

Grass-legume intercropping systems in rotation with soybean crops: C and N stocks and CO₂ and NH₃ emissions

Camila Dias Pinaffi (✉ camila_pinaffi@hotmail.com)

Universidade do Oeste Paulista

Ana Carolina Mônico Moreira

Universidade do Oeste Paulista

Flávia Alessandra Mignacca

Universidade do Oeste Paulista

Carlos Sérgio Tiritan

Universidade do Oeste Paulista

Carlos Henrique dos Santos

Universidade do Oeste Paulista

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Abstract

Understanding factors that contribute to carbon dioxide (CO₂) losses and ammonia (NH₃) volatilization in agricultural soils, mainly in sandy soils, is essential for determining strategies to decrease emissions of these gases and improving carbon (C) and nitrogen (N) stocks in the soil. The objective of this study was to quantify C and N inputs to the soil and CO₂ and NH₃ emissions in a crop-livestock integration system composed of pastures with grass-legume intercropping and N fertilizer application. The experiment was carried out in a Typic Hapludox, evaluating three consecutive soybean crops grown in rotation with the following pasture systems: mombaca grass (*Panicum maximum* cv. Mombaca) with N fertilizer (M + N); mombaca grass without N fertilizer (M-N); mombaca grass intercropped with the forage legume pigeon pea (*Cajanus cajan*) (M + G); and mombaca grass intercropped with the forage legume java (*Macrotyloma axillare* cv. Java) (M + J). Soil samples were collected at the beginning and end of each crop and analyzed for total C (TCS) and N (TNS) stocks. NH₃ volatilization and CO₂ emissions were evaluated every 15 days, with simultaneous evaluations of soil moisture and temperature. Soybean rotation with grass-legume intercropping or grass with mineral fertilizer application improved N and C inputs to the agricultural systems, although there were losses in CO₂ and NH₃. The M + G and M + J intercrops after soybean crops increased NH₃ volatilization, whereas the use of M + N tended to decrease it. The soil moisture affected the C and N input-output balance in the production systems evaluated.

Introduction

Agriculture in sandy soils in Brazil has increasing due to restrictions on the opening of new agricultural areas and the increase in food demand, requiring the adaptation of agricultural systems to adverse climate and soil conditions (Silva et al. 2020). Sandy soils present low fertility, thus, the growth of crops in these soils has been questioned regarding their technical, economic, and environmental viabilities; growth of annual crops is usually not recommended for these soils, mainly due to the risks of compaction of the soil surface layer, erosive processes, water deficit, low moisture retention, and loss of fertilizers (Castro and Hernani 2015). The adoption of agronomic practices, such as the use of intercropping systems, can promote the cycling of nutrients and improve the production potential of sandy soils (Morais et al. 2020). The diversity of crops affects the soil nitrogen (N) availability (Rock *et al.* 2020), which is the main limiting nutrient in sandy soils due to low organic matter contents (Masvaya et al. 2017).

In this context, legumes such as soybean contribute to increase soil N through biological N fixation (Wu et al. 2017). In addition, grass species with high biomass above and below ground increase the incorporation of carbon (C) and improve soil N stocks (Raphael et al. 2016).

Soil is an important C compartment and is essential for mitigating global carbon dioxide (CO₂) concentrations in the atmosphere and, consequently, global climate changes (Carvalho et al. 2010). Therefore, strategies for increasing soil C involve increases in C inputs and decreases in C losses. In this

context, crop-livestock integration systems are a strategy for replacing degraded pastures (Sarto et al. 2020a).

The use of grass species is essential for the viability and sustainability of agricultural production systems in sandy soils, as it favors biomass production and enables higher animal densities in pastures (Carvalho et al. 2014). However, tropical conditions and low clay contents promote a fast decomposition of soil organic matter (Gmach et al. 2020), requiring a high and constant supply of dry matter, C, and N to the soil (Hati et al. 2020).

In this context, the crop-livestock integration system can be improved by adding grass-legume intercropping to the pasture. Grass species present slow decomposition and high dry matter production potential, whereas legumes promote biological N fixation, a strategy to increase soil N, and have a faster decomposition (Rosolem et al. 2016, Calonego et al. 2017).

The objective of this study was to quantify C and N inputs to the soil profile and characterize the soil CO₂ emission dynamics and its relation with soil edaphoclimatic properties, as well as NH₃ volatilization, in areas with pastures with N fertilizer application and biological N fixation.

Material And Methods

Description of the experimental area

The experiment was conducted in the 2017–2018, 2018–2019, and 2019–2020 crop seasons, in Presidente Bernardes, state of São Paulo, Brazil (22°16'59"S, 51°40'34"W, and altitude of 401 m). The soil of the area was chemically characterized (Raij et al. 2001) at the beginning of the experiment (Table 1) and classified as a Typic Hapludox (Latossolo Vermelho-Amarelo distrofico argiluvico; Santos et al., 2008), with 17% clay in the 0–10 cm layer, according to granulometric analysis (EMBRAPA, 1997) carried out up to the depth of one meter (Table 2).

Table 1
Soil chemical characterization of the experimental area, 2017

Layer	pH	SOM ^a	P _(resin)	S	H+ Al	K	Ca	Mg	SB ^b	CEC ^c	BS ^d
(cm)	(CaCl ₂)	(g dm ⁻³)	— (mg dm ⁻³) — —		———— (mmol _c dm ⁻³) ————						(%)
0–20	5.9	20.7	6.3	5.9	13.5	1.0	22.9	16.5	40.5	54.0	73.8
20–40	5.3	14.1	3.3	6.7	17.4	0.4	13.4	10.2	24.0	41.4	56.5
^a soil organic matter; ^b sum of bases; ^c cation exchange capacity; ^d base saturation											

Table 2
Soil granulometric analysis (g kg^{-1}) of the experimental area, 2017.

Layer (cm)	Granulometry (g kg^{-1})			Textural class
	Sand	Silt	Clay	
0–10	773	48	179	Sandy Loam
10–20	763	68	169	Sandy Loam
20–40	736	41	223	Sandy Clay Loam
40–60	707	63	230	Sandy Clay Loam
60–80	695	55	250	Sandy Clay Loam
80–100	697	56	247	Sandy Clay Loam

(Table 1)

(Table 2)

The climate of the region was classified as Cwa, according to the Köppen classification, with a rainy season from October to March, a dry season from April to September, and a mean annual temperature of 25°C. Rainfall depths and temperatures in the experimental area were monitored by a Vantage Pro2 agroclimatic station (Fig. 1). The monthly water balance was also calculated to assess the effect of these data in the systems used (Fig. 2).

(Fig. 1)

(Fig. 2)

Experimental Design And Characterization Of The Systems

A randomized block experimental design with four treatments and four replications was used. The pasture treatments consisted of: mombaca grass (*Panicum maximum* cv. Mombaca) (M) with nitrogen (N) fertilizer application (200 kg ha^{-1} of N) (M + N); mombaca grass without N fertilizer application (M-N); mombaca grass intercropped with the forage legume pigeon pea (*Cajanus cajan*) (M + G); and mombaca grass intercropped with the forage legume java (*Macrotyloma axillare* cv. Java) (M + J).

The pastures were grown in 2015 and 2016. An area consisted of 16 padlocks of 69.0 m length and 49.3 m width was fenced for grazing in August 2017. The animals remained in the area until the pasture cut reached 30 cm from the ground. The area was then cleared using a burndown application (glyphosate at 6 L ha^{-1}), followed by liming using 1.0 Mg ha^{-1} of dolomitic limestone (total neutralizing power of 85%), and agricultural gypsum application (0.5 Mg ha^{-1}).

Seeds of the soybean cultivar TMG-7062 IPRO® were sown in October, in 2017, 2018, and 2019, to a plant stand of 13.8 plants m⁻¹. The inoculation with N was carried out in the sowing furrow, using 8 doses of colony forming units per hectare (Masterfix L Premier®). Fertilizers were applied at sowing, using the NPK formulation 04-30-10, plus 3.54% sulfur, 5.02% calcium, 0.084% manganese, 0.26% copper, 0.858% boron, 0.288% zinc, and 0.096% iron.

Topdressing was carried out at the R1 phenological stage, with broadcast application of 120 kg ha⁻¹ of potassium chloride (60% K₂O) in the first crop season and 110 kg ha⁻¹ of potassium chloride in the subsequent crop seasons. Insecticide application and topdressing with cobalt (Co) and molybdenum (Mo) were carried out at the R2 phenological stage.

Sowing of grass species and legumes was carried out after the annual harvest of each soybean crop season. In the system with N fertilizer application, N was applied using urea at the rate of 200 kg ha⁻¹ of N, in rainy periods, split into two applications. Grazing was carried out in July and August, and a burndown application with glyphosate at 6.0 L ha⁻¹ was carried out in October for soybean sowing in the subsequent summer crop season.

Determination Of Total Soil C And N Stocks

Sixteen trenches with dimensions of 1.2 m depth, 1.2 m length, and 0.9 m width were open, one in each experimental plot, in the pasture stage in 2017, 2018, and 2019, and during the soybean R5 stage in the 2017–2018, 2018–2019, and 2019–2020 crop seasons. Disturbed soil samples were collected for chemical analysis and undisturbed soil samples were collected, using volumetric rings of 5.0 cm³, for density analysis, in the soil 0–20, 20–40, 40–60, 60–80, and 80–100 cm layers.

The soil samples were air dried, ground, and sieved through a 2.0 mm mesh sieve at room temperature (25–30°C) for analysis of chemical properties. Total carbon (TC) was determined using the method of Mattos et al (2017) adapted by Yeomans and Bremner (1988). Total nitrogen was determined according to Cantarella and Trivelin (2001). Soil density was determined according to the methodology of EMBRAPA (1997). Total carbon stocks (TCS) and total nitrogen stocks (TNS) were calculated based on the equivalent soil weight (Ellert and Bettany 1995), according to the following equation: $TCS/TNS (Mg\ ha^{-1}) = Content\ of\ C(N) \times T \times D$, where *C* or *N* are values in g kg⁻¹, *T* is the layer thickness (cm), and *D* is the soil density (g cm⁻³) in the layer.

Soil Carbon Dioxide (Co) Emissions

Soil CO₂ emissions were recorded using of a portable system (LI-8100; LI-COR, Lincoln, USA), coupled to PVC tubes of 20.0 cm diameter inserted 2.0 cm into the soil surface. Simultaneously, the temperature of the 0–10 cm soil layer was recorded using a portable thermometer, and the soil moisture was determined in the same layer, using the gravimetric method (EMBRAPA 1997).

A PVC pipe was inserted into the soil in each experimental plot and the soil temperature and moisture next to the pipe were measured to evaluate CO₂ emissions. The evaluations were carried out every 15 days from August 2017 to March 2020, between 8:00 and 11:00 hours.

Soil Ammonia (Nh) Volatilization

Ammonia (NH₃) volatilization was evaluated every 15 days during the experiment, from August 2017 to March 2020, using tubular NH₃ PVC collectors of 20.0 cm diameter and 35.0 cm height, which were inserted into a PVC base of 19.0 cm diameter and 10.0 cm height. The bases were fixed at 2.5 cm depth into the soil and protected with a polyethylene plate, with an opening of 2.0 cm between the plate and the collecting base.

Two foam discs of 5.0 cm thickness and 19.5 cm diameter were arranged at 10.0 and 20.0 cm height from the ground inside the PVC structures. They were moistened with 100 mL of phosphoric acid (0.167 mol L⁻¹) to capture volatilized NH₃. The foams were replaced every 15 days; they were collected, placed in plastic bags, and immediately subjected to NH₃ determination, following the method of Cantarella and Trivellin (2001).

Statistical analysis

The results were subjected to analysis of variance and the effects of the treatments were compared by the Tukey's test at 5% probability level, using the statistical software SISVAR (Ferreira 2011). The Pearson's correlation between CO₂ flow and soil moisture and temperature was also carried out. Graphics were made in SigmaPlot, version 10.0 (Systat Software 2006).

Results And Discussion

Total carbon stocks (TCS) were higher in the 0–20 and 20–40 cm soil layers due to the higher organic matter accumulation in these layers (Fig. 3). TCS in the 0–20 cm layer was higher in systems with intercropping (M + G and M + J) in 2017 (Fig. 3a), representing increases of 15.5% and 12.0%, respectively, when compared to the pasture without N fertilizer application (M-N). The high input of residues deposited on the soil resulted in higher incorporation of C and nutrients to the production systems. According to Laroca et al. (2018), the intercropping with cowpea resulted in an increase of 33.6% in TCS, when compared to the system without intercropping. Moraes et al. (2021) also found increase in total soil C and N stocks, mainly under intercropping with pigeon pea, compared to grass species. These results reinforce the importance of a high plant biodiversity to maintain the functioning of soil agronomic and environmental services.

(Fig. 3)

The introduction of soybean in the summer crop season in 2017–2018 did not alter TCS suddenly in the 0–20 and 20–40 cm soil layers (Fig. 3b), when compared to the previous pasture systems. It is shown by the line in each figure, which denotes the TCS at the beginning of experimental evaluations in the 0–20 cm soil layer.

However, after soybean harvesting in 2018, the systems M + N, M + J, M + G, and M-N presented positive results, with relative increases in TCS in the 0–20 cm layer: 65.6%, 53.1%, 47.9%, and 28.7%, respectively (Fig. 3c). The base line shows that TCS exceeded the level found in previous crop cycles. The introduction of N through biological N fixation by using legumes and through residual N left by mineral fertilizer applied to the soybean and used by the pasture contributed to increases in plant and microbiological biomasses and, consequently, to a positive effect on C stocks. The grass species increased total organic C stocks in the soil surface layer, since these species explore more the soil and invest more energy in root development to acquire soil nutrients (Maire et al. 2009).

The system M + J significantly contributed to C input in the 20–40, 40–60, and 60–80 cm soil layers, with 21.5%, 17.3%, and 16.2%, respectively (Fig. 3c). The results showed that this association of grass and legume species favored the cycling of nutrients in the soil profile, reinforcing that the introduction of legume species to production systems increases microbial biomass, nutrient cycling, organic matter contents, and soil production capacity (Morillas et al. 2015). In addition, after establishment in the area, grass species promote a higher transfer of underground C, increasing root development and exploration of the soil profile (Rosset et al. 2014, Sarto et al. 2020b).

M + N resulted in higher TCS in the 0–20, 20–40, 40–60, and 60–80 cm soil layers in the soybean crop grown in the 2018–2019 crop season, after burndown application to the pasture (Fig. 3d). It denotes that the application of mineral N fertilizer to the pasture resulted in higher biomass production and total soil C in the subsequent systems.

All subsequent pasture systems in 2019 showed increases in TCS above the base line of 0–20 cm (Fig. 3e), including M-N. The results denote that TCS improved in the systems over time because of increases in plant biomass accumulation from the soybean crops, intercropped legumes, and grass species, mainly in the soil surface layer. In addition, the grass species used present higher C to N ratio (C/N) and slow decomposition, which gradually promote better TCS results.

In the summer soybean crop season in 2019–2020, TCS was lower in all system and layers (Fig. 3f), which are similar results to those found in 2017–2018 (Fig. 3b) and below the base line. However, climate data of the two previous years showed that the rainfall depths from October to December were satisfactory for microbiological action and, therefore, for decomposition of plant biomass on the soil surface and in surface layers. The rainfall index decreased significantly from December 2019 to November 2020 (Figs. 1 and 2), which hindered organic matter decomposition and increases of C in the systems.

In the 2019–2020 crop season, the system also presented similar TCS in the 0–20, 20–40, and 40–60 cm soil layers, whereas the 60–80 and 80–100 cm layer showed some differences in the systems M + N and M + G (Fig. 3f).

The C dynamics in the soil-atmosphere system can also be evaluated considering soil CO₂ emissions. The CO₂ emission rates were affected by the soil nitrogen (N) managements; the mean CO₂ emissions recorded in the system M-N were 24.2%, 14.7%, and 14.6% lower than those in M + G, M + J, and M + N, respectively, during the soybean crop in 2017–2018 (Fig. 4). In the pasture in 2018, M-N presented CO₂ emission rates 11.6% and 15.9% lower than those of M + N and M + J, respectively (Fig. 4). The addition of mineral and organic N to the soil (M + N) increases CO₂ emissions, as it stimulates the decomposition of plant residues, mainly the most recalcitrant ones (Marques et al. 2000). Considering that residues of soybean crops and intercropped legumes previously grown present low C/N, decomposition begins soon after burndown or harvesting and CO₂ emissions are stimulated. The results found (Fig. 4) corroborate those reported by Wang et al. (2020), who used urea and ammonium nitrate in a clayey soil and found that CO₂ emissions significantly increased due to microbial respiration.

(Fig. 4)

These variations in CO₂ rate can be connected to the amount and type of crop residues on the soil surface. Soybean crops present high amounts of residues from previous plants, in this case, the grass and intercropped legume species. Thus, high CO₂ emissions can occur in both situations, as the maintenance of crop residues on the soil surface significantly affects the C dynamics. Tavares et al (2015) identified higher CO₂ emissions in an area managed under sugarcane crop residues with maintenance of straw for 10 years, considering that this area was converted from managements with pre-harvest burning, when compared to an area that continued subjected to burning of sugarcane residues.

The highest CO₂ losses were found during the soybean development, mainly in the 2017–2018 and 2018–2019 crop seasons (Fig. 4), whereas TCS decreased 7.6% and 9.0% in these crop seasons when compared to those found in the pasture in 2017 and 2018, respectively (Figs. 3b and 3d). However, CO₂ emissions were lower after the last evaluations (pasture in 2019, and soybean in 2019–2020) (Fig. 4), denoting that the system was under the effect of external factors. Thus, the pluviometric data showed decreases in rainfall index and water balance from December 2019 to November 2020 (Figs. 1 and 2), which hindered microbial respiration and organic matter decomposition and increased C contents in the system (Fig. 3e).

Soil management can affect soil C storage and emissions. Moitinho et al (2013) found that the management with no soil preparation, leaving sugarcane crop residues on the surface was responsible for the lowest soil CO₂ loss found (367.23 kg ha⁻¹ of CO₂), differing from those with no soil preparation and no residues (501.75 kg ha⁻¹ of CO₂) and with soil preparation and no residues (534.84 kg ha⁻¹ of CO₂).

CO₂ emissions were not higher than 350 kg ha⁻¹ in any of the systems and periods evaluated (Fig. 4), i.e., they were under no-tillage and with maintenance of residues of previous crops and, thus, the soil microbiology was potentiated, generating conditions for increasing microbial respiration and CO₂ loss, but also C immobilization. The climate conditions affected these processes, but it was considered that, in general, the results found are consistent with those reported by Moitinho et al. (2013).

Most CO₂ produced in the soil is released to the atmosphere, thus, the CO₂ flow (FCO₂) reflects the soil respiration. Soil moisture and temperature are two highly variable environmental factors that affect CO₂ emissions (Griscom et al. 2017).

Simple linear correlation analyses showed significant correlations between FCO₂ and soil moisture in the systems M + N ($r = 0.37$; $p < 0.05$), M-N ($r = 0.36$; $p < 0.05$), and M + G ($r = 0.43$; $p < 0.05$) (Figs. 5a, 5b and 5c). These results are consistent with those found by Wang et al. (2020), who reported positive correlation ($r = 0.66$; $p < 0.05$) between these variables, denoting that soil water content affects the FCO₂ temporal evolution in the rainy season. Soil moisture is a determining factor for the intensity of microbiological activity and, therefore, effectively contributes to the process of CO₂ emissions to the atmosphere (La Scala Jr, Bolonhezi and Pereira 2006). The moistening of a dry soil causes a burst of microbial respiration (Slessarev and Schimel 2020).

(Fig. 5)

Moitinho et al. (2013) also found positive and significant correlation ($r = 0.55$; $p < 0.05$) between these parameters for no-tillage and conventional soil preparation systems. Xavier et al. (2020) found positive correlation between soil moisture and FCO₂, with rainfall events concentrated in a rainy season. However, significant correlation between FCO₂ and soil temperature was not found for any of the systems evaluated ($p > 0.05$), as shown in Figs. 6a, 6b, 6c, and 6d, confirming the results found by Moitinho et al. (2013 and 2015).

(Fig. 6)

Although some studies show positive correlation between these two variables (Wang et al. 2020, Buragiene et al. 2015), Moitinho et al. (2015) reported that commonly no spatial correlation is found between these two parameters, mainly due to the low spatial variability in soil temperature. This parameter affects the intensity of metabolic activity of soil microorganisms, affecting the organic matter cycling and CO₂ emissions (Wang et al. 2020). However, this correlation is not commonly found under tropical conditions, as in the present study.

The maintenance of no-tillage system for long periods provides conditions to avoid variations in FCO₂, affecting it only when the soil moisture varies (Xavier et al. 2020).

Total nitrogen stocks (TNS) were also higher in upper layers (Fig. 7). The systems M + N and M-N in the pasture in 2017 were similar regarding TNS in the 0–20 and 20–40 cm soil layers; however, it was higher

in M + N in the 40–60 and 80–100 cm layers (Fig. 7a). Differences were found between systems in the pastures in 2018 from 40 cm depth onwards (Fig. 7c); the 0–20 cm layer in M + N stood out with an increase of 13.6% in TNS in relation to the base line, denoting the positive effect of mineral fertilizer applications to the pasture in 2017 and 2018 and the input of organic N by soybean biomass residues. This scenario improved in 2019: M + N and M + J, despite statistically equal, increased soil TNS, surpassing the base line. Moreover, M + J stood out with increases in TNS in the 20–40 and 40–60 cm soil layers. Thus, the permanence of these management systems in the area over the years may significantly contribute to increases in TNS in the soil (Fig. 7e).

(Fig. 7)

TNS was 20% higher after the soybean crops (Figs. 7d and 7f) when compared to those found during the pasture system (Figs. 7c and 7e), considering the overall mean of all soil layers. The results denote that the soybean increased N input to the soil, as approximately 17 kg of N per Mg of grains were added to the soil, contributing to the crop rotation (Figs. 7c and 7e). Soybean residues present low C/N, i.e., the plant matter decomposition is fast and provides a high N supplying to the soil. Legume crops can reduce soil N losses (Li et al. 2016) and increase C sequestration due to increases in C inputs by the plant (De Deyn et al. 2011).

The intercropping systems M + J and M + G also increased TNS over time, not only in the surface layers, but also in the 60–80, 80–100 cm (Fig. 7b), and 60–80 cm layers (Fig. 7f). The biological N fixation by these legumes contributed to the increase in N inputs to the soil-plant system. Positive results began to appear 1 year after the implementation of the systems, since the organic N mineralization needs time and satisfactory environmental conditions. Cicek et al. (2014) and Pacheco et al. (2017) found that N was slowly added through residues of forage legumes to a crop livestock integration system.

M-N presented similar TNS to the intercropping systems M + G and M + J and to M + N (Figs. 7b and 7d) after the addition of soybean crops to the systems. It denotes that the strategy of using legume crops in rotation with pasture species results in an important balance of N, which contributes to the development of soil fertility.

N loss by NH_3 volatilization is one of the main factors responsible for low efficiency of N fertilizer applications; in addition, an ammonification process, which also releases NH_3 , occurs during the N mineralization cycle (Wang et al. 2020).

The pasture in M + G in 2017 presented higher volatilization than that in the system M-N (Fig. 8). Therefore, NH_3 volatilization was higher when the system was enriched with legume biomass, as the combination of grass straw and legume crop residues increased the organic matter input and, consequently, the release of amino radical (NH_2) from molecules during the ammonification process.

After adding soybean crops to the production system, NH_3 volatilization rates in the pastures increased in 2018 and 2019, probably due to the activation of soil microbiology and decomposition of residues. The

decomposition process of soybean residues is fast during the initial stage and responsible for approximately 75% of the total decomposition in the first six months (Dong et al. 2019).

In the subsequent soybean crop season (2018–2019), the intercropping system M + G also presented higher NH_3 volatilization rate, and the addition of pigeon pea biomass to that of soybean promotes higher ammonification and volatilization. Moreover, the monitoring carried out in the pasture in 2019 showed an increase in NH_3 volatilization rate, probably due to the time of implementation of the system and increases in biomass on the soil surface. The volatilization intensity was, in general, similar between systems, with only some exceptions. Exceptions were also found in 2019–2020, although with lower volatilization rates (Fig. 8).

A broad analysis on the addition of a fast-decomposing biomass (soybean) in the system from 2018 onwards shows that volatilization tends to increase when evaluated during pasture and to decrease when evaluated during the soybean development in the following system (Fig. 8). This dynamic is connected to C/N of the plant matter added to the system in each crop season.

Despite this natural NH_3 loss, the results denote that N contents were, in general, increased in the system by the mineralization of organic matter from grasses legumes. Moreover, the N volatilization rate in the system M + N tended to decrease over time, denoting that the increased microbiological activity also contributed to a temporary immobilization of N in the soil, decreasing the mineral N availability and, consequently, the possibility of NH_3 volatilization in the system. This strategy improves the soil fertility over time, resulting in sustainability and resilience of production systems in regions with high climate instability.

(Fig. 8)

Conclusion

Crop rotation of legumes with pasture species significantly increases total carbon stocks (TCS) and total nitrogen stocks (TNS) in the soil, mainly up to 40 cm depth, and affects positively the 80–100 cm layer.

The highest CO_2 emissions, found for mombaca grass intercropped with the forage legumes pigeon pea (M + G) and java (M + J) and for mombaca grass with N fertilizer application (M + N), occurred during the period with pastures and after rotation with soybean crops.

The intercropping systems M + G and M + J after rotation with soybean crops resulted in favorable conditions for increases in NH_3 volatilization, whereas M + N tends to decrease NH_3 volatilization.

Soybean rotation with grass-legume intercropping or grass with mineral fertilizer application improved N and C inputs to the agricultural systems, although losses in CO_2 and NH_3 were found.

The soil moisture affected the C and N input-output balance in the production systems evaluated.

Declarations

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Figures

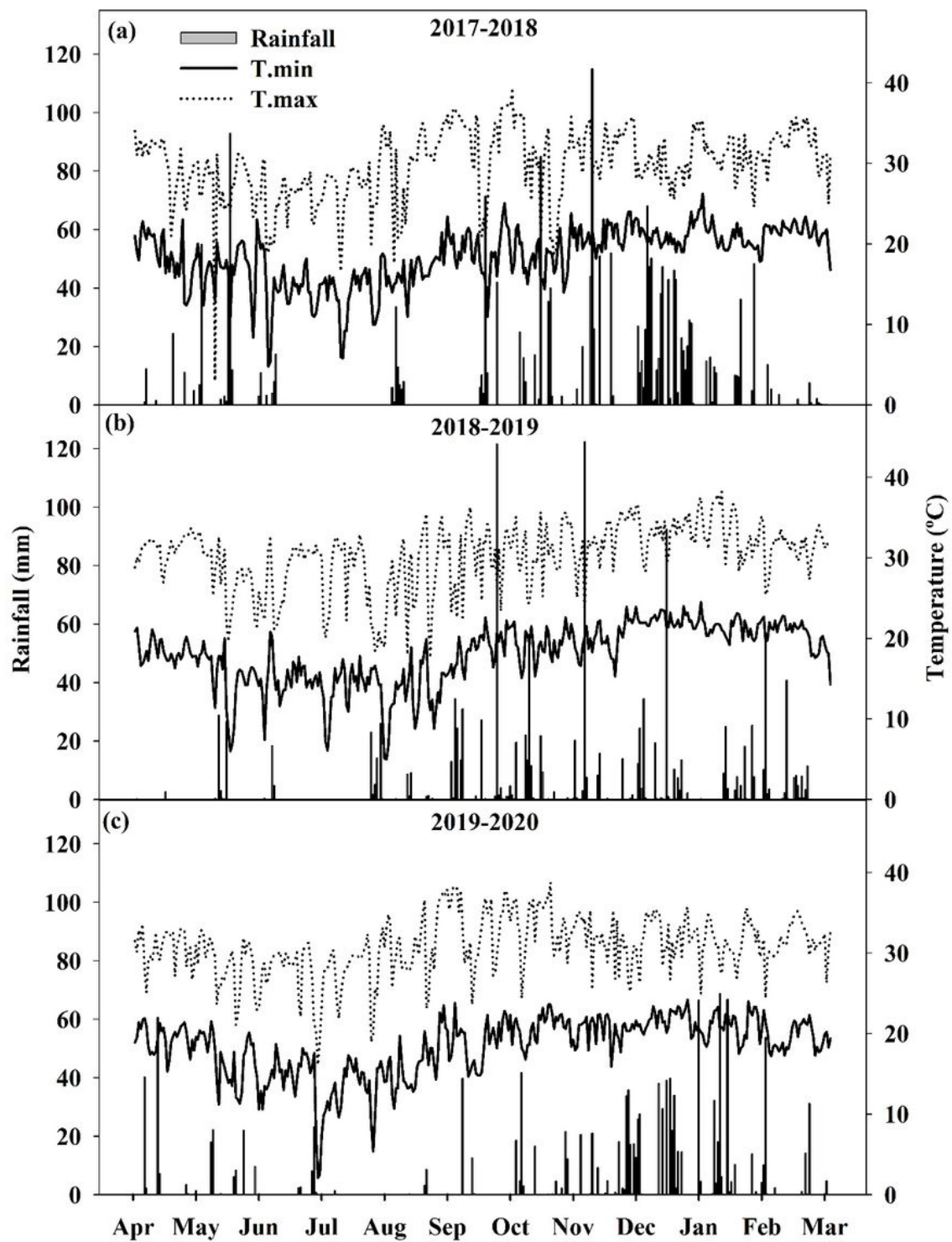


Figure 1

Climate conditions in the Experimental Farm throughout the evaluation periods

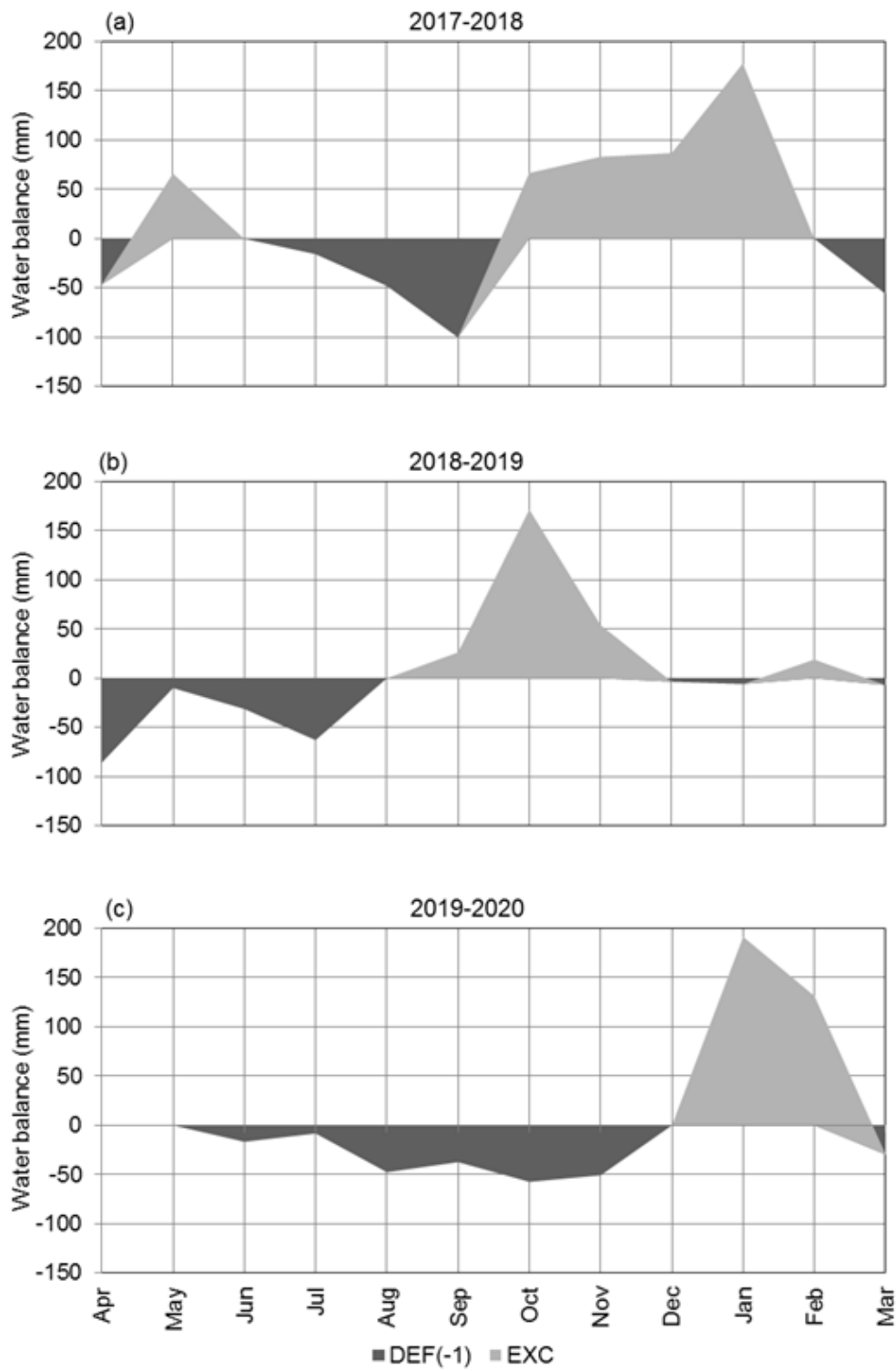


Figure 2

Monthly water balance throughout the evaluation periods

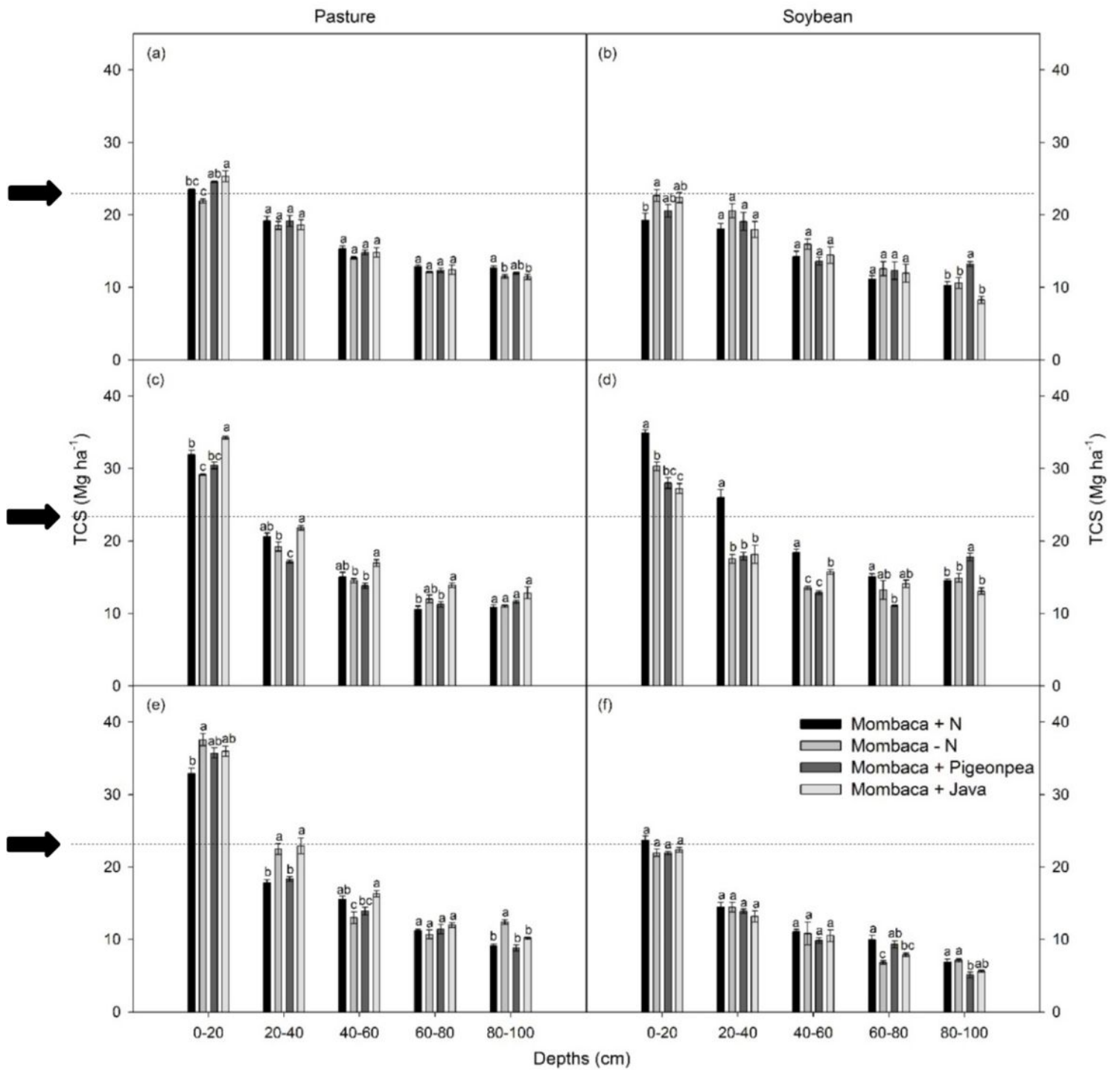


Figure 3

Total carbon stocks (TCS) in the soil during 2017, pasture (a); 2017-2018, soybean (b); 2018, pasture (c); 2018-2019, soybean (d); 2019, pasture (e); and 2019-2020, soybean (f). Means followed by the same letter, comparing systems, are not statistically different from each other by the Tukey's test at 5% probability. Error bars represent the standard deviation

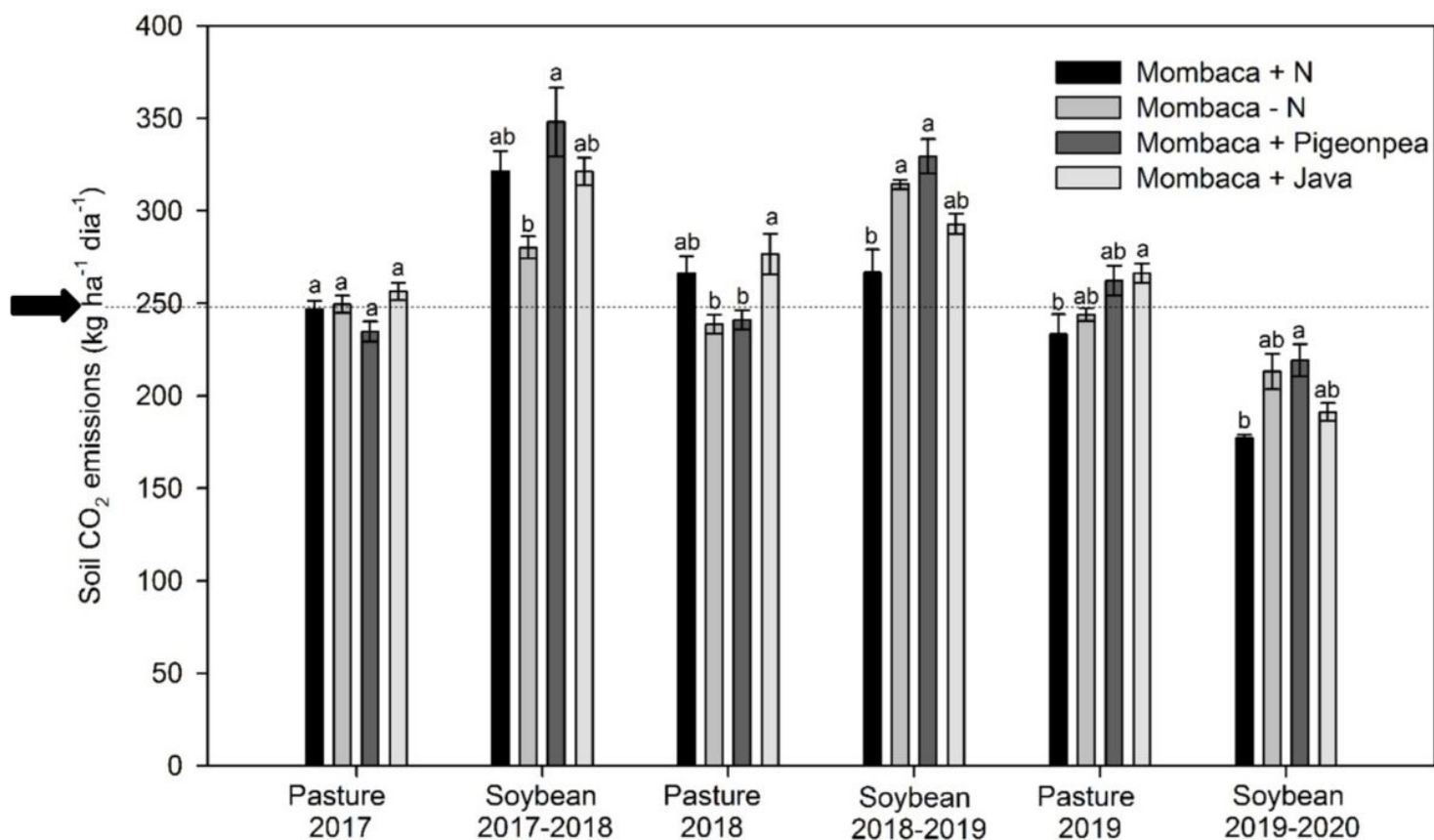


Figure 4

Soil CO₂ emissions during 2017 (pasture), 2017-2018 (soybean), 2018 (pasture), 2018-2019 (soybean), 2019 (pasture), and 2019-2020 (soybean). Means followed by the same letter, comparing systems, are not statistically different from each other by the Tukey's test at 5% probability. Error bars represent the standard deviation

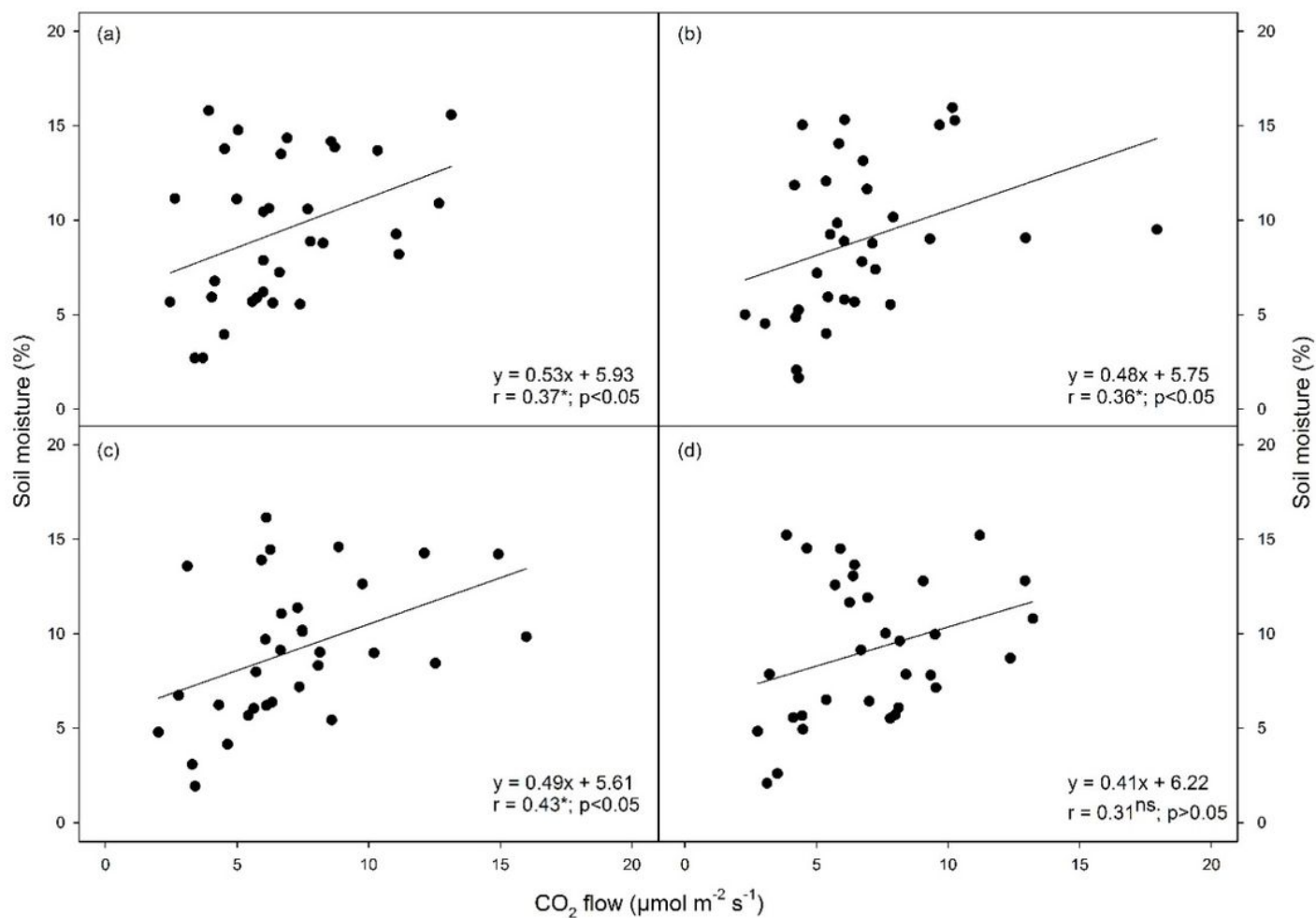


Figure 5

Correlation between CO₂ flow and soil moisture in the systems: Mombaca + N (a); Mombaca - N (b); Mombaca + pigeon pea (c), and Mombaca + java (d). * = significant at 5%; ^{ns} = not significant

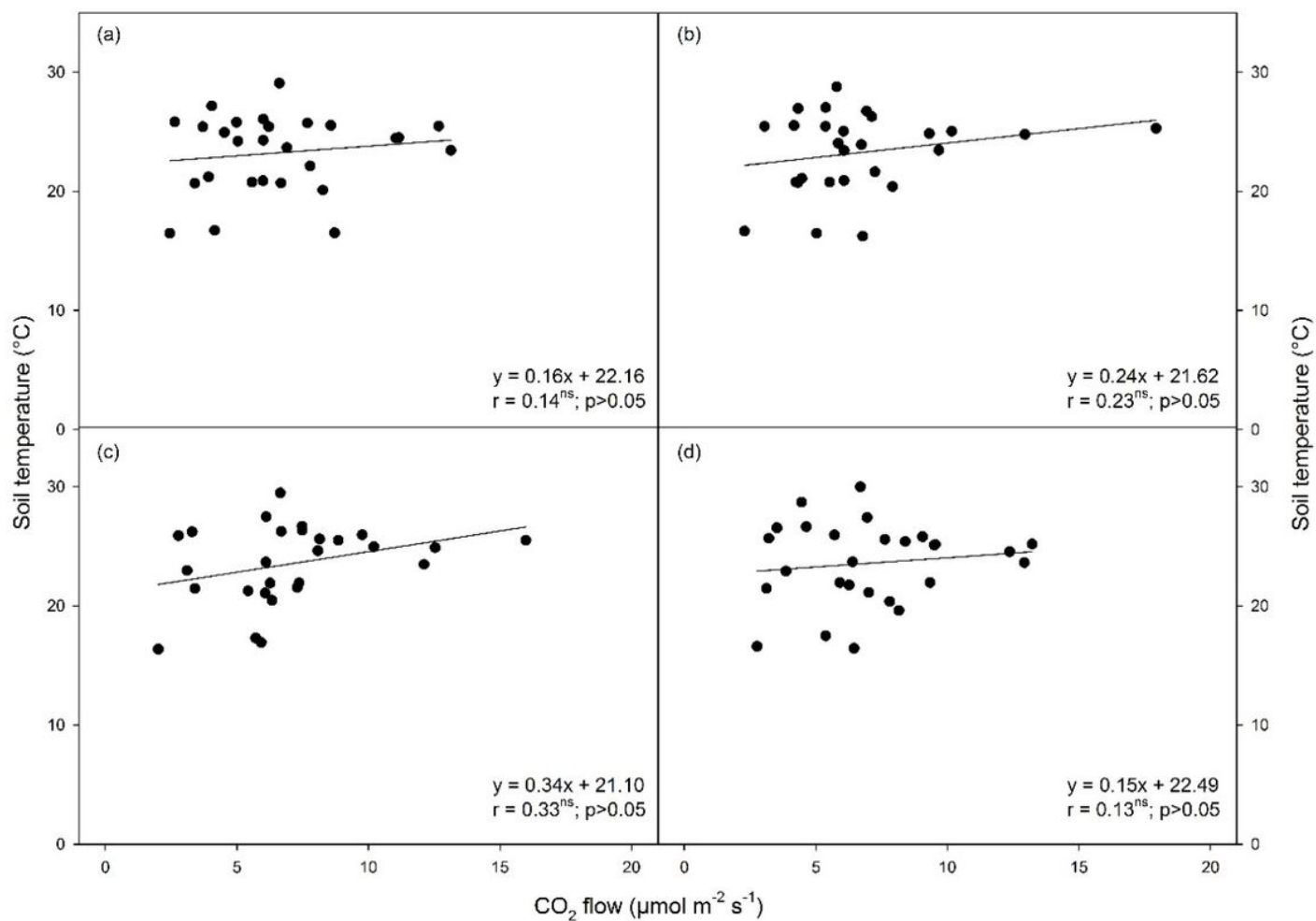


Figure 6

Correlation between CO₂ flow and soil temperature in the systems: Mombaca + N (a); Mombaca - N (b); Mombaca + pigeon pea (c), and Mombaca + java (d). ^{ns} = not significant

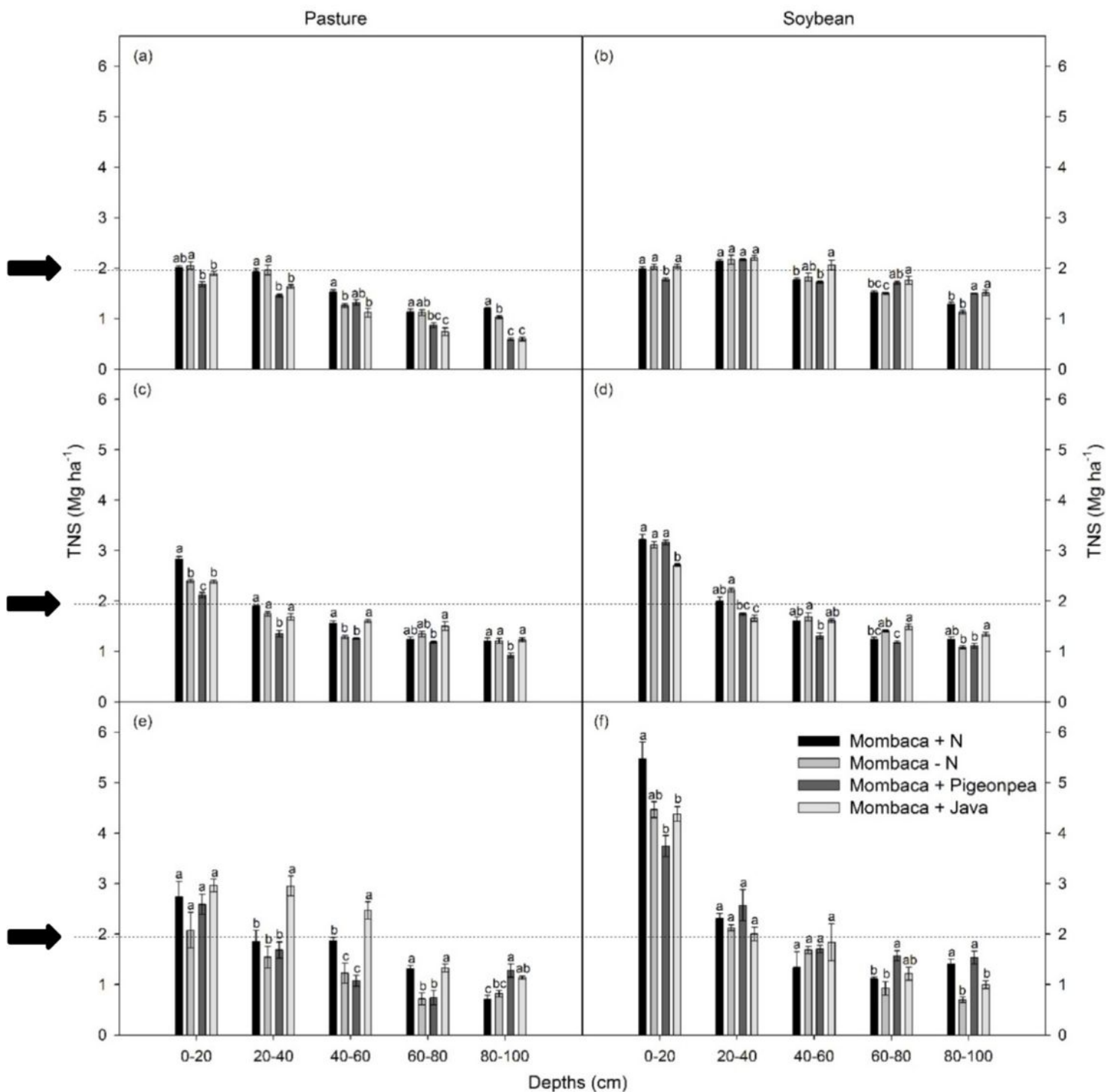


Figure 7

Total nitrogen stocks (TNS) in the soil during 2017, pasture (a); 2017-2018, soybean (b); 2018, pasture (c); 2018-2019, soybean (d); 2019, pasture (e); and 2019-2020, soybean (f). Means followed by the same letter, comparing systems, are not statistically different from each other by the Tukey's test at 5% probability. Error bars represent the standard deviation

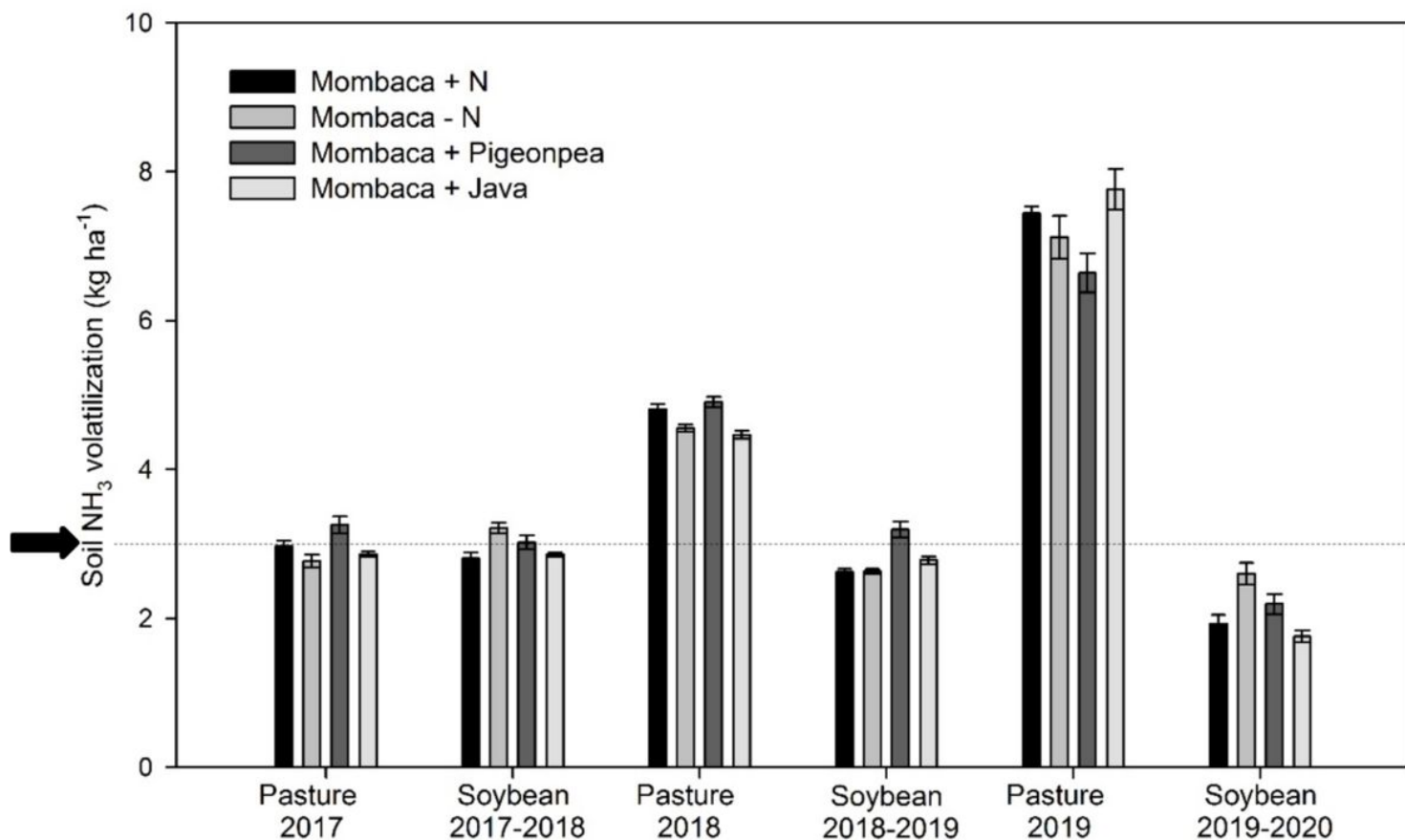


Figure 8

Soil NH₃ volatilization during 2017 (pasture), 2017-2018 (soybean), 2018 (pasture), 2018-2019 (soybean), 2019 (pasture), and 2019-2020 (soybean). Means followed by the same letter, comparing systems, are not statistically different from each other by the Tukey's test at 5% probability. Error bars represent the standard deviation