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RESEARCH ARTICLE

Live fences reduce the diurnal and seasonal fluctuations of soil CO_2 emissions in livestock systems

Gilberto Villanueva-López[1] · Pablo Martínez-Zurimendi[1,2] · Luis Ramírez-Avilés[3] · Deb Raj Aryal[4] · Fernando Casanova-Lugo[5]

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Abstract Deforestation of tropical forests for the establishment of grass monoculture for livestock production is responsible for about 30 % of CO_2 emissions. This issue is particularly severe in degraded pastures because degraded soils favor CO_2 flow to the soil surface. Silvopastoral systems could reduce CO_2 emissions, notably by using live fences. Here, we hypothesized that live fences of *Gliricidia sepium* in livestock systems should reduce variations in environmental relative humidity and soil temperature and, in turn, reduce soil CO_2 emissions. Here, we studied two livestock systems: (1) grass monoculture of *Brachiaria decumbens* with live fences of *G. sepium* and (2) grass monoculture of *B. decumbens* without live fences. We measured soil CO_2 seasonal emissions at different times of the day, soil temperature, and environmental relative humidity. Nine 600-m^2 plots were established in each system. All variables were measured over four 6-h period during a 24-h period, twice a month from April to September. Our results show that soil CO_2 emissions showed less variability with *G. septum* live fences than without live fences. This lower variability is explained by the creation of a microclimate with a higher and more stable environmental relative humidity, provided by the shade of trees. Results also show, however, that global soil CO_2 emissions did not differ between the two systems, with and without live fence. Moreover, soil CO_2 emissions varied according to season, as shown by 1.082 g CO_2 m^{-2} h^{-1} in the wet season versus 0.871 g CO_2 m^{-2} h^{-1} in the dry season. Soil CO_2 emissions varied also according to sampling time, as shown by 1.116 g CO_2 m^{-2} h^{-1} in the night versus 0.960 CO_2 m^{-2} h^{-1} in the morning.

Keywords Global warming · Climate change · Greenhouse gases · Soil respiration · Silvopastoral system · *Gliricidia sepium*

✉ Gilberto Villanueva-López
gvillanueva@ecosur.mx; gvillanueva_69@hotmail.com

Pablo Martínez-Zurimendi
pmartinez@ecosur.mx

Luis Ramírez-Avilés
raviles@uady.mx; luis.ramirez@correo.uady.mx

Deb Raj Aryal
debraj.aryal@hotmail.com

Fernando Casanova-Lugo
fernando215_45@hotmail.com; fkzanov@gmail.com

1 El Colegio de la Frontera Sur, Carretera a Reforma km 15.5 s/n Ra. Guineo 2ª sección, CP. 86280 Villahermosa, Tabasco, Mexico

2 Sustainable Forest Management Research Institute UVa-INIA, Palencia, Spain

3 Campus de Ciencias Biológicas y Agropecuarias, Universidad Autónoma de Yucatán, Carretera Mérida Xmatkuil km 15.5 Aptdo. 116 Itzimná, Mérida, Yucatán, Mexico

4 Catedras CONACyT, Facultad de Ciencias Agronómicas, Universidad Autónoma de Chiapas, Campus V, Villaflores, Chiapas, Mexico

5 Instituto Tecnológico de la Zona Maya, Carretera Chetumal-Escárcega km 21.5, C.P. 77965 Ejido Juan Sarabia, Quintana Roo, Mexico

1 Introduction

Recent studies show that anthropogenic emissions of carbon dioxide (CO_2) have increased significantly during the last 150 years (from 280 ppm in pre-industrial times to 397 ppm in 2013; Bond-Lamberty and Thomson 2010; NOAA 2013). Approximately 30 % of these emissions originate from deforestation of tropical forests for the establishment of pastures for extensive livestock production (Wang et al. 2009; De Jong et al. 2010). These pastures have the potential to store significant amounts of soil carbon (C) and can hold a similar amount of soil C stocks than forest soils; however, many pastures in the tropics are degraded and therefore act as sources of CO_2 rather than C sinks (Guo et al. 2006).

CO_2 emissions from the soil surface represent the second most important flow of this gas between land ecosystems and the atmosphere (Tang et al. 2006; Wu et al. 2006) after anthropogenic fossil fuel emissions (Kabwe et al. 2002). Therefore, any increase in soil CO_2 emissions can further increase CO_2 concentrations in the atmosphere, contributing to a positive feedback on global warming (David et al. 2006). According to Liu et al. (2002), Joffre et al. (2003), and Yuste et al. (2007), the amount of soil CO_2 depends mainly on temperature, humidity, and land use. Other studies (e.g., Lee et al. 2003; Lohila et al. 2003; Xu et al. 2006; Jassal and Black 2006) have reported a relationship between soil respiration and biotic factors such as root biomass, soil microbial biomass, soil nitrogen availability, soil physical and chemical properties, and soil drainage. In addition, the type of vegetation can also influence soil CO_2 emissions (Raich and Tufekcioglu 2000).

The southeast region of Mexico, particularly the state of Tabasco, was originally covered by native tropical forest containing canopy species.[1] However, at the start of the 1960s, the forests in this region began to be cleared for the establishment of pasture monocultures for cattle grazing. Subsequently, live fences composed of species such as *Gliricidia sepium* (Jacq.) Kunth ex Walp were gradually established in conjunction with livestock systems (Fig. 1). This combination can be considered as a silvopastoral system and consists of planting lines of trees instead of using dead fence posts to support barbed wire. They are generally used for delimiting farm boundaries and dividing pasture and frequently run along the edge of paths and tracks. Currently, live fences represent the only tree cover present in tropical livestock systems that encompass large and ever increasing areas of land; they are not the only system, but one of the most important in the landscape of the region of the study (Grande et al. 2010; Villanueva-López et al. 2014). Despite the importance they play in terms of tree cover and as man-made biological corridors, there are very few studies on the role of live fences in reducing CO_2 emissions (Soto et al. 2010). The aim of this study was to quantify soil CO_2 emissions in two livestock systems: (1) a livestock grass monoculture of *Brachiaria decumbens* (Stapf) with live fences of *G. sepium* and (2) a livestock grass monoculture of *B. decumbens* without live fences. We also examined the variation in soil CO_2 emissions during the wet and dry seasons and different times of day, in addition to monitoring soil temperature and environmental relative humidity in both systems.

[1] Native tropical forest contains species such as *Cedrela odorata* (L.), *Swietenia macrophylla* (King), *Cordia alliodora* (Ruiz & Pav.) Oken, *Tabebuia rosea* (Bertol.) DC., *Blepharidium mexicanum* (Standl.), and *Dialium guianense* (Aubl.) Sandwith., amongst others.

2 Materials and methods

2.1 Site description

This study was carried out in the municipality of Tacotalpa Sierra, located in the south of the state of Tabasco, Mexico (17°15′; 17°45′ N and 90°38′; 93°46′ W). The climate in the region is warm humid with a mean annual temperature of 25 °C, maximum monthly mean of 43 °C in June, and minimum monthly mean of 18 °C in December (according to the climatic classification of Köppen, modified by García 2004). Total mean rainfall is 3000 to 4000 mm per year, with a maximum of 570 mm in September and a minimum of 167 mm in April. Total precipitation recorded during the experimental period was 1809 mm (weather information provided by the Tapijulapa weather station, Tacotalpa, Tabasco).

2.2 Characteristics of study systems and plots

Two pasture livestock systems were selected and hereafter will be referred to as treatments. The first was a livestock system dominated by *B. decumbens* grass and live fences (LF) consisting of *G. sepium* trees. The trees had an average height of 4.6 and 0.90 m apart. Ninety-five percent of the tree species in the live fences were of *G. sepium.* The main function of live fences is to delimit properties, divide paddocks, and provide shade for animals. Trees are pruned every 2 years in order to obtain firewood and posts to repair and establish new fences; the remaining biomass is usually deposited on the ground within the pastures.

The second livestock system was a grass monoculture of *B. decumbens* without live fences (GM). Instead of live fences, this system used wooden posts and barbed wire to delimit properties and divide paddocks. This system was established over 30 years ago and has been grazed on ever since. Both systems are located on flat topography at an altitude of 50 m.a.s.l., and consist of intensive cattle grazing using the *Bos indicus* L. or *Cebu* breeds of cow for meat production under a daily rotational system. The stocking rate ranges from 1 to 5 animal units per hectare (Grande et al. 2010). Soils in the study area were red, thick (1.5 to 2.0 m deep), slightly acidic, and with a clay loam texture. Some physical and chemical characteristics of soils in the two livestock systems are shown in Table 1.

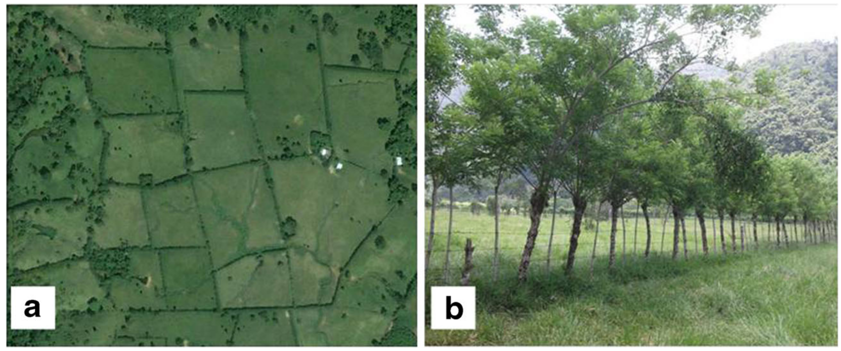


Fig. 1 Territorial land use in the Sierra sub-region of the state of Tabasco, Mexico. **a** Aerial view of landscape. **b** Livestock systems with live fences (LF) of *G. sepium* trees

2.3 Experiment and methods of sampling soil CO_2 emissions and environmental variables

Three farms were selected for each of the pasture livestock systems. In each farm, a live fence was selected from which three plots were randomly allocated, making a total of 18 sampling plots. A minimum distance of 30 m was maintained between plots. In both livestock systems, 600-m^2 (30 × 20 m) plots were used. In the livestock systems with live fences (LF), each plot included a row of trees of *G. sepium* intercropped with *B. decumbens* grass. In each plot, a sampling area, at a distance of 0–3 m from the live fence (beneath the tree crown), was assigned. In each sampling area, a 9-m^2 (3 × 3 m) sub-plot was randomly selected, at a distance of 1.5 m from the fence. In the livestock systems in grass monoculture (GM), each plot contained only *B. decumbens* grass. Measurements were taken randomly from each sub-plot. To prevent damage by cattle, all experimental plots were fenced with barbed wire from 30 days prior to the start of the experiment (March 2012) until completion (September 2012).

Soil CO_2 emissions were measured in situ with a dynamic closed-chamber EGM-4 (PP Systems, UK). This contains an infrared gas analyzer (IRGA) and a soil respiration chamber (SRC-1) responsible for capturing and transporting the air to the IRGA for calculation of soil CO_2 emissions. The chamber is cylindrical, measuring a height of 15 cm and a diameter of 10 cm. The recorded CO_2 emissions included autotrophic respiration from plant roots and heterotrophic respiration from soil organisms. We recorded the total soil CO_2 emission readings shown by EGM-4 and present the findings as grams of carbon dioxide per square meter per hour (g CO_2 m^{-2} h^{-1}). Measurements were made fortnightly from April to September 2012 during both the dry (April to June) and wet seasons (July to September). Four daily measurements were taken over a period of 24 h: night (00:00 to 06:00 h), morning (06:00 to 12:00 h), afternoon (12:00 to 18:00 h), and evening (18:00 to 24:00 h). For each emission measurement, a different point of the sub-plot was selected, and after removing the uppermost layer of mulch, one CO_2 emission measurement was taken at each sampling plot. Soil temperature (°C) was taken at a depth of 5 cm using a data logger (HOBO H8 and U12 Onset Computer Corp, Pocasset, Mass. EEUU) with an external sensor that was installed adjacent to the respiration chamber. Temperatures were recorded every 30 s during each CO_2 emission measurement. Atmospheric environmental relative humidity was measured at a height of 1 m from the ground using the same HOBO and at the same frequency used for recording soil temperatures.

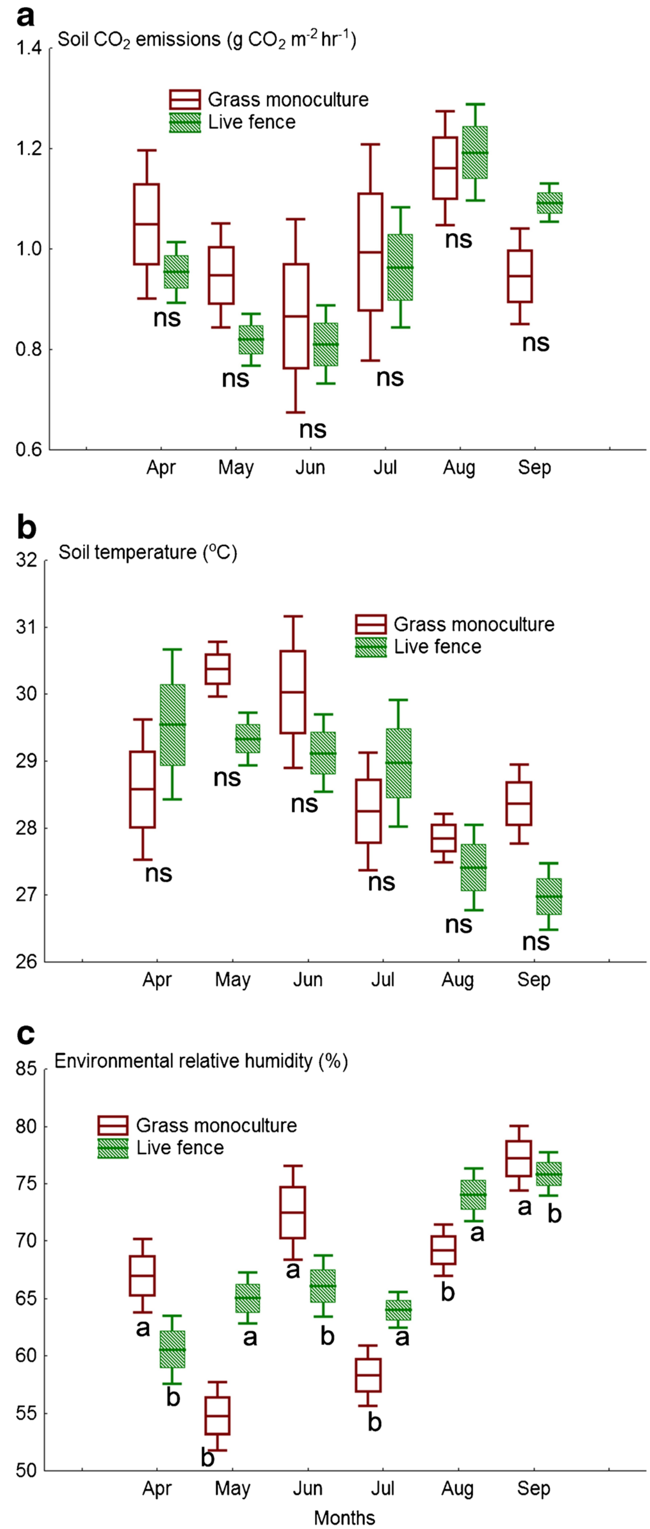
Table 1 Mean values (±SE, $n = 162$) and comparison of percentages of physical and chemical properties in livestock systems with live fences (LF) and livestock systems in grass monoculture (GM) using a multivariate analysis of variance

Soil properties	Livestock systems with live fences	Livestock systems in grass monoculture
pH	7.25 (±0.05) b*	7.57 (±0.06) a*
Bulk density (g/cm^3)	1.30 (±0.03) b*	1.55 (±0.02) a*
Organic matter (%)	4.81 (±0.50) a	4.40 (±0.43) a
Soil organic carbon (%)	2.80 (±0.29) a	2.56 (±0.25) a
Nitrogen (%)	0.24 (±0.03) a	0.22 (±0.02) a
Sand (50–1000 μm, %)	25.06 (±1.12) a	26.97 (±1.64) a
Silt (2–50 μm, %)	41.27 (±1.25) a	37.10 (±1.22) a
Clay (<2 μm, %)	33.67 (±1.25) a	35.93 (±2.00) a

Samples were taken at depths of 0–30 cm at each sampling plot (Villanueva-López et al. 2014)

*The small letters in each row indicate significant differences between means ($p \leq 0.05$) obtained by a Tukey post hoc test

Fig. 2 **a** Monthly variation of soil CO_2 emissions. **b** Soil temperature (0- to 5-cm depth). **c** Environmental relative humidity at 1-m height, measured in livestock systems with live fences (LF) and livestock systems in grass monoculture (GM). The mean values of soil CO_2 emissions are expressed in g of CO_2 m^{-2} h^{-1}; soil temperature expressed in °C and environmental relative humidity in %. *Box plots* represent means, while *vertical bars* represent standard error per month on each system. ANOVA (Tukey test $p \leq 0.05$) was performed; *different letters* in each box of the same month indicate significant differences between means. *ns* no significant differences. Each column represents the mean of nine replications



2.4 Statistical analysis

A repeated measures analysis of variance (ANOVA) was used to compare the values of soil CO_2 emissions, soil temperature, and environmental relative humidity between both livestock systems and across seasons and different times of the day. Multiple comparison Tukey HSD tests at 95 % were used to determine if there were significant differences between systems, seasons, and sampling hours. Analyses were performed using Statistic version 8.0 for Windows (StatSoft Inc. 2007).

3 Results and discussion

3.1 Soil CO_2 emissions, soil temperature, and environmental relative humidity

Soil CO_2 emissions did not present significant differences between the two livestock systems; the mean soil CO_2 emission for both systems was 0.983 g CO_2 m^{-2} h^{-1}; 1.004 g CO_2 m^{-2} h^{-1} was emitted in the livestock systems with live fences (LF) and 0.972 g CO_2 m^{-2} h^{-1} in the livestock systems in grass monoculture (GM) (Fig. 2a). The absence of significant differences is probably due to several factors: (i) the wide distribution of CO_2 emissions recorded in the livestock systems in grass monoculture (GM), both between months (Fig. 2a) and days (Fig. 4a), presents a range of extremes that covers the level of typical soil respiration recorded for both the systems under study, resulting in any statistically significant differences between systems remaining undetected at the level of global means; (ii) the live fences in the livestock production systems are found only around the perimeter of the pasture fields, have low density of plants, are of low density, and are comprised of small-sized trees; and (iii) therefore, live fences do not have a significant effect on soil temperatures in both systems. Monthly mean soil temperatures were slightly higher during April, May, and June (29.1, 29.9, and 29.6 °C, respectively) than in July, August, and September (28.6, 27.6, and 27.7 °C, respectively) (Fig. 2b). In contrast, the relative environmental humidity demonstrated significant differences between the two systems, being higher in the systems with live fences (LF) (68 %) than the systems in grass monoculture (GM) (63 %) during the wet season (Fig. 2c).

However, others studies indicate that high soil CO_2 emissions are produced in mixed crop systems rather than in monocultures, demonstrating that vegetation type significantly influences soil CO_2 emissions. For example, Raich and

Tufekcioglu (2000) found that CO_2 emissions from the soil were 20 % higher in broadleaf forests associated with pasture than in conifer forests growing on the same soil type. Similarly, Peichl et al. (2006) found higher soil CO_2 emissions in mixed crops when compared with monocultures. In the Chilean Patagonia, Dube et al. (2012) found soil CO_2 emissions of 22.77 and 23.65 Mg ha^{-1} year^{-1} in pine plantations and natural pastures, respectively.

We also found that mean soil CO_2 emissions, soil temperatures, and environmental relative humidity presented less variability, although these variables were more stable in the livestock systems with live fences (LF) than in the livestock systems in grass monoculture (GM) (Fig. 2a). These results provide evidence of the role of *G. sepium* trees and their rhizosphere in reducing the diurnal variability of soil CO_2 emissions in the systems with live fences (LF); this is most likely as a result of the creation of a microclimate with a higher and more stable environmental relative humidity, encouraged by the shade-producing trees.

In addition, factors such as root activity and density per area, the presence of mycorrhizal fungi, availability of C substrates for microbial biomass, nitrogen content, organic matter content, and other soil physical and chemical properties also influence soil CO_2 emissions (Lohila et al. 2003; Xu et al. 2006; Dube et al. 2009). In accordance with Villanueva-López et al. (2014), in this zone, soil pH and bulk density were higher in the systems with live fences (LF) than in the livestock systems in grass monoculture (GM) (Table 1), indicating that the presence of *G. sepium* trees in the systems with live fences (LF) may have improved bulk density and soil pH, probably through an increase in leaf litter entering the system as reported by Berninger and Salas (2003), Eldridge and Wong (2005), and Villanueva-López et al. (2014). However, our results show that there were no significant differences in soil CO_2 emissions between systems, and they show the same trend as the content of organic matter (Table 1), suggesting that improved physical and chemical soil properties do not necessarily result in higher soil CO_2 emissions, while the lower contents of organic matter (Table 1) in the livestock systems in grass monoculture (GM), due to the absence of trees, may have resulted in emissions being more sensitive to diurnal changes.

3.2 Seasonal variation of soil CO_2 emissions, soil temperature, and environmental relative humidity

Soil CO_2 emissions and environmental relative humidity in both systems presented significant differences and were higher during the wet season (Fig. 3a, c). The results showed that in the wet season, emissions were highest in the livestock systems with live fences (LF), probably due to lower temperatures (Fig. 3b) that increased environmental relative humidity

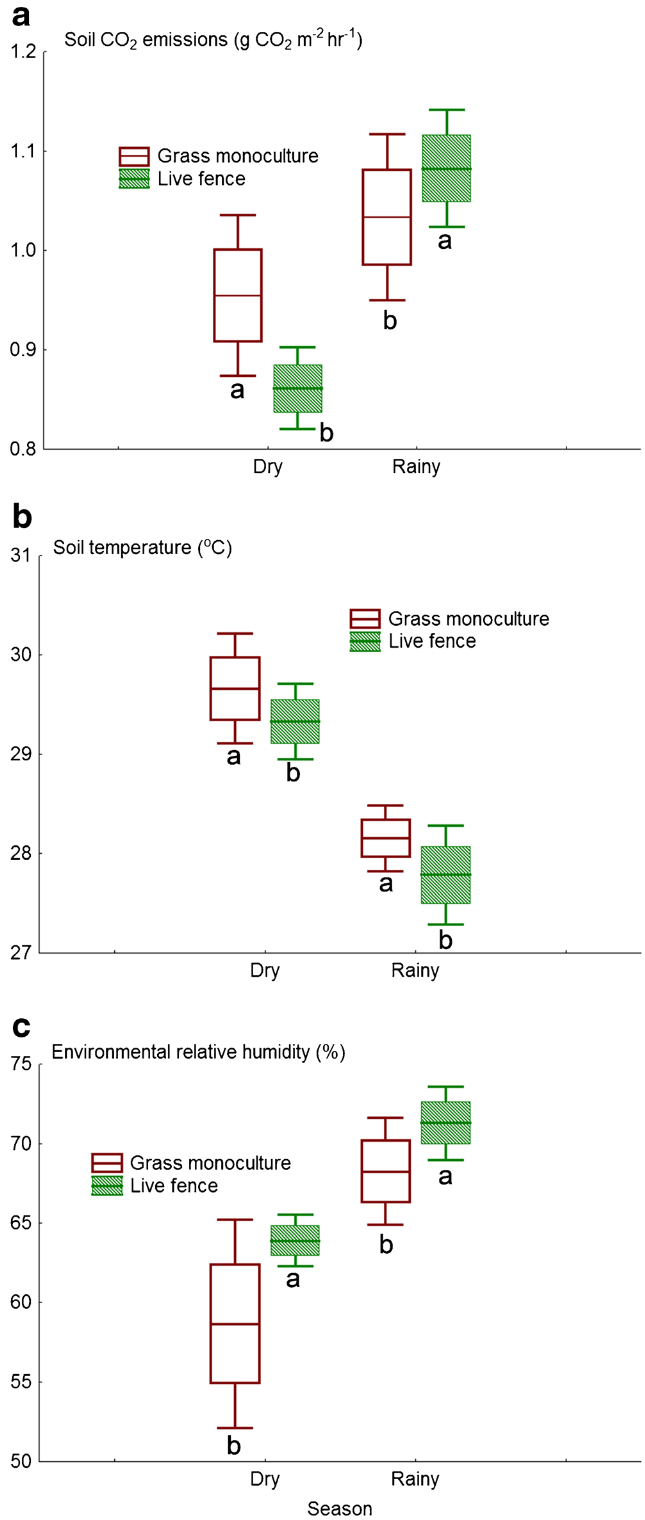


Fig. 3 **a** Seasonal variation of soil CO_2 emissions. **b** Soil temperature (0- to 5-cm depth). **c** Environmental relative humidity at 1-m height, measured in livestock systems with live fences (LF) and livestock systems in grass monoculture (GM). Soil CO_2 emissions are expressed in g m^{-2} h^{-1}, soil temperature in °C, and environmental relative humidity in %. *Box plots* represent means, while *vertical bars* represent standard error per season and system. ANOVA (Tukey test $p \leq 0.05$) was performed; *different letters* in each box of the same season indicate significant differences between means. *ns* no significant differences. Each column represents the mean of nine replications

(Fig. 3c) and high water soil content during this period, as reported by Liu et al. (2002); Frank et al. (2002); David et al. (2006); Yuste et al. (2007); Li et al. (2008); Zhang et al. (2009); Kutsch et al. (2010); Dube et al. (2012). High soil CO_2 emissions during the wet season could partly be a consequence of higher organic matter concentrations, given that root growth increases microbial respiration (Kutsch et al. 2010). In addition, high precipitation enhances mineralization which stimulates biological activity and high soil CO_2 emissions (Lou et al. 2003). Another possible factor is that soil quality is improved during this period due to a greater input and availability of organic residue (energy sources) for soil microorganisms, thus incrementing the soil microbial community and biological activity, which in turn increases soil CO_2 emissions (Atkin et al. 2000). Although pH and bulk density were more suitable for microorganism activity in the systems with live fences (LF) (Table 1), there were no significant differences in soil CO_2 emissions between both systems.

3.3 Diurnal fluctuations of soil CO_2 emissions, soil temperature, and environmental relative humidity

In both systems, soil CO_2 emissions, soil temperature, and environmental relative humidity presented significant variations in relation to the time of day these variables were recorded (Fig. 4a–c), except for the soil temperature recorded during the night (00:00 to 06:00 h) and the relative humidity registered during morning (06:00 to 12:00 h). In the livestock systems in grass monoculture (GM), the highest emissions were recorded at night. In contrast, in the livestock systems with live fences (LF), emissions were highest in the afternoon (12:00 to 18:00 h) (Fig. 4a). These trends can be explained by (i) lower soil temperatures during the night (00:00 to 06:00 h); (ii) higher soil temperatures during the afternoon (12:00 to 18:00 h) (Fig. 4b); and (iii) higher environmental relative humidity during the morning when compared to all other times (Fig. 4c). Similar results were reported by Kirschbaum (2000) and Zhang et al. (2009). Mean daytime CO_2 emissions were 0.972 g CO_2 m^{-2} h^{-1} in the systems with live fences (LF) and 0.949 g CO_2 m^{-2} h^{-1} in the livestock in grass monoculture (GM); during the night, emissions were 0.981 g CO_2 m^{-2} h^{-1} in the systems with live fences (LF) and 1.251 g CO_2 m^{-2} h^{-1} in the systems in grass monoculture (GM) (Fig. 4a). Furthermore, CO_2 emissions presented lower variability in the systems with live fences (LF) than in the systems in grass monoculture (GM) (Fig. 4a), which suggests a more stable microclimate in the pastures with tree cover when compared with grass monocultures.

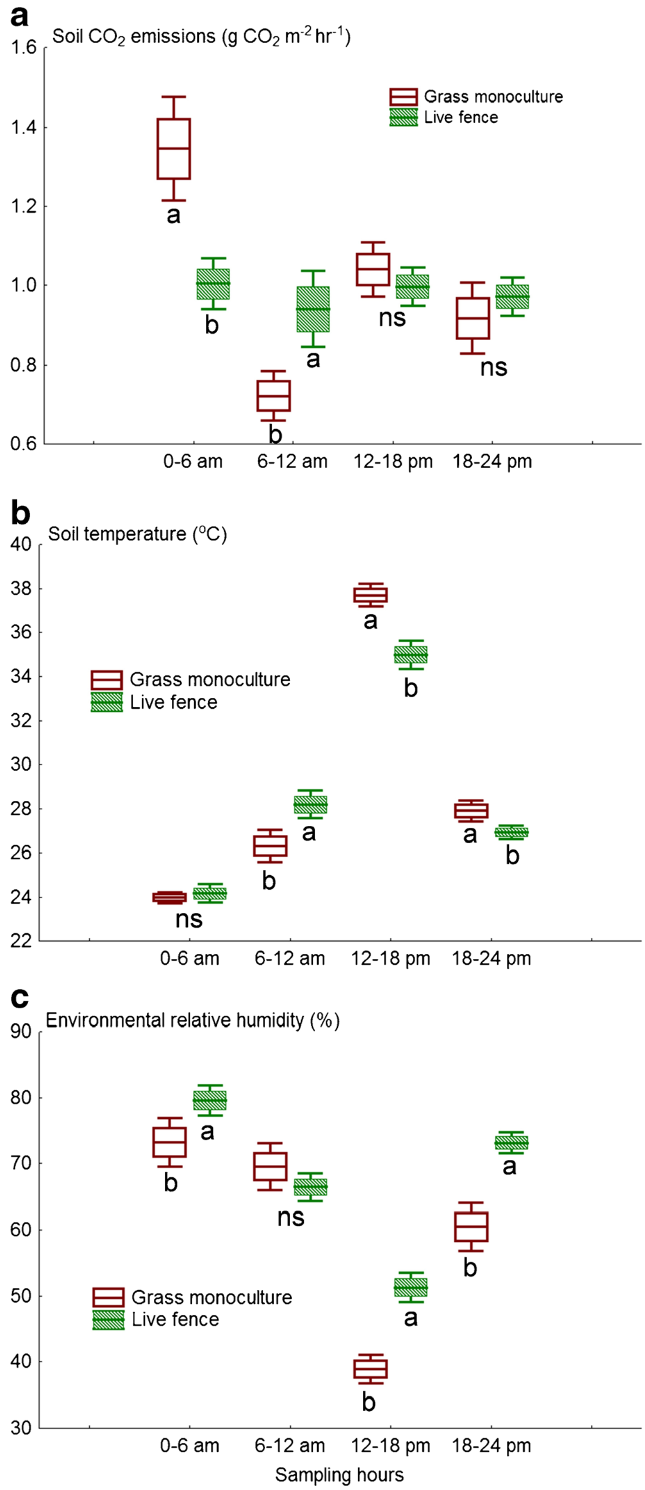


Fig. 4 **a** Fluctuations of soil CO_2 emissions at four different times of the day. **b** Soil temperature (0- to 5-cm depth). **c** Environmental relative humidity at 1-m height, measured in livestock systems with live fences (LF) and livestock systems in grass monoculture (GM). Soil CO_2 emissions are expressed in g m^{-2} h^{-1}, soil temperature in °C, and environmental relative humidity in %. *Box plots* represent means, while *vertical bars* represent standard error per time and system. ANOVA (Tukey test $p \leq 0.05$) was performed; *different letters* in each box at the same time of the day denote significant differences between means. *ns* no significant differences. Each column represents the mean of nine replications

4 Conclusions

The results of this study indicate that total soil CO_2 emissions did not differ between pasture livestock systems with and without live fences in a humid tropical climate. However, in both systems, CO_2 emissions varied according to season and time of day. In the livestock systems in grass monoculture (GM), emissions were highest at night during the wet season, while in the livestock systems with live fences (LF), these were highest in the afternoon during the dry season. Lower emissions occurred during the morning in both systems and seasons analyzed due to lower soil temperatures and higher environmental relative humidity at this time of day. The variations in emissions between seasons and time of day were associated with changes in soil temperature and atmospheric humidity. Furthermore, soil CO_2 emissions, soil temperatures, and environmental relative humidity presented less variability and therefore more stability in the livestock systems with live fences (LF) when compared with the systems in grass monoculture (GM).

These results show that systems with live fences (LF) composed of *G. sepium* trees have a greater potential to reduce the variability of CO_2 emissions and soil temperature than the livestock systems in grass monoculture (GM). In addition, the systems with live fences (LF) improved conditions of environmental humidity within their area of influence. Although soil CO_2 emissions are similar in both systems, the additional effects of trees in stabilizing emissions might be substantial at the landscape level, particularly in areas such as the state of Tabasco, where 70 % of the total land area has been converted to monoculture grass prairies for extensive livestock farming. The following mitigation strategies are recommended for livestock production systems: (i) The shade generated by the *G. sepium* trees in the live fence does not affect grass production, therefore establish more live fences inside and along the edges of pastures and farms, (ii) establish new live fences instead of using wooden posts in livestock production systems where they do not yet exist, (iii) undertake new research on the role of trees comprising live fences in livestock systems, such as the effects of an increase in tree density and the inclusion of other tree species in different strata, and finally, although this study shows that optimum physical and chemical properties of the soil, particularly pH and apparent density, do not necessarily contribute to soil CO_2 emissions, (iv) use the live fences to improve the physical and chemical characteristics of the soil. In this study, the livestock systems with live fences (LF) are characterized by soils with high organic matter content and nitrogen contents and the low pH and apparent density values. Other studies have reported that *G. sepium* trees improve soil nitrogen content through biological fixation by microorganisms from the *Rhizobium* genus found in the root nodules, therefore contributing to a more neutral soil pH.

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