A., Neto, C.Q., Ferreira, A. de O., Canalli, L.B., Santos, J.B. dos, 2012. Soil organic matter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. Geoderma 170, 80–88.

Campos, M.C.C., Ribeiro, M.R., Júnior, V.S.S., Filho, M.R.R., Souza, R.V.C.C., Almeida, M.C., 2011. Características mineralógicas de latossolos e argissolos na região sul do Amazonas. Rev. Acad., Ciênc. Agrár. Ambient. 9, 11-18.

Condron, L.M., Goh, K.M., Newman, R.H., 1985. Nature and distribution of soil phosphorus as revealed by a sequential extraction method followed by 31P nuclear magnetic resonance analysis. J. Soil Sci. 36, 199–207.

Costa, S.E.V.G.A., Souza, E.D., Anghinoni, I., Carvalho, P.C.F., Martins, A.P., Kunrath, T.R., Cecagno, D., Balerini, F., 2014. Impact of an integrated no-till crop–livestock system on phosphorus distribution, availability and stock. Agric. Ecosyst. Environ. 190, 43–51.

Costa, M.P., Schoeneboom, J.C., Oliveira, S.A., Vinas, R.S., Medeiros, G.A., 2018. A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. J. Clean Prod. 171, 1460-1471.

Conte, E., Anghinoni, I., Rheinheimer, D.D.S., 2003. Phosphorus accumulation fractions in a clayey oxisol in relation to phosphate doses under no-tillage. Rev. Bras. Cienc. Solo 27, 893–900.

Cortner, O., Garrett, R.D., Valentim, J.F., Ferreira, J., Niles, M.T., Reis, J., Gil, J., 2019. Perceptions of integrated crop-livestock systems for sustainable intensification in the Brazilian Amazon. Land use policy 82, 841-853.

Chaudhary, A., Gustafson, D., Mathys, A., 2018. Multi-indicator sustainability assessment of global food systems. Nat. Commun. 9, 1-13.

Cherubin, M.R., Franco, A.L.C., Cerri, C.E.P., Karlen, D.L., Pavinato, P.S., Rodrigues, M., Davies, C.A., Cerri, C.C., 2016. Phosphorus pools responses to land-use change for sugarcane expansion in weathered Brazilian soils. Geoderma 265, 27–38.

Chen, C., Condron, L., Turner, B., Mahieu, N., Davis, M., Xu, Z., Sherlock, R., 2004. Mineralisation of soil orthophosphate monoesters under pine seedlings and ryegrass. Aust. J. Soil Res. 42, 189–196.

Cross, A.F., Schlesinger, W.H., 1995. A literature review and evaluation of the Hedley fractionation: applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 64, 197–214.

Christensen, B.T., 1992. Physical Fractionation of Soil and Organic Matter in Primary Particle Size and Density Separates. In: Stewart, B.A. (Ed), Advances in Soil Science, Springer, New York, pp. 1–90.

Dick, W.A., Tabatabai, M.A., 1977. Determination of orthophosphate in aqueous solutions containing labile organic and inorganic phosphorus compounds. J. Environ. Qual. 6, 82–85.

Deiss, L., Moraes, A., Dieckow, J., Franzluebbers, A.J., Gatiboni, L.C., Sassaki, G.L., Carvalho, P.C.F., 2016. Soil phosphorus compounds in integrated crop-livestock systems of subtropical Brazil. Geoderma 274, 88–96.

Dias Filho, M.B. Diagnóstico das pastagens no Brasil-Embrapa. Brasil, Brasília, pp. 1-36.

Ellert, B. H., Bettany, J. R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soit Sci. 75, 529-538.

Fan, H., Wu, J., Liu, W., Yuan, Y., Hu, L., Cai, Q., 2015. Linkages of plant and soil C:N:P stoichiometry and their relationships to forest growth in subtropical plantations. Plant Soil 392, 127–138.

Fernandes, L.A., Faquin, V., Furtini, A.E., Curi, N., 2002. Phosphorus forms in lowland soils and hbioavailability to bean plants. Pesq. Agropec. Bras. 37, 373–383.

FAO, 2003. Food and agriculture organization of the united nations. FAO, Rome.

Fonte, S.J., Nesper, M., Hegglin, D., Velasquez, J.E., Ramirez, B., Rao, I.M., Bernasconi, S.M., Bünemann, E.K., Frossard, E., Oberson, A., 2014. Pasture degradation impacts soil phosphorus storage via changes to aggregate-associated soil organicmatter in highly weathered tropical soils. Soil Biol. Biochem. 68, 150–157.

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., Rumpel, C., 2007. Stability of organic carbon in deep soil depths controlled by fresh carbon supply. Nature 450, 277–280.

Floate, M.J.S., Torrance, C.J.W., 1970. Decomposition of the organic materials from hill soils and postures. J. Sci. Food Agric. 21, 116–120.

Franco, A.L.C., Cherubin, M.R., Pavinato, P.S., Cerri, C.E.P., Six, J., Davies, C.A., Cerri, C.C., 2015. Soil carbon, nitrogen and phosphorus changes under sugarcane expansion inBrazil. Sci. Total Environ. 515-516, 30–38.

Gatiboni, L.C., Smyth, T.J., Schmitt, D.E., Cassol, P.C., Oliveira, C.M.B., 2015. Soil phosphorus thresholds in evaluating risk of environmental transfer to surface waters in Santa Catarina, Brazil. Rev. Bras. Cienc. Solo. 39:1225-34.

Ghahramania, A., Bowranb, D., 2018. Transformative and systemic climate change adaptations in mixed croplivestock farming systems. Agr. Syst. 164, 236-251.

Gama-Rodrigues, A.C., Sales, M.V.S., Silva, P.S.D., Comerford, N.B., Cropper, W.P., Gama-Rodrigues, E.F., 2014. An exploratory analysis of phosphorus transformations in tropical soils using structural equation modeling. Biogeochemistry 118, 453–469.

Hedley, M.J., Stewart, J.W.B., Chauhan, B.S., 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46, 970–976.

Hagyóa, A., Tóth, G., 2018. The impact of environmental policy on soil quality: Organic carbon and phosphorus levels in croplands and grasslands of the European Natura 2000 network. J. Environ. Manage. 223, 9–15.

Humer, E., Zebeli, Q., 2015. Phytate in feed ingredients and potentials for improving the utilization of phosphorus in ruminant nutrition. Anim. Feed Sci. Technol. 209, 1–15.

IBGE, 2017. Instituto Brasileiro de Geografia e Estatística. Censo Agropecuário 2017. IBGE, Rio de Janeiro, Rio de Janeiro.

INMET, 2019. Instituto Nacional de Meteorologia. INMET, Brasília, Distrito Federal.

Jose, S., Walter, D., Kumar, B.M., 2019. Ecological considerations in sustainable silvopasture design and management. Agroforest Syst. 93, 317–331.

Kruse, J., Abraham, M., Wulf Amelung, W., Baum, C., Bol, R., Oliver Kuhn, O., Hans Lewandowski, H., Niederberger, J., Oelmann, Y., Ruger, C., Santner, J., 2015. Innovative methods in soil phosphorus research: A review. J. Plant Nutr. Soil Sci. 178, 43–88.

Lee, J., Hopmans, J.W., Rolston, D.E., Baer, S.G., Six, J., 2009. Determining soil carbon stock changes: simple bulk density corrections fail. Agric. Ecosyst. Environ. 134, 251–256.

Liebig, M.A., Ryschawy, J., Kronberg, S.L., Archer, D.W., Scholljegerdes, E.J., Hendricksona, J.R., Tanaka, D.L., 2017. Integrated crop-livestock system effects on soil N, P, and pH in a semiarid region. Geoderma 289, 178–184.

Michalk, D.L., Kemp, D.R., Badgery, W.B., Wu, J., Zhang, Y., Thomassin, P.J., 2019. Sustainability and future food security—A global perspective for livestock production. Land Degrad. Dev. 30, 561–573.

Merlin, A., Rosolem, C.A., He, Z.L., 2015. Non-labile phosphorus acquisition by brachiarias. J. Plant. Nutr. 39, 1319–27.

MacDonald, G.K., Bennett, E.M., Taranu, Z.E., 2012. The influence of time, soil characteristics, and land-use history on soil phosphorus legacies: a global meta-analysis. Glob. Chang. Biol. 18, 1904–1917.

MacDonald, G.K., Bennett, E.M., Potter, P.A., Ramankutty, N., 2011. Agronomic phosphorus imbalances across theworld's croplands. Proc. Natl. Acad. Sci. U. S. A. 108, 3086–3091.

Nash, D.M., Haygarth, P.M., Turner, B.L., Condron, L.M., McDowell, R.W., Richardson, A.E., Watkins, M., Heaven, M.W., 2014. Using organic phosphorus to sustain pasture productivity: a perspective. Geoderma 221, 11–19.

Nesper, M., Bünemann, E.K., Fonte, S.J., Rao, I.M., Velásquez, J.E., Ramirez, B., Hegglin, D.J., Frossard, E., Oberson, A., 2015. Pasture degradation decreases organic P content of tropical soils due to soil structural decline. Geoderma 257-258, 123–133.

Novais, R.F., Smyth, T.J., Nunes, F.N., 2007. Fósforo. In: Novais, R.F., Alvarez, V.V.H., Barros, N.F., Fontes, R.L.F., Cantarutti, R.B., Neves, J.C.L. (Eds.), Fertilidade do Solo. Sociedade Brasileira de Ciência do Solo, Viçosa – MG, pp. 471–550.

Portilho, I.I.R., Savin, M.C., Borges, C.D., Tsai, S.M., Mercante, F.M., Roscoe, R., Carvalho, L.A., 2018. Maintenance of N cycling gene communities with crop-livestock integration management in tropical agriculture systems. Agric Ecosyst Environ. 267, 52-62.

Pavinato, P.S., Merlin, A., Rosolem, C.A., 2009. Phosphorus fractions in Brazilian Cerradosoils as affected by tillage. Soil Tillage Res. 105, 149–155.

Pavinato, P.S., Soltangheisi, M.R.M.A., Sartor, L.R., Withers, P.J.A., 2017. Effects of cover crops and phosphorus sources on maize yield, phosphorus uptake, and phosphorus use efficiency. Agron. J. 109, 1039-1047.

Raij, B., Andrade, J.C., Cantarella, H., Quaggio, J.A., 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico de Campinas, Campinas. pp. 285.

Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob. Biogeochem. Cycles 22, 1-9.

Rotta, L.R., Barbosa, H., Anghinoni, I., De Souza, E.D., Lopes, G., Carneiro, A.C., 2015. Phosphorus fractions and availability in a haplic plinthosol under under no-tillage system in the Brazilian cerrado. Ciênc. Agrotec. 39, 216–224.

Rocha, J.H.T., Santos, A.J.M., Diogo, F.A., Backes, C., Melo, A.G.C., Borelli, K., Godinho, T.O., 2015. Reflorestamento e recuperação de atributos químicos e físicos do solo. Floresta Ambient. 22, 299- 306.

Roy, E.D., Willig, E., Richards, P.D., Martinelli, L.A., Vazquez, F.F., Pegorini, L., Spera, S.A., Porder, S., 2017. Soil phosphorus sorption capacity after three decades of intensive fertilization in Mato Grosso, Brazil. Agr. Ecosyst. Environ. 249, 206–214.

Rheinheimer, D.S., Anghinoni, I., 2003. Accumulation of soil organic phosphorus by soil tillage and cropping systems under subtropical conditions. Comm. Soil Sci. Plant Anal. 34, 2339–2354.

Salas, A.M., Elliott, E.T., Westfall, D.G., Cole, C.V., Six, J., 2003. The role of particulate organic matter in phosphorus cycling. Soil Sci. Soc. Am. J. 67 (1), 181–189.

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M., 2014. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agric. Ecosyst. Environ. 190, 70–79.

Sulc, R.M., Franzluebbers, A.J., 2014. Exploring integrated crop–livestock systems in different ecoregions of the United States. Eur. J. Agron. 57, 21-30.

Semmartin, M., Garibaldi, L.A., Chaneton, E.J., 2008. Grazing history effects on above- and below-ground litter decomposition and nutrient cycling in two co-occurring grasses. Plant Soil 303, 177–189.

Strassburg, B.B.N., Latawiec, A.E., Barioni, L.G., Nobre, C.A., Silva, V.P., Valentim, J.F., Vianna, M., Assad, E.D., 2014. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Global Environ Chang. 28, 84-97.

Six, J., Feller, C., Denef, K., Ogle, S.M., Moraes, Sa, J.C., Albrecht, A., 2002. Soil organic matter, biota and aggregation in temperate and tropical soils – Effects of no-tillage. Agronomie 22, 755–775.

Torres, C.M.M.E., Jacovine, L.A.G., Neto, S.N.O., Fraisse, C.W., Soares, C.P.B., Neto, F.C., Ferreira, L.R., Zanuncio, J.C., Lemes, P.G., 2017. Greenhouse gas emissions and carbon sequestration by agroforestry systems in southeastern Brazil. Sci. Rep. 7, 1-7.

Turner, B.L., Cade-Menun, B.J., Westermann, D.T., 2003. Organic phosphorus composition and potential bioavailability in semi-arid arable soils of the western united states. Soil Sci. Soc. Am. J. 67, 1168–1179.

USDA, 2014. Keys to Soil Taxonomy, USDA—Natural Resources Conservation Service; Washington, USA.

Upson, M.A., Burgess, P.J., Morison, J.I.L., 2016. Soil carbon changes after establishing woodland and agroforestry trees in a grazed pasture. Geoderma 283, 10–20.

Von Lutzow, M., Kogel-Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., 2007. SOM fractionation methods: Relevance to functional pools and to stabilization mechanisms. Soil Biol. Biochem. 39, 2183–2207.

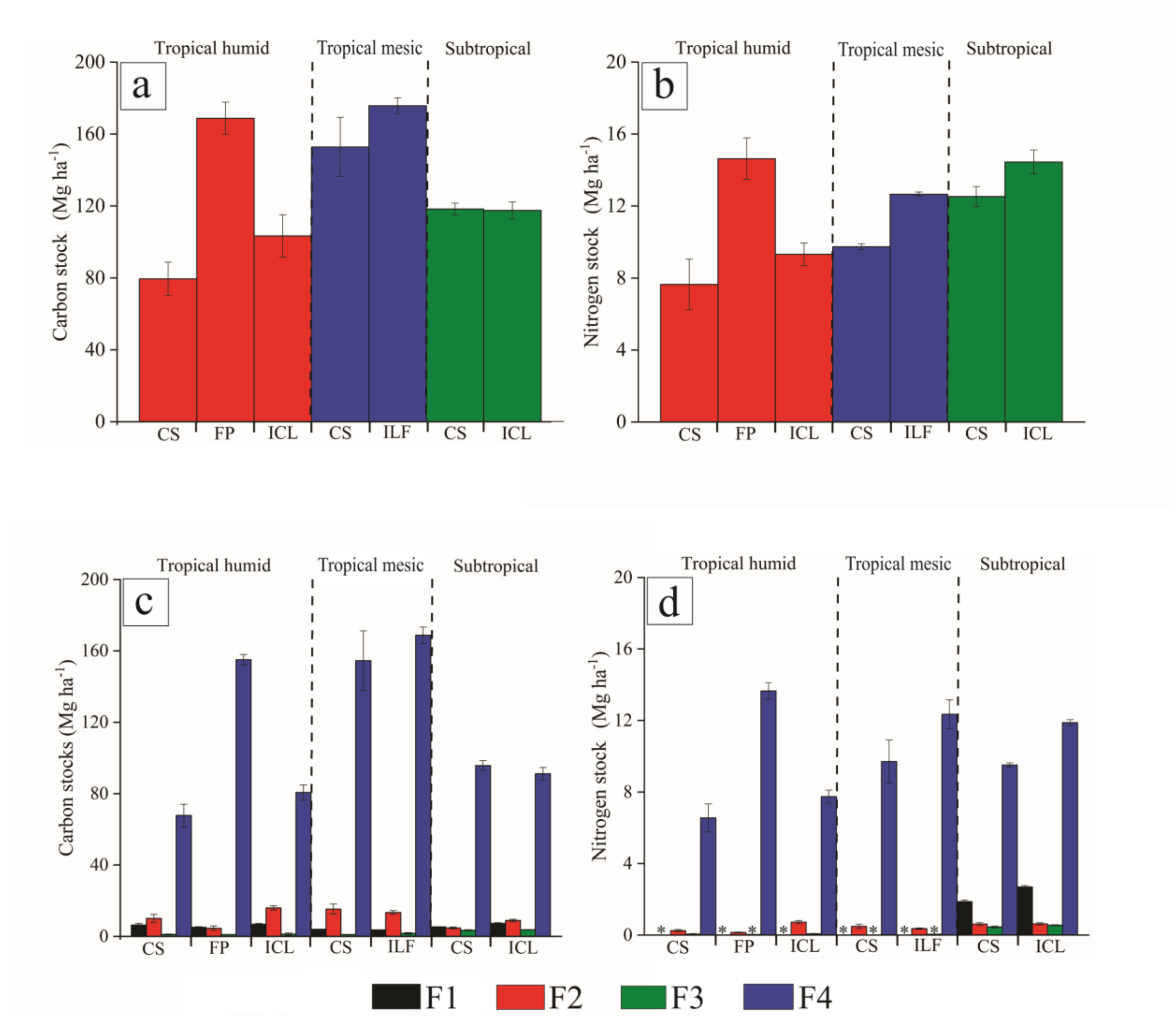
Wang, J., Ren, C., Cheng, H., Zou, Y., Bughio, M.A., Li, Q., 2017. Conversion of rainforest into agroforestry andmonoculture plantation in China: Consequences for soil phosphorus forms and microbial community. Sci. Total Environ. 595, 769–778.

Withers, P.J.A., Rodrigues, M., Soltangheisi, A., Carvalho, T.S., Guilherme, L.R.G., Benites, V.M., Gatiboni, L.C., Sousa, D.M.G., Nunes, R.S., Rosolem, C.A., Andreote, F.D., Oliveira Jr, A., Coutinho, E.L.M., Pavinato, P.S., 2018. Transitions to sustainable management of phosphorus in Brazilian agriculture. Sci. Rep. 8, 2537.

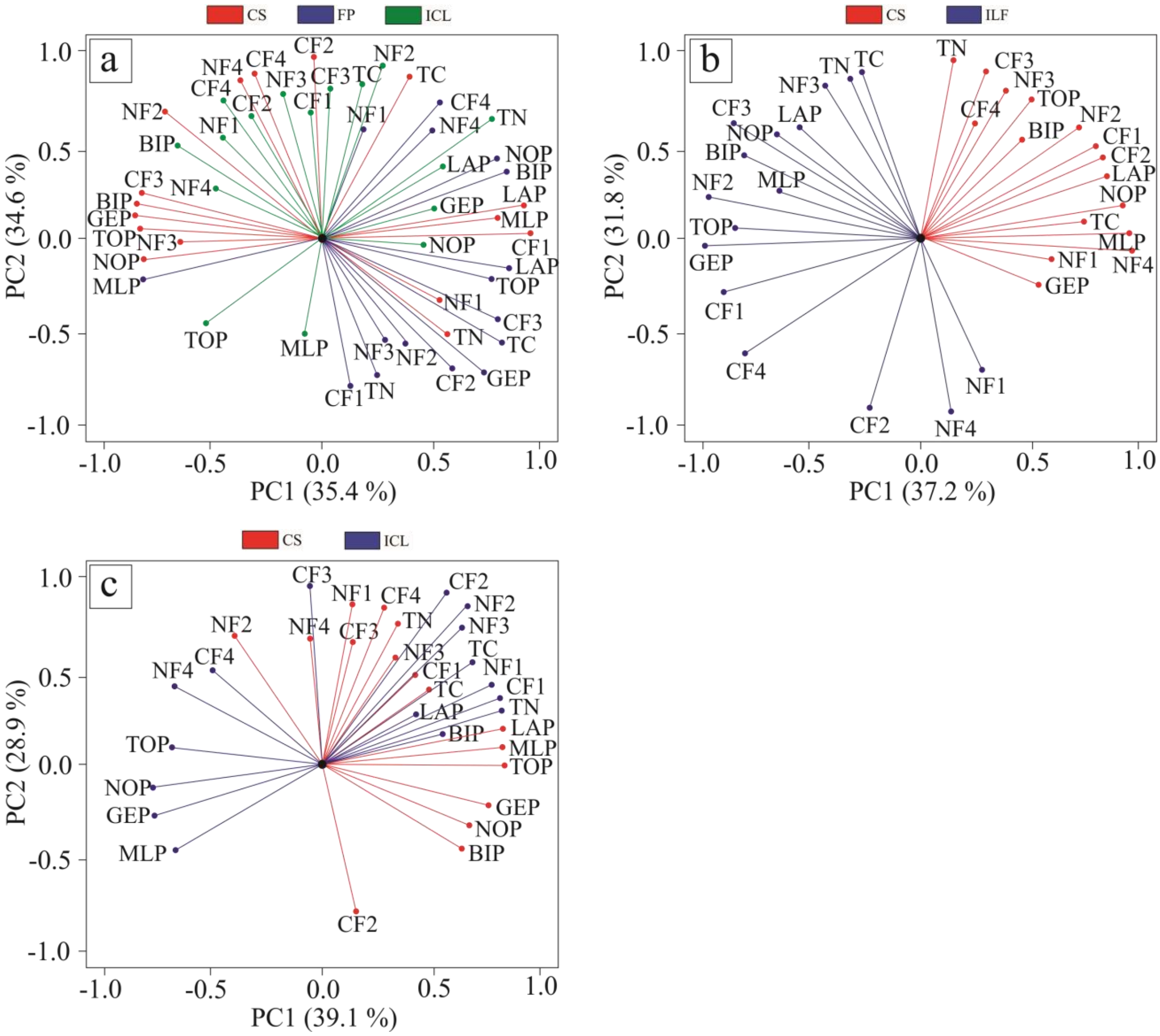
Xiao-guang, J., Chong-sheng, G., Guo-hong, L., Yu-yu, S., 2011. Effect of long-term fertilization on soil enzyme activities under different hydrothermal conditions in northeast china. Agric. Sci. China 10, 412-422.

Ziadi, N., Bélanger, G., Cambouris, A.N., Tremblay, N., Nolin, M.C., Claessens, A., 2008. Relationship between phosphorus and nitrogen concentrations in spring wheat. Agron. J. 100, 80-86.

Supplementary material



Supplementary Figure S1. Total soil C and N stocks (a and b) and C and N stocks in different SOM fractions (c and d) in pasture management systems under different climatic conditions in the soil layer 0-100 cm. Bars represent the standard deviation of the mean values (n = 3). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system; and ILF, integrated livestock-forest. Subtropical: CS, conventional system; and ICL, integrated crop-livestock. F1, organomineral fraction (75-2000 μm); F2, organic fraction (75-2000 μm); F3, organomineral fraction (53-75 μm); F4, organomineral fraction (<53 μm). *Below the detection limit.



Supplementary Figure S2. Principal component analysis between P fractions in the soil and C and N stocks in the soil, and SOM fractions in pasture management systems under tropical humid (a), tropical mesic (b) and subtropical (c) climate conditions, by taking into account the 0-100 cm layer. LAP, Labile P; MLP, moderately Labile P; NOP, Non-Labile P; GEP, geochemical P; BIP, biological P; and TOP, total P. TC, total soil C; TN, total soil N; CF1, total C in fraction F1; NF1, total N in fraction F1; CF2, total C in fraction F2; NF2, total N in fraction F2; CF3, total C in fraction F3; NF3, total N in fraction F3; CF4, total C in fraction F4; and NF4, total N in fraction F4. Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system; and ILF, integrated livestock-forest. Subtropical: CS, conventional system; and ICL, integrated crop-livestock.

Supplementary Table S1. Soil bulk density (g cm^{-3}) in pasture management systems under tropical humid, tropical mesic and subtropical climate.

Depth	Tropical humid		Tropical mesic		Subtropical	
0-10 cm						
	CS	1.33±0.10	CS	1.03±0.23	CS	1.60±0.12
	FP	1.18±0.06	ILF	1.24±0.08	ICL	1.44±0.09
	ICL	1.40±0.13				
10-20 cm						
	CS	1.46±0.09	CS	1.55±0.14	CS	1.60±0.18
	FP	1.27±0.27	ILF	1.58±0.02	ICL	1.51±0.06
	ICL	1.44±0.04				
20-40 cm						
	CS	1.40±0.11	CS	1.69±0.04	CS	1.55±0.04
	FP	1.20±0.10	ILF	1.63±0.07	ICL	1.56±0.02
	ICL	1.43±0.04				
40-60 cm						
	CS	1.39±0.13	CS	1.67±0.02	CS	1.50±0.09
	FP	1.22±0.14	ILF	1.60±0.12	ICL	1.53±0.02
	ICL	1.35±0.07				
60-80						
	CS	1.43±0.02	CS	1.59±0.12	CS	1.43±0.02
	FP	1.31±0.25	ILF	1.50±0.04	ICL	1.47±0.01
	ICL	1.38±0.03				
80-100 cm						
	CS	1.14±0.29	CS	1.51±0.09	CS	1.50±0.04
	FP	1.30±0.21	ILF	1.53±0.05	ICL	1.45±0.07
	ICL	1.38±0.03				

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

Supplementary Table S2. Characterization of soil chemical attributes for pasture management systems under tropical humid climate.

Deph	Manangemant systems	pH $CaCl_2$	P*	K	Ca	Mg	Al	H+Al	SB	CEC_{pH7}	BS	AS
0-10 cm			mg kg^{-1}	mmol$_c$ dm^{-3}							%	
	CS	4.33± 0.21	3.70± 0.26	2.37± 0.50	6.01± 0.79	1.99± 0.13	0.19± 0.07	20.10± 1.72	10.73± 0.79	32.43± 3.32	31.18± 0.75	0.00± 0.00
	FP	4.70± 0.43	5.83± 0.15	2.13± 0.35	15.41± 1.41	3.92± 0.63	0.91± 0.08	33.10± 4.36	22.47± 1.28	59.60± 2.76	40.06± 3.54	5.23± 0.99
	ICL	4.93± 0.26	14.29± 0.37	3.12± 1.07	12.11± 1.01	5.63± 0.94	0.47± 0.32	19.73± 2.02	22.57± 1.30	44.60± 0.75	54.18± 4.10	3.50± 0.69
10-20 cm												
	CS	4.50± 0.03	3.04± 0.23	1.50± 0.07	6.18± 0.68	1.84± 0.27	0.51± 0.14	17.27± 1.18	9.86± 0.69	27.69± 0.82	33.56± 1.88	5.34± 0.87
	FP	4.85± 0.13	5.88± 0.16	1.78± 0.15	14.46± 1.51	3.59± 0.46	0.92± 0.07	32.87± 2.74	20.15± 1.32	55.34± 1.56	37.59± 2.28	5.22± 1.02
	ICL	4.88± 0.11	9.85± 0.21	2.24± 0.34	9.94± 0.34	6.21± 0.37	0.42± 0.22	18.08± 2.20	18.45± 1.41	37.76± 1.27	46.64± 2.97	5.84± 0.84
20-40 cm												
	CS	4.33± 0.15	2.38± 0.35	0.64± 0.36	6.34± 0.61	1.69± 0.42	0.82± 0.22	14.43± 0.70	8.98± 0.60	22.94± 1.95	35.93± 3.27	10.67± 1.74
	FP	5.00± 0.20	3.93± 0.22	1.43± 0.59	13.51± 1.61	3.27± 0.37	0.93± 0.10	32.63± 2.07	17.82± 1.60	51.07± 0.39	35.11± 1.06	5.21± 1.04
	ICL	4.83± 0.20	5.42± 0.13	1.32± 0.59	6.69± 0.76	3.70± 0.55	0.38± 0.15	16.43± 2.48	14.75± 2.84	30.91± 1.80	39.11± 2.41	8.18± 1.06
40-60 cm												
	CS	4.33± 0.45	3.12± 0.26	0.62± 0.36	5.92± 0.64	1.71± 0.40	0.02± 0.01	15.72± 2.15	9.58± 0.87	25.91± 1.67	34.35± 2.88	0.00± 0.00
	FP	4.64± 0.25	3.31± 0.15	0.64± 0.34	10.72± 1.69	4.19± 0.34	0.82± 0.22	26.83± 3.75	14.25± 1.82	46.45± 1.60	33.25± 1.10	6.20± 1.96
	ICL	4.78± 0.16	2.02± 0.28	1.27± 0.47	5.20± 1.31	1.82± 0.39	0.02± 0.01	13.58± 1.86	8.50± 1.29	21.97± 1.49	34.51± 2.69	0.00± 0.00
60-80 cm												
	CS	4.42± 0.21	2.30± 0.20	0.29± 0.18	5.49± 0.84	1.62± 0.51	0.83± 0.17	13.98± 1.88	8.09± 0.63	23.51± 0.97	34.26± 4.41	11.58± 1.83
	FP	4.77± 0.15	2.27± 0.15	0.74± 0.20	6.02± 0.22	3.08± 0.54	0.93± 0.08	21.58± 3.09	9.94± 1.22	35.63± 1.03	32.42± 6.31	10.26± 2.08
	ICL	5.05± 0.20	1.80± 0.21	0.89± 0.34	4.22± 0.98	1.70± 0.52	0.02± 0.01	11.93± 1.91	6.98± 1.61	19.13± 1.56	31.92± 2.02	0.00± 0.00
80-100 cm												
	CS	5.17± 0.15	2.50± 0.10	0.37± 0.25	5.57± 0.63	0.79± 0.25	0.02± 0.01	14.46± 1.57	8.79± 1.38	23.67± 2.77	35.14± 1.00	0.00± 0.00
	FP	4.90± 0.20	2.60± 0.15	0.81± 0.12	5.96± 0.59	1.68± 0.32	0.90± 0.11	20.61± 1.23	8.61± 4.71	28.91± 1.50	20.37± 1.20	14.56± 3.73
	ICL	4.94± 0.17	2.25± 0.13	0.70± 0.28	5.04± 0.68	1.37± 0.26	0.01± 0.01	12.44± 1.92	10.47± 1.34	22.12± 3.59	31.19± 2.47	0.00± 0.00

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). CS, conventional system; PF, fertilized pasture and ICL, integrated crop-livestock.). H+Al: potential acidity; SB: sum of bases; CECpH7: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation. * Anionic Resin.

Supplementary Table S3. Characterization of soil chemical attributes in pasture management systems under tropical mesic climate.

Deph	Manangemant systems	pH CaCl$_2$	P*	K	Ca	Mg	Al	H+Al	SB	CEC$_{pH7}$	BS	AS
0-10 cm			mg kg^{-1}				mmol$_c$ dm^{-3}				%	
	CS	4.73± 0.21	2.97± 0.15	1.60± 0.10	5.94± 0.40	5.78± 0.45	2.39± 0.72	31.30± 1.82	11.90± 1.58	41.85± 2.59	29.79± 1.24	12.29± 0.84
	ILF	5.19± 0.18	7.88± 0.80	1.36± 0.17	17.93± 1.30	8.53± 0.84	1.78± 0.23	29.78± 2.69	23.78± 3.29	59.72± 4.68	50.43± 3.68	5.15± 1.10
10-20 cm												
	CS	4.70± 0.17	2.98± 0.18	1.41± 0.10	4.98± 0.20	4.97± 0.09	2.60± 0.11	29.20± 1.30	10.15± 1.30	38.88± 1.99	26.44± 1.37	16.74± 1.86
	ILF	4.89± 0.19	4.22± 0.43	1.10± 0.06	13.48± 0.99	7.02± 0.81	3.28± 0.19	30.11± 1.35	18.43± 2.47	53.72± 2.98	41.45± 2.53	15.19± 2.48
20-40 cm												
	CS	4.67± 0.15	3.00± 0.50	1.25± 0.15	4.00± 0.80	4.18± 0.60	2.82± 0.54	27.10± 4.08	8.40± 1.10	35.91± 1.39	23.08± 1.68	21.19± 2.89
	ILF	4.60± 0.31	2.55± 0.27	0.84± 0.11	9.04± 0.68	5.52± 0.97	4.08± 0.39	30.43± 2.71	13.19± 1.93	47.72± 1.30	32.48± 2.15	25.23± 4.14
40-60 cm												
	CS	4.07± 0.25	2.83± 0.15	1.38± 0.16	3.05± 0.58	2.08± 0.87	6.97± 1.70	32.98± 1.50	5.49± 0.81	39.35± 1.08	16.30± 1.82	43.77± 7.61
	ILF	5.20± 0.33	2.68± 0.24	0.85± 0.13	7.75± 0.78	5.80± 0.76	5.53± 0.65	23.24± 2.45	11.94± 1.32	38.25± 1.40	33.62± 4.10	4.27± 4.74
60-80 cm												
	CS	4.20± 0.36	2.30± 0.10	0.55± 0.13	2.08± 0.88	0.81± 0.17	6.30± 1.23	30.75± 2.01	2.65± 0.75	34.22± 1.78	10.96± 3.29	46.71± 14.36
	ILF	4.85± 0.26	2.73± 0.23	0.77± 0.06	2.78± 0.45	2.21± 0.31	8.29± 0.90	35.43± 3.92	4.11± 1.15	42.53± 3.33	16.39± 1.64	48.39± 10.73
80-100 cm												
	CS	4.36± 0.14	2.97± 0.15	0.56± 0.05	3.96± 0.40	0.74± 0.25	5.82± 0.54	25.07± 3.54	4.61± 0.95	30.31± 0.88	18.15± 1.98	46.10± 8.46
	ILF	4.71± 0.16	2.65± 0.23	0.78± 0.08	2.33± 0.19	1.58± 0.16	7.45± 1.13	28.21± 2.92	3.17± 0.59	33.31± 1.00	14.58± 3.04	56.74± 10.12

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). CS, conventional system and ILF, integrated livestock-forest. H+Al: potential acidity; SB: sum of bases; CECpH7: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation. *Anionic Resin.

Supplementary Table S4. Characterization of soil chemical attributes in pasture management systems under subtropical climate.

Depth	Manangemant systems	pH $CaCl_2$	P*	K	Ca	Mg	Al	H+Al	SB	CEC_{pH7}	BS	AS
0-10 cm			mg kg^{-1}	$mmol_c$ dm^{-3}							%	
	CS	4.50± 0.30	6.00± 0.50	2.13± 0.15	5.80± 0.53	4.95± 0.28	3.84± 0.47	52.73± 4.78	12.11± 1.29	63.88± 2.43	18.57± 2.54	20.88± 1.82
	ICL	3.64± 0.24	89.75± 5.14	2.07± 0.18	9.95± 0.99	5.22± 0.87	13.80± 1.23	73.66± 4.29	15.35± 2.09	89.57± 3.33	20.76± 1.97	39.48± 7.79
10-20 cm												
	CS	4.57± 0.19	14.74± 5.50	2.06± 0.07	5.32± 0.55	4.03± 0.39	4.67± 0.87	46.72± 4.57	10.49± 1.40	58.84± 1.86	18.06± 1.24	32.18± 5.71
	ICL	3.62± 0.15	56.42± 2.84	2.00± 0.09	11.11± 1.09	5.82± 0.39	13.54± 0.76	44.82± 2.88	16.65± 2.11	64.36± 3.88	37.54± 1.79	37.12± 7.93
20-40 cm												
	CS	4.64± 0.14	23.48± 2.41	1.98± 0.03	4.84± 0.58	3.11± 0.55	5.49± 1.30	40.70± 4.38	8.87± 1.60	53.81± 2.33	17.55± 1.96	43.49± 10.28
	ICL	3.85± 0.19	23.09± 2.04	1.92± 0.06	12.27± 1.93	6.42± 0.83	13.29± 1.41	15.97± 1.75	17.96± 1.99	39.15± 1.40	54.32± 3.29	8.19± 8.19
40-60 cm												
	CS	4.57± 0.15	5.63± 2.85	0.21± 0.03	4.87± 0.57	1.79± 0.25	21.82± 2.04	66.09± 5.02	7.38± 0.80	77.95± 1.74	11.40± 0.93	65.55± 7.31
	ICL	3.72± 0.19	17.63± 2.30	1.04± 0.07	9.22± 1.43	3.55± 0.68	11.49± 1.09	43.72± 2.81	11.93± 1.73	52.51± 2.56	27.99± 2.58	28.52± 7.17
60-80 cm												
	CS	4.21± 0.11	2.57± 0.42	0.79± 0.16	3.42± 1.11	1.44± 0.45	21.63± 1.57	28.88± 2.02	5.44± 0.66	43.33± 1.04	13.47± 1.71	65.54± 5.85
	ICL	3.78± 0.18	13.36± 2.85	0.78± 0.09	4.14± 1.08	2.09± 0.46	7.51± 1.44	18.50± 1.07	6.65± 0.73	37.67± 2.23	20.22± 2.84	37.34± 8.10
80-100 cm												
	CS	4.57± 0.31	2.34± 0.35	0.86± 0.04	3.30± 0.73	3.73± 0.24	22.32± 1.86	75.11± 11.55	7.55± 0.90	91.95± 3.45	8.29± 1.87	63.40± 11.12
	ICL	4.04± 0.21	3.33± 0.47	0.60± 0.06	1.90± 0.48	1.41± 0.62	11.64± 1.63	38.68± 5.53	4.18± 0.45	50.22± 1.49	9.41± 2.25	12.57± 19.29

Unless indicated otherwise, data are the mean±s.e.m. (n = 3). CS, conventional system and ICL, integrated crop-livestock. H +Al: potential acidity; SB: sum of bases; CECpH7: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation. * Anionic Resin.

Supplementary Table S5. Persons' correlation coefficient between soil chemical attributes and clay (soil properties), and P fractions in the soil in different pasture management systems under each of the assessed climatic conditions.

Soil P pools (Mg ha^{-1})	Soil properties																				
	Clay			pH			K			Ca			Mg			BS			CEC$_{pH7}$		
										Tropical humid											
	CS	FP	ICL	CS	FP	ICL	CS	FP	ICL	CS	FP	ICL	CS	FP	ICL	CS	FP	ICL	CS	FP	ICL
Labile	-0.51	**-0.95****	**-0.91****	-0.04	**0.83***	**0.81***	-0.12	0.33	0.12	-0.31	**0.88***	**0.83***	-0.29	**0.73***	**0.82***	0.30	**0.86***	**0.78***	-0.75	**0.70***	-0.42
Mod. labile	**0.85****	**0.86****	**0.96****	-0.40	**0.71***	**0.86***	-0.42	-0.61	0.22	-0.63	**0.75***	**0.70***	-0.24	**0.87***	**0.75***	-0.05	-0.16	**0.85***	-0.86	**0.75**	**0.73***
Nonlabile	**0.81****	**0.91***	**0.96****	0.49	-0.69	-0.25	0.43	0.60	0.11	0.58	0.14	0.56	0.15	0.28	-0.25	0.15	0.42	0.52	-0.65	0.65	-0.62
Biological	-0.75	**-0.93****	**-0.95****	0.39	-0.62	-0.36	0.32	0.62	0.68	0.12	**0.71***	**0.83***	0.19	**0.89***	**0.90***	0.21	0.58	0.56	0.82	0.74	-0.33
Geochemical	**0.86****	**0.96****	**0.89***	0.41	0.32	-0.22	0.42	-0.11	0.41	0.62	0.18	0.42	0.31	0.04	-0.44	0.25	-0.10	0.62	0.75	-0.88	-0.52
Total	**0.97****	**-0.89****	**-0.97****	0.52	-0.41	-0.16	0.42	0.35	0.73	0.65	-0.18	0.56	0.12	-0.15	-0.68	0.09	0.22	0.43	0.63	0.74	-0.52
										Tropical mesic											
	CS	ILF		CS	ILF		CS	ILF		CS	ILF		CS	ILF		CS	ILF		CS	ILF	
Labile	**-0.95****	**-0.94****		**-0.72***	**0.76***		-0.18	0.08		-0.51	**0.75***		-0.47	**0.81***		-0.61	**0.73***		-0.22	**0.76***	
Mod. labile	**-0.92****	**0.92****		-0.61	**0.81***		-0.41	-0.32		-0.45	**0.85***		-0.10	**0.71***		-0.53	**0.85***		-0.08	**0.84***	
Nonlabile	**0.90****	**0.93****		-0.53	0.62		-0.10	0.44		-0.61	-0.53		-0.12	-0.42		-0.72	-0.19		-0.11	-0.35	
Biological	**-0.93****	**-0.86****		0.17	0.53		-0.25	0.12		-0.15	-0.32		-0.63	-0.53		-0.63	-0.41		-0.63	-0.36	
Geochemical	**-0.91****	**0.93****		**0.86***	-0.16		-0.61	-0.68		-0.53	0.43		-0.53	-0.62		-0.15	**0.81***		-0.68	**0.71***	
Total	**-0.92****	**0.92****		-0.22	-0.64		-0.11	-0.13		-0.62	0.55		-0.15	-0.42		-0.55	**0.71***		-0.56	0.45	
										Subtropical											
	CS	ICL		CS	ICL		CS	ICL		CS	ICL		CS	ICL		CS	ICL		CS	ICL	
Labile	0.60	**-0.97****		0.61	**0.70***		0.58	0.58		0.69	-0.14		**0.74***	**0.73***		-0.18	**0.74***		0.59	**0.70***	
Mod. labile	0.67	-0.75		0.67	**0.86***		0.67	**0.72***		0.16	0.16		**0.72***	**0.78***		-0.09	**0.79***		0.66	**0.75***	
Nonlabile	**0.96****	**0.96****		**0.88***	0.84*		**0.86***	**0.85***		**0.85***	-0.09		0.34	-0.67		0.67	-0.55		**0.87***	0.26	
Biological	**0.95****	**-0.95****		**0.75***	**0.84***		**0.71***	**0.74***		**0.82***	-0.15		0.41	-0.52		0.52	-0.61		**0.72***	0.35	
Geochemical	0.52	**0.96****		0.35	**0.71***		0.47	-0.15		0.18	-0.11		-0.19	-0.68		**0.84***	-0.15		0.13	0.31	
Total	0.76	**0.94****		0.15	**0.73***		0.64	-0.12		0.68	-0.19		-0.33	-0.14		**0.15****	-0.65		0.18	0.52	

* significant at 5% probability (*p <0.05*) and ** significant at 1% probability (*p <0.01*). Clay: clay content (g kg^{-1}); K, potassium (mmolc dm^{-3}); Ca, calcium (mmolc dm^{-3}); Mg, magnesium (mmolc dm^{-3}); BS, base saturation (%) e CECpH7, potential cation exchange capacity (mmolc dm^{-3}). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system; and ILF, integrated livestock-forest. Subtropical: CS, conventional system; and ICL, integrated crop-livestock.

4. PASTURELAND INTENSIFICATION AND DIVERSIFICATION IN BRAZIL MEDIATE SOIL BACTERIAL COMMUNITY STRUCTURE CHANGES AND SOIL C ACCUMULATION[*]

Abstract

Conventional pasture management has been responsible for diffuse soil degradationin tropical pastures. However, sustainable management practices can be used to improve soil health. We tested the effect of adopting intensive and diversified pasture management systems, i.e., fertilized pasture (FP), integrated crop-livestock (ICL) and integrated livestock-forest (ILF), in comparison to conventional pasture management (CS) in Brazil. The treatments were located under contrasting climate conditions (tropical humid, tropical mesic and subtropical) and soil types (Oxisol and Ultisol). The conversion time from CS to FP, ICL and ILF ranged from 6, 3-15 and 3 years, respectively. We focus on management effects on soil chemical and biochemical properties and their interactions with the soil bacterial community structure and soil C accumulation. The results showed that pasture intensification and diversification in sites previously managed under CS, increased by 82% the soil chemical properties related to soil fertility and shifted the soil bacterial community structure. The soil biochemical properties such as microbial biomass C, geochemical P and the enzymes β-glucosidase and acid phosphatase were the most sensitive in the conversion of CS to FP, ICL and ILF. The structural equation modeling suggested that for FP, ICL and ILF there was a positive impact of soil bacterial community structure and mainly soil chemical properties on soil C accumulation. Results in the present study provided useful knowledge for the best understanding of soil-management-microbe interactions, and provide more insights into the controlling factors of soil C accumulation during management system changes in pastures sites in Brazil.

Keywords: Pasture, Agroforestry; Soil organic carbon; Structural equation modelling.

4.1. Introduction

Pasture areas represent ~20% of the Earth terrestrial surface, and they have been in the mainstream for the last decades given their great influence over the ecological balance and human subsistence. Moreover, they have been the object of much research, which demonstrated that approximately half of these sites present different degrees of degradation (Yang et al., 2019a). In Brazil, where pasture is the most common land use (~159 million hectares), it is estimated that 50% to 70% of pasture land are degraded (Dias Filho, 2014; IBGE, 2017).

The conventional pasture management system in Brazil needs to be enhanced given the direct (low yield and profitability) and indirect (erosion and silting of water source) effects of pasture site degradation (Koyanagi et al., 2019), and the great international pressure to implement sustainable alternative production processes (Ghahramania and Bowranb, 2018). Encouraged by this scenario, the Brazilian government launched the "ABC Plan" that among other aims finances measures such as the adoption of more intensive and diversified pasture management systems, such as pasture fertilization (FP), integrated crop-livestock (ICL) and integrated livestock-forest (ILF) systems. These initiatives are in compliance with up to date exploration strategies, such as the concept of ecosystem services (Chaudhary et al., 2018). Besides, some studies in Brazil have already showed positive effects of adoption of more intensive and diversified pasture management systems over C sequestration (Torres et al., 2017; Ghahramania and

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Bowranb, 2018), as well as over soil chemical (e.g., N, P and K) (Liebig et al., 2017; Moreira et al., 2018) and biochemical (e.g., soil enzyme activities, C an N stored in the microbial biomass) (Acosta-Martínez et al., 2010; Costa et al., 2018) properties. Nevertheless, knowledge about the relationships between chemical and biochemical properties with soil microorganisms under more intensive and diversified pasture management systems remains unclear, especially in the different edaphoclimatic conditions of Brazil (Melillo et al., 2017).

Soil microorganisms are highly sensitive to changes in management and in climate conditions; therefore, these are effective indicators to assess the soil quality (Xu et al., 2017). It is important pointing out that bacteria account for the most abundant and diversified group of soil microorganisms, they have multiple functions in the soil such as decomposition, biochemical cycles and nutrient transformation (Zhang et al., 2017). Accordingly, among the main initial effects of adopting more intensive and diversified pasture management systems is the increase in organic compounds, because these management systems allow greater biomass inflow above and below ground. Moreover, higher amounts of plant residues can increase microbial necromass accumulation overtime under these management systems (Lange et al., 2015). These effects can also have a significant impact on the soil bacterial community structure and in soil C accumulation (Salton et al., 2014). According to Zhou et al. (2018), soil C accumulation is strongly interlinked and controlled through chemical and biochemical processes, as the soil organic matter (SOM) input and subsequent decomposition. Therefore, although some studies in Brazil have already indicated the soil C accumulation increased with the adoption of more intensive and diversified pasture management systems (Assmann et al., 2014; Segnini et al., 2019), the underlying mechanisms still need to be understood.

Thus, the hypothesis in the current study lied on the assumption that intensifying and diversifying pastures managed based on the extensive form (conventional management system), changes the dynamics of soil chemical and biochemical properties and that such change affects soil bacterial community structure and soil C accumulation. In order to test this hypothesis, management systems such as FP, ICL and ILF were evaluated in different climate zones (tropical humid, tropical mesic, and subtropical) and soil types (Oxisol and Ultisol) in Brazil. The study aimed to examine the following: (1) changes and the relationship between the soil C pools, soil chemical and biochemical properties and the soil bacterial community structure and (2) assess the controlling factors on soil C accumulation in the conversion of CS to more intensive and diversified pasture management systems.

4.2. Materials and Methods

4.2.1. Description of the study sites

Study sites were selected under contrasting soil and climatic conditions in Brazil (Figure 1a). The first site is located in Nova Guarita, Mato Grosso, Midwest Brazil (Lat.: 10° 9' 10.41"S; Long.: 55° 31' 49.53"W) at 380 m elevation. The prevailing soil in this site was classified as Oxisol (USDA, 2014) and the climate as Aw (Köppen), tropical hot and humid, with a mean annual temperature 25.9 °C and a mean annual rainfall of 2628 mm. The second site is located in Nova Odessa, São Paulo, South-eastern Brazil (Lat.: 22° 75' 12"S; Long.: 47° 27' 81"W) at 550 m elevation. The prevailing soil in this region was also classified as Oxisol (USDA, 2014) and the climate as Cwa (Köppen), tropical rainy with dry winter, with a mean annual temperature 20.2 °C and a mean annual rainfall of 1262 mm. The third site is located in Eldorado do Sul, Rio Grande do Sul, Southern Brazil (Lat.: 30° 05' 22"S; Long.: 51° 39' 08"W) at 46 m elevation. The prevailing soil in this region is classified as Ultisol (USDA, 2014) and the climate as

Cfa (Köppen), subtropical at mean annual temperature 19.3 °C and a mean annual rainfall of 1398 mm. More details about the climatic conditions in Mato Grosso (tropical humid), São Paulo (tropical mesic) and Rio Grande do Sul (subtropical) states can be found in Figure 1b.

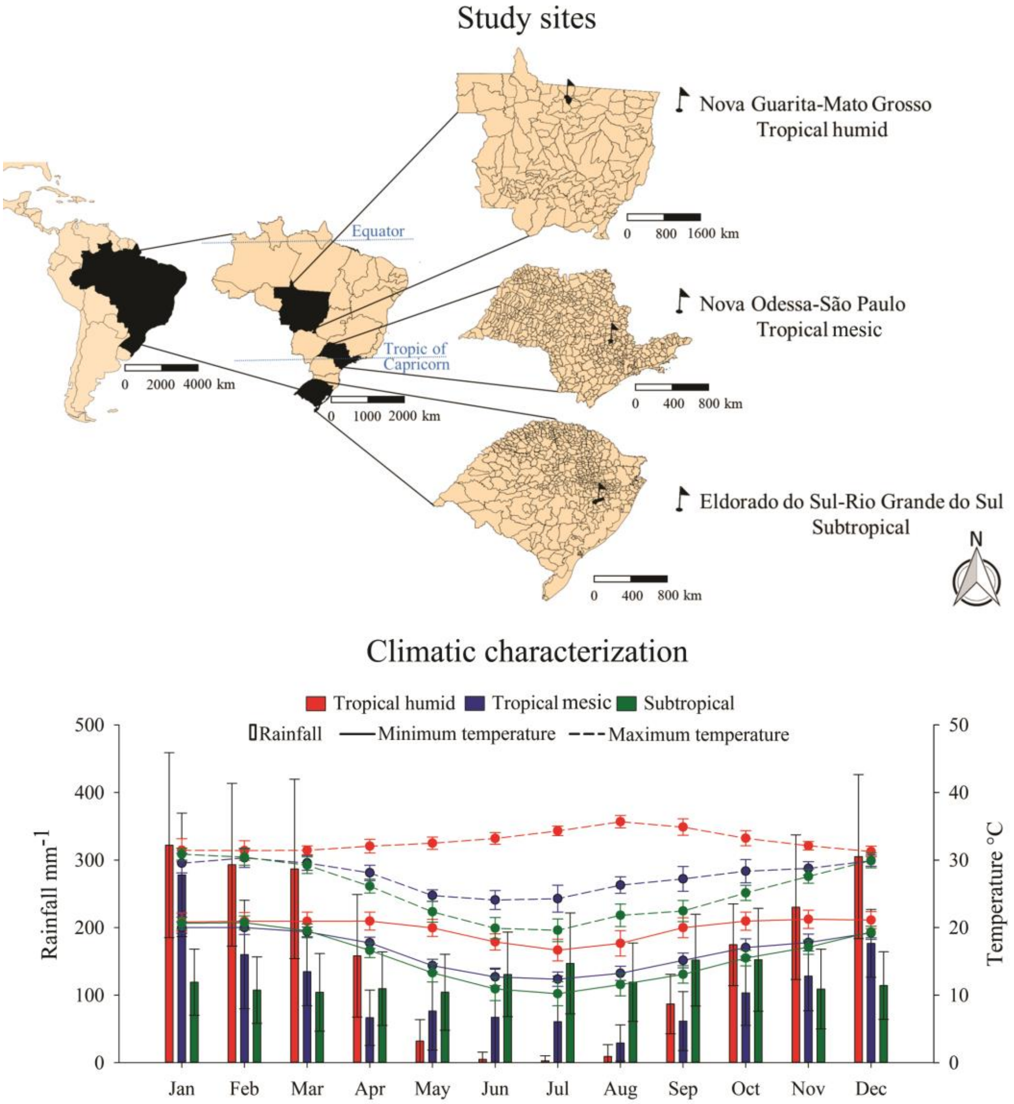


Figure 1. Geographic location and the climatic characterization in the study sites during the 38-year period. Bars represent the standard deviation of the mean values (n = 38). Source: https://portal.inmet.gov.br/.

4.2.2. Pasture management systems and soil sampling

Soil samples were collected in conventional (extensive) pasture management systems in each region. Areas with conventional pasture management systems are mainly characterized by lack of control over grazing pressure and no fertilization. The different pasture management systems evaluated under the tropical climate are located on the "JP Agropecuária" farm, while in the tropical mesic and subtropical climates experimental sites are located in public institutions (Instituto de Zootecnia and Faculty of Agronomy/UFRGS, respectively). Specifically, the following pasture management systems were evaluated in each climatic condition:

i) Tropical humid - treatments included: 1) conventional system (CS); 2) fertilized pasture (FP) and 3) integrated crop-livestock (ICL). The site is located in the Amazonian biome and, back in 2004, its native vegetation was removed for pasture implementation under CS. FP and ICL were established in 2012 and 2015, respectively, in a previously area under CS (equivalent edaphoclimatic conditions).

ii) Tropical mesic - treatments included: 1) conventional system (CS) and 2) integrated livestock-forest (ILF). This site is located in the Atlantic Forest biome, where native vegetation was removed to implement the CS in 1995. In the CS (equivalent edaphoclimatic conditions), the ILF were implemented in 2015 as the current land use.

iii) Subtropical - treatments included: 1) conventional system (CS) and 2) integrated crop-livestock (ICL). CS is located in the Pampa biome and in 2003 it was chosen for the installation of a long-term experiment focused on the ICL.

More details about the characterization of soil texture and management adopted in the study sites can be found in Table 1 and in Supplementary Table S1.

Table 1. Characterization of soil texture under tropical humid, tropical mesic and subtropical climates.

Layers (cm)	Tropical humid†			Tropical mesic‡			Subtropical§		
	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
0-10	620±21.23	67±4.24	313±8.49	561±13.44	175±7.78	264±8.49	630±7.78	220±15.56	150±8.49
10-20	610±56.57	88±7.07	302±12.02	569±0.71	176±14.14	254±11.31	625±12.03	203±2.83	170±6.36
20-40	480±21.23	67±4.24	453±20.51	520±15.56	149±7.74	331±7.07	552±11.31	221±7.07	227±6.36
40-60	412±14.85	32±2.82	556±10.61	508±25.46	143±33.23	329±16.97	525±4.95	195±8.49	280±5.66
60-80	333±72.83	47±2.83	580±81.32	493±30.41	180±9.46	327±5.66	415±7.07	201±4.24	384±19.80
80-100	385±3.53	29±2.12	585±28.25	492±46.67	179±17.68	329±4.58	350±9.90	185±4.95	464±24.75

† Oxisol formed from tertiary sediments - the clay fraction is predominantly formed by kaolinite and Al oxide (gibbsite) (Campos, et al., 2011); ‡ Oxisol formed from basalt rocks - the clay fraction is predominantly formed by kaolinite, Fe oxides (goethite, hematite and magnetite/maghemite), Al oxide (gibbsite) (Cherubin et al., 2016); § Ultisols formed by granite rocks - the clay fraction is predominantly formed by kaolinite and Fe oxides (hematite and goethite) (Bayer et al., 2011).

Soil samples were taken in August and October 2017 at the tropical humid and subtropical sites, respectively, and in January 2018 at the tropical mesic site. Nine soil cores at each site, under each management system, were taken and composited into three samples. Soil samples were removed at the top 0–10 cm soil layer, along transects placed 50 m away from each other with a Dutch auger. The soil samples for chemical analysis and were air-dried, ground, sieved (2 mm) and storage at 4 °C for subsequent analyses. The soil samples for biochemical analysis (e.g., microbial biomass, enzymatic activity and DNA extraction) were stored in ice boxes and transported to the laboratory; aliquots of each sample were separated and kept in a freezer at −80 °C for DNA extraction.

4.2.3. Analytical procedures

4.2.3.1. Soil chemical properties

The soil chemical properties of soil samples were determined based on the methods described by van Raij et al. (2001). The soil chemical properties studied were: active acidity (pH $CaCl_2$), available phosphorus (P), potassium

(K), calcium (Ca), magnesium (Mg), aluminum (Al), potential acidity (H + Al), sum of bases (SB), potential cation exchange capacity (CECpH7), base saturation (BS) and aluminum saturation (AS) (Table 2).

Table 2. Characterization of soil chemical properties in pasture management systems under tropical humid, tropical mesic and subtropical climates.

Manangemant systems	pH $CaCl_2$	P*	K	Ca	Mg	Al	H+Al	SB	CEC_{pH7}	BS	AS
		mg kg^{-1}	mmol$_c$ dm^{-3}							%	
Tropical humid											
CS	4.33± 0.21a	3.70± 0.26b	2.37± 0.50b	6.01± 0.79b	1.99± 0.13b	0.19± 0.07b	20.10± 1.72b	10.73± 0.79b	32.43± 3.32b	31.18± 0.75b	0.00± 0.00b
FP	4.70± 0.43a	5.83± 0.15a	2.13± 0.35b	15.41± 1.41a	3.92± 0.63a	0.91± 0.08a	33.10± 4.36a	22.47± 1.28a	59.60± 2.76a	40.06± 3.54a	5.23± 0.99a
ICL	4.93± 0.26a	14.29± 0.37a	3.12± 1.07a	12.11± 1.01a	5.63± 0.94a	0.47± 0.32b	19.73± 2.02b	22.57± 1.30a	42.60± 0.75a	54.18± 4.10a	3.50± 0.69a
Tropical mesic											
CS	4.73± 0.21b	2.97± 0.15b	1.60± 0.10a	5.94± 0.40b	5.78± 0.45b	2.39± 0.72a	31.30± 1.82a	11.90± 1.58b	41.85± 2.59b	29.79± 1.24b	12.29± 0.84a
ILF	5.19± 0.18a	7.88± 0.80a	1.36± 0.17a	17.93± 1.30a	8.53± 0.84a	1.78± 0.23a	29.78± 2.69a	23.78± 3.29a	59.72± 4.68a	50.43± 3.68a	5.15± 1.10b
Subtropical											
CS	4.50± 0.30a	6.00± 0.50b	2.13± 0.15a	5.80± 0.53b	4.95± 0.28a	3.84± 0.47b	52.73± 4.78b	12.11± 1.29a	63.88± 2.43b	18.57± 2.54a	20.88± 1.82b
ICL	3.64± 0.24b	9.85± 2.21a	2.07± 0.18a	9.95± 0.99a	5.22± 0.87a	13.80± 1.23a	73.66± 4.29a	15.35± 2.09a	89.57± 3.33a	20.76± 1.97a	39.48± 7.79a

Unless indicated otherwise, data were expressed in mean ± s.e.m. (n = 3). Mean values followed by the same letter in the columns did not statistically differ in the Tukey's test at 5% probability ($p \leq 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock. H +Al: potential acidity; SB: sum of bases; CECpH7: potential cations exchange capacity; BS: base saturation (%); AS: aluminum saturation. * Anionic Resin.

4.2.3.2. C and N of soil, SOM fractions and of microbial biomass

Soil C and N were measured on dry soil samples that were ground and sieved in 100 mesh (0.149 mm). SOM was physically fractionated through the granulometric method modified by Christensen (1992), who used air-dried soil samples sieved in 2 mm mesh (TFSA). After the end of the process (sieving+ultrasound), soil samples (20 g) were divided into the following fractions: F1-organomineral and F2-organic fraction (75–2000 µm); F3-organomineral fraction (53–75 µm) and F4-organomineral fraction (< 53 µm). Soil C and N contents were determined using an elemental analyzer (Leco CN-2000®, St. Joseph, MI, USA). Total C and N contents in SOM fractions were calculated by multiplying C and N concentration in each fraction by its corresponding mass.

The microbial biomass C (MBC) was determined through the fumigation-extraction method (Vance et al., 1987). Extracts were analyzed for organic carbon content (Shimadzu - TOC 5000A), and microbial biomass was determined by the difference between the values obtained in fumigated and non-fumigated samples. To determine the microbial biomass nitrogen (MBN), the extracts were analyzed by the Ninhydrin method (Joergensen and Brookes, 1990).

4.2.3.3. Soil P fractionation

The soil P fractionation was performed according to the methodology proposed by Hedley et al. (1982), with modifications made by Condron et al. (1985) changing the original sonication step by 0.5 M NaOH extraction. The inorganic P was expressed by the amount of P extracted through anion exchange resin membrane, 0.5 M of sodium bicarbonate ($NaHCO_3$), 1.0 M of chloridric acid (HCL), 0.1 M of sodium hydroxide (NaOH), 0.5 M of NaOH and by concentrated H_2SO_4 + 30% H_2O_2 (residual P). The organic P fractions were estimated as the difference between total P fractions, determined after digestion of the alkaline extracts with 7.5% (w/v) ammonium persulfate $[(NH_4)_2S_2O_8]$ solution and 50% H_2SO_4 in an autoclave (103 kPa,121 °C) for 2 h (Kopp and McKee, 1979), and the respective inorganic fractions. An appropriate approach was used for highly weathered soils, the organic P fractions and inorganic P were defined as biological P and geochemical P pools, respectively (Cross and Schlesinger, 1995). More details about the P fractionation can be found in Damian et al. (2020).

4.2.3.4. Enzymatic activity

Soil enzymes evaluated were the β-glucosidase (C-cycle), acid phosphatase (P-cycle) and arylsulfatase (S-cycle), which were determined through the method described by Tabatabai (1994). This method is based on the colorimetric p-nitrophenol formed after the addition of colorless substrates specific to each assessed enzyme. Concentration of p-nitrophenol was determined by measuring the absorbance at 400 nm in a spectrophotometer (Digimed DM-ESPEC-2). Soil enzymatic activity was expressed as μg p-nitrophenol released per gram of dry soil per hour.

4.2.3.5. Soil bacterial community

The soil bacterial community was evaluated in triplicate for each management system by DNA-based T-RFLP. Total DNA was extracted from 0.4 g of fresh soil samples using the PowerSoilDNA Isolation Kit following the manufacturer's instructions (MoBioLabs, Inc. Solana Beach, USA). The DNA quality was verified by electrophoresis in a 1.5% agarose gel using TAE 1× (400 mM Tris, 20 mM glacial acetic acid, 1 mM EDTA). For this, 5.0 μL of DNA sample plus 2.0 μL of GelRed (Biotium, Cafifórnia, USA) were applied to the gel and run for 60 min at 100 V. The soil DNA was used as a template for the amplification of 16S rDNA gene by polymerase chain reaction (PCR). PCR reactions and amplification conditions were adapted by Shütte et al. (2009). PCR reaction consisted from: 1× buffer (Applied Biosystems, Califórnia, USA), 3.0 mM $MgCl_2$ (Applied Biosystems, Califórnia, USA), 480.0 $\mu g\ mL^{-1}$ of BSA (Roche Applied Science, Indianapolis, USA), 200.0 μM dNTP (Amersham Bioscience, New Jersey, USA), 0.2 μM forward primer 8 fm (AGAGTTTGATCMTGGCTCAG) labeled with VIC, 0.2 μM reverse primer 926r (CCGTCAATTCCTTTRAGTTT) labeled with 6-carboxyfluorescein (6FAM) and 0.02 U/μL Taq DNA polymerase (Applied Biosystems, Califórnia, USA). The amount of 35.2 μL of milli-Q water and 1.0 μL of DNA template completed the final PCR reaction volume of 50 lL. The amplification conditions were: initial denaturation at 94 °C for 4 min, followed by 34 cycles of denaturation at 94 °C for 1 min, annealing of primers at 55 °C for 1 min and an extension at 72 °C for 2 min. The final extension was 10 min at 72 °C. After DNA amplification, the samples were precipitated with isopropanol and purified with ethanol. The purified samples were re-suspended in 50 mL of Milli-Q water and quantified in agarose gel 1.5%. The 16S rDNA gene was quantified by quantitative real-time PCR using the

SyberGreen PCR Master Mix 2× fluorescent probe (Applied Biosystems). The primers used in the assay were 341F (5'-CCTACGGGAGGCAGCAG-3') and 534R (5'-ATTACCGCGGCTGCTTGG-3') and the PCR reaction had a final volume of 25.0 µL (24.0 µL of PCR mix +1.0 µL of the template). The 16S rRNA gene copy number per gram of soil will be determined by interpolating Ct (Cycle threshold) data with a known standard curve (Kleyer et al., 2017).

4.2.4. Data analysis

An analysis of variance (ANOVA) was computed using the SPSS 23.0 software to test the influence of the pasture management systems under different climate conditions on individual C and N pools and soil chemical and biochemical properties. If the ANOVA F statistic was significant ($p < 0.05$), the means were compared using Tukey's test ($p < 0.05$).

The principal coordinates (PCoA) and the similarity analysis (ANOSIM) were carried out in the Past software (v.3.2) to visualize the changes and differences in soil bacterial community structure between pasture management systems. Based on this analysis, it was possible estimating ecological parameters such as the diversity indices by Chao 1, Simpson and Shannon (Lemos et al., 2011). To further investigate the effects of soil chemical (pH, P, K, Ca, Mg, CEC, SB, BS, AL, AS and H + Al) properties, biochemical (MBC and MBN, P fractions, enzymatic activity and diversity indices) properties and the C and N pools (soil C and N and in the different SOM fractions) on soil bacterial community structure, the redundancy discriminatory analysis (RDA) in the Canoco R software (v.4.5) was used.

To investigate how explanatory variables affecting soil C accumulation under different pasture management systems (CS, FP, ICL and ILF), we performed structural equation modeling (SEM). Seeking to create multivariate indices to represent each group and exclude the variables' auto-correlation, the principal component analysis (PCA) analysis was performed according to Wang et al. (2018). The multivariate indices were used to elaborate the SEM. Together, the two principal components (PC1 and PC2) represented 57–80%, 69–81% and 47–84% of the total variation in soil chemical and biochemical properties, soil bacterial community structure and of the C and N pools respectively. We defined a hypothetical model according to our current knowledge and results of previous studies of pasture management change impacts on soil C accumulation. Our hypothetical model involves multiple-path linkages, containing all plausible interaction paths between the soil chemical and biochemical properties, soil bacterial community structure and of the C and N pools. The SEM analysis was conducted using Amos 17.0 (IBM, SPSS, New York, USA), taking into account the soil C variation in the 0–10 and 0–30 cm (Supplementary Figure S1) layers, as also suggested by Lange et al. (2015). The criteria adopted to evaluate the fit of the models were the root mean squared error of approximation (RMSEA, < 0.05), chi-square value (χ^2), Fisher's statistic ($0.05 < p \leq 1.00$) and Akaike information criterion (AIC).

4.3. Results

4.3.1. C and N pools and soil chemical and biochemical properties

The conversion of CS to more intensive and diversified management systems gave an increase in soil C and N and in the different SOM fractions, and also in the soil chemical and biochemical properties. Under the tropical humid climate, the adoption of FP relative to CS gave an increase of approximately 89% in most soil chemical properties related to soil fertility (P, Ca, Mg, SB, CEC and BS) (Table 2). Soil C and N were also increased by approximately 113% (Figures 2a and 2b). Similarly, increases were also seen in the C and N of the F4 fraction, with an average of 133% (Figures 2c and 2d). The conversion of CS to FP also increased MBC by 14% (Figure 3a). The highest ratios of MBC to soil C (MBC:SC) and MBN to soil N (MBN:SN) were seen under FP (Fig. 3b and d). FP also showed increases in the levels of geochemical P, in addition to the higher enzyme activity of the enzymes β-glucosidase and acid phosphatase when compared to CS (Table 3). The levels of geochemical P and enzyme activity were respectively 32%, 137% and 100% higher than the values seen under CS.

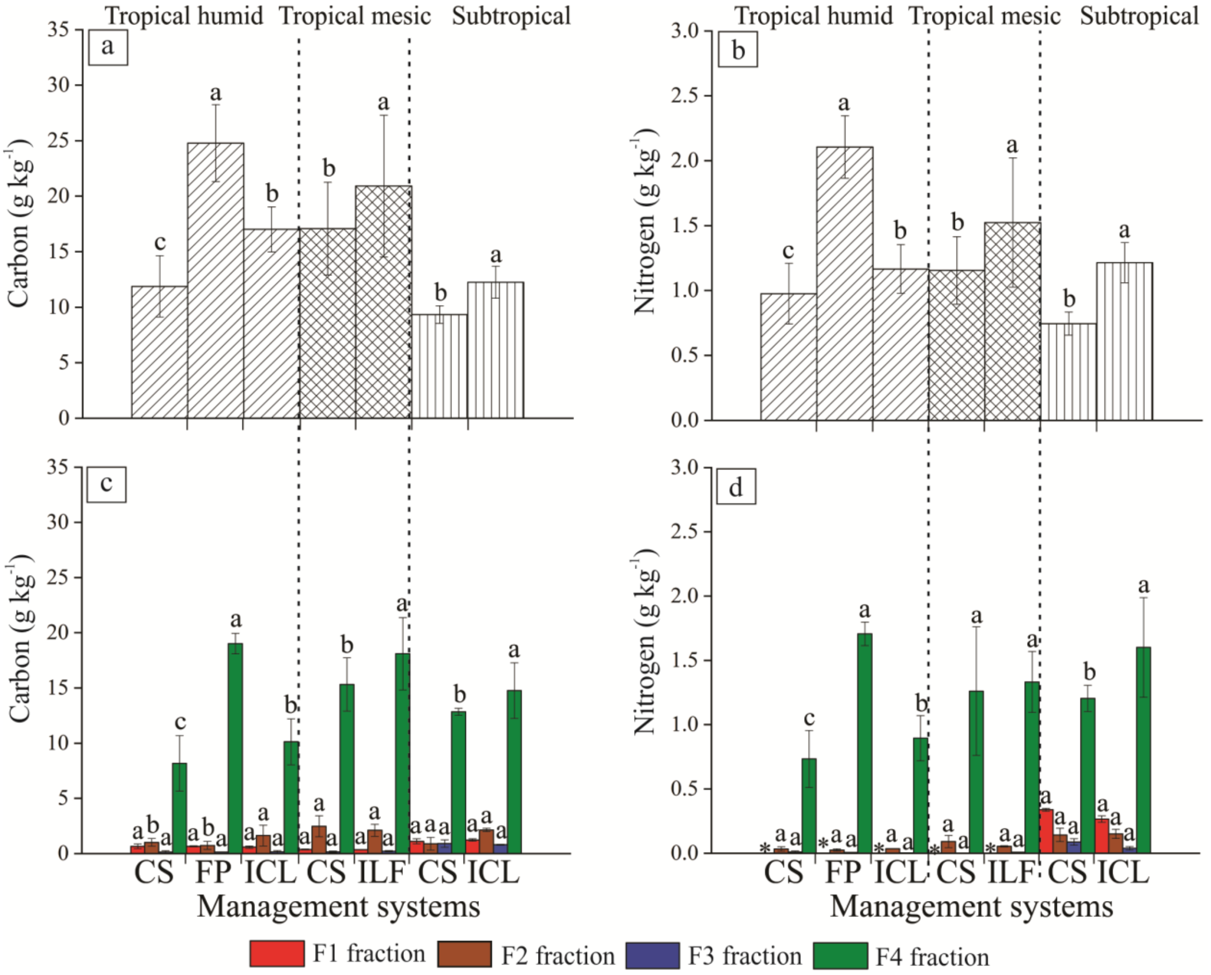


Figure 2. Soil C and N (a and b) and in the different SOM fractions(c and d) in pasture management systems under different climatic conditions in the soil layer 0-10 cm. Bars represent the standard deviation of the mean values (n = 3). Mean values followed by the same letter did not differ from each other by Tukey test ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock. F1, organomineral fraction (75-2000 μm); F2, organic fraction (75-2000 μm); F3, organomineral fraction (53-75 μm); F4, organomineral fraction (<53 μm). *Below the detection limit.

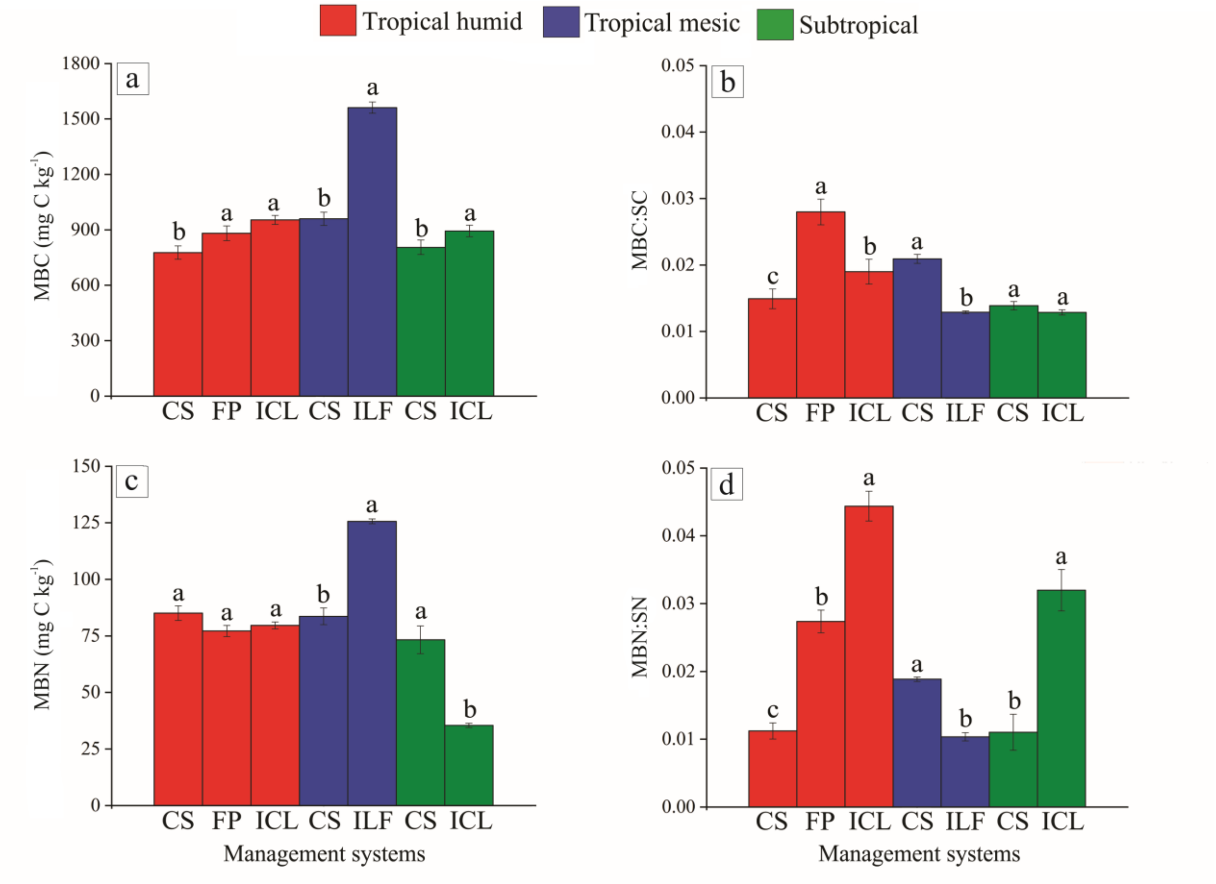


Figure 3. Soil MBC and MBN (a and c) and the MBC:SC and MBN:SN ratios (b and d) in pasture management systems under different climatic conditions. Bars represent the standard deviation of the mean values (n = 3). Mean values followed by the same letter did not differ from each other by Tukey test ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

Table 3. P fractions and enzymatic activity in different pasture management systems under tropical humid, tropical mesic and subtropical climates.

Management systems	Fractions of P (mg kg^{-1})		Enzymatic activity (µg pNF g^{-1} h^{-1})		
	Biological P	Geochemical P	β-glucosidase	Arylsulfatase	Acid phosphatase
			Tropical humid		
CS	196.11±27.54a	202.27±26.72b	80.66±11.87b	61.41±9.47b	116.33±12.97b
FP	170.70±20.60a	266.50±36.94a	191.06±5.99a	62.71±5.00b	232.14±10.42a
ICL	140.18±14.57b	285.58±38.98a	166.84±6.46a	135.05±2.82a	122.41±8.80b
			Tropical mesic		
CS	124.79±9.24b	210.67±23.15b	32.51±9.49b	181.14±13.41b	240.45±12.09b
ILF	198.02±0.10a	253.53±33.82a	56.16±10.27a	246.73±14.02a	340.56±13.35a
			Subtropical		
CS	102.98±18.88b	144.43±11.10b	128.83±7.35b	142.80±9.43a	142.89±15.07b

ICL	219.31±11.58a	263.72±10.36a	152.22±7.78a	156.41±7.84a	243.27±9.08a

Unless indicated otherwise, data were expressed in mean ± s.e.m. (n = 3). Mean values followed by the same letter in the columns did not statistically differ in the Tukey's test at 5% probability ($p \leq 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

Under the tropical humid and subtropical climates, the conversion of CS to ICL enabled a 98% increase mainly for the soil chemical properties related to P, Ca and CEC (Table 2). The adoption of ICL gave increases in soil C and N in relation to CS, which averaged 42 and 37% respectively (Fig. 2a and b). Increases were also seen in the C and N of the F4 fraction under this conversion, with an average of 29 and 17% respectively (Figures 2c and 2d). Under both climate conditions, the conversion of CS from ICL also increased MBC (>17%) and the MBC:TC ratio (Figures 3a and 3b). In addition, the adoption of ICL in relation to CS gave increases in the levels of geochemical P, which averaged 63% under both climate conditions (Table 3). The activity of the enzyme β-glucosidase was particularly influenced by the adoption of ICL under the tropical humid and subtropical climates, with an increase of 108 and 18% respectively in relation to CS. Moreover, under the tropical humid climate, the conversion of CS to ICL increased the activity of the arylsulfatase enzymes (>120%) and, under the subtropical climate, the conversion increased the activity of the acid phosphatase enzyme (>70%).

Under the tropical mesic climate, the adoption of ILF in relation to CS gave an average increase of 82% in approximately all soil chemical properties related to soil fertility (P, Ca, Mg, SB, CEC and BS) (Table 2). For the conversion of CS to ILF an average increment of 20% in soil C and N and in the F4 SOM fraction was also observed (Figures 3a–b). Similarly, this conversion increased the MBC and MBN by 63 and 50% respectively (Figures 3a and 3c). However, a decrease was seen in the MBC:TC and MBN:TN ratios (Figures 3b and 3d). The conversion of CS to ILF also increased the P fractions and enzyme activity (Table 3). The adoption of ILF presented increases of 113 and 83% in biological and geochemical P respectively in relation to CS. For the enzymes β-glucosidase, arylsulfatase and acid phosphatase, the average increment for the conversion of ILF to CS was 45%.

4.3.2. Soil bacterial community structure

The adoption of more intensive and diversified pasture management systems relative to FP under the tropical humid climate, and to ICL under the tropical humid and subtropical climates, altered the soil bacterial community structure (Figures 4a and 4c). This effect was confirmed by the similarity analysis of FP and ICL with CS, where the Rvalue was greater than 0.75 ($P_{value} < 0.002$). Under the tropical humid and subtropical climates, the two PCoA coordinates explained 61.50 and 49.80% of the bacterial structures of the management systems under these climate conditions respectively. As such, only the tropical mesic climate presented no differences between the soil bacterial community structure in ILF relative to CS (Figure 4b), as seen in the similarity analysis (R_{value} less than 0.75; $P_{value} < 0.296$). The two PCoA coordinates under the tropical mesic climate explained 58.81% of the bacterial structure.

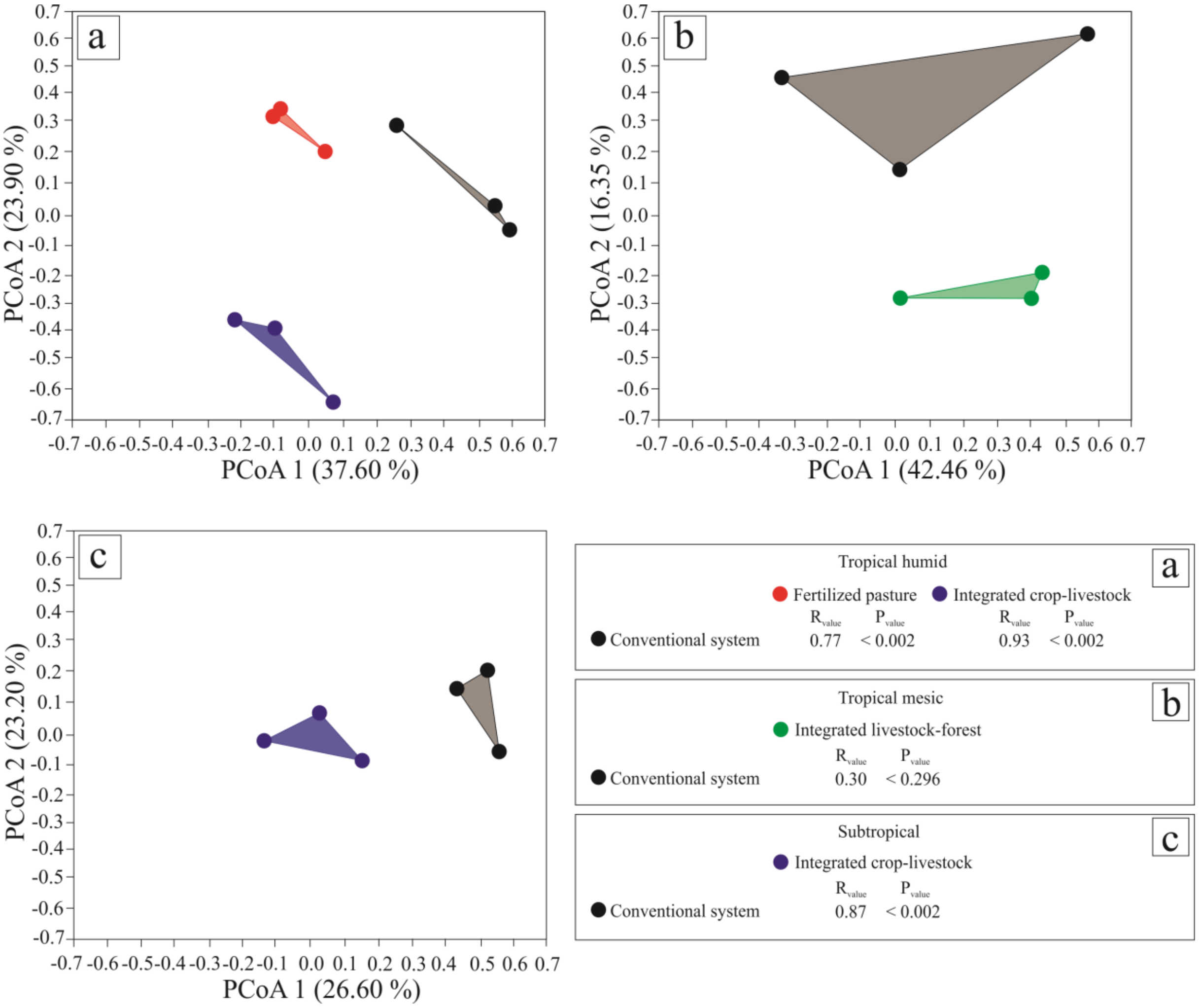


Figure 4. Principal coordinates analysis (PCoA) and analysis of similarity (ANOSIM) for the soil bacterial community structure on pasture management systems subjected to tropical humid (a), tropical mesic (b) and subtropical (c) climates.

Between the three estimated diversity indices, only the Simpson index showed no significant difference between management systems under the different climate conditions (Table 4). Under the tropical humid climate, FP presented increases in the Chao and Shannon index of 174 and 68% in relation to the same indices presented by CS. For ICL under the tropical humid and subtropical climates, the main effect was on the Chao index, which was 474 and 42% higher than the estimated index for CS respectively. In the case of ILF under the tropical mesic climate, the main effect was also on the Chao index, where this index was 52% higher than estimated under CS.

Table 4. Soil bacterial diversity indices of the pasture management systems under tropical humid, tropical mesic and subtropical climates.

Management systems	Diversity indices		
	Chao1	Simpson (1-D)	Shannon-Wiener (H)
		Tropical humid	
CS	19.33±10.93c	0.89±0.04a	2.08±0.47b
FP	53.05±15.89b	0.96±0.02a	3.49±0.23a

ICL	111.01±8.02a	0.92±0.03a	4.08±0.08a
		Tropical mesic	
CS	60.64±11.46b	0.94±0.01a	3.11±0.08a
ILF	92.02±10.99a	0.96±0.02a	3.81±0.09a
		Subtropical	
CS	43.33±23.48b	0.91±0.02a	2.88±0.37a
ICL	61.67±3.84a	0.93±0.01a	3.28±0.70a

Unless indicated otherwise, data were expressed in mean ± s.e.m. (n = 3). Mean values followed by the same letter in the columns did not statistically differ in the Tukey's test at 5% probability ($p \leq 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock.

4.3.2.1. Relationship between the C and N pools, soil chemical and biochemical properties and the soil bacterial community structure

According to the RDA, it was found that among the soil chemical properties under evaluation, those related to acidity showed the strongest relationship to the soil bacterial community structure under CS for the different climate conditions being evaluated. Among the chemical properties, H + Al (tropical humid) (Figure 5a), Al (tropical mesic) (Figure 5d) and pH (subtropical) (Figure 5g) should be mentioned. In the case of the soil biochemical properties, the strongest relationships with CS were particularly seen for MBN (Figure 5b and 5h). For soil C and N and the different SOM fractions, a relationship was only seen for the soil bacterial community structure under CS with total soil N under the tropical mesic climate (Figure 5f).

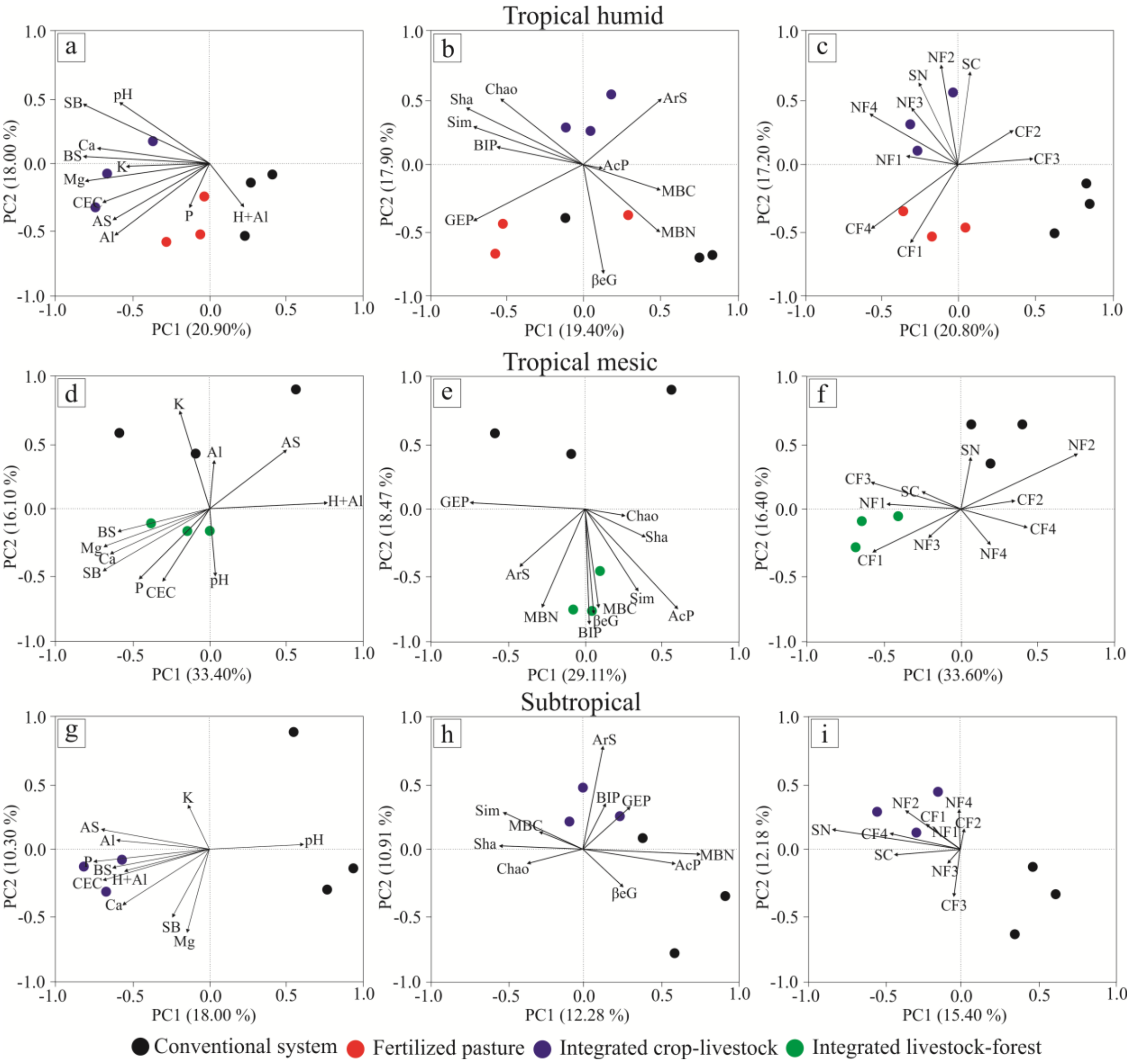


Figure 5. Redundancy discriminatory analysis (RDA) showing the effects of soil chemical (a, d and g) properties, biochemical (b, e and g) properties and C and N pools (c, f and i) on soil bacterial community structure in different pasture management systems. BIP, Biological P; GEP, Geochemical P; βeG, β-glucosidase; ArS, arylsulfatase; AcP, acid phosphatase; Chao, Chao index; Sim, Simpson index; Sha, Shannon index; SC, soil C; SN, soil N; CF1, C in fraction F1; NF1, N in fraction F1; CF2, C in fraction F2; NF2, N in fraction F2; CF3, C in fraction F3; NF3, N in fraction F3; CF4, C in fraction F4; NF4, N in fraction F4.

According to the RDA for FP under the tropical humid climate, it was found that among the soil chemical properties, only the P showed a stronger relationship with the soil bacterial community structure for this management system (Figure 5a). Regarding the soil biochemical properties, the strongest relationship to the soil bacterial community structure under this management system was shown by the geochemical P and MBN (Figure 5b). Furthermore, the C of the F1 and F4 SOM fractions also showed a relationship with the structure of the soil bacterial community structure under FP (Figure 5c).

For ICL under the tropical humid and subtropical climates, it was generally found that for both climate conditions, and among the soil chemical properties under evaluation, CEC, SB, BS and Mg presented the strongest relationship with the soil bacterial community under this management system (Figures 5a and 5g). Whereas for the soil biochemical properties, the enzyme arylsulfatase and the P fractions (biological and geochemical) showed the strongest relationship with the soil bacterial community (Figures 5b and 5h). In addition, N from the F2 and F4 SOM fractions also showed the strongest relationship with the soil bacterial community in ICL, under the tropical humid and subtropical climates (Figures 5c and 5i).

From the results for ILF under the tropical mesic climate, it was found that the soil chemical properties of the soil which presented the strongest relationship with the soil bacterial community under this management system were BS, pH, P and CEC (Figure 5d). Under the same system, the soil biochemical properties related to β-glucosidase and biological P showed the strongest relationship with the soil bacterial community (Figure 5e). Finally, under ILF, the soil bacterial community was related to the C and N of the F1 SOM fraction only (Figure 5f).

4.3.3. Pathways of the impact of the soil chemical and biochemical properties and soil bacterial community structure on C accumulation

SEM was used to verify the impact of the soil chemical and biochemical properties on C accumulation in the soil and in the different SOM fractions. The defined SEM models fit the significance criteria well, where especially the χ^2 and RMSEA values were close to zero (Supplementary Table S2). The results obtained for CS showed that enzyme activity caused a greater impact on soil C and N (path coefficient = 0.49) and the different SOM fractions (0.76) (Figure 6a). The soil bacterial community structure and the diversity indices showed a negative impact on soil C and N (−0.53), and positive impact on the different SOM fractions (0.33) respectively. In the case of FP, the soil chemical properties mainly had a positive impact on the C and N of the soil (0.90) and of the different SOM fractions (0.88) (Figure 6b). For FP, was observed the positive impact of soil bacterial community structure on the C and N of the different SOM fractions (0.21); C and N of the different SOM fractions also had a positive impact on C and N of the soil (0.26) under this management system. The soil chemical properties (0.36), in addition to the P fractions (0.36), microbial biomass (0.31) and the diversity indices (0.54), showed positive impact on the C and N of the different soil SOM fractions under ICL (Figure 6c). In addition, it is worth highlighting the indirect and positive impact of the soil bacterial community structure on the C and N of the different SOM fractions (0.26) under this management system. Under ILF, there were positive impact from the chemical properties and soil bacterial community structure on the C and N of the different SOM fractions (0.61) and on soil C and N (0.28) respectively (Figure 6d). Under this management system, the indirect and positive impact of the microbial biomass (0.41), enzyme activity (0.65) and diversity indices (0.39) were also seen on the soil C and N.

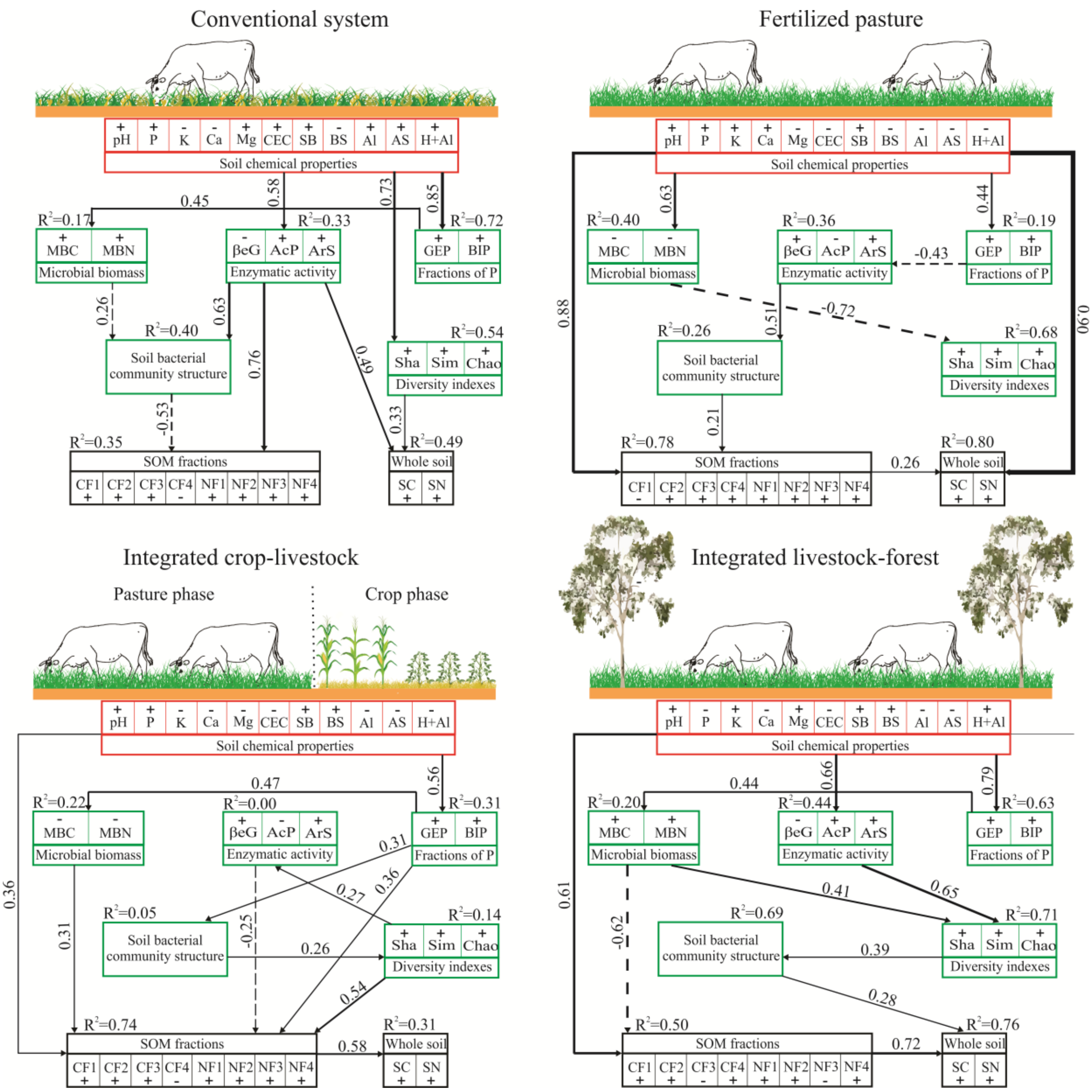


Figure 6. Structural equation modeling (SEM) showing the impact of soil chemical and biochemical properties, soil bacterial community structure and diversity indices on C accumulation under different pasture management systems. Straight and dashed arrows highlight the positive and negative associations, respectively. Only significant direct effects are plotted (*P* < 0.05). Non-significant pathways are not included in the model. Numbers over the arrows are the path coefficients. Arrow length indicates the power of the standardized path coefficient. R^2 represents the proportion of variance explained for each dependent variable in the model. The symbols "+" and "-" indicate a positive or negative relationship between the variables, respectively. The model fits are presented in Supplementary Table S2.

4.4. Discussion

4.4.1. Effects of adopting more intensive and diversified pasture management systems on the C and N pools and soil chemical and biochemical properties

The adoption of more intensive and diversified management systems relative to CS, had positive effects on the C pools, as well as on the soil chemical and biochemical properties under the different climate conditions evaluated. The conversion of CS to FP under the tropical humid climate, increased the soil chemical properties related to soil fertility (P, Ca, Mg, SB, CEC and BS) (Table 2) and the C and N of the soil (Figures 2a and 2b) and the F4 SOM fraction (Figures 2c and 2d). For this conversion was also verified an increase in microbial biomass C (Figure 3a), geochemical P, and β-glucosidase and acid phosphatase enzyme activity (Table 3). According to Xu et al. (2017), more intensive pasture management systems than CS (i.e., FP) not only enable greater nutrient cycling but also increase the input of organic residue above and below ground. Greater input of organic residues is important for increasing C in the soil and in the microbial biomass, as well as increasing C accumulation in the more-stable SOM fractions (F4). This process also provides greater SOM turnover, which may have afforded a greater proportion of soil microbial C, as seen with the higher MBC:TC ratio under FP (Wang et al., 2011). Greater SOM turnover promotes the greater activity of the enzyme β-glucosidase due to an increase in the source of soil organic matter for microorganisms. Under FP, the increased input of plant biomass, together with mineral fertilization with P, contributed to an increase in acid phosphatase activity. This enzyme is related to reactions that increase geochemical P in the soil (Nesper et al., 2015).

When converting CS to ICL under tropical humid and subtropical climates, there were also increased in the soil chemical properties related to P, Ca and CEC (Table 2) and in the C and N of the soil (Figures 2a and 2b) and the F4 SOM fraction (Figures 2c and 2d), besides increases in microbial biomass C (Figure 3a), geochemical P and enzyme activity (Table 3). Laroca et al. (2018), in studies with different management systems, found increases in soil C (>34%) and N (>31%) and microbial biomass C (>15%) under ICL compared to a management system of pasture only (CS). These values agree with the increases found under this management system in the present study, which were 42, 37 and 17% respectively. According to these authors, the rotated use of grasses and legumes under ICL offers a greater supply of energy to the soil microorganisms due to the maintenance of nutrient balance in the soil (fertility) and the greater quantity and better quality of the plant residue supplied by this management system. This effect may explain the higher MBC:TC ratio under ICL in relation to CS for the two climate conditions under study. The increase in the levels of soil C with the conversion of CS to ICL may also have been important for increasing β-glucosidase activity. Concerning the increase in geochemical P with the adoption of ICL under these climate conditions, this effect agrees with Deiss et al. (2016), who point out that ICL can be an effective strategy for increasing P use efficiency in agroecosystems, as it promotes greater bioavailability of inorganic P in the soil.

Under the tropical mesic climate, adopting ILF in relation to CS resulted in an increase in approximately all soil chemical properties related to soil fertility (P, Ca, Mg, SB, CEC and BS) (Table 2), in the C and N of the soil and in the SOM F4 fraction (Figures 2a-d), in the C and N of the microbial biomass (Fig. 3a and c) and in the P fractions and enzyme activity (Table 3). Upson and Burgess (2013) point out the larger volume of thin roots (~1.85 mg cm^{-3}) under ILF that are responsible for greater rhizodeposition (sugars, amino acids and organic acids), which results in a positive increase in the C and N of the soil and of the microbial biomass. Increases in the C and N of the microbial biomass may also be associated to higher enzyme activity (e.g., β-glucosidase, arylsulfatase and acid phosphatase). Furthermore, the cultivation of grasses+trees+animals provides residues that can increase the organic forms of P in the soil (biological P) that are less susceptible to strong adsorption on functional groups of Fe and Al oxides and hydroxides than are the inorganic forms (Pavinato et al., 2017). In addition, animals are able to hydrolyse the phytate in orthophosphate through faeces and urine, which increases the cycling of inorganic P (geochemical P) available to plants and microorganisms (Humer and Zebeli, 2015).

4.4.2. Response of the soil bacterial community structure to the adoption of more intensive and diversified pasture management systems

The conversion of CS to FP under a tropical humid climate, and to ICL under a tropical humid and subtropical climates, altered the soil bacterial community structure (Figures 4a and 4c) and increased the diversity indices of the soil bacteria (Table 4). Among the main reasons for the change in soil bacterial community structure with the adoption of more intensive and diversified pasture management systems (i.e., FP and ICL), greater plant diversity and the addition of fertilizers should be highlighted (Li et al., 2012). Together, these alter nutrient dynamics in the soil and consequently end up selecting specific bacterial communities that act under these management systems (Chen et al., 2018). In the case of the higher Chao and Shannon indices under FP in the tropical humid climate, and the Chao index under ICL in the tropical humid and subtropical climates, the results are important for evaluating the soil biological quality after the adoption of these management systems in relation to CS. These indices indicate biological stability, as well as the intensity and direction of biochemical processes in the soil (Chernov et al., 2015).

The absence of an effect on the soil bacterial community with the conversion of CS to ILF under the tropical mesic climate (Figure 4b) is also consistent with the results found by Cubillos et al. (2016). Those authors found significant changes only for the first three years immediately following the conversion of CS to ILF, where the succession between bacterial communities, although in transition, only stabilised eight years after the implantation of the ILF. These results agree with those of the present study, where despite there being no changes in the soil bacterial community structure, the conversion of CS to ILF presented an increase in the Chao index (Table 4).

In general, according to the RDA the soil chemical properties related to H + Al, Al and pH showed the strongest relationship with the soil bacterial community structure under CS (Figures 5a, 4d and 5g). According to Navarrete et al. (2015), under management systems that involve the excessive removal and/or burning of native vegetation, as is the case of CS under the different climate conditions evaluated in this study, characteristics related to soil fertility (i.e., N, P, K, CEC, etc.) are reduced and those of acidity (i.e., H + Al, Al, pH, etc.) increase. High acidity (copiotrophic environment) and low fertility (oligotrophic environment), although reducing the diversity of the soil bacteria, also promotes the adaptation of bacterial groups to these environments (Wu et al., 2017). The soil bacterial community structure under CS also showed a strong relationship with microbial biomass N (Figures 5b and h) among the soil biochemical properties, and with total soil N (Figure 5f). For Chen et al. (2015), the low levels of inorganic N (soil N) and organic N (microbial biomass N) may cause a high dependence on the soil bacterial community structure under CS.

In FP under the tropical humid climate, it was particularly possible to see the relationship of the soil bacterial community structure with P (chemical properties) (Figure 5a) and with geochemical P (biochemical properties) (Figure 5b). Leff et al. (2015), highlight the importance of P fertilization and the greater input of C in changing the soil bacterial community structure under FP management systems. Under the conditions of this study, the effect of mineral fertilization may have been indirect, i.e. through greater C input above and below ground. This hypothesis can be confirmed by the relationship between the soil bacterial community structure under FP and the C of the F1 and F4 SOM fractions (Figure 5c).

In the case of ICL under the tropical humid and subtropical climates the CEC, SB, BS and Mg (chemical properties) (Figures 5a and g), in addition to the enzyme arylsulfatase and the biological and geochemical P fractions (biochemical properties) (Figures 5b and 5h), showed the strongest relationship with the soil bacterial community structure. These results agree with those of Acosta-Martínez et al. (2010), who reported that ICL management provide larger sources and greater amounts of substrate systems for the soil bacterial communities compared to CS. Furthermore, a relationship was seen between the soil bacterial community structure and the N of the F2 and F4 SOM fractions (Figures 5c and 5i). This effect demonstrates that, under ICL, the N originating mainly from labile fractions, such as the F2 SOM fraction, is closely related to the activity of the soil bacterial community (Yang et al., 2019b).

With ILF under the tropical mesic climate, it is important to highlight the relationship between the soil chemical properties related to BS, pH, P and CEC (Figure 5d) and the structure of the microbial community under this management system. The influence of the soil chemical properties related to fertility on the soil bacterial community structure under ILF may be related to the litter added to the soil by the integration of tree and grass cultivation. These components favour nutrient cycling and, consequently, the metabolic activity of soil bacteria. This hypothesis can also be confirmed by the relationship between the soil bacterial community structure under ILF and the biochemical properties of β-glucosidase and biological P (Figure 5e), and the C and N of the F1 SOM fraction (Figure 5f). The relationship between these properties and the soil bacterial community structure under ILF may be a direct effect, especially of increases in the sources of labile C (F1 SOM fraction) provided by the adoption of ILF compared to CS.

4.4.3. Exploring the impact of adopting more intensive and diversified pasture management systems on C accumulation

The SEM models demonstrated that the adoption of more intensive and diversified management systems in relation to CS, causes changes in the pathways for the C accumulation in the soil and in the different SOM fractions. In the case of CS, it is worth noting the positive impact of enzyme activity and the negative impact of the soil bacterial community structure on soil C and N, and the positive impact on the different SOM fractions (Figure 6a). Under management systems with CS, the high C/N ratio and lignin content, which is due only to the presence of grasses, stimulates the production of enzymes for degrading this plant material, as this is the only source of energy for the soil microorganisms (Jian et al., 2016). Chen et al. (2015), in the decomposition process of organic material under management systems such as CS, point out that losses through respiration by microorganisms is greater than the accumulation of C in the soil. This processes can in parts explain the negative impact of the soil bacterial community structure on the C and N of the different SOM fractions found in this study. Furthermore, Dignac et al. (2017) hypothesized that low natural fertility, as found in the areas of CS evaluated in this study, causes excessive mineralization of the native SOM, which hinders the accumulation of C in the soil. This hypothesis can be confirmed by an analysis of the SEM for ICL, FP and ILF, where the positive impact of the soil chemical properties was seen, particularly on the C and N in the soil and on the different SOM fractions. Therefore, despite the new issues raised in this study, further studies should be carried out proposing other models that explain the mechanisms that control the soil C accumulation under more intensive and diversified pasture management systems.

4.5. Conclusions

Collectively, pasture intensification and diversification in sites previously managed under extensive practices (CS) can notably alter soil chemical and biochemical properties and the soil bacterial community structure across different soil type and climatic conditions. The adoption of FP, ICL and ILF provided approximately 89%, 98% and 82% improvement in chemical properties related to soil fertility (P, Ca and CEC), respectively. The soil biochemical properties such as microbial biomass C, geochemical P and the enzymes β-glucosidase and acid phosphatase were the most sensitive in the conversion of CS to FP, ICL and ILF. The soil bacterial community structure shifted as a result of adopting more intensive and diversified pasture management systems, and a clear distinction was observed mainly among the CS to FP and ICL.

The conversion of CS to more intensive and diversified pasture management systems, besides changing the soil chemical and biochemical properties and the soil bacterial community structure, also modified the mechanisms that control the soil C accumulation. For CS, the enzyme activity and the soil bacterial community structure had both positive and negative impact on soil C. However for FP, ICL and ILF there was a positive impact of soil bacterial community structure and mainly soil chemical properties on soil C. Altogether, these findings provide useful knowledge of understanding soil-management-microbe interactions and provide more insights into the controlling factors of soil C accumulation during management system changes in tropical pasture areas. Moreover, the results found in this study may help efforts (e.g., Brazil's NDC and ABC Program) focused on recovering degraded pasture sites in Brazil.

References

Acosta-Martínez., V., Bell, C.W., Morris, B.E.L., Zak, J., Allen, V.G., 2010. Long-term soil microbial community and enzyme activity responses to an integrated cropping-livestock system in a semi-arid region. Agric. Ecosyst. Environ. 137, 231–240.

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G.A., Cecagno, D., Carlos, F.S., Carvalho, P.C.F., 2014. Soil carbon and nitrogen stocks and fractions in a long-term integrated crop–livestock system under no-tillage in southern Brazil. Agric. Ecosyst. Environ. 190, 52-59.

Ashworth, A.J., DeBruyn, J.M., Allen, F.L., Radosevich, M., Owens, P.R., 2017. Microbial community structure is affected by cropping sequences and poultry litter under long-term no-tillage. Soil Biol. Biochem. 114, 210-219.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pillon, C.N., Sangoi, L., 2001.Changes in soil or-ganic matter fractions under subtropical no-till cropping systems. Soil Sci. Soc. Am.J. 65, 1473–1478.

Campos, M.C.C., Ribeiro, M.R., Júnior, V.S.S., Filho, M.R.R., Souza, R.V.C.C., Almeida, M.C.,2011. Mineralogical characteristics of oxisols and ultisols in Southern Amazonas. Rev. Acad., Ciênc. Agrár. Ambient. 9, 11–18.

Costa, M.P., Schoeneboom, J.C., Oliveira, S.A., Vinas, R.S., Medeiros, G.A., 2018. A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. J. Clean. Prod. 171, 1460-1471.

Cubillos, A.M., Vallejo, V.E., Arbeli, Z., Terán, W., Dick, R.P., Molina, C.H., Molina, E.N., Roldan, F., 2016. Effect of the conversion of conventional pasture to intensive silvopastoral systems on edaphic bacterial and ammonia oxidizer communities in Colombia. Eur. J. Soil Biol. 72, 42-50.

Condron, L.M., Goh, K.M., Newman, R.H., 1985. Nature and distribution of soil phosphorus as revealed by a sequential extraction method followed by 31P nuclear magnetic resonance analysis. J. Soil Sci. 36 (2), 199–207.

Chaudhary, A., Gustafson, D., Mathys, A., 2018. Multi-indicator sustainability assessment of global food systems. Nat. Commun. 9, 1-13.

Chen, H., Xia, Q., Yang, T., Shi, W., 2018. Eighteen-year farming management moderately shapes the soil microbial community structure but promotes habitat-specific taxa. Front. Microbiol. 9, 1-14.

Chen, W., Huang, D., Liu, N., Zhang, Y., Badgery, W.B., Wang, X., Shen, Y., 2015. Improved grazing management may increase soil carbon sequestration in temperate steppe. Sci. Rep. 5, 1-13.

Christensen, B.T., 1992.Physical fractionation of soil and organic matter in primary parti-cle size and density separates. In: Stewart, B.A. (Ed.), Advances in Soil Science.Springer, New York, pp. 1–90.

Chernov, T.I., Tkhakakhova, A.K., Kutovaya, O.V., 2015. Assessment of diversity indices for the characterization of the soil prokaryotic community by metagenomic analysis. Soil Biology 48, 462–468.

Cherubin, M.R., Franco, A.L.C., Cerri, C.E.P., Karlen, D.L., Pavinato, P.S., Rodrigues, M., Davies, C.A., Cerri, C.C., 2016. Phosphorus pools responses to land-use change for sug-arcane expansion in weathered Brazilian soils. Geoderma 265, 27–38.

Cross, A.F., Schlesinger, W.H., 1995. A literature review and evaluation of the Hedley frac-tionation: applications to the biogeochemical cycle of soil phosphorus in natural eco-systems. Geoderma 64, 197–214.

Damian, J.M., Firmano, R.F., Cherubin, M.R., Pavinato, P.S., Soares, T.M., Paustian, K., Carlos Eduardo Pellegrino Cerri, C.E.P., 2020. Changes in soil phosphorus pool induced by pastureland intensificationand diversification in Brazil. Sci. Total Environ. 703, 1-12.

Dias Filho, M.B., 2014. Diagnóstico das pastagens no Brasil-Embrapa. Brasil, Brasília. pp. 1–36.

Dignac, M.F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G.T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.A., Nunan, N., Roumet, C., Basile-Doelsch, I., 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review Agron. Sustain. Dev. 37, 1-27.

Deiss, L., Moraes, A., Dieckow, J., Franzluebbers, A.J., Gatiboni, L.C., Sassaki, G.L., Carvalho, P.C.F., 2016. Soil phosphorus compounds in integrated crop-livestock systems of sub-tropical Brazil. Geoderma 274, 88–96.

Ghahramania, A., Bowranb, D., 2018. Transformative and systemic climate change adaptations in mixed croplivestock farming systems. Agr. Syst. 164, 236-251.

Hedley, M.J., Stewart, J.W.B., Chauhan, B.S., 1982. Changes in inorganic and organic soilphosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Sci. Soc. Am. J. 46, 970–976.

Humer, E., Zebeli, Q., 2015. Phytate in feed ingredients and potentials for improving the utilization of phosphorus in ruminant nutrition. Anim. Feed Sci. Technol. 209, 1–15.

IBGE, 2017. Instituto Brasileiro de Geografia e Estatística. Censo Agropecuário 2017. IBGE, Rio de Janeiro, Rio de Janeiro.

Joergensen, R.G., Brookes, P.C., 1990. Ninhydrin-reactive nitrogen measurements of microbial biomass in 0.5 M K2SO4 soil extracts. Soil Biol. Biochem. 22, 1023-1027, 1990.

Jian, S., Li, J., Chen, J., Wang, G., Mayes, M.A., Dzantor, K.E., Hui, D., Luo, Y., 2016. Soil extracellular enzyme activities, soil carbon and nitrogen storage under nitrogen fertilization: A meta-analysis. Soil Biol. Biochem. 101, 32-43.

Koyanagi, T.F., Yamada, S., Matsuzaki, H., Kato, Y., 2019. Impacts of previous maintenance of river embankments on the grassland communities by changing soil properties. Ecol. Eng. 131, 73-80.

Kopp, J.F., McKee, G.D., 1979. Methods for Chemical Analysis of Water and Wastes. National Technical Information Service, Springfield, Va, pp. 490 Report No. PB 297686, (32319).

Kleyer, H.; Tecon, R.; Or, D., 2017. Resolving specijes level changes in a representative soil bacterial community using microfluidic quantitative PCR. Front. Microbiol. 8, 1-13.

Lange, M., Eisenhauer, N., Sierra, C.A., Bessler, H., Engels, C., Griffiths, R.I., Perla G. Mellado-Vázquez, P.G., Malik, A.A., Roy, J., Scheu, S., Steinbeiss, S., Thomson, B.C., Trumbore, S.E., Gerd Gleixner, G., 2015. Plant diversity increases soil microbial activity and soil carbon storage. Nat. Commun. 6, 1-8.

Leff, J.W., Jones, S.E., Prober, S.M., Barberán, A., Borer, E.T., Firn, J.L., Harpole, W.S., Hobbie, S.E., Hofmockel, K.S., Knops, J.M.H., McCulley, R.L., Pierre, K.L., Risch, A.C., Seabloom, E.W., Schütz, M., Steenbock, C., Stevens, C.J., Fierer, N., 2015. Consistent responses of soil microbial communities to elevated nutrient inputs in grasslands across the globe. PNAS 112, 10967-10972.

Lemos, L.N., Fulthorpe, R.R., Triplett, E.W., Roesch, L.F.W., 2011. Rethinking microbial diversity analysis in the high throughput sequencing era. J. Microbiol. Methods 86, 42-51.

Laroca, J.V.S., Souza, J.M.A., Pires, G.C., Pires, G.J.C., Pacheco, L.P., Silva, F.D., Wruck, F.J., Carneiro, M.A.C., Silva, L.S., Souza, E.D., 2018. Soil quality and soybean productivity in crop-livestock integrated system in no-tillage. Pesqui. Agropecu. Bras. 53, 1248-1258.

Liebig, M.A., Ryschawy, J., Kronberg, S.L., Archer, D.W., Scholljegerdes, E.J., Hendricksona, J.R., Tanaka, D.L., 2017. Integrated crop-livestock system effects on soil N, P, and pH in a semiarid region. Geoderma 289, 178–184.

Li, R., Khafipour, E., Krause, D.O., Entz, M.H., Kievit, T.R., W. G. Fernando, W.G.D., 2012. Pyrosequencing reveals the influence of organic and conventional farming systems on bacterial communities. PLoS One 12, 1-12.

Melillo, J.M., Frey, S.D., De Angelis, K.M., Werner, W.J., Bernard, M.J., Bowles, F.P., Pold, G., Knorr, M. A., Grandy, A.S., 2017. Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science 358, 101–105.

Moreira, G.M., Neves, J.C.L., Magalhães, C.A.S., Neto, A.L.F., Sauer, G., Silva, J.F.V., Fernandes, R.B.A., 2018. Soil chemical attributes in response to tree distance and sun-exposed faces after the implantation of an integrated crop-livestock-forestry system. Revista Árvore 42, 420-405.

Navarrete, A.A., Soares, T., Rossetto, R., Van Veen, J.A., Tsai, S.M., Kuramae, E.E., 2015. Verrucomicrobial community structure and abundance as indicators for changes in chemical factors linked to soil fertility. Antonie van Leeuwenhoek 108, 741–752.

Nesper, M., Bünemann, E.K., Fonte, S.J., Rao, I.M., Velásquez, J.E., Ramirez, B., Hegglin, D., Frossard, E., Oberson, A., 2015. Pasture degradation decreases organic P content of tropical soils due to soil structural decline. Geoderma 257–258, 123–133.

Pavinato, P.S., Soltangheisi, M.R.M.A., Sartor, L.R., Withers, P.J.A., 2017.Effects of covercrops and phosphorus sources on maize yield, phosphorus uptake, and phosphorususe efficiency. Agron. J. 109, 1039–1047.

Raij, B. van, Andrade, J.C., Cantarella, H., Quaggio, J.A., 2001. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico de Campinas, Campinas. pp. 285.

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M., 2014. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agric. Ecosyst. Environ. 190, 70–79.

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., 2019. Soil carbon stock and humification in pastures under different levels of intensification in Brazil. Sci. agric. 76, 33-40.

Shütte, U.E., Abdo, Z., Bent, S.J., Williams, C.J., Schneider, G.M., Solheim, B., Forney, L.J., 2009. Bacterial succession in a glacier foreland of the High Arctic. ISME J. 3, 1258-1268.

Tabatabai, M.A., 1994. Soil enzymes. In: Weaver, R.W., Angle, S., Bottomley, P. (Eds.), Methods of Soil Analysis. Part 2: Microbiological and Biochemical Properties. Soil Science Society of America, Madison, pp. 775–833.

Torres, C.M.M.E., Jacovine, L.A.G., Neto, S.N.O., Fraisse, C.W., Soares, C.P.B., Neto, F.C., Ferreira, L.R., Zanuncio, J.C., Lemes, P.G., 2017. Greenhouse gas emissions and carbon sequestration by agroforestry systems in southeastern Brazil. Sci. Rep. 7, 1-7.

Upson, M.A., Burgess, P.J., 2013. Soil organic carbon and root distribution in a temperatearable agroforestry system. Plant Soil 373, 43–58.

USDA, 2014. Keys to Soil Taxonomy. USDA—Natural Resources Conservation Service, Washington, USA.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703-707.

Wang, J., Sun, J., Xia, J., He, N., Li, M., Niu, S., 2018. Soil and vegetation carbon turnover times from tropical to boreal forests. Funct. Ecol. 32, 71–82.

Wang, Y., Tu, C., Cheng, L., Li, C., Gentry, L.F., Hoyt, G.D., Zhang, X., Hu, S., 2011. Long-term impact of farming practices on soil organic carbon and nitrogen pools and microbial biomass and activity. Soil Till. Res. 117, 8-16.

Wu, Y., Zeng, J., Zhu, Q., Zhang, Z., Xiangui Lin, X., 2017. pH is the primary determinant of the bacterial community structure in agricultural soils impacted by polycyclic aromatic hydrocarbon pollution. Sci. Rep. 7, 1-7.

Xu, S., Silveira, M.L., Inglett, K.S., Sollenberger, L.E., Gerber, S., 2017. Soil microbial community responses to long-term land use intensification in subtropical grazing lands. Geoderma 293, 73–81.

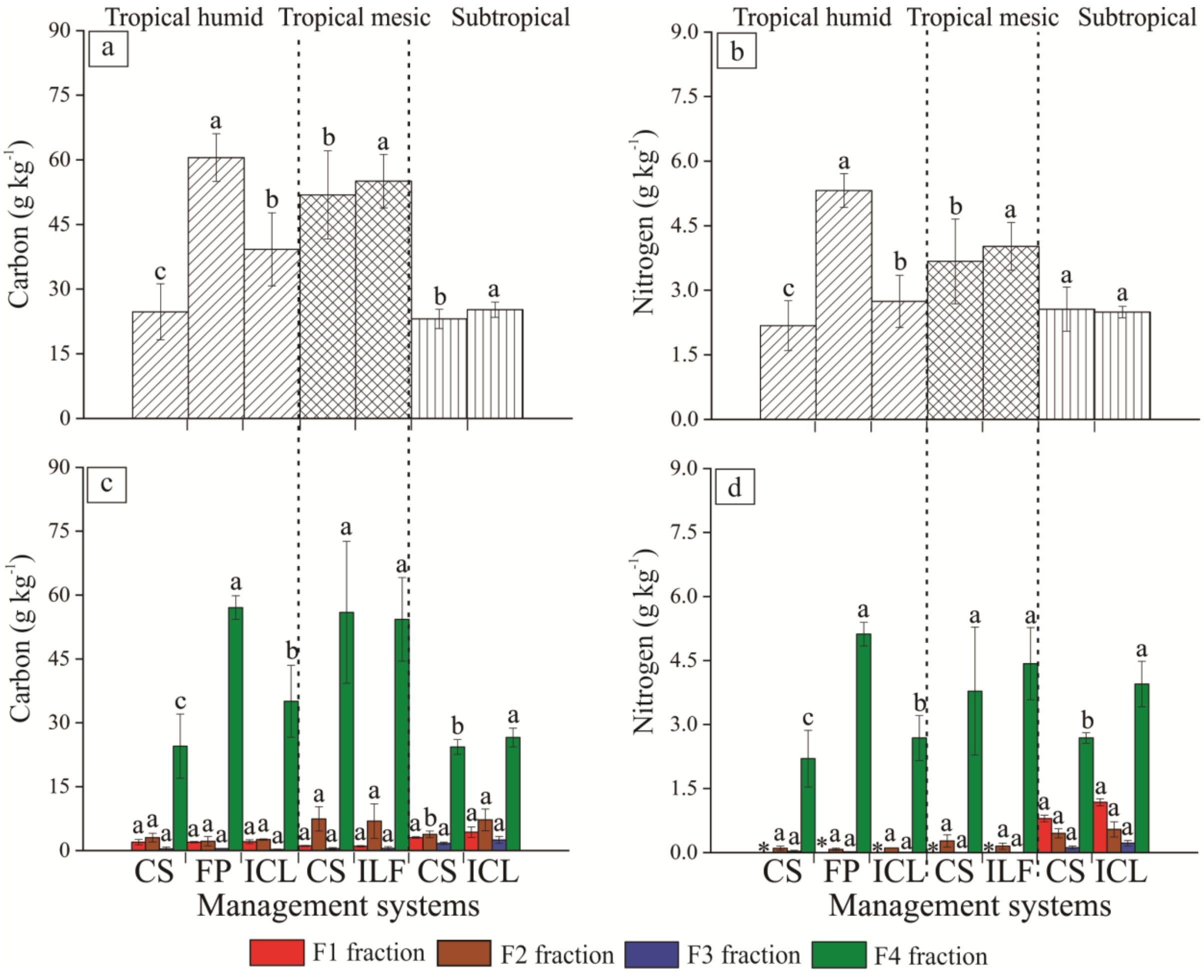
Yang, S., Hao, Q., Liu, H., Zhang, X., Yu, C., Yang, X., Xia, S., Yang, W., Li, J., Song, Z., 2019. Impact of grassland degradation on the distribution and bioavailability of soil silicon: Implications for the Si cycle in grasslands. Sci. Total Environ. 657, 811–818a.

Yang, Y., Wang, P., Zeng, Z., 2019. Dynamics of bacterial communities in a 30-year fertilized paddy field under different organic–inorganic fertilization strategies. Agronomy 9, 1-13b.

Zhang, Y., Dong, S., Gao, Q., Liu, S., Ganjurjav, H., Wang, X., Su, X., Wu, X., 2017. Soil bacterial and fungal diversity differently correlated with soil biochemistry in alpine grassland ecosystems in response to environmental changes. Sci. Rep. 43077, 1-10.

Zhou, Y., Boutton, T.W., Wu, B., 2018. Soil phosphorus does not keep pace with soil carbon and nitrogen accumulation following woody encroachment. Glob. Change Biol. 24, 1992-2007.

Supplementary material



Supplementary Figure S1. Soil C and N (a and b) and in the different SOM fractions (c and d) in pasture management systems under different climatic conditions in the soil layer 0-30 cm. Bars represent the standard deviation of the mean values (n = 3). Mean values followed by the same letter did not differ from each other by Tukey test ($p < 0.05$). Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock. F1, organomineral fraction (75-2000 μm); F2, organic fraction (75-2000 μm); F3, organomineral fraction (53-75 μm); F4, organomineral fraction (<53 μm). *Below the detection limit.

Supplementary Table S1. Description of the management practices adopted under tropical humid, tropical mesic and subtropical climates.

Climatic condition	Tropical humid	Tropical mesic	Subtropical
Description	*Brachiaria ruziziensis* Germ. & C.M. Evrard was used for pasture in CS, FP and ICL. CS: In this management system is characterized by grazing all year. The stocking rate is ~0.5 AU·ha^{-1}. FP: In this management system is characterized by grazing all year. The stocking rate is ~1.2 AU·ha^{-1}. ICL: In this management system, the cultivation period is divided by the crop (october to march) and pasture (may to september) phase. The stocking rate is ~1.8 AU·ha^{-1}.	*Brachiaria brizantha* cv. Marandu was used as pasture in CS and ILF. Two rows of African mahogany trees (*Kaya ivorensis* A. Chev.) spaced 15x5m away from each other were used in ILF. CS: In this management system is characterized by grazing all year. The stocking rate is ~0.7 AU·ha^{-1}. ILF: In the management system with integrated livestock-forest with rotational grazing, the grazing phase is between may and january. The stocking rate is ~2.9 AU·ha^{-1}.	*Lolium multiflorum* Lam. was used for pasture in ICL. The prevailing grass specie in the CS (Pampa) was *Paspalum notatum* Flügge. CS: In this management system is characterized by grazing all year. The stocking rate is ~0.6 AU·ha^{-1}. ICL: In this management system, the cultivation period is divided by the crop (november to may) and pasture (july to october) phase. The stocking rate is ~2.1 AU·ha^{-1}.
Crop nutritional management	15 kg ha^{-1} of N and 60 kg ha^{-1} of P_2O on a yearly basis.	-	18 kg ha^{-1} of N and 40 kg ha^{-1} of P_2O and 40 kg ha^{-1} of K_2O on a yearly basis.
Pasture nutritional management	15 kg ha^{-1} of N; 80 kg ha^{-1} of P_2O and 40 kg ha^{-1} of K_2O on a yearly basis. Application of 2000 kg ha^{-1} of limestone at the time of system deployment.	100 kg ha^{-1} of N on a yearly basis.	150 kg ha^{-1} of N and 60 kg ha^{-1} of P_2O and 60 kg ha^{-1} of K_2O on a yearly basis. Application of 1000 kg ha^{-1} of limestone at the time of system deployment.

CS, conventional system; FP, fertilized pasture; ICL, integrated crop-livestock and ILF, integrated livestock-forest. AU, animal unit (250 kg liveweight).

Supplementary Table S2. Indices of fit for the structural equation modeling presented in Figure 6.

Management systems	Fit index									
	c^2	P	DF	RFI	NFI	IFI	RMSEA	AIC	BCC	ECVI
CS	23.400	0.220	19	0.745	0.827	0.962	0.061	71.742	99.272	2.759
FP	63.377	0.112	21	0.225	0.419	0.518	0.002	109.377	120.425	13.372
ICL	27.352	0.159	21	0.421	0.566	0.849	0.033	73.352	125.102	4.315
ILF	84.444	0.101	17	-0.047	0.364	0.418	0.070	128.444	159.563	17.306

Tropical humid: CS, conventional system; FP, fertilized pasture and ICL, integrated crop-livestock. Tropical mesic: CS, conventional system and ILF, integrated livestock-forest. Subtropical: CS, conventional system and ICL, integrated crop-livestock. c^2, chi-square; P, *p* value; DF, degrees of freedom; RFI, relative fit index; NFI, normed fit index; IFI, incremental fit index; RMSEA, root mean square error of approximation; AIC, Akaike information criterion; BCC, Browne-Cudeck criterion; ECVI, expected cross validation index.

5. PREDICTING SOIL C CHANGES AFTER PASTURE INTENSIFICATION AND DIVERSIFICATION IN BRAZIL[*]

Abstract

Globally, poorly managed pasture can contribute to increasing greenhouse gas (GHG) emissions. In Brazil, sustainable management systems are being proposed to reduce carbon dioxide (CO_2) emissions and increase the soil C stock under degraded pasture. However, despite the potential benefits in the adoption of sustainable management systems, few studies have been carried out seeking to analyze their long-term effects on the soil C cycle. In this study, we used the DayCent model to simulate the effects of converting poorly managed pastures (PMP) to more-intensive and diversified systems of pasture management [fertilized pasture (FP), integrated crop-livestock (ICL) and integrated livestock-forest (ILF)] on long-term soil C stocks and microbial biomass C (MBC). We also evaluated the effects of different pasture management scenarios for FP (fertilization frequency), ICL (time of implementation of the crop phase) and IFL (spacing between the tree rows). The DayCent model estimated that the conversion of PMP to FP, ICL and ILF increases the soil C stocks by 0.95, 0.04-0.70 and 0.16 Mg ha^{-1} yr^{-1}, respectively. Similarly, the MBC contents also increased with conversion, mainly for ICL and ILF. In addition, the fertilization of the pasture every year (FP), the implementation of the crop phase within two years (ICL) and the spacing between the tree rows of 15 m (ILF) showed the highest soil C stocks and MBC contents. FP, ICL and IFL were also GHG sinks of 43, 57 and 116 Mg CO_2eq ha^{-1}, respectively. These results can help national initiatives associated with the recovery of degraded pasture in Brazil.

Keywords: DayCent model, Integrated systems; GHG mitigation; Environmental security.

5.1. Introduction

The soil plays an important role as a regulator of carbon dioxide (CO2) emissions to the atmosphere, and approximately 2300 Pg of carbon (C) is stored in the top 3 m of soils for a total area of 121 x 1012 m^2 (Jobbágy and Jackson, 2000). Globally, pastures are important in the C cycle, covering ~40% of the Earth's land surface and responsible for ~30% of the global pool of soil organic carbon (SOC) (Conant et al., 2001; Schipper et al., 2007). Despite the great C sequestration potential, poorly managed pastures around the world (e.g., overgrazing and no fertilization) could become a source rather than a sink of greenhouse gas (GHG) emissions (Abdalla et al., 2018).

In Brazil, pastures encompass 159 million ha, but approximately 50% to 70% of this area is considered degraded or in some degree of degradation (Dias Filho, 2014; IBGE, 2017). Given the degradation of Brazilian pastures, the government created the “ABC Plan” in an attempt to encourage sustainable recovery measures. The adoption of more-intensive and diversified systems of pasture management, such as fertilized pasture (FP), integrated crop-livestock (ICL) and integrated livestock-forest (ILF), has shown to be promising in achieving this goal (Herrero et al., 2016; Cortner et al., 2019; Pezzopane et al., 2020). Several previous studies revealed the potential of integrated systems to increase soil C stocks (Carvalho et al., 2010; Siqueira et al., 2019) and mitigate GHG emissions (Buller et al., 2015; Torres et al., 2017). However, changes in management practices commonly carried out in pastures, such as frequency of fertilization (FP), time of implementation of the crop phase (ICL) and spacing between the tree rows (ILF), can change these results (Carvalho et al., 2018).

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In Brazil, few long-term studies have been conducted seeking to assess changes in soil C stocks with the intensification and diversification of pastures. Likewise, as Zago and Ramalho (2019) highlight, little is known about the effects on soil microbiota and the important biochemical processes that regulate C and gas flows in the soil. According to Sousa et al. (2020), long-term monitoring of management system changes is necessary to consolidate ecosystem effects. Mathematical models have been shown to be a viable option in predicting changes in soil C and GHG emissions in different agricultural ecosystems (Bonan and Doney, 2018). The DayCent model is among the main biogeochemical models used for this purpose and is widely applied in long-term predictions in pastures under different climatic conditions (Parton et al., 1998; Yeluripati et al., 2009). Gomez-Casanovas et al. (2016), using the DayCent model in pastures under temperate, Mediterranean, subtropical and tropical climates, found correlation coefficient (r^2) values of 0.72, 0.99 and 0.97 between the observed and simulated values for aboveground and belowground net primary production and SOC, respectively. Similarly, Sándor et al. (2018) concluded that mathematical models such as DayCent were efficient in predicting GHG emissions (e.g., CO_2, N_2O and CH_4) in pastures under different management systems. In addition, Cerri et al. (2004) also found satisfactory results with the prediction of microbial biomass (r^2=0.84) in pastures with different ages (0 to 88 years) using the Century model (the precursor to the DayCent model). Therefore, studies on predictions of soil C stocks and GHG emissions using biogeochemical models, as the DayCent model, can provide unprecedented results about the pastureland intensification and diversification in Brazil.

Azevedo et al. (2018) evaluated soil C sequestration in several management systems in Brazil from 1970 to 2015 and found that degraded pastures were GHG sources (4.00 Mg CO_2eq ha^{-1} y^{-1}), while more-intensive and diversified systems of pasture management were sinks (5.51 to 6.24 Mg CO_2eq ha^{-1} y^{-1}). However, the authors agree that these estimates remain unclear due to the lack of long-term information about those management systems. Indeed, there are not published papers on predictions of soil C stocks and GHG emissions due to the intensification and diversification of pastures in Brazil. In this context, we hypothesize that mathematical models can be efficient and cost-effective tools to predict soil C pool changes (i.e., whole soil and microbial biomass) and to monitor GHG emissions of pastures. Our aim is to use the DayCent model to predict the soil C changes with the intensification and diversification of poorly managed pastures in tropical humid (Midwest), tropical mesic (Southeast), and subtropical (South) Brazilian climate zones. In parallel, we intend to evaluate soil C changes with different management practices, such as frequency of fertilization (FP), time of implementation of the crop phase (ICL) and the spacing between the tree rows (ILF).

5.2. Materials and Methods

5.2.1. Experimental data

The field data set used in this study for modeling soil C changes was collected from three regions with contrasting climatic conditions in Brazil. The first site is located in Nova Guarita, Mato Grosso, Midwest Brazil (Lat.: 10° 9' 10.41"S; Long.: 55° 31' 49.53"W; 380 m.a.s.l). The prevailing soil at this site was classified as Oxisol (USDA, 2014), and the climate was classified as Am (Köppen), tropical hot and humid, with a mean annual temperature of 25.9°C and a mean annual rainfall of 2,628 mm. The second site is located in Nova Odessa, São Paulo, southeastern Brazil (Lat.: 22° 75' 12"S; Long.: 47° 27' 81"W; 550 m.a.s.l). The prevailing soil in this region was also classified as Oxisol (USDA, 2014) and the climate as Cwa (Köppen), tropical rainy with dry winter, with a mean annual temperature of 20.2°C and a mean annual rainfall of 1,262 mm. The third site is located in Eldorado do Sul, Rio Grande do Sul, southern Brazil (Lat.: 30° 05' 22"S; Long.: 51° 39' 08"W; 46 m.a.s.l). The prevailing soil in this region is classified as Ultisol (USDA, 2014), and the climate is classified as Cfa (Köppen), subtropical at a mean annual temperature of 19.3°C and a mean annual rainfall of 1,398 mm. More details about the climatic information in Mato Grosso (tropical humid), São Paulo (tropical mesic) and Rio Grande do Sul (subtropical) states can be found in Damian et al. (2020).

For each climatic condition, we evaluate the soil C changes with the adoption of more-intensive and diversified systems of pasture management in areas previously with poorly managed pasture. Areas of poorly managed pasture are mainly characterized by a lack of control over grazing pressure and no fertilization. Specifically, the following pasture management systems were evaluated in each climatic condition:

i) Tropical humid treatments included poorly managed pasture (PMP), fertilized pasture (FP), integrated crop-livestock system with maize/soybean (ICL_{MS}) and integrated crop-livestock with rice/soybean (ICL_{RS}). The site is located in the Amazonian biome, and in 2004, its native vegetation was removed for pasture implementation under PMP. FP and ICL systems were established in 2012 and 2015, respectively, in a previous area under PMP (equivalent edaphoclimatic conditions).

ii) Tropical mesic treatments included poorly managed pasture (PMP), integrated livestock-forest with rotational grazing (ILF_{RG}) and integrated livestock-forest with no grazing (ILF_{NG}). This site is located in the Atlantic Forest biome, where native vegetation was removed to implement the PMP in 1995. In the PMP (equivalent edaphoclimatic conditions), the integrated livestock-forest systems were implemented in 2015 as the current land use.

iii) Subtropical treatments included poorly managed pasture (PMP), integrated crop-livestock with no grazing (ICL_{NG}), integrated crop-livestock with rotational stocking and moderate-intensity grazing (ICL_{RM}), integrated crop-livestock with continuous stocking and moderate-intensity grazing (ICL_{CM}), integrated crop-livestock with rotational stocking and low-intensity grazing (ICL_{RL}) and integrated crop-livestock with continuous stocking and low-intensity grazing (ICL_{CL}). PMP is located in the Pampa biome and in 2003, it was chosen for the installation of a long-term experiment focused on the integrated crop-livestock system. Forage supplies were defined as those presenting 2.5 times (moderate grazing intensity) and 5 times (low grazing intensity) more daily consumption of dry matter based on NRC (1985) by lambs or lactating ewes. The resulting forage supply reached 10 kg (moderate grazing intensity) and 20 kg (low grazing intensity) of forage dry mass per 100 kg ha− 1 animal live weight.

Information regarding soil sampling, laboratory analysis and results for soil C pools, physical and chemical soil properties for each climatic condition can be found in Damian et al. (2020). The determination of the microbial biomass C (MBC) and N (MBN) in the 0-10 cm layer were performed by the fumigation-extraction (Vance et al., 1987) and Ninhydrin (Joergensen and Brookes 1990) methods, respectively.

5.2.2. Model setup and parameterization

In this study, the DayCent (version 2017) biogeochemical model was used to assess the soil C pool changes under more-intensive and diversified systems of pasture management. The DayCent model (Parton et al., 1998; Del Grosso et al., 2001) is a daily time step version of the Century model to simulate exchanges of C, nutrients (N, P, S) and gases (CO_2, CH_4, N_2O, NO_x, N_2) between soil, vegetation and atmosphere. DayCent uses several mechanistic submodels to simulate daily plant production, soil water and temperature, decomposition of dead plant material and soil organic matter (SOM) and trace gas flux leaching (N_2O, NO_x and N_2). The model considers that plant growth and production are controlled by water, light, soil temperature and nutrient availability. SOM decomposition processes and flows of C and nutrients are controlled by C pools, N and lignin concentrations, C/N ratio, and soil water content and temperature. The model calculates trace gas emissions from soils resulting from nitrification and denitrification as well as CH_4 oxidation in soils (Del Grosso et al., 2002). More details about the submodels can be found in Del Grosso et al. (2001).

DayCent model inputs can be divided into four categories: weather information, soil information, plant information, and land use information. In this study, we used weather data (daily maximum and minimum average temperature and precipitation) from 1980 to 2018, provided by the Brazilian National Institute of Meteorology (www.inmet.gov.br). The DayCent model uses daily weather data (precipitation, minimum temperature, maximum temperature). The soil information in the three assessed sites, under each management system, were collected in cross-sections with nine sampling spots (repetitions) placed 50m away from each other (see Damian et al. 2020). For the plant information, we mainly adjusted the potential production, while other parameters, the default model values for cropland and pasture, were used. In this case, the productive potential adjusted for the soybean, maize and rice crops was 6, 14 and 9 Mg ha^{-1} of aboveground biomass, respectively, as found in studies by Crusciol et al. (2003) and suggested by Silva-Olaya et al. (2017). The aboveground biomass production of the grasses (*Brachiaria ruziziensis, Brachiaria brizantha, Lolium multiflorum and Paspalum notatum*) used in this study was adjusted according to the specificities of the management system (e.g., grazing intensity and stocking methods) used in the pastures in each climatic condition. Moreover, historical land use information for each climatic condition was included in the model. This information includes the interval in years of the areas under native vegetation (Amazon, Atlantic Forest and Pampa biomes), PMP and the implementation of more-intensive and diversified systems of pasture management (FP, ICL and ILF). Other management events characteristic of each land use, such as harvest, burning, fertilisation and tillage, were also simulated in the model.

The first step before simulating native vegetation clearing and pasture establishment was to estimate the equilibrium of C pool levels under forest and/or grass vegetation conditions through the DayCent forest and grassland submodels. For the Amazon (tropical humid climate condition) and Atlantic (tropical mesic climate condition) forests, 2000 years of equilibrium were simulated, and the parameterization of vegetation was carried out according to Cerri et al. (2004) and Silva-Olaya et al. (2017), respectively. In the Pampa biome (subtropical mesic climate condition), grassland equilibrium (native conditions) was simulated over a 500-year simulation period. The simulation period used for this biome was based on the introduction of livestock activity by Spanish colonization in the 17th century (Chomenko and Bencke, 2016). Furthermore, the native vegetation parameterization in the Pampa biome was carried out according to Boldrini and Eggers (1996) and Carvalho et al. (2006). For both native vegetation types under the three climatic conditions (tropical humid, tropical mesic and subtropical climates), disturbances such as fire events, tree mortality and deforestation processes following the slash-and-burn procedure were simulated according to Cerri et al. (2004).

The PMP evaluated in this study was characterized by some degree of degradation, as is characteristic of poorly managed pastures in Brazil. To simulate the PMP on the DayCent model, the following procedures were adopted: low aboveground biomass production (~3.7 Mg ha^{-1}, Lilienfein and Wilcke, 2003), low stocking rate (~0.6 AU ha^{-1}, Arantes et al. 2018), continuous grazing throughout the year (wet and dry periods) and no fertiliation. The main difference for the simulations of the conversion of PMP to FP (tropical humid climate condition) was the application of 10 g N m^{-2} $year^{-1}$ and the increase in aboveground biomass production by ~6.4 Mg ha^{-1} (Wilcke and Lilienfein, 2004). For the simulation of ILF management systems (tropical mesic climate condition), we perform the cultivation of pastures intercropped by trees in the same area. In the ILF management system with grazing (ILF_{RG}), animal entry into the area was simulated from May until April with 2.0 AU ha^{-1}. For both management systems with ILF (ILF_{RG} and ILF_{NG}), parameterization of the tree component was carried out according to Orwa et al. (2009), and the application of 1 g N m^{-2} $year^{-1}$. For the management systems with ICL, the simulations were performed according to the management events characteristic of the tropical humid and subtropical climate conditions. For example, the crop phase was between November and March under the tropical humid climate region and December to June in the subtropical climate region. For these climate conditions, the aboveground biomass production of grass in intercropping with crops under ICL was parameterized according to Pariz et al. (2011) and Neto et al. (2014). Furthermore, for ICL management systems in both climatic conditions, the application of 7 g N m^{-2} $year^{-1}$ with 1.2 AU ha^{-1} in the pasture phase was simulated.

The simulations of soil C dynamics in this study were performed for the 0-30 cm soil layer. Originally the DayCent model was set up to approximate the 0-20 cm soil layer. To change the reference layer in the model, the decay rate of all C pools was reduced by 15% (Hartman et al., 2018). By this process, it was possible to obtain estimates of soil C and N stocks for the 0-30 cm layer, as recommended by the IPCC (Intergovernmental Panel on Climate Change) for soil C assessments. To simulate the MBC and MBN values, the active soil pool in the model was used. In the DayCent model, the active pool represents microbial biomass and metabolites that turn over relatively rapidly (less than one year). However, as our MBC and MBN data were evaluated in the 0-10 cm layer and the model output is for the 0–20 cm layer, some adjustments to the final values were performed. Therefore, we multiplied the simulated results of the active pool by 0.65, as recommended by Cerri et al. (2004). The 0.65 factor represents the percentage (65%) of the total soil C present in the 0-10 cm layer in relation to the total soil C contained in the 0-20 cm layer.

For performance evaluation, the simulated results of soil C stocks, soil N stocks, MBC and MBN contents were subjected to visual comparison with actual values from field measurements. This is a qualitative way of assessing whether a model is producing simulated values close to those actually measured (Smith et al., 1996). The quantitative evaluation of the simulated and observed values was performed in accordance with the tests proposed by Smith et al. (1997). Based on this methodology, the following test statistics were calculated: correlation coefficient (r), root mean square error (RMSE), mean difference (M), relative error (E), and lack of fit (LOFIT).

5.2.3. Development of future pasture management scenarios

To assess the impacts of changes commonly performed in more-intensive and diversified systems of pasture management in Brazil, we simulate the effects of different management practices on soil C changes over a fifty-year projection (Fig. 1, Table S1). For the FP (tropical humid climate condition), we simulate the effect of the following frequency of pasture fertilization: 1, 3, 6, 9 and 12 years. Based on the results of the previous simulations, among the management scenarios ICL (tropical humid and subtropical climate conditions) and IFL (tropical mesic climate conditions), only those with the highest results in soil C stocks, soil N stocks, MBC and MBN contents were used in this simulation. In the case of ICL management systems, we evaluated the intervals of 1, 2, 4, 6, and 8 years for crop phase implantation in the pasture. The interval of 1 year essentially means the rotation with pasture crops every year in the same area; this same sequence applies to the other years evaluated (2, 4, 6 and 8 years).

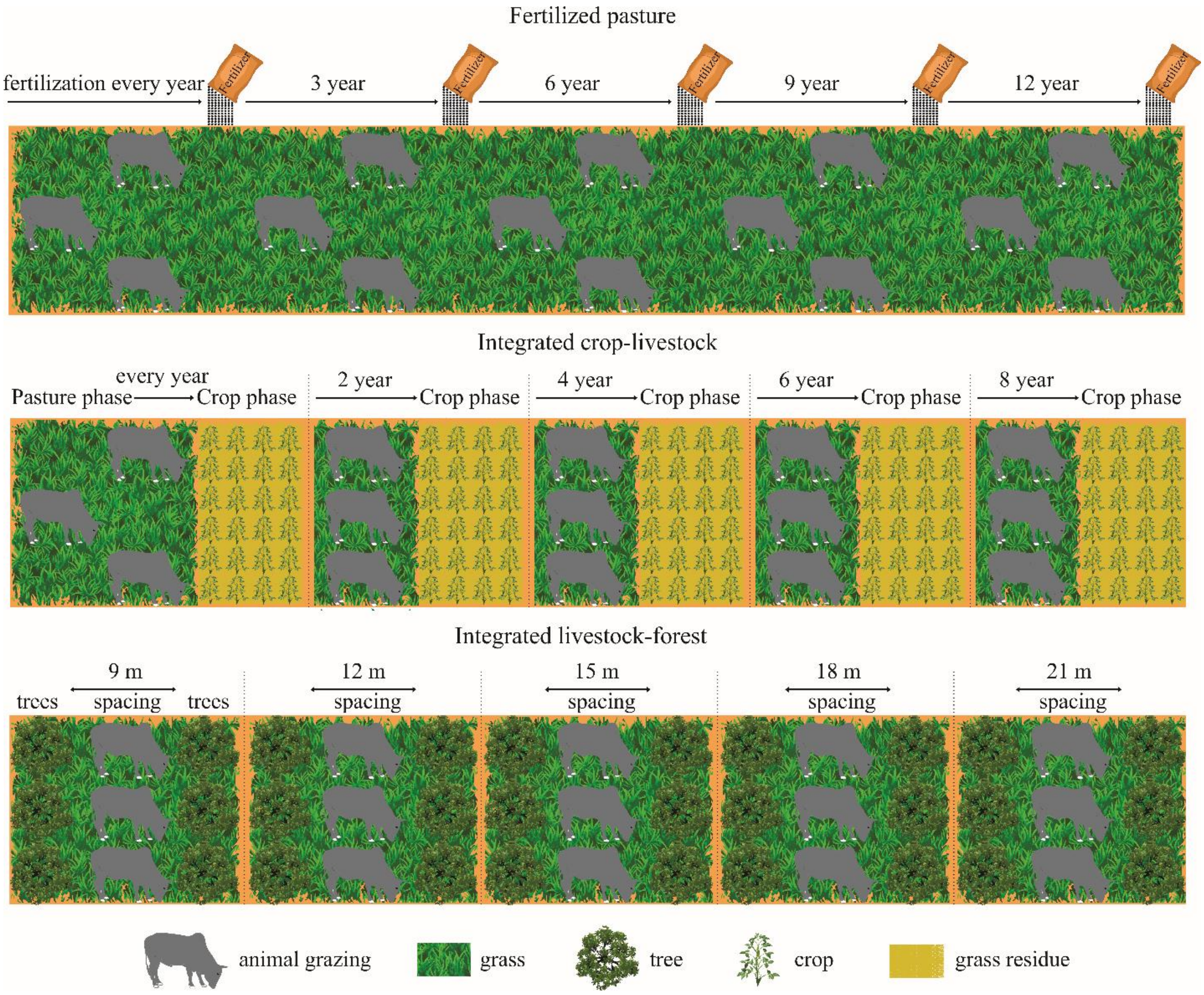


Figure 1. Schematic representation of the future management practices scenarios adopted for the more- intensive and diversified systems of pasture management.

For IFL management systems, the spacings between tree rows of 9, 12, 15, 18 and 21 m were simulated. To carry out the simulations in the DayCent model, we modified the number and the total C production by the trees to meet these spacings in the following order: 250 (2939 g C m^{-2}), 222 (2610 g C m^{-2}), 200 (2352 g C m^{-2}), 182 (2140 g C m^{-2}), and 167 (1964 g C m^{-2}) trees. In addition, according to the spacing, we adjust the parameters ("SITPOT" in the model) that control dominance and competition for N; the smaller the spacing the faster will be the dominance of trees on grass and less competition will be the grass by the N available.

5.2.4. Socioeconomic and environmental indicators

In order to estimate the impacts of the conversion of PMP to the more-intensive and diversified systems of pasture management, socioeconomic indicators were created. For the economic indicators, the production of beef (@ ha^{-1}), soybean (kg ha^{-1}) maize (kg ha^{-1}) and wood (m^3 ha^{-1}) was selected, considering that these indicators are the main economic factors taken into consideration for the adoption of new management systems. To perform the calculations, we adjusted the stocking rates and the production costs according to the degree of intensification of the pasture management systems. Among the social indicators, we selected the numbers of employees (laborers ha^{-1}) and annual income (US$ ha^{-1} y^{-1}), since the same are the most sensible social factors due to the land use change in Brazil. While annual income was the sum of the sales minus production costs, the numbers of employees was calculated according to the demand for services required in each pasture management systems.

The ecosystem flows of carbon, nitrogen and greenhouse gases related to the conversion of PMP to the more-intensive and diversified systems of pasture management were also accounted for using specific DayCent output variables. The simulations were performed during 2010 to 2060. The daily flows of soil C and GHG were summed to calculate the total flows in the ecosystem between the beginning and the end of a year, with the net balance being presented as CO_2 equivalent (CO_2eq) and factored in by the warming potential (e.g., $CO_2 = 1$, $CH_4 = 23$, $N_2O = 296$). For estimate the total GHG emissions, the CH_4, N_2O and total system C flux were summed and expressed as CO_2eq. It is important to highlight that this study did not account the carbon stored in the trees for the GHG balance. Due to the scarcity of data on the flow of GHG in the process of intensification and diversification of pastures in Brazil, we carried out validation through aboveground plant biomass production. According to Duval et al. (2013), this is a reliable way to measure the GHG flow in agricultural ecosystems, as aboveground production is a variable measured widely across a range of sites.

5.3. Results

5.3.1. Measured vs simulated analyses

According to the results, the DayCent model was efficient in predicting the field-observed soil C and N stocks and MBC and MBN contents for NV and for pasture management systems (PMP, FP, ICL and ILF) under different climatic conditions (tropical humid, tropical dry and subtropical) (Table 1 and Fig. 2). The measured and simulated soil C (r = 0.98) and N (r = 0.97) stocks were strongly correlated. However, the DayCent model overestimates C and N stock values by 2.10% and 3.97%, respectively, when compared to the measured values. The MBC (r= 0.84) and MBN (r= 0.81) contents also showed good correlation with the measured and simulated values. However, while for the MBC content, there was an overestimation (>16.63%), the model showed a tendency to underestimate the MBN contents (<6.76%) in relation to the measured contents.

Table 1. Measured and simulated soil C and N stocks at the 0–30 cm layer and MBC and MBN contents at the 0-10 cm layer in different systems of pasture management under tropical humid, tropical mesic and subtropical climate conditions.

	Management systems	Stocks (Mg ha^{-1})				Microbial biomass (mg kg^{-1})			
		C		N		C		N	
		Measur.	Simul.	Measur.	Simul.	Measur.	Simul.	Measur.	Simul.
Tropical humid	NV	50.50±2.60	50.86	4.40±0.18	4.79	550.00±18.00	719.06	37.89±7.09	59.37
	PMP	34.74±2.32	38.56	3.07±0.17	3.81	776.84±26.08	852.49	85.07±3.21	70.62
	FP	85.62±2.59	82.67	7.53±0.19	8.07	881.46±9.93	890.79	77.18±2.46	97.69
	ICL$_{\text{MS}}$	54.45±1.94	56.08	3.88±0.14	3.73	953.64±24.04	1027.22	79.63±1.53	92.47
	ICL$_{\text{RS}}$	41.41±2.30	41.15	2.49±0.20	2.50	451.33±5.51	626.28	39.69±1.88	27.60
Tropical mesic	NV	81.89±2.79	85.61	6.64±0.29	6.76	693.08±9.34	628.48	37.38±3.22	50.76
	PMP	71.59±2.08	75.41	5.03±0.13	5.24	959.45±25.53	505.96	83.65±3.70	46.73
	ILF$_{\text{NG}}$	76.45±4.22	76.62	4.21±0.34	5.16	1764.10±68.16	2463.45	134.59±1.51	198.55
	ILF$_{\text{RG}}$	76.08±3.34	76.20	5.56±0.23	5.15	1359.17±12.82	1808.10	116.73±0.58	143.35
Subtropical	NV/PMP	39.26±1.68	39.55	3.87±0.05	3.91	805.52±26.61	719.21	73.28±6.10	57.55
	ICL$_{\text{NG}}$	31.73±0.72	32.48	3.92±0.08	3.96	876.22±4.58	1035.32	41.81±0.78	25.16
	ICL$_{\text{RM}}$	38.65±0.45	39.01	3.76±0.04	3.90	476.01±11.14	827.23	33.42±1.99	24.40
	ICL$_{\text{CM}}$	40.53±0.25	40.84	4.00±0.02	4.04	482.20±7.11	856.00	56.81±3.03	27.44
	ICL$_{\text{RL}}$	36.13±0.58	37.03	3.67±0.05	3.60	1371.98±34.63	1116.25	34.63±0.93	21.82
	ICL$_{\text{CL}}$	35.47±0.31	36.66	3.71±0.01	3.59	1245.36±1.37	1310.99	43.53±2.23	26.81

Unless indicated otherwise, data are the mean±s.e.m. (n = 9). Tropical humid: NV, native vegetation; PMP, poorly managed pasture; FP, fertilized pasture; ICL$_{\text{MS}}$, integrated crop-livestock with maize/soybean; ICL$_{\text{RS}}$, integrated crop-livestock with rice/soybean. Tropical mesic: NV, native vegetation; PMP, poorly managed pasture; ILF$_{\text{RG}}$, integrated livestock-forest with rotational grazing; ILFNG, integrated livestock-forest with no grazing. Subtropical: NV/PMP, native vegetation/poorly managed pasture; ICLNG, integrated crop-livestock with no grazing; ICLRM, integrated crop-livestock with rotational stocking and moderate-intensity grazing; ICLCM, integrated crop-livestock with continuous stocking and moderate-intensity grazing; ICLRL, integrated crop-livestock with rotational stocking and low-intensity grazing; ICLCL, integrated crop-livestock with continuous stocking and low-intensity grazing.

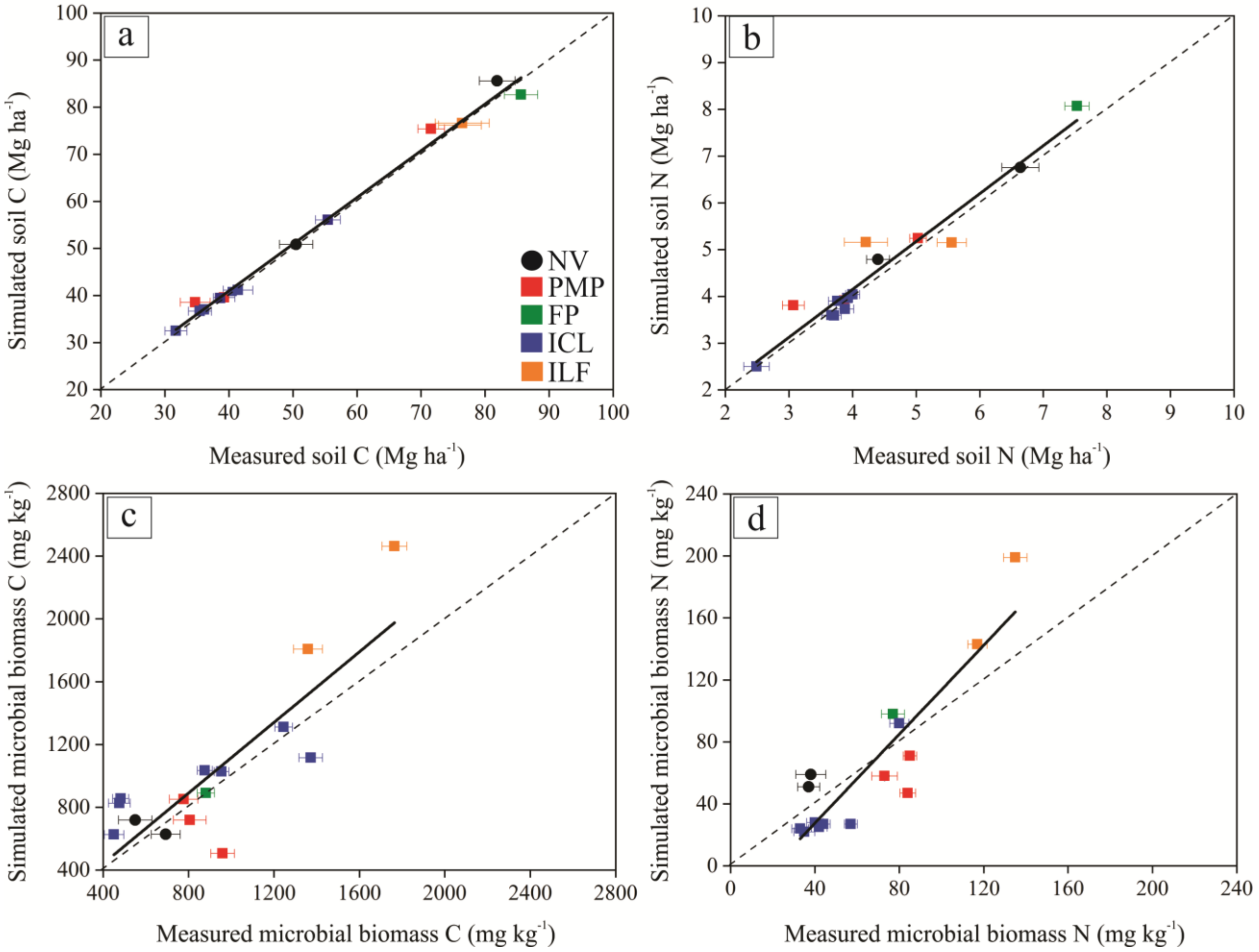


Figure 2. Measured versus simulated soil C stocks (a), soil N stocks (b), MBC (c) and MBN (d) contents under native vegetation (NV) and in the different pasture management systems (PMP, FP, ICL, IFL). Bars represent the standard deviation from the mean values n=9.

With the evaluation of the goodness-of-fit of the simulated and measured values, it was observed that the DayCent model represented well the changes in the soil C and N stocks and the MBC and MBN contents with the management changes in the different climatic conditions evaluated (Table 2). The E and M_t statistics were lower than the $E_{95\%}$ and $M\_t_{95\%}$ statistics, indicating that the bias presented by the simulated values is within the confidence interval (95%). With the exception of the MBC and MBN contents, the simulated soil C and N stocks presented small differences and were within the confidence interval of the measurements ($RMSE < RMSE_{95\%}$). Finally, the F-test for LOFIT showed no lack of fit between measured and simulated values ($F < F_{5\%}$).

Table 2. Statistical tests were applied to validate the measured and simulated values of soil C stocks, soil N stocks, MBC and MBN contents under native vegetation and in the different pasture management systems (PMP, FP, ICL, IFL).

Statistical test	Stocks (Mg ha^{-1})		Microbial biomass (mg kg^{-1})	
	C	N	C	N
r = Correlation coefficient	0.98	0.97	0.84	0.81
F = ((n-2) r^2) / (1-r^2)	1324.94	280.67	20.49	27.84
F-value at (P=0.05)	2.18	2.18	2.18	2.18
RMSE = Root mean squared error of model	3.87%	6.89%	24.70%	33.20%
RMSE (95% Confidence limit)	14.24%	17.33%	15.56%	25.36%
M = Mean Difference	-0.93	-0.11	-38.62	4.92
t = Student's t of M	-1.91	-1.38	-0.68	0.92
t-value (Critical at 2.5% - Two-tailed)	2.16	2.16	2.16	2.16
E = Relative error	-2.09	-2.64	-8.20	10.64
E (95% Confidence Limit). = +/-	12.69	15.81	9.43	20.42
LOFIT = Lack of fit	459.43	10.35	5841505.64	51098.90
F = Mean squared/Mean squared error	0.30	0.88	8.04	0.19
F (Critical at 5%)	1.82	1.82	1.78	1.78

5.3.2. Long-term simulations

The long-term simulations, fifty-year projections, performed with the DayCent model, showed that the conversion of NV to PMP under the three climatic conditions (tropical humid, tropical mesic and subtropical) resulted in an average reduction of 0.49 and 0.05 Mg ha^{-1} yr^{-1} in soil C and N stocks, respectively (Fig. 3a, 3c and 3e; Fig. 1Sa, 1Sc, 1Se). As for the microbial biomass, despite the increase in MBC and MBN (~14%) contents in the conversion of NV to PMP under tropical humid conditions (Fig. 3b and Fig. 1Sb), for this same conversion under tropical mesic conditions, there was a reduction of 12.20 and 0.81 mg kg^{-1} yr^{-1} in MBC and MBN (Fig. 3d and Fig. 1Sd), respectively.

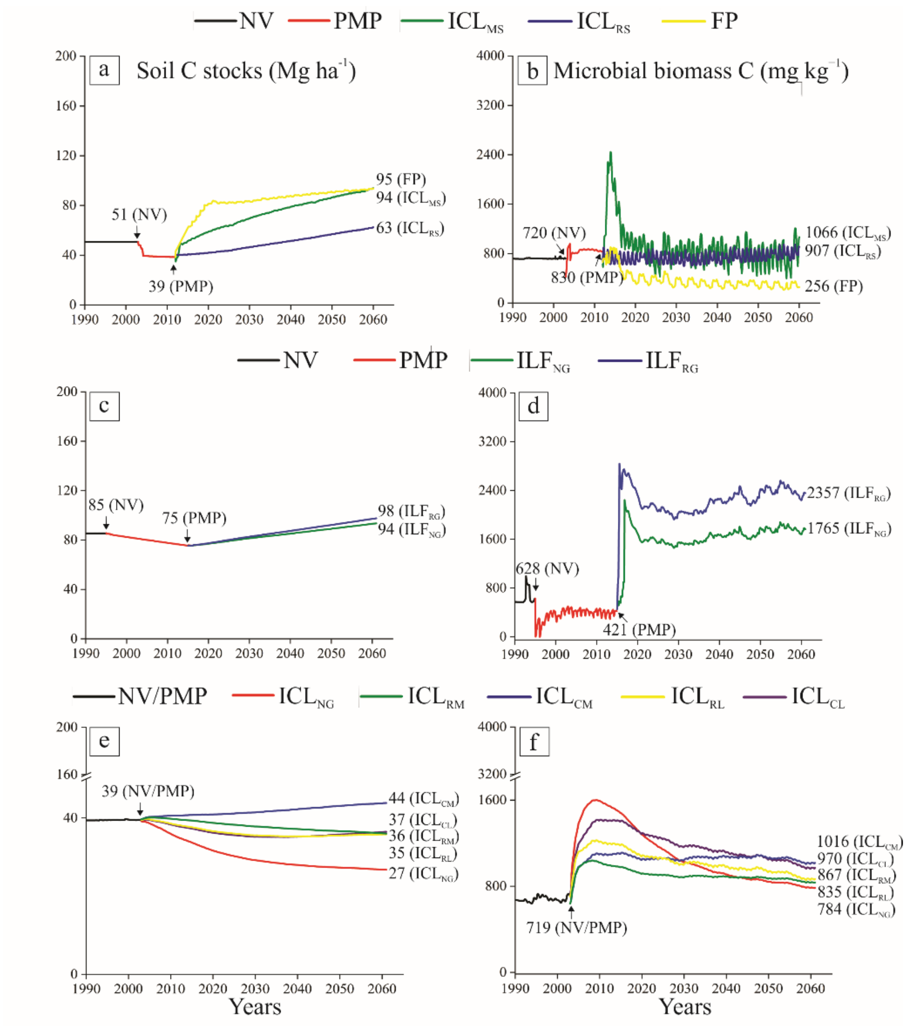


Figure 3. Long-term simulations of soil C stocks and MBC contents through the conversion from native vegetation to different pasture management systems under tropical humid (a and b), tropical mesic (c and d) and subtropical (e and f) climate conditions.

In the simulations for the conversion of PMP to FP in the tropical humid climate, there were increases of 0.95 and 0.07 Mg ha^{-1} yr^{-1} in soil C and N stocks, respectively (Fig. 3a and Fig. 1Sa). However, in this conversion, there was no increase in the MBC and MBN contents (Fig. 3b and Fig. 1Sb). Conversely, the conversion of PMP to management systems with ICL under tropical humid and subtropical climate, in general, was efficient in increasing the soil C and N stocks (Fig. 3a and Fig. 1Sa) and MBC and MBN contents (Fig. 3b and Fig. 1Sb). In the tropical humid climate, among the evaluated management systems with ICL, the ICLMS showed the largest increases in soil C (0.70 Mg ha^{-1} yr^{-1}) and N (0.10 Mg ha^{-1} yr^{-1}) stocks and MBC (3 mg kg^{-1} yr^{-1}) and MBN (0.33 mg kg^{-1} yr^{-1}) contents. For the long-term simulations between ICL management systems under subtropical climate, the ICL$_{CM}$ showed the largest increases in soil C (0.04 Mg ha^{-1} yr^{-1}) and N (0.01 Mg ha^{-1} yr^{-1}) stocks (Fig. 3e and Fig. 1Se), as well as in MBC (7 mg kg^{-1} yr^{-1}) and MBN (0.50 mg kg^{-1} yr^{-1}) contents (Fig. 3f and Fig. 1Sf).

In the tropical mesic climate condition, the conversion of PMP to the ILF management systems also showed increases in the soil C and N stocks (3c and Fig. 1Sc) and in MBC and MBN contents (3d and Fig. 1Sd) in the long-term simulations. While the changes seen in the ILFNG, the ILFRG presented the highest results, with increments of 0.16 and 0.02 Mg ha^{-1} yr^{-1} for soil C and N stocks and 40 and 3 mg kg^{-1} yr^{-1} of MBC and MBN contents, respectively.

5.3.3. Future pasture management scenarios

Changes commonly made in more-intensive and diversified systems of pasture management in Brazil can alter soil C and N stocks and MBC and MBN contents. For the FP under a tropical humid climate, the results of long-term simulations showed that 3 years (FP_3F) of pasture fertilization can reduce soil C and N stocks by 13% (Fig. 4a and Fig. 2Sa) and the MBC and MBN contents by 11% (4b and Fig. 2Sb) when compared to fertilization performed every year (FP_1F). The frequencies of pasture fertilization of 6 (FP_6F), 9 (FP_9F) and 12 (FP_12F) years showed similar results, with a 40% reduction in the soil C and N stocks and 88% in the MBC and MBN contents.

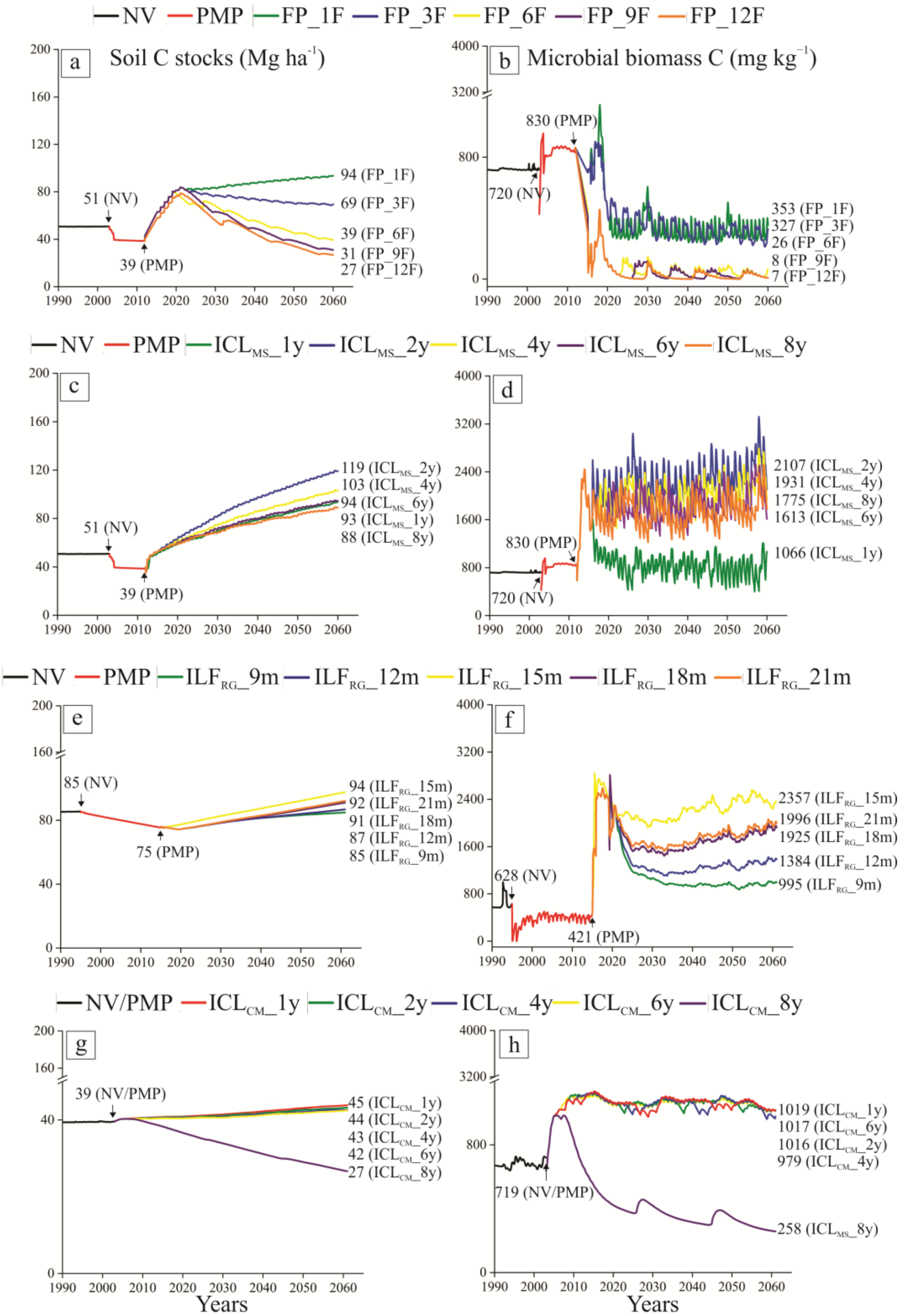


Figure 4. Effects of different future pasture management scenarios on soil C stocks and the MBC content in FP (a and b), ICL under tropical humid (c and d) and subtropical climatic conditions (g and h) and ILF (e and f). FP under a tropical humid climate with time interval for fertilization of 1 (FP_1F), 3 (FP_3F), 6 (FP_6F), 9 (FP_9F) and 12 (FP_12F) years. ICL$_{MS}$ under tropical humid climate with time for the implementation of the crop phase of 1 (ICL$_{MS}$_1y), 2 (ICL$_{MS}$_2y), 4 (ICL$_{MS}$_4y), 6 (ICL$_{MS}$_6y) and 8 (ICL$_{MS}$_8y) years. ILF$_{RG}$ under tropical mesic climate with the spacing between the tree rows of 9 (ILF$_{RG}$_9m), 12 (ILF$_{RG}$_12m), 15 (ILF$_{RG}$_15m), 18 (ILF$_{RG}$_18m) and 21 (ILF$_{RG}$_21m) m. ICL$_{CM}$ under

subtropical climate with time for the implementation of the crop phase of 1 (ICL_{CM}_1y), 2 (ICL_{CM}_2y), 4 (ICL_{CM}_4y), 6 (ICL_{CM}_6y) and 8 (ICL_{CM}_8y) years.

The effect of the change in the time for the implementation of the crop phase in the management systems with ICL presented different results in the long-term simulations under tropical humid and subtropical climates. Under the tropical humid climate, the time period of two years (ICL_{MS}_2y) for the implementation of the crop phase presented the highest soil C and N stocks (Fig. 4c and Fig. 2Sc) and MBC and MBN (Fig. 4d and Fig. 2Sd) contents. The increments of ICL_{MS}_2y in relation to the time period of one year (ICL_{MS}_1y) for the implementation of the crop phase were 16% and 67%, respectively. For the long-term simulations performed for ICL management systems under subtropical climate, the implementation of the crop phase every year (ICL_{CM}_1y) showed the highest soil C and N stocks (Fig. 4g and Fig. 2Sg) and MBC and MBN contents (Fig. 4h and Fig. 2Sh). The results for the implantation times of 2 (ICL_{CM}_2y), 4 (ICL_{CM}_4y) and 6 (ICL_{CM}_6y) years showed similar results, but the implantation time of eight years (ICL_{CM}_8y) showed a reduction of 20% in the soil C and N stocks and 69% in MBC and MBN contents when compared to ICL_{CM}_1y.

With the results of the long-term simulations performed for the ILFRG under tropical mesic climate, it was observed that the reduction of the spacing between the tree rows in the pasture tends to reduce the soil C and N stocks (Fig. 4e and Fig. 2Se), as well in MBC and MBN (Fig. 4f and Fig. 2Sf) contents. The reduction of the spacing to 12 m (ILF_{RG}_12m) and 9 m (ILF_{RG}_9m) presented similar results, with a reduction of 13% and 42% in the soil C and N stocks and in MBC and MBN contents, respectively, when compared to the 15 m spacing (ILF_{RG}_15m), which presented the highest results.

The adoption of more-intensive and diversified systems of pasture management (i.e., FP, ICL and IFL) in relation to the PMP allowed for increases in the socioeconomic and environmental indicators evaluated (Table 3). Among the socioeconomic indicators, we highlight the increase in the annual income, where the adoption of FP_1F, ICL and ILF_{RG}_15m provided increments of 44%, 202% and 267%, respectively, in relation to the PMP. Furthermore, adopting more-intensive and diversified systems of pasture management requires more laborers, which creates more job opportunities in rural areas. For the environmental indicators, it was observed that there was an increase in the amount of soil organic carbon (SOC) in all the more-intensive and diversified systems of pasture management in relation to the PMP. As expected, the addition of mineral fertilizers (e.g., N fertilizer) increased the rate of N mineralization in FP_1F and ICL; this effect was not verified only for ILF_{RG}_15m. Finally, it was found that the more-intensive and diversified systems of pasture management enabled the mitigation of GHG. The adoption of FP_1y, ICL and ILF$_{RG}$_15m were GHG sinks of 43, 57 and 116 Mg CO$_2$eq ha^{-1}, respectively. It is important to highlight that this effect was mainly due to the reduction of heterotrophic respiration and the CH$_4$ and N$_2$O emissions to the atherosphere.

Table 3. Changes in socioeconomic and environmental indicators with the conversion of PMP to the more-intensive and diversified systems of pasture management.

	Indicators	Management systems			
		PMP	FP_1F	ICL	ILF$_{RG}$_15m
Socioeconomic	Beef (@ ha^{-1})	9	18	29	30
	Soybean (kg ha^{-1})	-	-	1648	-
	Maize (kg ha^{-1})	-	-	5118	-
	Wood (m^3 ha^{-1})	-	-	-	300
	Employees (laborers ha^{-1})	1	2	3	3
	Income (US$ ha^{-1} y^{-1})	264	380	796	968

		PMP	FP_1F	Δ (FP_1F - PMP)	ICL	Δ (ICL - PMP)	ILF$_{RG}$_15m	Δ (ILF$_{RG}$_15m - PMP)
Environmental	SOC (g C m^{-2})	5868	8742	2874	5995	127	8362	2494
	Nitrogen Mineralization (g N m^{-2})	1551	5984	4433	3283	1732	929	-622
	Heterotrophic Respiration (g C m^{-2})	3874	2217	-1657	4433	559	1942	-1932
	Total Soil CO$_2$ Efflux (g C m^{-2})	5384	2660	-2724	9368	3984	3638	-1746
	CH$_4$ (g CO$_2$eq m^{-2})	2956	206	-2750	106	-2850	112	-2844
	N$_2$O (g CO$_2$eq m^{-2})	2689	1930	-759	955	-1734	302	-2387
	Total system C flux (g CO$_2$eq m^{-2})	-2377	-3181	-5558	-3453	-5830	-8781	-11158
	Total greenhouse gas flux (g CO$_2$eq m^{-2})	3268	-1045	-4313	-2392	-5660	-8367	-11635

The results for the ICL represent the average of the values found in the tropical humid (ICL$_{MS}$_2y) and subtropical (ICL$_{CM}$_1y) climates. Socioeconomic indicators: To perform the calculations, we adopted 1-dollar (US$) equivalent to 4 reais (R$). For FP, ICL and IFL, stocking rates of 0.6, 1.2 and 2.0 AU ha^{-1} were used, respectively. Production costs were adjusted according to ABIEC (2019) taking into account the degree of intensification of the production system. Environmental indicators: Delta (Δ) represents the values for FP, ICL and IFL minus PMP. Greenhouse gas and N mineralization values are the sum of values during the 2010 to 2060 period. Positive values indicate a flux to the atmosphere, and negative values indicate uptake from the atmosphere by the different pasture management systems. Total GHG values are the sums of CH$_4$, N$_2$O and total system C flux expressed as CO$_2$eq.

5.4. Discussion

5.4.1. Model simulation efficiency

In general, the DayCent model was efficient in predicting soil C and N stock changes, as observed with the measured and simulated values (Table 1 and Fig. 2). This finding is in accordance with other studies conducted with the DayCent model under different agricultural management systems (Del Grosso et al., 2001; Del Grosso et al., 2008; Smith et al., 2012; Begum et al., 2018; Weiler et al., 2019). As was also observed by Oliveira et al. (2017) and Weiler et al. (2018), the model modified in this study overestimated the soil C and N stocks. However, this result is considered acceptable considering the complexity of the management systems evaluated in these studies.

The predictions for the MBC and MBN contents also followed the same trend for the soil C and N stocks, where the difference was overestimation for MBC contents and underestimation for MBN contents. Similar results were also found by Cerri et al. (2004), with the prediction of microbial biomass C and N in changing land use from forest to pasture in the Amazon forest with the Century model. The authors attributed those differences due to the high variability of the observed data imposed by soil temperature and humidity. Xu and Yuan (2017) reported that the different responses from MBC and MBN are due to the fact that microbial models were developed and incorporated into ecosystem models to simulate the C cycle by considering the changes in microbial biomass physiological activities. In addition, the authors believe that by integrating MBN into ecosystem models, more accurate results can be obtained for MBC and MBN. Nevertheless, taking into account that the microbial biomass is represented by the active pool (turnover relatively rapidly) of the DayCent model, it can be considered that the model simulated reasonably well the MBC and MBN changes for the more-intensive and diversified systems of pasture management under the different climatic conditions.

The use of mathematical models to simulate the soil C changes in complex systems, such as agriculture and pasture, needs continuing studies to increase the reliability of the results. Todd-Brown et al. (2013) verified a wide discrepancy in the comparison of 11 models for estimates of the global soil C stock, where the variations in the estimates ranged between 510-3040 Pg C. For this reason, we recommend more studies regarding the predictions of soil C changes under more-intensive and diversified systems of pasture management in Brazil, searching increase the reliability and quality of the results.

5.4.2. Soil C changes in long-term simulations

The long-term simulations for the conversion of NV to PMP under the three climatic conditions evaluated (tropical humid, tropical mesic and subtropical) showed that there was a decrease in the soil C and N stocks (Fig. 3a, 3c and 3e; Fig. 1Sa, 1Sc, 1Se). Don et al. (2011) and Assad et al. (2013) found losses of 12% and 16% in the soil C and N stocks after conversion of native vegetation to pasture, which is also similar to the values found for this study (22% and 33% for the soil C and N stocks, respectively). The losses in the soil C and N stocks are probably due to lower input of residues, as well as lower residue quality when compared to those provided by native vegetation (Thomaz et al., 2020). Additionally, soil C and N losses can also be increased by management practices that contribute to soil physical disturbance and exposition of soil organic matter to microbial decomposition. In addition, for the same conversion (NV to PMP), microbial biomass showed contrasting results, mainly for tropical humid (Amazon rainforest) (Fig. 3b and Fig. 1Sb) and tropical mesic (Atlantic Forest) (Fig. 3d and Fig. 1Sd) climatic conditions. Vieira et al. (2011) reported that the Amazon rainforest produces more aboveground live biomass C stocks (~200 Mg ha^{-1} of C) due to the higher density proportion of large trees (>50 cm in diameter at breast height) than Atlantic forest (100 to 150 Mg·ha^{-1} of C). Thus, the maintenance, reduction or increase in soil carbon content in pastures compared to native vegetation are dependent on several factors, including climate, soil type, management practices and nutrient inputs.

In the conversion of PMP to FP under a tropical humid climate, the long-term predictions showed increases in soil C and N stocks (Fig. 3a and Fig. 1Sa). The C and N stocks increased by 143 and 75%, respectively, and the rates of changes corresponded to 0.95 and 0.07 Mg ha^{-1} yr^{-1}, respectively. Under similar soil and climate conditions, Braz et al. (2013) found increases of 15% and 13% in the soil C and N stocks, respectively, in addition to a rate of C stock change of 0.25 to 2.95 Mg ha^{-1} yr^{-1}. These findings demonstrate the high variability in the soil C and N changes. However, according to the predictions performed for the conversion from PMP to FP, there was no increase in MBC and MBN contents (Fig. 3b and Fig. 1Sb). Li et al. (2014) also found a reduction in microbial biomass with fertilization of pastures, even with an increase in soil C. The authors reported that this effect is because the nutrients provided by fertilization may be toxic to some species of microbes while benefiting others. Nevertheless, further studies in FP under tropical humid climate conditions should be carried out to clarify these findings.

Among the management systems with ICL evaluated under tropical humid and subtropical climates, ICL$_{MS}$ and ICL$_{CM}$ had the largest increments in the soil C and N stocks (Fig. 3a and 3e; Fig. 1Sa and 1Se) as well for MBC and MBN contents (Fig. 3b and 3f; Fig. 1Sb and 1Sf) compared to PMP. In the tropical humid climate, the better results in the long-term predictions for ICL$_{MS}$ in relation to ICL$_{RS}$ are due to the use of maize crops in the rotation scheme during the crop phase. The maize aboveground net primary productivity is approximately 8.52 Mg ha^{-1} yr^{-1}, while the rice reaches 5.30 Mg ha^{-1} yr^{-1} (Song et al., 2015; Carvalho et al., 2016). The higher input of biomass in the soil by the maize crop certainly contributed to the increase in the soil C and N stocks and MBC and MBN contents in the long-term predictions. Under the subtropical climate, the management systems with ICL and with continuous stocking and moderate grazing intensity (ICL$_{CM}$) had the largest increases in the soil C and N stocks and for MBC and MBN contents, especially for the ICL$_{CM}$. In general, under ICL$_{CM}$, the inputs and outputs are balanced, contributing to total residue accumulation, which favors soil C and N accumulation and microorganism activity (Assmann et al., 2014).

For the long-term simulations under the tropical mesic climate, the conversion of PMP to IFL management systems increased the soil C and N stocks (3c and Fig. 1Sc) and the MBC and MBN contents (3d and Fig. 1Sd). Among management systems with IFL, the IFL$_{RG}$ showed better results in relation to ILF$_{NG}$. Steinshamn et al. (2018) reported that the main effects of grazing (IFL$_{RG}$) in relation to non-grazing (ILF$_{NG}$) are increased photosynthetic rates in residual tissue, reallocation of carbohydrates from other plant parts (i.e., roots), removal of older tissues, increased light intensities upon more active underlying tissues, reduction of the rate of leaf senescence and nutrient recycling from dung and urine. Moreover, it is important to highlight that the use of trees+grass+animal combinations enhances fauna, biodiversity (>45%) and soil microbial activity, thus improving soil aggregation as well as soil C and N protection (Hoosbeek et al., 2018; Santos et al., 2019; Matos et al., 2020).

5.4.3. Long-term simulations with different pasture management scenarios

Through the long-term simulations performed with the DayCent model, changes provided by more-intensive and diversified systems of pasture management influence soil C and N stocks and MBC and MBN contents. With regard to the FP under the tropical humid climate, the frequencies of pasture fertilization of 3 (FP_3F), 6 (FP_6F), 9 (FP_9F) and 12 (FP_12F) years significantly reduced the soil C and N stocks (<13-40%) (Fig. 4a and Fig. 2Sa) and MBC and MBN contents (<11-88%) (4b and Fig. 2Sb) in relation to the ferlitization carried out every year (FP_1F). Despite the mineralization increase of the organic material of grass used in this study (*Brachiaria* spp.), pasture fertilization increases the input of C and N and microbial activity in the soil due to the high annual net primary productivity, above and belowground (Borges et al., 2019). Thus, reducing the frequency of fertilization reduces *Brachiaria* spp. potential (65.3 Mg ha^{-1} y^{-1}, including animal dejects and roots) as energy for soil microorganisms and the quality of the material, which is responsible for the greater accumulation of C in more stable fractions of the soil (Fisher et al., 2007; Lavallee et al., 2020). These results are important for a better understanding of the management of fertilization in pasture areas in the long term, since in Brazil, these studies are limited, which hinders future predictions about the dynamics of soil C and N and microbial activity (Lammel et., 2017).

For the ICL, according to the results of long-term predictions and taking into account the time for the implementation of the crop phase, contrasting responses were observed under tropical humid and subtropical climates. While in the tropical humid climate, the highest soil C and N stocks (Fig. 4c and Fig. 2Sc) and MBC and MBN contents (Fig. 4d and Fig. 2Sd) were found with the implantation of the crop phase every two years (ICL_{MS}_2y), in the subtropical climate condition, the highest results were obtained with the implantation of the crop phase every year (ICL_{CM}_1y) (Fig. 4c and 4h; Fig. 2Sg and 2Sh). The highest results with the longest time for the implantation of the crop phase in the ICL under a tropical humid climate may be due to the characteristics of the grass used in the pasture phase (*Brachiaria ruziziensis* Germ. & C.M.), when compared with the grass used under subtropical climate (*Lolium multiflorum* Lam.). In addition to the greater potential for biomass production (>35%), the grass used under tropical humid climate has a higher lignin proportion (~6.00%) than grass used under subtropical climate (~5.00%) (Pariz et al., 2010; Balbinot et al., 2007; Fluck et al., 2018). The higher availability of N for soil microorganisms provided by ICL systems and the great contribution of C derived from lignin may explain the better results obtained with the longest cultivation time of the grass under tropical humid climate (Stewart et al., 2015; Huang et al., 2019). Moreover, based on the soil C and N stocks and in the MBC and MBN content results for these two climatic conditions, it is not recommended to use the pasture phase for more than two years. This is mainly due to the greater diversity of plants and nutrient input and cycling provided by the crop phase under ICL systems.

For the ILF under the tropical humid climate, the reduction in spacing between the tree rows to 12 m (ILF_{RG}_12m) and 9 m (ILF_{RG}_9m) showed the largest decreases in the soil C and N stocks (Fig. 4e and Fig. 2Se) and in the MBC and MBN contents (Fig. 4f and Fig. 2Sf). This effect is mainly related to shading in the grass (Brachiaria brizantha cv. Marandu) due to the increase in the number of trees, which culminates in the reduction of its above and belowground biomass production capacity. Further studies are still needed to evaluate the effect of the interaction between grasses and trees on the dynamics of soil C and N under integrated production systems. Guenni et al. (2008) explain that despite the morphological plasticity of Brachiaria species, under low irradiance, these grasses tend to increase the C allocation to the aboveground biomass and the proportion of shoot:root ratio (6.5–10.7 times higher). In general, these effects mean an increase in C losses as CO_2 and a reduction in biomass inputs to support soil microbial activity, respectively. In addition, Paciullo et al. (2011), in studies about the pasture productive traits under ILF systems with spacing between the tree rows of 30 m, hypothesized that the best response of the grass could be with the spacing between 14 to 18 m. For these authors, this spacing provides an adequate balance between the production of biomass by grasses and the proportion of shading. This hypothesis was confirmed by this study, where the spacing between the tree rows with 15 m (ILF_{RG}_15m) also provided the highest soil C and N stocks and MBC and MBN contents.

The conversion of the PMP to more-intensive and diversified systems of pasture management also provided positive effects on socioeconomic and environmental indicators (Table 3). In general, the adoption of FP, ICL and IFL provides a more diversified (i.e., beef, grains and wood) and stable (climate and market shocks) source of income throughout the year when compared to the PMP (Garrett et al., 2017). The higher annual income (>267%) obtained for the ILF systems in relation to PMP is mainly due to the high wood value (African mahogany), where that value can change when used for other tree species (Lucena et al., 2016). This study also considered the increase in the number of workers in the FP, ICL and IFL due to the more continuous labor needs throughout the year, in contrast to the seasonal nature of the labor demands with the PMP (Thornton and Herrero, 2015). Among the social benefits due to the increase in the number of workers with the adoption of more-intensive and diversified systems of pasture management are better quality of life, higher food quality, reduction of rural exodus and urban agglomeration.

Substantial effects of the conversion from the PMP to the more-intensive and diversified systems of pasture management were also verified in the environmental indicators. In this conversion, there was an increase in SOC and N mineralization. The increase in SOC combined with a higher rates of N mineralization indicates that FP, ICL and IFL provide greater support for soil microbial activity due to the continuous input of fresh biomass and nutrients through fertilization (Duval et al., 2013). Likewise, the reduction in heterotrophic respiration and the CH_4 and N_2O

emissions with the adoption of more-intensive and diversified systems of pasture management in relation to PMP allowed the reduction of GHG flux to the atmosphere.

For Figueiredo et al. (2017) the conversion of PMP to FP, ICL and IFL can reduce the associated GHG emissions in terms of kg CO_2eq emitted per kg of cattle produced, increasing the production of meat, grains and wood. Moreover, the optimization of the stocking rate (reduction of N2O emissions) and the improvement of forage quality (reduction of CH_4 emissions) under these management systems, were preponderant factors for the more-intensive and diversified systems of pasture management becoming a net GHG sink (Sykes et al., 2020). In this sense, it is important to highlight that conditions of over-intensification (i.e., over-fertilization and over-grazing) may leads to increased GHG emissions and increase the soil degradation, and must be taken into account during the process of pasture intensification and diversification in Brazil. The GHG mitigation through the pastureland intensification and diversification in Brazil, as it is a controversial topic, needs more evidence in addition to the results showed in this study. As example, more studies can be carried out seeking to include the carbon stored by trees, mainly for management systems such as IFL, which will allow for more complete estimates of the GHG sequestration potential.

5.4.4. Modeling limitations and future perspectives

Despite the important results obtained in this study, some limitations should be pointed out in order to assist the continuation of others studies about the pastureland intensification and diversification in Brazil. The limitations of this study can be grouped in two: a) The first limitation referents to the different regional characteristics in Brazil, that may limit the scope of the results found in this study. Among these characteristics are the climate, soil type, variation of the aboveground net primary production, grassy species and local management factors. b) The model is another limitation, where accordingly to Del Grosso et al. (2012) can be divided into two categories. The first category refers to the model output error, being derived from uncertainty in model drivers and imperfections in model algorithms and parameterizations. The second category refers to the model limitation to accurately represent, some land management strategies (e.g., fertilizer placement and type) and currently available technologies (e.g., poly coated urea, nitrification inhibitors).

Although the present study has some limitations, the predictions made with the DayCent model can be applied to soil (i.e., Oxisol and Ultisol) and climatic (i.e., tropical humid tropical mesic, and subtropical climates) conditions similar to this study. In this sense, the soil C stocks and GHG emissions can be greater or less than estimated here, but our study can be a starting point for development plans with sustainable management practices to mitigate possible soil C losses in pasture areas in Brazil. As previously discussed, due to the wide edaphoclimatic diversity in Brazil, further study should be carried out in order to reduce the uncertainties and facilitate spatial extrapolations on the soil C dynamics. In addition, field experiments carried out in different regions can be used to improve predictions with the DayCent model, generating information applicable on a large scale (e.g., maps with the potential for soil C stock due to the adoption of different sustainable pasture management systems in Brazil).

5.5. Conclusions

The DayCent model proved to be an efficient tool to predict the soil C changes with the intensification and diversification of poorly managed pastures in Brazil. The model estimated that the conversion of PMP to FP (tropical humid climate), ICL (tropical humid and subtropical climate) and ILF (tropical mesic condition) increased the soil C stocks by 0.95, 0.70 and 0.04, and 0.16 Mg ha^{-1} yr^{-1}, respectively. Similarly, the microbial biomass C contents also showed increases in this conversion, mainly for ICL (3 and 7 mg kg^{-1} yr^{-1}) and ILF (40 mg kg^{-1} yr^{-1}).

The soil C stocks and the microbial biomass C contents were changed according to the simulations carried out with different pasture management systems. In the FP, the results indicated that the fertilization of the pasture every year was the most adequate. For ILC systems, the use of the pasture phase for more than two years without the crop phase is not recommended. In the case of ILF systems, the spacing between the tree rows of 15 m showed the highest soil C stocks and the microbial biomass C contents.

The adoption of more-intensive and diversified systems of pasture management in relation to the PMP provided increases in the annual income of 44-267%. Furthermore, while PMP (33 Mg CO2eq ha^{-1}) was a GHG source to the atmosphere, FP to ICL and IFL were GHG sinks of 43, 57 and 116 Mg CO_2eq ha^{-1}, respectively, during the 2010 to 2060 period. Therefore, we believe that the results found in this study can assist national initiatives aimed at restoring degraded pasture areas (e.g., "ABC Plan"), as well as meeting Brazilian goals for mitigating GHG emissions (reduce emissions 37% by 2025 and 43% by 2030).

References

Abdalla, M., Hastings, A., Chadwick, D.R., Jones, D.L., Evans, C.D., Jones, M.B., Rees, R.M., Smith, P., 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agric. Ecosyst. Environ. 253, 62–81. https://doi.org/10.1016/j.agee.2017.10.023

ABIEC, 2019. BeefREPORT. Brazilian Beef Exporters Association, Brasília, Brasil.

Azevedo, T.R., Junior, C.C., Junior, A.B., Cremer, M.S., Piatto, M., Tsai, D.S., Barreto P., Martins, H., Sales, M., Galuchi, T., Rodrigues, A., Morgado, R., Ferreira, A.L., Silva, F.B., Viscondi, G.F., Santos, K.C.., Cunha, K.B., Manetti, A., Coluna, I.M.E., Albuquerque, I.R., Junior, S.W., Leite, C., Kishinami, R., 2018. SEEG initiative estimates of Brazilian greenhouse gas emissions from 1970 to 2015. Sci. Data 5, 1-43. https://doi.org/10.1038/sdata.2018.45

Arantes, A.E., Couto, V.R.M., Sano, E.E., Ferreira, L.G., 2018. Livestock intensification potential in Brazil based on agricultural census and satellite data analysis. Pesq. agropec. bras. 53, 1053-1060. https://doi.org/10.1590/S0100-204X2018000900009

Assad, E.D., Pinto, H.S., Martins, S.C., Groppo, J.D., Salgado, P.R., Evangelista, B., Vasconcellos, E., Sano, E.E., Pavão, E., Luna, R., Camargo, P.B., Martinelli, L.A., 2013. Changes in soil carbon stocks in Brazil due to land use: paired site comparisons and a regional pasture soil survey. Biogeosciences 10, 6141–6160. https://doi.org/10.5194/bg-10-6141-2013

Assmann, J.M., Anghinoni, I., Martins, A.P., Costa, S.E.V.G.A., Cecagno, D., Carlos, F.S., Carvalho, P.C.F., 2014. Soil carbon and nitrogen stocks and fractions in a long-term integrated crop–livestock system under no-tillage in southern Brazil. Agric. Ecosyst .Environ. 190, 52–59. http://dx.doi.org/10.1016/j.agee.2013.12.003

Balbinot, A.A., Moraes, A., Backes, R.L., 2007. Efeito de coberturas de inverno e sua época de manejo sobre a infestação de plantas daninhas na cultura de milho. Planta Daninha 25, 473-480. https://doi.org/10.1590/S0100-83582007000300006

Buller, L.S., Bergier, I., Ortega, E., Moraes, A., Bayma-Silva, G., Zanetti, M.R., 2015. Soil improvement and mitigation of greenhouse gas emissions for integrated crop–livestock systems: Case study assessment in the Pantanal savanna highland, Brazil. Agric. Syst. 137, 206-2019. https://doi.org/10.1016/j.agsy.2014.11.004

Bonan, G.B., Doney, S.C., 2018. Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. Science 359, 1-9. https://doi.org/10.1126/science.aam8328

Boldrini, I.I., Eggers, L., 1996. Vegetação campestre do sul do Brasil: dinâmica de espécies à exclusão do gado. Acta Bot. Bras. 10, 37-50.

Borges, B.M.M.N., Bordonal, R.O., Silveira, M.L., Coutinho, E.L.M., 2019. Short-term impacts of high levels of nitrogen fertilization on soil carbon dynamics in a tropical pasture. Catena 174, 413-416. https://doi.org/10.1016/j.catena.2018.11.033

Begum, K., Kuhnert, M., Yeluripati, J., Ogle, S., Parton, W., Kader, M.A., Smith, P., 2018. Soil organic carbon sequestration and mitigation potential in a rice cropland in Bangladesh – a modelling approach. Field Crops Res. 226, 16-27. https://doi.org/10.1016/j.fcr.2018.07.001

Braz, S.P., Urquiaga, S., Alves, B.J.R., Jantalia, C.P., Guimarães, A.P., dos Santos, C.A., dos 1077 Santos, S.C., Machado Pinheiro, É.F., Boddey, R.M., 2013. Soil carbon stocks under productive and degraded pastures in the Brazilian Cerrado. Soil Sci. Soc. Am. J. 77, 914. https://doi.org/10.2136/sssaj2012.0269

Carvalho, P.C.F., Fisher, V., Santos, D.T., Ribeiro, A.M.L., Quadros, F.L.F., Castilhos, Z.M.S., Poli, C.H.E.C., Monteiro, A.L.G., Nabinger, C., Genro, T.C.M., Jacques, A.V.A., 2006. Produção animal no Bioma Campos Sulinos. Braz. J. Vet. Res. Anim. Sci. 35, 156-202.

Carvalho, J.L., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri, C.C., 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Till. Res. 110, 175-186. https://doi.org/10.1016/j.still.2010.07.011

Carvalho, J.N., Hudiburg, T.W., Franco, H.C.J., Delucia, E.H., 2017. Contribution of above- and belowground bioenergy crop residues to soil carbon. GCB Bioenergy 9, 1333–1343. https://doi.org/10.1111/gcbb.12411

Carvalho, P.C.F., Barro, R.S., Neto, A.B., Nunes, P.A.A., Moraes, A., Anghinoni, I., Bredemeier, C., Bayer, C., Martins, A.P., Kunrath, T.R., Santos, D.T., Carmona, F.C., Barros, T., Filho, W.S., Almeida, G.M., Caetano, L.A.M., Cecagno, D., Arnuti, F., Denardin, L.G.O., Bonetti, J.A., Toni, C.A.G., Borin, J.B.M., 2018. R. Bras. Zootec. 47, 1-12. https://doi.org/10.1590/rbz4720170001

Conant, R., Paustian, K., Elliott, A.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol. Appl. 11, 343–355. https://doi.org/10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2

Cortner, O., Garrett, R.D., Valentim, J.F., Ferreira, J., Niles, J., Reis, J., Gil, J., 2019. Perceptions of integrated crop-livestock systems for sustainable intensification in the Brazilian Amazon. Land Use Policy 82, 841-853. https://doi.org/10.1016/j.landusepol.2019.01.006

Cerri, C.E.P., Paustian, K., Bernoux, M.A.L., Victoria, R.L., Melillo, J.M., Cerri, C.C., 2004. Modeling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. Glob Chang. Biol. 10, 815–832. https://doi.org/10.1111/j.1365-2486.2004.00759.x

Crusciol, C.A.C., Arf, O., Soratto, R.P., Andreotti, M., Rodrigues, R.A.F., 2003. Absorção, exportação e eficiência de utilização de nutrientes pela cultura do arroz de terras altas em função de lâminas de água aplicadas por aspersão. Acta Sci., Agron. 25, 97-102. https://doi.org/10.4025/actasciagron.v25i1.2454

Chomenko, L., Bencke, G.A., 2016. Nosso pampa desconhecido. Fundação Zoobotânica do Rio Grande do Sul, Porto Alegra, Rio Grande do Sul, Brazil, pp. 210.

Damian, J.M., Firmano, R.F., Cherubin, M.R., Pavinato, P.S., Soares, T.M., Paustian, K., Cerri, C.E.P., 2020. Changes in soil phosphorus pool induced by pastureland intensification and diversification in Brazil. Sci. Total Environ. 703, 1-12. https://doi.org/10.1016/j.scitotenv.2019.135463

Del Grosso, S., Ojima, D., Parton, W., Mosier, A., Peterson, G., Schimel, D., 2002. Simulated effects of dryland cropping intensification on soil organic matter and greenhouse gas exchanges using the DayCent ecosystem model. Environ. Pollut. 116, S75-S83. https://doi.org/10.1016/S0269-7491(01)00260-3

Del Grosso, S.J., Parton, W.J., Mosier, A.R., Hartman, M.D., Brenner, J., Ojima, D.S., Schimel, D.S., et al., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DayCent model. In: Schaffer, M. (Ed.), Modeling Carbon and Nitrogen Dynamics for Soil Management. CRC Press, Boca Raton, Florida, USA, pp. 303–332.

Del Grosso, S.J., Halvorson, A.D., 2008. Testing DayCent model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. J. Environ. Qual. 37, 1383–1389. https://doi.org/10.2134/jeq2007.0292

Del Grosso, S.J., Parton, W.J., Adler, P.R., Davis, S.C., Keough, C., Marx, E., 2012. DayCent model simulations for estimating soil carbon dynamics and greenhouse gas fluxes from agricultural production systems. In: Liebig, M.A., Franzluebbers, A. J., Follett, R.F. (Eds.), Managing agricultural greenhouse gases. Academic Press, Florida, USA, pp. 241–250.

Dias Filho, M.B., 2014. Diagnóstico das pastagens no Brasil-Embrapa. Brasil, Brasília. pp. 1–36.

Duval, B.D., Anderson-Teixeira, K.J., Davis, S.C., Keogh, C., Long, S.L., Parton, W.J., DeLucia, E.H., 2013. Predicting Greenhouse Gas Emissions and Soil Carbon from Changing Pasture to an Energy Crop. PLoS One 8, 1-12. https://doi.org/10.1371/journal.pone.0072019

Don, A., Schumacher, J., Freibauer, A., 2011. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. Glob. Chang. Bio. 17, 1658–1670. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Fisher, M.J., Braz, S.P., Santos, R.S.M., Urquiaga, S., Alves, B.J.R., Boddey, R.M., 2007. Another dimension to grazing systems: soil carbon. Trop. Grasslands 41, 65–83.

Figueiredo, E.B., Jayasundara, S., Bordonal, R.O., Berchielli, T.T., Reis, A.R., Wagner-Riddle, C., La Scala Jr, N., 2017. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. J. Clean. Prod. 141, 420-431. https://doi.org/10.1016/j.jclepro.2016.03.132

Fluck, A.C., Schafhäuser Júnior, J., Alfaya Júnior, H., Costa, O.A.D., Farias, G.D., Scheibler, R.B., Rizzo, F.A., Manfron, J.A.S., Fioreze, V.I., Rösler, D.C., 2018. Composição química da forragem e do ensilado de azevém anual em função de diferentes tempos de secagem e estádios fenológicos. Arq. Bras. Med. Vet. Zootec. 70, 1979-1987. http://dx.doi.org/10.1590/1678-4162-9981

Garrett, R.D., Niles, M.T., Gil, J.D.B., Gaudin, A., Chaplin-Kramer, R., Assmann, A., Assmann, T.S., Brewer, K., Faccio Carvalho, P.C., Cortner, O., Dynes, R., Garbach, K., Kebreab, E., Mueller, N., Peterson, C., Reis, J.C., Snow, V., Valentim, J., 2017. Social and ecological analysis of commercial integrated crop livestock systems: Current knowledge and remaining uncertainty. Agric. Syst. 155, 136–146. http://dx.doi.org/10.1016/j.agsy.2017.05.003

Gomez-Casanovas, N., Hudiburg, T.W, Bernacchi, C.J., Parton, W.J., Delucia, E.H., 2016. Nitrogen deposition and greenhouse gas emissions from grasslands: uncertainties and future directions. Glob Chang. Biol. 22, 1348–1360. https://doi.org/10.1111/gcb.13187

Guenni, O., Seiter, S., Figueroa, R., 2008. Growth responses of three Brachiaria species to light intensity and nitrogen supply. Trop. Grassl. 42, 75–87.

Hartman, M.D., Parton, W.J., Del Grosso, S.J., Easter, M., Hendryx, J., Hilinski, T., Kelly, R., Keough, C.A., Killian, K., Lutz, S., Marx, E., McKeown, R., Ogle, S., Ojima, D.S., Paustian, K., Swan, A., Willians, S., 2018. The daily century ecosystem, soil organic matter, nutrient cycling, nitrogen trace gas, and methane model: User manual, scientific basis, and technical documentations. Colorado State University, Natural Resource Ecology Laboratory, Fort Collins, USA, pp. 361.

Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S., Hristov, A.N., Gerber, P., Gill, M., Butterbach-Bah, K., Valin, H., Garnett, T., Stehfest, E., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Change 6, 452–461. https://doi.org/10.1038/nclimate2925

Hoosbeek, M.R., Remme, R.P., Rusch, G.M., 2018. Trees enhance soil carbon sequestration and nutrient cycling in a silvopastoral system in south-western Nicaragua. Agroforest Syst. 92, 263–273. https://doi.org/10.1007/s10457-016-0049-2

Huang, W., Hammel, K.E., Hao, J., Thompson, A., Timokhin, V.I., Hall, S.J., 2019. Enrichment of lignin-derived carbon in mineral-associated soil organic matter. Environ. Sci. Technol. 53, 7522−7531. https://doi.org/10.1021/acs.est.9b01834

IBGE, 2017. Instituto Brasileiro de Geografia e Estatística. Censo Agropecuário 2017. IBGE, Rio de Janeiro, Rio de Janeiro.

Joergensen, R.G., Brookes, P.C., 1990. Ninhydrin-reactive nitrogen measurements of microbial biomass in 0.5 M K2SO4 soil extracts. Soil Biol. Biochem. 22, 1023-1027. https://doi.org/10.1016/0038-0717(90)90027-W

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10, 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Lavallee, J.M., Soong, J.L., Cotrufo, M.F., 2020. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob. Change Biol. 26, 261–273. https://doi.org/10.1111/gcb.14859

Lammel, D.R., Butterbach-Bahl, K., Cerri, C.E.P., Louis, S., Schnitzler, J.P., Feigl, B.J., Cerri, C.C., 2017. C and N stocks are not impacted by land use change from Brazilian Savanna (Cerrado) to agriculture despite changes in soil fertility and microbial abundances. J. Plant Nutr. Soil Sci. 180, 436–445. https://doi.org/10.1002/jpln.201600614

Li, J.H., Yang, Y.J., Li, B.W., Li, W.J., Wang, G., Knops, J.M.H., 2014. Effects of nitrogen and phosphorus fertilization on soil carbon fractions in alpine meadows on the Qinghai-Tibetan Plateau. PLoS One 9, 1-11. https://doi.org/10.1371/journal.pone.0103266

Lilienfein, J., Wilcke, W., 2003. Element storage in native, agriand silvicultural ecosystems of the Brazilian savanna I. Biomass, carbon, nitrogen, phosphorus, and sulfur. Plant Soil 254, 425– 442. https://doi.org/10.1023/B:PLSO.0000016503.59527.ea

Lucena, H.D., Paraense, V.C., Carlos Henrique Andrade Mancebo, C.H.A., 2016. Viabilidade econômica de um sistema agroflorestal com cacau e essências florestais de alto valor comercial em Altamira-PA. RARA 8, 73-84. https://doi.org/10.18361/2176-8366/rara.v8n1p73-84

Matos, P.S., Fonte, S.J., Lima, S.S., Pereira, M.G., Kelly, C., Damian, J.M., Fontes, M.A., Chaer, G.M., Brasil, F.C., Zonta, E., 2020. Linkages among soil properties and litter quality in agroforestry systems of southeastern Brazil. Sustainability 12, 1-22. https://doi.org/10.3390/su12229752

Neto, A.B., Savian, J.V., Schons, R.M.T., Bonnet, O.J.F., Canto, M.W., Moraes, A., Lemaire, G., Carvalho, P.C.F., 2014. Italian ryegrass establishment by self-seeding in integrated crop-livestock systems: Effects of grazing management and crop rotation strategies. Eur. J. Agron. 53, 67-73. https://doi.org/10.1016/j.eja.2013.11.001

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., Anthony, S., 2009. Agroforestree Database: a tree reference and selection guide version 4.0. World Agroforestry Centre, Kenya.

Oliveira, D.M.S., Williams, S., Cerri, C.E.P., Paustian, K., 2017. Predicting soil C changes over sugarcane expansion in Brazil using the DayCent model. Glob. Chang. Biol. 9, 1436–1446. https://doi.org/10.1111/gcbb.12427

Pariz, C.M., Andreotti, M., Azenha, M.V., Bergamaschine, A.F., Mello, L.M.M., Lima, R.C., 2011. Produtividade de grãos de milho e massa seca de braquiárias em consórcio no sistema de integração lavoura-pecuária. Cienc. Rural 41, 875-882. https://doi.org/10.1590/S0103-84782011000500023

Pariz, C.M., Andreotti, M., Azenha, M.V., Bergamaschine, A.F., Mello, L.M.M., Lima, R.C., 2010. Massa seca e composição bromatológica de quatro espécies de braquiárias semeadas na linha ou a lanço, em consórcio com milho no sistema plantio direto na palha. Acta Sci. Anim. Sci. 32, 147-154. https://doi.org/10.4025/actascianimsci.v32i2.8498

Parton, W.J., Hartman, M., Ojima, D., Schimel, D., 1998. DAYCENT and its land surface model: description and testing. Glob. Planet. Chang. 19, 35-48. https://doi.org/10.1016/S0921-8181(98)00040-X

Paciullo, D.S.C., Gomide C.A.M., Castro, C.R.T., Fernandes, P.B., Müller M.D., Pires, M.F.A., Fernandes, E.N., Xavier, D.F., 2011. Características produtivas e nutricionais do pasto em sistema agrossilvipastoril, conforme a distância das árvores. Pesq. agropec. bras. 46, 1176-1183. https://doi.org/10.1590/S0100-204X2011001000009

Pezzopane, J.R.M., Bernardi, A.C.C., Azenha, M.V., Oliveira, P.P.A., Bosi, C., Pedroso, A.F., Esteves, S.N., 2020. Production and nutritive value of pastures in integrated livestock production systems: shading and management effects. Sci. agric. 77, 1-9. https://doi.org/10.1590/1678-992x-2018-0150

Santos, P.Z.F., Crouzeilles, R., Sansevero, J.B.B., 2019. Can agroforestry systems enhance biodiversity and ecosystem service provision in agricultural landscapes? A meta-analysis for the Brazilian Atlantic Forest. For. Ecol. Manag. 433, 140-145. https://doi.org/10.1016/j.foreco.2018.10.064

Sándor, R., Ehrhardt, F., Brilli, L., Carozzi, M., Recous, S., Smith, P., Snow, V., Soussana J.F., Dorich, C.D., Fuchs, K., Fitton, N., Gongadze, K., Klumpp, K., Liebig, M., Martin, R., Merbold, L., Newton P.C.D., Rees, R.M., Rolinski, S., Bellocchi, G., 2018. The use of biogeochemical models to evaluate mitigation of greenhouse gas emissions from managed grasslands. Sci. Total Environ. 642, 292–306. https://doi.org/10.1016/j.scitotenv.2018.06.020

Siqueira, C.C.Z., Chiba, M.K., Moreira, R.S., Abdo, M.T.V.N., 2019. Carbon stocks of a degraded soil recovered with agroforestry systems. Agroforest Syst. 94, 1059–1069. https://doi.org/10.1007/s10457-019-00470-9

Silva-Olaya, A.M., Cerri, C.E.P., Williams, S., Cerri, C.C., Davies, C.A., Paustian, K., 2017. Modelling SOC response to land use change and management practices in sugar-cane cultivation in South-Central Brazil. Plant and Soil 410, 483–498. https://doi.org/10.1007/s11104-016-3030-y

Sousa, H.M., Correa, A.R., Silva, B.M., Oliveira, S.S., Campos, D.T.S., Wruck, F.J., 2020. Dynamics of soil microbiological attributes in integrated crop-livestock systems in the Cerrado-Amazonônia ecotone. Rev. Caatinga 33, 09 – 20. http://dx.doi.org/10.1590/1983-21252020v33n102rc

Song, A., Ning, D., Fan, F., Li, Z., Provance-Bowley, M., Liang, Y., 2015. The potential for carbon bio-sequestration in China's paddy rice (Oryza sativa L.) as impacted by slag-based silicate fertilizer. Sci. Rep. 5, 1-12. http://dx.doi.org/10.1038/srep17354

Schipper, L.A., Baisden, W.T., Parfitt, R.L., Ross, C., Claydon, J.J., Arnold G., 2007. Large losses of soil C and N from soil profiles under pasture in New Zealand during the past 20 years. Glob. Chang. Biol. 13, 1138–1144. https://doi.org/10.1111/j.1365-2486.2007.01366.x

Steinshamn, H., Grøva, L., Adler, S.A., Brunberg, E., Lande, U.S., 2018. Effects of grazing abandoned grassland on herbage production and utilization, and sheep preference and performance. Front. Environ. Sci. 6, 1-12. https://doi.org/10.3389/fenvs.2018.00033

Stewart, C.E., Moturi, P., Follett, R.F., Halvorson, A.D., 2015. Lignin biochemistry and soil N determine crop residue decomposition and soil priming. Biogeochemistry 124, 335–351. https://doi.org/10.1007/s10533-015-0101-8

Sykes, A.J., Macleod, M., Eory, V., Rees, R.M., Payen, F., Myrgiotis, V., Williams, M., Sohi, S., Hillier, J., Moran, D., Manning, D.A.C., Goglio, P., Seghetta, M., Williams, A., Harris, J., Dondini, M., Walton, J., House, J., Smith, P., 2020. Characterising the biophysical, economic and social impacts of soil carbon sequestration as a greenhouse gas removal technology. Glob. Change Biol. 26, 1085–1108. https://doi.org/10.1111/gcb.14844

Smith, J.U., Smith, P., Addiscott, T., 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: Evaluation of Soil Organic Matter Models using Existing, Long-term Datasets (eds Powlson DS, Smith P, Smith JU), NATO ASI Series I, Vol. 38. Springer-Verlag, Berlin, Germany, pp. 181–200.

Smith, P., Smith, J.U., Powlson, D.S., Mcgill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. Evaluation and comparison of soil organic matter models: a comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma, 81, 153–225. https://doi.org/10.1016/S0016-7061(97)00087-6

Smith, W.N., Grant, B.B., Campbell, C.A., McConkey, B.G., Desjardins, R.L., Kröbel, R., Malhi, S.S., 2012. Crop residue removal effects on soil carbon: Measured and intermodel comparisons. Agric. Ecosystems Environ. 161, 27-38. https://doi.org/10.1016/j.agee.2012.07.024

Torres, C.M.M.E., Jacovine, L.A.G., Neto, S.N.O., Fraisse, C.W., Soares, C.P.B., Neto, F.C., Ferreira, L.R., Zanuncio, J.C., Lemes, P.G., 2017. Greenhouse gas emissions and carbon sequestration by agroforestry systems in southeastern Brazil. Sci. Rep. 7, 1-7. https://doi.org/10.1038/s41598-017-16821-4

Todd-Brown, K.E.O., Randerson, J. T., Post, W. M., Hoffman, F.M., Tarnocai, C., Schuur, E.A.G., Allison, S.D., 2013. Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations. Biogeosciences 10, 1717–1736. https://doi.org/10.5194/bg-10-1717-2013

Thornton, P.K., Herrero, M., 2015. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. Nat. Clim. Change 5, 830–836. https://doi.org/10.1038/nclimate2754

Thomaz, E.L., Nunes, D.D., Watanabe, M., 2020. Effects of tropical forest conversion on soil and aquatic systems in southwestern Brazilian Amazonia: A synthesis. Environ. Res. 183, 1-11. https://doi.org/10.1016/j.envres.2020.109220

USDA, 2014. Keys to Soil Taxonomy. USDA—Natural Resources Conservation Service, Washington, USA.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703-707. https://doi.org/10.1016/0038-0717(87)90052-6

Vieira, S.A., Alves, L.F., Duarte-Neto, P.J., Martins, S.C., Veiga, L.G., Scaranello, M.A., Picollo, M.C., Camargo, P.B., Carmo, J.B., Neto, E.S., Santos, F.A.M., Joly, C.A., Martinelli, L.A., 2011. Stocks of carbon and nitrogen and partitioning between above- and belowground pools in the Brazilian coastal Atlantic Forest elevation range. Ecol. Evol. 1, 421–434. https://doi.org/10.1002/ece3.41

Wilcke, W., Lilienfein, J., 2004. Element storage in native, agri-, and silvicultural ecosystems of the Brazilian savanna. II. Metals. Plant and Soil 258, 31–41.

Weiler, D.A., Moro, V.J., Awe, G.O., Oliveira, D.M.S., Cerri, C.E.P., Reichert, J.M., Giacomini, S.J., 2019. Carbon balance in sugarcane areas under different tillage systems. Bioenerg Res. 12, 778–788. https://doi.org/10.1007/s12155-019-10002-z

Weiler, D.A., Tornquist, C.G., Zschornack, T., Ogle, S.M., Carlos, F.S., Bayer, C., 2018. DayCent simulation of methane emissions, grain yield, and soil organic carbon in a subtropical paddy rice system. Rev. Bras. Cienc. Solo 42, 1-12. https://doi.org/10.1590/18069657rbcs20170251

Xu, W., Yuan, W., 2017. Responses of microbial biomass carbon and nitrogen to experimental warming: A meta-analysis. Soil Biol. Biochem. 115, 265-274. https://doi.org/10.1016/j.soilbio.2017.08.033

Yeluripati, J.B., Van Oijen, M., Wattenbach, M., Neftel, A., Ammann, A., Parton, W.J., Smith, P., 2009. Bayesian calibration as a tool for initialising the carbon pools of dynamic soil models. Soil Biol. Biochem. 41, 2579-2583. https://doi.org/10.1016/j.soilbio.2009.08.021

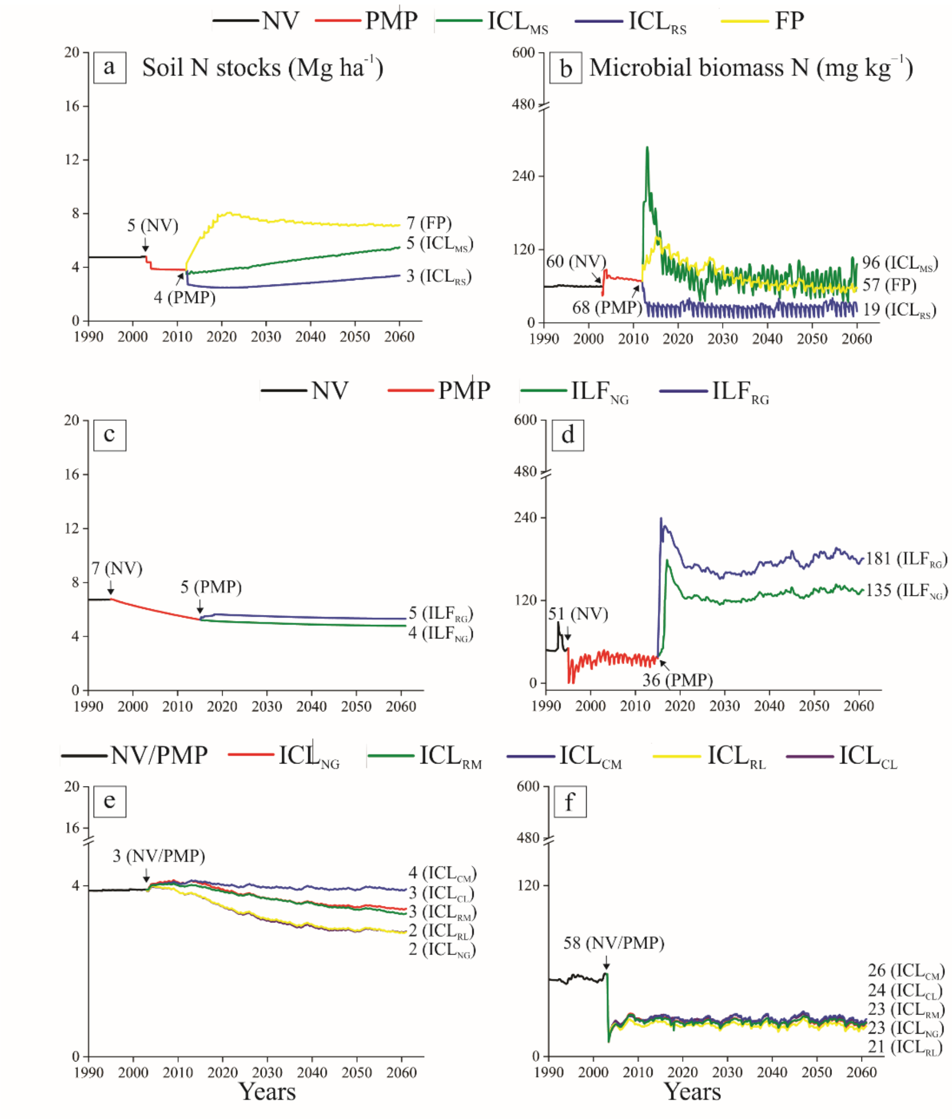
Zago, L.M.S., Ramalho, W.P., Caramori, S., 2019. Does crop-livestock-forest systems contribute to soil quality in Brazilian savannas? FLORAM 26, 1-10. https://doi.org/10.1590/2179-8087.034318

Supplementary material

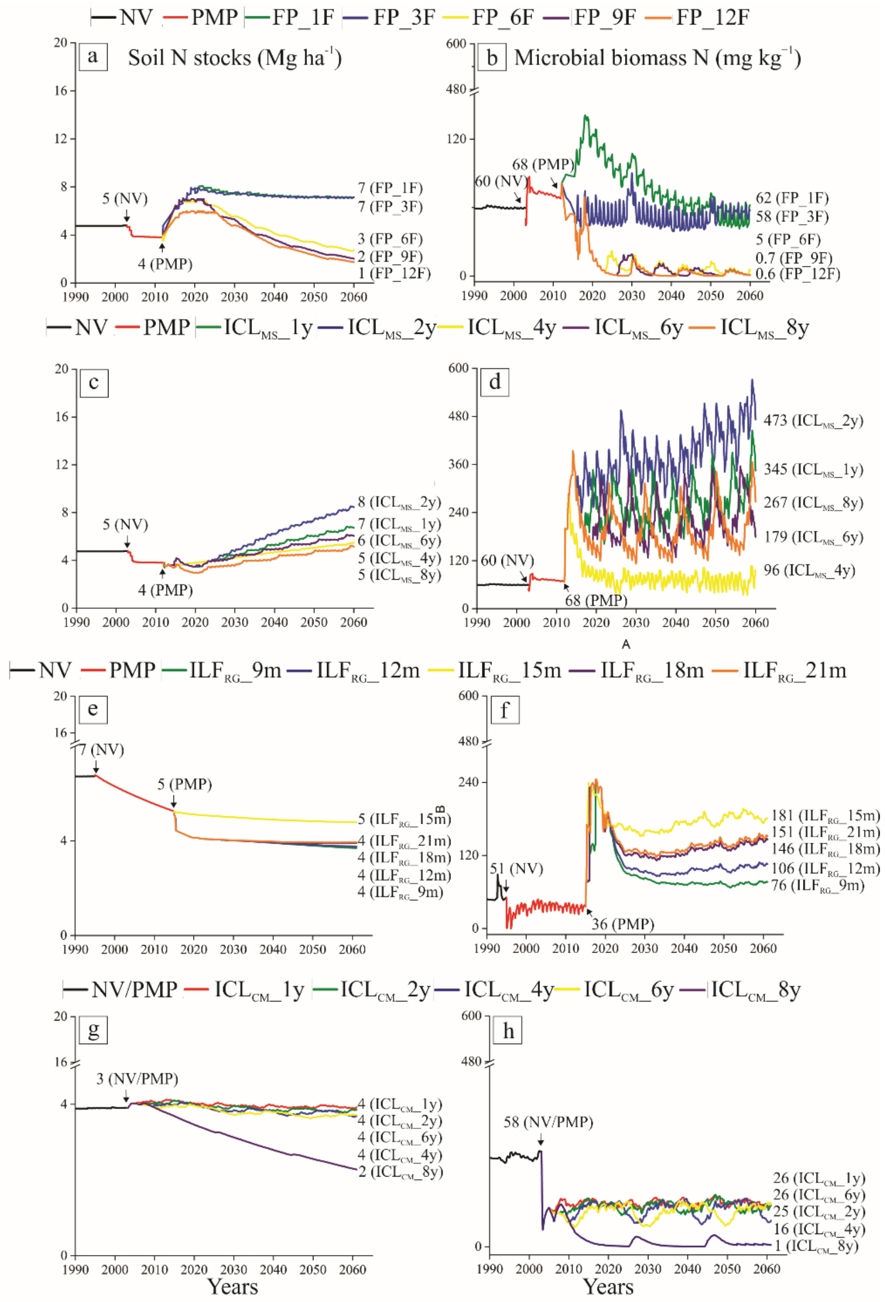
Supplementary Table S1. Description of the long-term simulations performed with the DayCent model.

Climate conditions	Initial data		Future pasture management scenarios	
Tropical humid	NV	native vegetation		
	PMP	poorly managed pasture		
	FP	**fertilized pasture**	FP_1F	fertilization every year
			FP_3F	fertilization every 3 years
			FP_6F	fertilization every 6 years
			FP_9F	fertilization every 9 years
			FP_12F	fertilization every 12 years
	ICL_{MS}	**integrated crop-livestock with Maize/Soybean**	ICL_{MS}_1y	implementation of the crop phase every year
			ICL_{MS}_2y	implementation of the crop phase every 2 years
			ICL_{MS}_4y	implementation of the crop phase every 4 years
			ICL_{MS}_6y	implementation of the crop phase every 6 years
			ICL_{MS}_8y	implementation of the crop phase every 8 years
	ICL_{RS}	integrated crop-livestock with Rice/Soybean		
Tropical mesic	NV	native vegetation		
	PMP	poorly managed pasture		
	ILF_{RG}	**integrated livestock-forest with rotational grazing**	ILF_{RG}_9m	spacing between the tree rows of 9 m
			ILF_{RG}_12m	spacing between the tree rows of 12 m
			ILF_{RG}_15m	spacing between the tree rows of 15 m
			ILF_{RG}_18m	spacing between the tree rows of 18 m
			ILF_{RG}_21m	spacing between the tree rows of 21 m
	ILF_{NG}	integrated livestock-forest with no grazing		
Subtropical	NV/PMP	native vegetation/poorly managed pasture		
	ICL_{NG}	integrated crop-livestock with no grazing		
	ICL_{RM}	integrated crop-livestock with rotational stocking and moderate-intensity grazing		
	ICL_{CM}	**integrated crop-livestock with continuous stocking and moderate-intensity grazing**	ICL_{CM}_1y	implementation of the crop phase every year
			ICL_{CM}_2y	implementation of the crop phase every 2 years
			ICL_{CM}_4y	implementation of the crop phase every 4 years
			ICL_{CM}_6y	implementation of the crop phase every 6 years
			ICL_{CM}_8y	implementation of the crop phase every 8 years
	ICL_{RL}	integrated crop-livestock with rotational stocking and low-intensity grazing		
	ICL_{CL}	integrated crop-livestock with continuous stocking and low-intensity grazing		

Highlights in bold correspond to management systems that showed the highest soil C stocks, soil N stocks, MBC and MBN contents.



Supplementary Fig. S1. Long-term simulations of soil N stocks and MBN contents through the conversion from native vegetation to different pasture management systems under tropical humid (a and b), tropical mesic (c and d) and subtropical (e and f) climate conditions.



Supplementary Fig. S2. Effects of different future pasture management scenarios on soil N stocks and the MBN contents in FP (a and b), ICL under tropical humid (c and d) and subtropical climatic conditions (g and h) and ILF (e and f). FP under tropical humid climate with time interval for fertilization of 1 (FP_1F), 3 (FP_3F), 6 (FP_6F), 9 (FP_9F) and 12 (FP_12F) years. ICL$_{MS}$ under tropical humid climate with time for the implementation of the crop phase of 1 (ICL$_{MS}$_1y), 2 (ICL$_{MS}$_2y), 4 (ICL$_{MS}$_4y), 6 (ICL$_{MS}$_6y) and 8 (ICL$_{MS}$_8y) years. ILF$_{RG}$ under tropical mesic climate with the spacing between the tree rows of 9 (ILF$_{RG}$_9m), 12 (ILF$_{RG}$_12m), 15 (ILF$_{RG}$_15m), 18 (ILF$_{RG}$_18m) and 21 (ILF$_{RG}$_21m) m. ICL$_{CM}$ under subtropical climate with time for the implementation of the crop phase of 1 (ICL$_{CM}$_1y), 2 (ICL$_{CM}$_2y), 4 (ICL$_{CM}$_4y), 6 (ICL$_{CM}$_6y) and 8 (ICL$_{CM}$_8y) years.

6. FINAL REMARKS

As summary of this study, it was observed that the adoption of more intensive and diversified systems of pasture management in areas previously used with extensive management systems increased the soil C stocks. As example, in the 0-100 cm layer the adoption of fertilized pasture, integrated crop-livestock and integrated livestock-forest provided average increases of 119%, 1% and 13% in the soil C stocks, respectively. These management systems provided greater inputs of plant biomass, and this effect generated an increase in the soil C lability. It is important to emphasize that the results found are related to specificities, such as edaphoclimatics (e.g., soil types and climatic conditions), duration of treatments (e.g., 2003-2018 in the case of this study) and management (e.g., cultivation system, crop rotation system, grass species and livestock management) adopted in the evaluated production environments. For this reason, more studies can be carry out seeking to assess the soil C stocks changes for contrasting conditions to those evaluated in this study.

In addition to the increases in the soil C stocks, the pastureland intensification and diversification provided improvements in the soil chemical properties related to soil fertility. Among the the soil chemical properties related to soil fertility, there is an increase in soil P contents. Additionally, there was a close relationship between the labile P fractions with the more labile SOM fractions (organomineral and organic fraction at 75–2000 μm). This results indicate that the soil P dynamics under more intensive and diversified systems of pasture management is closely related to SOM dynamics. Future studies can be used to better explain this relationship using diferente P assessment techniques (e.g., synchrotron light, x-ray diffraction, x-ray fluorescence, x-ray photoelectron spectroscopy and infrared spectroscopy). Furthermore, the soil chemical properties together with the biochemical properties and the soil bacterial community structure modified the mechanisms that control the soil C accumulation. This finding provide an important insights into the controlling factors of soil C accumulation during management system changes in tropical pasture areas. However, further long-term studies should be carried out in order to better elucidate the interactions and controlling factors for the soil C accumulation.

The mathematical modeling performed with the DayCent model proved to be an efficient and cost-effective tool to predict soil C pool changes and to monitor GHG emissions due to pastureland intensification and diversification in Brazil. The simulations carried out in this thesis are the first attempts to predict soil C pool changes and GHG emissions in more intensive and diversified systems of pasture management for the diferente Brazilian edaphoclimatic conditions. The simulations showed that while extensively managed pastures were a GHG source to the atmosphere, systems of pasture management, such as fertilized pasture, integrated crop-livestock and integrated livestock-forest were GHG sinks. Despite the good results obtained in the long-term simulations with the DayCent model, further studies are encouraged in order to validate these findings and better calibrate the model for contrasting conditions of managements. More specifically, future calculations should include animals methane emissions, as this gas represent a great contribution to the net balance of the GHG emissions. Finally, the results found in this thesis can also assist national initiatives aimed at restoring degraded pasture areas (e.g., "ABC Plan"), as well as fits the scope of the Brazil's NDC (Nationally Determined Contribution) for mitigating GHG emissions (reduce emissions 37% by 2025 and 43% by 2030).