Refining the Use of Ecosystem Services to Increase Sustainability and Resilience in Tropical Agriculture

Emanoel G. de Moura[1(✉)], Cinthya Sousa Vasconcelos[2], Katia Pereira Coelho[1], Jéssica de Freitas Nunes[1], Edaciano Leandro Losch[1], Layla Gabrielle Silva Oliveira[1], Edesio R. C. Pereira[3], and Alana C. F. Aguiar[4]

[1] Postgraduate Program in Agroecology, Maranhão State University, São Luis, Maranhão 65000-000, Brazil
egmoura@elointernet.com.br
[2] Department of Soil, Federal University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul 90040-060, Brazil
[3] Agroecology in Program, Maranhão State University, São Luís, Maranhão 65000-000, Brazil
[4] Department of Biology, Federal University of Maranhão, São Luís, Maranhão 65080-805, Brazil

Abstract. The humid tropics are highly suitable scenarios for exploiting ecosystem services for the sustainable management of agricultural lands. Accordingly, we hypothesized that the use of ecosystem services modifies the eco-physiological indices and soil organic carbon (SOC) accumulation. Therefore, the present study aimed to assess the eco-physiological indices and the content of SOC fractions by using different quality of leguminous biomass to compare the degree of energy optimisation and the possibility for SOC stabilisation/accumulation. The experiment was established in 2006 and four species of leguminous trees were used as biomass source, such that each plot received residues with different quality from combinations of the two legumes. The following treatments were performed: Leucaena + Clitoria; Leucaena + Gliricidia; Leucaena + Acacia; Gliricidia + Clitoria; Gliricidia + Acacia; and a control without legumes. Our results showed that eco-physiological indices were able to predict soil degradation by indicating whether organic C is accumulating to improve soil quality or whether the soil is being used exploitatively with declining C levels. They also showed that C accumulation in tropical agroecosystems depends on microbial growth favoured by a high-quality substrate. Even when low-quality biomass was used, the particulate fraction:mineral associated fraction ratio was almost always less than one, and recalcitrance seemed less important than microbial activity for C accumulation. In conclusion, tropical soil degradation can be avoided by ecosystem services such as: high-quality biomass production by nitrogen-fixing leguminous trees, efficient food-based web activities and recycled polyvalent cations for the build-up of stabilized organic-to-organic-complexes.

Keywords: Soil organic carbon · Soil Quality · Leguminous Biomass

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Gervasi et al. (Eds.): ICCSA 2023 Workshops, LNCS 14106, pp. 551–563, 2023.
https://doi.org/10.1007/978-3-031-37111-0_38

1 Introduction

Atmospheric carbon dioxide removal and offsetting the unavoidable non-renewable emissions in the global environment may also be a strategy for increasing soil organic carbon (SOC) and ensuring sustainability and climate change resilience on tropical farmlands [1, 2]. Globally, soil organic matter (SOM) contains more carbon (C) than that stored in vegetation and the atmosphere combined, or three times more C than in the atmosphere [3]. Thus, minor changes in the balance between inputs to and outputs from SOC would have a significant impact on atmospheric C and, therefore, soil can serve as a sink or source of C, depending on the strategy adopted for land use [4, 5]. As a result, effective climate change mitigation and agricultural adaptation strategies must be based mainly on processes that promote the stabilisation and accumulation of SOC [6].

Despite the difficulties in generating alternatives to shifting cultivation systems in the humid tropics, there are highly suited opportunities for using ecosystem services for sustainable farmlands management. Due to a combination of long periods of soil moisture with consistent year-round warm weather, the fast growth of nitrogen fixers, leguminous trees, and soil community decomposers can contribute decisively to the production and transformation of biomass in SOC [7]. Since SOC is the most closely correlated attribute to crop productivity and sustainability in tropical agriculture due to its effect on nutrient use efficiency, ecosystem services must be mainly directed towards improving the environment of the root zone [8].

Plant litter is the primary source of all SOM and stabilisation of plant-derived organic matter in soils. Therefore, steering the responses of the cycle of C towards SOC accumulation and climatic change attenuation is the challenge to be overcome for the next decades to achieve sustainability of tropical agriculture [9, 10].

Plant-derived organic matter in soils is primarily stabilised by two mechanisms: the formation of mineral-associated organic carbon (MAOC) and biochemical recalcitrance [11]. The latter is a controversial mechanism referring to complex molecules, such as lignin, which persists longer in the soil than simple molecules like glucose [12]. The first accounts for most of the stabilised SOC and has been increasingly recognised as the consequence of microbial growth and activity and as dependent on the proportion of C substrates used by microbes for their growth instead of being respired [13]. Thus, the efficiency of SOC stabilisation by mineral association will depend on microbial carbon use efficiency or how efficiently plant compounds are turned into microbial products to interact with available cation and soil minerals, increasing MAOC [14, 15].

Beyond the physical-chemical environment and the decomposer microorganism's community, the quality of the substrate is the principal factor that regulates microbial activities in the decomposition process [16]. Thus, since the ability of the substrate to be incorporated into microbial biomass is easier to change, the choice of quality of applied biomass via agroecosystem management has been used to drive the C cycle towards a higher level of stabilised SOC [17]. However, the results of the effect of litter quality on SOC stabilisation are inconsistent [18]. Indeed, if on one side, complex biomass biomolecules will not necessarily persist in the soil, on the other side, rich-N biomolecules are not necessarily decomposed and mineralized. Evidently, the effective management of soils as a C sink needs this uncertainty clarified, as it constrains the understanding of the link between substrate quality, microbial decomposition process,

and the build-up of stabilised SOM and C stocks [20]. The eco-physiological approach in soil microbiology introduced by [21] makes it possible to study this challenging question regarding the activity of the soil microbial community on substrate and SOC storage. The energetic metabolism balance of soil microbial communities has been a possible measurement of the capacity of microbial activities to contribute to storing SOC [22].

According to Odum's theory and extrapolated onto the microbial community, we should expect less community respiration with increasing below-ground species diversity in natural ecosystems [23]. In agricultural systems, where the quality and quantity of heterogeneous resource inputs can be partially controlled, there is an opportunity to increase microbial diversity, accelerating the maturity of the system [8]; this is especially true in the humid tropics, where the high risk of soil degradation can be offset by harnessing the ecosystem services provided by a diversity of efficient aboveground producers of biomass. Thus, the maturity of the system might avoid the detrimental effect of soil use intensification, increasing climate change resilience on tropical farmlands [24]. Accordingly, we hypothesise that the use of ecosystem services for producing different biomass-quality applied in the long-term modify the eco-physiological indices in tropical agricultural systems, and the measurement of these modifications can indicate the way to energy optimisation. Thus, knowing these processes, it would be possible to anticipate whether microbial community activity or service leads to lower or higher SOC content, evidencing the future agroecosystem sustainability degree and resilience status. The present study aimed to assess the eco-physiological indices and the content of SOC fractions of modified alley cropping systems with different quality of leguminous biomass to compare the degree of energy optimisation and the possibility for SOC stabilisation/accumulation.

2 Material and Methods

The experiment was installed in 2002 in the northern Amazonian periphery of Brazil. The region presents equatorial climate, hot and semi-humid with 1500 mm of an average annual precipitation and two well-defined seasons. A rainy season extending from January to June and a dry season with a marked water deficit from July to December. The local soil was classified as arenic hapludults, which consist of 240 g kg^{-1} coarse sand, 560 g kg^{-1} fine sand, 80 g kg^{-1} silt and 120 g kg^{-1} clay. Its chemical characteristics were as follows: pH ($CaCl_2$) 4.3, organic carbon (Walkley–Black) 9.3 g dm^{-3}, P 1.4 mg dm^{-3}, K 0.6 mmolc dm^{-3}, Ca 4.0 mmolc dm^{-3}, Mg 10.0 mmolc dm^{-3}, potential acidity (resin) 26.0 mmolc dm^{-3}, sum of bases 14.6 mmolc dm^{-3}, cation exchange capacity 40.6 mmolc dm^{-3}, base-saturation percentage 36 and bulk density 1.3 g cm^{-3}.

Soil liming was performed twice, once in January 2002 and once in 2007, by applying slaked lime at a rate of 1 Mg ha^{-1} to the surface (corresponding to 279 and 78 kg ha^{-1} Ca and Mg, respectively). In order to increase soil calcium content without change pH natural gypsum was applied in January 2017 at a rate of 6 Mg ha^{-1}, which corresponds to 1.010 kg/ha of Ca. Gypsum was grain size such that 95% by weight passed through a 0.25-mm screen mesh.

It was installed a modified alley cropping system (where trees are pruning and branches and leaves are applied in soil surface) included six treatments with four

replicates in a randomized block design. Four leguminous species were sow, including two that produce higher-quality residue (*Leucaena leucocephala* (Leucaena) and *Gliricidia sepium* (Gliricidia)) and two trees that produce lower-quality residue (*Clitoria fairchildiana* (Clitoria) and *Acacia mangium* (Acacia)) [25, 26]. The experiment was established in 2006 and four species of leguminous trees were used as biomass source, such that each plot received residues with different quality from combinations of the two legumes. The following treatments were performed: Leucaena + Clitoria (L + C); Leucaena + Gliricidia (L + G); Leucaena + Acacia (L + A); Gliricidia + Clitoria (G + C); Gliricidia + Acacia (G + A); and a control with bare soil (BS) and without legumes. In January of each year, maize (*Zea mays* L.) was sown with an inter-row spacing of 90 cm and an inter-plant spacing of 20 cm. Immediately, after planting the maize, the biomass produced from pruning the legumes was distributed homogeneously throughout the plots with the same treatments. The amounts of dry biomass that resulted from the leguminous plant combinations that were applied to the soil between 2008 and 2019 were quantified (Table 1). The plant biomass quality was assessed using the equation of Tian et al. [27] (Table 2).

Table 1. Amounts of the dry biomass of leguminous plants combinations (Mg ha^{-1}) applied to the soil since 2008 up to 2020, in a modified alley cropping system located in the Amazonian periphery of Brazil

Year	*Leucaena* + *Clitoria*	*Leucaena* + *Gliricidia*	*Leucaena* + *Acacia*	*Gliricidia* + *Acacia*	*Gliricidia* + *Clitoria*
2008	16.44	6.59	34.65	28.06	9.85
2009	10.50	10.60	22.60	20.40	9.50
2010	22.00	16.00	39.00	30.00	24.00
2011	11.05	7.48	27.20	22.87	6.72
2012	4.90	6.30	7.50	6.80	4.20
2013	7.80	8.90	12.50	13.20	9.20
2014	8.20	10.30	11.20	13.50	6.30
2015	10.10	8.20	11.20	13.50	10.50
2016	9.30	9.53	11.54	12.82	11.01
2017	9.82	8.90	10.92	13.14	9.54
2018	8.32	9.10	11.34	12.82	10.62
2019	8.92	9.02	12.04	13.06	10.30
Total	163.63	136.28	269.21	254.19	151.42

Table 2. Chemical composition and plant biomass quality index (PBQI) of the combinations of leguminous trees used

Treatments	C/N	Lignin (%)	Polyphenols (%)	PBQI
L + G	10.0	10.5	3.5	11.1
S + G	17.5	10.2	4.3	8.5
S + L	17.2	9.4	4.5	8.2
A + G	19.5	11.2	6.5	7.2
A + L	20.5	11.5	6.5	6.7

2.1 Soil Sampling

Soil sampling was carried out in 2020 to undertake the analyses of Ca, physical fractionation of soil organic matter and to determine the biological indicators of soil quality. The soil samples were collected with a probe-type auger in two dephts: 0–15 and 15–30 cm. A total of three single samples per plot were collected to obtain a composite sample. Part of the samples obtained were separated for biological analysis and kept under refrigeration until use. The other part of the samples was air-dried and passed through a 2 mm sieve before analysis.

2.2 Physical Fractionation of Organic Matter

The physical fractionation of soil organic matter was carried out according to the methodology proposed by Cambardella and Elliot [28]. Air-dried soil samples of 20 g were sieved through 2 mm mesh and weighed in 250 ml polyethylene cups, to which 80 ml of 5 g L^{-1} sodium hexametaphosphate was added. Each mixture was shaken for 15 h in a horizontal shaker, with 130 oscillations min^{-1}. After this process, the entire contents of each vial were placed into a 0.053 mm mesh sieve and washed with a weak jet of distilled water until the clay was completely removed. The material retained on the sieve was defined as total particulate organic matter (>53 μm) and was dried at 50 °C. After drying, each sample was ground in a porcelain mortar, after which an aliquot was collected, weighed and analysed for its C content, representing the soil particulate organic carbon (POC) in particulate organic matter, according to the Walkley-Black method. An aliquot of the 2 mm sieved subsample was ground in a porcelain mortar and weighed and analysed for the analysis of soil total organic carbon (TOC). Soil mineral-associated organic carbon (MAOC) was calculated as the difference between TOC and POC. The total organic carbon stock (TOCS) of each of the 0–15 cm layers was calculated by the following expression [29]:

$$TOCS = (MAOC \times \rho s \times E)/10 \quad (1)$$

where: TOCS = organic C stock at a given depth (Mg ha^{-1}), MAOC = mineral associated organic C content at the sampled depth (g kg^{-1}), ρs = soil bulk density (kg dm^{-3}), and E = thickness of the layer (15 cm).

2.3 Biological Indicators of Soil Quality

Metabolic Quotient (qCO2)
The metabolic quotient (qCO2) was determined by the Microbial Respiration/Microbial Biomass ratio, as proposed by Anderson and Domsch [30]. Soil basal respiration was determined according to the method proposed by Jenkinson and Powlson [31]. The carbon of the microbial biomass was determined by the irradiation-extration method, proposed by Islam and Weil [32] and adaptated by Mendonça and Matos [33]. 20 g of each soil sample were weighed in petri dishes, totaling six petri dishes per soil sample, three of which were submitted to irradiation in an Electrolux microwave oven model MTD30 (2,450 MHz) for three minutes and three remained non-irradiated. Subsequently, the samples were subjected to a rapid extraction, with K_2SO_4 0.5 mol L^{-1}, proceeding sequentially to carbon determination [34, 35]. Soil microbial biomass carbon (SMBC) was calculated by the equation

$$\mathrm{SMBC} = \mathrm{CI} - \mathrm{CNI}/\mathrm{kc} \tag{2}$$

where: SMBC = soil microbial biomass carbon in mg of C per kg of soil (or ug g^{-1}); CI = amount of C (mg kg^{-1}) recovered in the irradiated sample; CNI = amount of C (mg kg^{-1}) recovered in the non-irradiated sample; kc = correction factor that represents the efficiency of the extractor in extracting C from the soil microbial biomass (dimensionless), kc = 0.33 [36].

Microbial Quotient (qMIC)
The microbial quotient (qMIC) is an index used to provide indications on the quality of organic matter. The qMIC is expressed by the ratio between the C of the microbial biomass and the total organic C. To calculate this index, the results of the analyzes already described were used.

2.4 Soil Chemical Properties

Soil Ca was analyzed using an ion exchangeable resin, according to Van Raij and Quaggio [37]. Ca measurements were obtained using a Varian 720-ES ICP Optical Emission Matter Analysis Spectrometer. The accumulations of Ca, in kg ha^{-1}, in the 0–30 cm layer of the soil profile, were calculated according to the equation:

$$\mathrm{SCaA} = \mathrm{SEC} \times \rho s \times \mathrm{E} \times 10 \tag{3}$$

where: SCaA = Soil Ca accumulated in the 0–30 cm layer (kg ha^{-1}); SEC = soil element content (mg kg^{-1}); ρs = soil bulk density (Mg m^{-3}); and E = thickness of the layer (m). In order to obtain the SCaA in the treatments with biomass.

2.5 Statistical Analyzes

The results obtained were submitted to analysis of variance. Subsequently, the Tukey test was applied to compare the effect of the treatments on the dependents variables, at 5% probability. All statistical analyzes were performed using R, version 4.1.0 [38].

3 Results

Both metabolic coefficient (qCO2) and microbial quotient (qMic) were significantly affected by the quality of leguminous biomass applied. However, while qCO_2 was lower in the treatments with gliricidia (G), qMic was higher in those treatments than in other treatments with biomass. As such, in the 0–15 cm layer, qCO_2 was eight times lower in the treatment leucaena (L) with gliricidia (L + G) than in the treatments without G (Fig. 1). Surprisingly, in the treatment without leguminous biomass, qCO2 was lower than in other treatments except for the L + G treatment. In the same way, in the 15–30 cm layer, qCO2 was lower in the treatment with G and much lower in the L + G treatment other treatments with biomass. The higher qCO_2 was found in the treatments (A + L) and (S + L) in the 0–30 cm layer (Fig. 1).

In contrast, qMic was higher in the treatments with G, except for A + L, in the 0–15 cm layer. The qMic was more than twice as high in L + G than in A + L and S + L. In the 15–30 cm layer, qMic was more than twice as high in L + G compared to all the other treatments. Once again, among the treatments with biomass, the lower qMic was in (A + L) and (S + L) in the entire layer of 0–30 cm (Fig. 1).

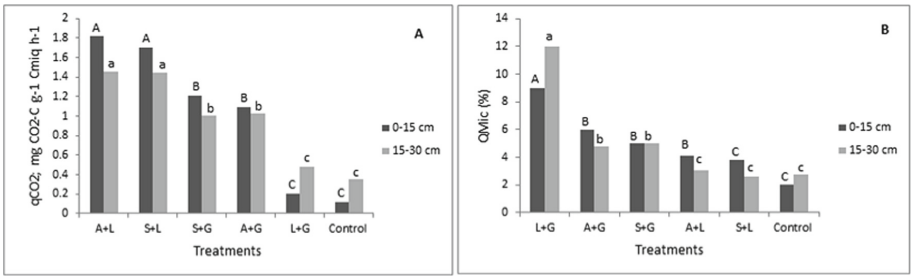


Fig. 1. Metabolic quotient (qCO_2) (A) and microbial quotient (qMic) (B). Columns with the same letters within each parameter do not differ by Tukey's test at 5% probability.

As for carbon-storing, both the SOC fractions were increased by the high-quality G biomass, mainly when combined with L. However, a larger contribution to the increase in TOC was provided by MAOC. Indeed, in the treatment, the L + G MAOC fraction was more than twice as higher as in other treatments in all 0–30 cm layers. Combining acacia (A) with L was less efficient in storing TOC compared to treatments with biomass. Surprisingly, even POC was higher in the L + G treatments than in treatments using lower-quality biomass (Fig. 2).

Total accumulated C in L + G (13,065 t ha-1) was almost the same as {(A + G) + (A + L) + (S + L) (13,787 t ha^{-1})}. According to Johannes [39], the TOC:clay ratio indicated that the soil is structurally degraded in the control area and A + L treatments, structurally median in S + L, good in S + G and A + G, and structurally very good in L + G. The Ca content was higher in the treatments with biomass than in the control area in the 0–30 cm layer. In L + G, it was higher than in the other plots with biomass and 31% higher than in the control area. Therefore, the Ca accumulated in L + G was 44% higher than in A + L (Table 3).

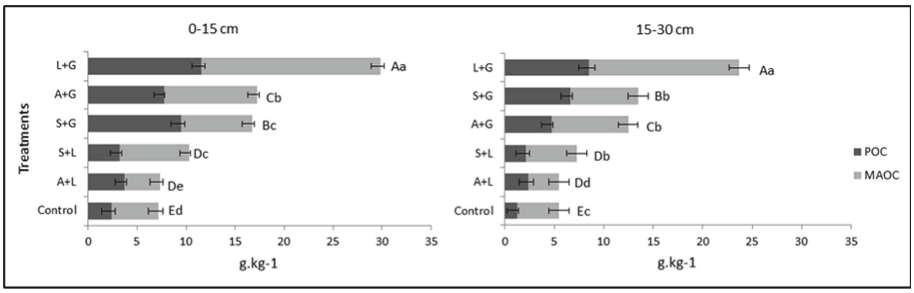


Fig. 2. Particulate organic carbon (POC) and mineral associated organic carbon (MAOC). Columns with the same letters (uppercase for POC and lowercase for MAOC) within each parameter do not differ by Tukey's test at 5% probability.

Table 3. Means of calcium contents, soil accumulated calcium (SACa), soil accumulated carbon (SAC), clay:TOC ratio and POC:MAOC ratio.

Treatments	Ca ($mmol_c\ dcm^{-3}$)		SACa ($t\ ha^{-1}$)	SAC ($t\ ha^{-1}$)	Clay:TOC	POC:MAOC	
	0–15 cm	15–30 cm	0–30 cm	0–30 cm	0–30 cm	0–15 cm	15–30 cm
L + G	61.5 a	59.5 a	1.77	13,065	1:5	0.6	0.6
S + G	58.9 b	56.3 b	1.42	5,470	1:8	1.3	1.0
S + L	59.8 b	55.1 b	1.40	4,778	1:12	0.8	1.0
A + G	58.1 b	57.4 b	1.38	6,717	1:8	0.8	0.6
A + L	56.8 b	55.2 b	1.23	3,539	1:18	0.5	0.3
Control	47.0 c	44.5 c	-	2,603	1:19	0.7	0.3

TOC – total organic carbon; POC – particulate organic carbon; MAOC- mineral-associated organic carbon.

4 Discussion

The variation in PBQI (from 6.7 in A + L, up to 11 in L + G) decisively affected the eco-physiological indices, the C utilization/accumulation and, consequently, the soil structure classification. According to Cotrufo [40], in a high-quality microbial substrate, as in the plots of L + G, some molecules can readily diffuse across the membrane, producing an additional resource for microbial growth. Therefore, the microbial anabolism:catabolism ratio is high, leading to more C production, which can be stabilised if polyvalent cations are available [41, 42]. The results of qCO2 in Fig. 1 showed that using low-quality biomass may not lead to higher C accumulated due to less energy optimisation of the microbial community under conditions of fast turnover, contrary to what common sense might suggest. Indeed, in a low-quality substrate or one rich in lignin and cellulose, as in A + L, the demand for resources is high, and the catabolism:metabolism ratio is low.

Thus, litter microbial biomass may be relatively low and fewer microbial residues are produced per amount of plant litter metabolised [43]. In addition, greater competition for few available C may favour bacteria-based food webs, which are less efficient in C assimilation than the more efficient fungal-based food webs [44].

Coherently with qCO2 results, the qMic increased when high-quality biomass was used. This quotient increases if organic carbon (C) accumulates in the soil and declines if the soil is used exploitatively [45]. Therefore, qMic was proposed by Powlson and Jenkinson [46] as a sensitive index of soil changes since microbial biomass responds more rapidly to soil changes than organic matter. This means that in the plots S + L, where the soil is in a structurally median stage, a degradation process could be ongoing and was primarily detected by microbial activities before degradation achieved the stage of A + L. In conclusion, both qCO_2 and qMic parameters showed to be potential tools for studying tropical agroecosystem performance forecasts, soil management effects, and sustainable alternatives for shifting cultivation. However, the values of these parameters in the control area suggest that they should be used together and never alone; otherwise, the small values of qCO_2 in the control area would tend to be interpreted as a positive soil attribute.

As expected, lower qCO_2 and higher qMic in treatments with G were followed by higher TOC contents, such as in the surface layer L + G, with PBQI equal to 11.1, where TOC was four times higher than in A + L with PBQI equal to 6.7 (29.9 g Kg^{-1} to 7.3 g Kg^{-1}). Although some authors like Witzgall et al. [47] and Lavallee et al. [48] have highlighted the essentiality of labile fractions for soil management for structurally fragile tropical soils as in this experiment, stabilised SOM fraction has been considered as the correlated closest attribute to soil rootability and maize productivity[8, 47]. The small values of the POC:MAOC ratio, almost always smaller than one even when low-quality of biomass was used, suggest that recalcitrance has had little importance for C accumulation in humid tropical conditions. This confirms the key role of ecosystem services provided by microorganisms, not just as promoters of C release to the atmosphere but also as promoters of SOC stocks through stabilising C into a not easily decomposed form [47]. The amount of C accumulated in L + G (13,065 t ha^{-1}) accredits this treatment as a C sink.

Recent studies [49, 50] have highlighted that the mechanisms through which SOC can be biologically stabilised depend on the capacity of the biomass added to increase the microbial necromass, which interacts with available polyvalent cations by incrustation and formation of organo-mineral complexes [42, 51]. In the present experiment, the low clay content of the soil and highly favourable climate conditions for biomass decomposition could also have harmed POC physic-chemical permanence or its intra-aggregates occlusion.

The higher Ca content in the treatments with G strengthens the hypothesis that interactions between microbial C and Ca are more important for maintaining Ca in the root zone than the recycling process [8, 42]. On the other hand, it is also clear that Ca availability is essential to take advantage of the increase in microbial C to construct adequate levels of MAOC [51]. Beyond avoiding Ca loss by leaching, Ca X SOC interactions contribute to the structural quality of soil, increasing MAOC. Thus, in L + G plots, the TOC:clay ratio was 1:5, very higher than the threshold of 1:8 established

by [39] for the optimal value of organic C for very good soil structure. Meanwhile, it was 1:18 in A + L TOC: clay ratio when the threshold for structurally degraded soil was 1:13.

5 Conclusion

Eco-physiological indices were able to predict soil degradation by indicating whether organic C is accumulating to improve soil quality or whether the soil is being used exploitatively with declining C levels. Our results also showed that C accumulation in tropical agroecosystems depends on microbial growth favoured by a high-quality substrate. Even when low-quality biomass was used, the particulate fraction:mineral associated fraction ratio was almost always less than one, and recalcitrance seemed less important than microbial activity for C accumulation in these circumstances. In conclusion, tropical soil degradation can be avoided by ecosystem services such as: high-quality biomass production by nitrogen-fixing leguminous trees, efficient food-based web activities to increase microbial biomass, and recycled polyvalent cations for the build-up of stabilized organic-to-organic-complexes.

Acknowledgments. This research was funded by "NUCLEUS, a virtual joint center to deliver enhanced N-use efficiency via an integrated soil–plant systems approach for the United Kingdom and Brazil", grant number: FAPESP - São Paulo Research Foundation [grant number 2015/50305-8]; FAPEG – Goiás Research Foundation [grant number 2015-10267001479]; and FAPEMA - Maranhão Research Foundation [grant number RCUK-02771/16]; and in the United Kingdom by the Biotechnology and Biological Sciences Research Council [grant number BB/N013201/1] under the Newton Fund scheme. The authors thanks the National Council for Scientific and Technological Development (CNPq), Maranhão Scientific and Technological Research and Development Support Foundation (FAPEMA) and the Coordination for the Improvement of Higher Education Personnel (CAPES).

References

1. Aich, A., Dey, D., Roy, A.: Climate change resilient agricultural practices: a learning experience from indigenous communities over India. PLOS Sustain. Transformation **1**, e0000022 (2022). https://doi.org/10.1371/journal.pstr.0000022
2. Rogelj, J., Geden, O., Cowie, A., Reisinger, A.: Net-zero emissions targets are vague: three ways to fix. Nature **591**, 365–368 (2021). https://doi.org/10.1038/d41586-021-00662-3
3. Georgiou, K., et al.: Global stocks and capacity of mineral-associated soil organic carbon. Nat Commun. **13**, 3797 (2022). https://doi.org/10.1038/s41467-022-31540-9
4. Dignac, M.-F., et al.: Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agron. Sustain. Dev. **37**(2), 1–27 (2017). https://doi.org/10.1007/s13593-017-0421-2
5. Liang, C., Schimel, J.P., Jastrow, J.D.: The importance of anabolism in microbial control over soil carbon storage. Nat. Microbiol. **2**, 1–6 (2017). https://doi.org/10.1038/nmicrobiol.2017.105
6. Castellano, M.J., Mueller, K.E., Olk, D.C., Sawyer, J.E., Six, J.: Integrating plant litter quality, soil organic matter stabilization, and the carbon saturation concept. Glob. Change Biol. **21**, 3200–3209 (2015). https://doi.org/10.1111/gcb.12982

7. Berenguer, E., et al.: Tree growth and stem carbon accumulation in human-modified Amazonian forests following drought and fire. Philos. Trans. R. Soc. B Biol. Sci. **373**, 20170308 (2018). https://doi.org/10.1098/rstb.2017.0308
8. Sena, V.G.L., et al.: Ecosystem services for intensification of agriculture, with emphasis on increased nitrogen ecological use efficiency. Ecosphere **11**, e03028 (2020). https://doi.org/10.1002/ecs2.3028
9. Lal, R.: Reducing carbon footprints of agriculture and food systems. Carbon Footprints **1**(3) (2022). https://doi.org/10.20517/cf.2022.05
10. Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P.: Climate-smart soils. Nature **532**, 49–57 (2016). https://doi.org/10.1038/nature17174
11. Mirabito, A.J., Chambers, L.G.: Quantifying mineral-associated organic matter in wetlands as an indicator of the degree of soil carbon protection. Geoderma **430**, 116327 (2023). https://doi.org/10.1016/j.geoderma.2023.116327
12. Lützow, M.V., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H.: Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. Eur. J. Soil Sci. **57**, 426–445 (2006). https://doi.org/10.1111/j.1365-2389.2006.00809.x
13. Buckeridge, K.M., et al.: Sticky dead microbes: Rapid abiotic retention of microbial necromass in soil. Soil Biol. Biochem. **149**, 107929 (2020). https://doi.org/10.1016/j.soilbio.2020.107929
14. Bradford, M.A., Keiser, A.D., Davies, C.A., Mersmann, C.A., Strickland, M.S.: Empirical evidence that soil carbon formation from plant inputs is positively related to microbial growth. Biogeochemistry **113**, 271–281 (2013). https://doi.org/10.1007/s10533-012-9822-0
15. Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., Paul, E.: The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob. Change Biol. **19**, 988–995 (2013). https://doi.org/10.1111/gcb.12113
16. Angst, G., Mueller, K.E., Nierop, K.G.J., Simpson, M.J.: Plant-or microbial-derived? A review on the molecular composition of stabilized soil organic matter. Soil Biol. Biochem. **156**, 108189 (2021). https://doi.org/10.1016/j.soilbio.2021.108189
17. Moinet, G.Y.K., Hijbeek, R., van Vuuren, D.P., Giller, K.E.: Carbon for soils, not soils for carbon. Glob. Change Biol. **29**, 2384–2398 (2023). https://doi.org/10.1111/gcb.16570
18. Córdova, S.C., Olk, D.C., Dietzel, R.N., Mueller, K.E., Archontouilis, S.V., Castellano, M.J.: Plant litter quality affects the accumulation rate, composition, and stability of mineral-associated soil organic matter. Soil Biol. Biochem. **125**, 115–124 (2018). https://doi.org/10.1016/j.soilbio.2018.07.010
19. Li, Y., et al.: Ammoniated straw incorporation increases wheat yield, yield stability, soil organic carbon and soil total nitrogen content. Field Crop Res. **284**, 108558 (2022). https://doi.org/10.1016/j.fcr.2022.108558
20. Cotrufo, M.F., Lavallee, J.M.: Chapter one - soil organic matter formation, persistence, and functioning: a synthesis of current understanding to inform its conservation and regeneration. Em: Sparks, D.L. (org.) Advances in Agronomy, pp. 1–66. Academic Press (2022)
21. Anderson, J.P.E., Domsch, K.H.: A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biol. Biochem. **10**, 215–221 (1978). https://doi.org/10.1016/0038-0717(78)90099-8
22. Anthony, M.A., Crowther, T.W., Maynard, D.S., van den Hoogen, J., Averill, C.: Distinct assembly processes and microbial communities constrain soil organic carbon formation. One Earth **2**, 349–360 (2020). https://doi.org/10.1016/j.oneear.2020.03.006
23. Odum, E.P.: The strategy of ecosystem development. Science **164**, 262–270 (1969). https://doi.org/10.1126/science.164.3877.262

24. Sainge, M.N., Nchu, F., Townsend Peterson, A.: Diversity, above-ground biomass, and vegetation patterns in a tropical dry forest in Kimbi-Fungom National Park. Cameroon. Heliyon. **6**, e03290 (2020). https://doi.org/10.1016/j.heliyon.2020.e03290
25. das Chagas Ferreira Aguiar, A., Bicudo, S.J., Costa Sobrinho, J.R.S., Martins, A.L.S., Coelho, K.P., de Moura, E.G.: Nutrient recycling and physical indicators of an alley cropping system in a sandy loam soil in the pre-Amazon region of Brazil. Nutr. Cycl. Agroecosyst. **86**, 189–198 (2010). https://doi.org/10.1007/s10705-009-9283-6
26. Vanlauwe, B., Sanginga, N., Merckx, R.: Decomposition of four Leucaena and Senna prunings in alley cropping systems under sub-humid tropical conditions: the process and its modifiers. Soil Biol. Biochem. **29**, 131–137 (1997). https://doi.org/10.1016/S0038-0717(96)00301-X
27. Tian, G., Brussaard, L., Kang, B.T.: An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics. Appl. Soil. Ecol. **2**, 25–32 (1995). https://doi.org/10.1016/0929-1393(94)00033-4
28. Cambardella, C.A., Elliott, E.T.: Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. **56**, 777–783 (1992). https://doi.org/10.2136/sssaj1992.03615995005600030017x
29. Veldkamp, E.: Organic carbon turnover in three tropical soils under pasture after deforestation. Soil Sci. Soc. Am. J. **58**, 175–180 (1994). https://doi.org/10.2136/sssaj1994.03615995005800010025x
30. Anderson, T.-H., Domsch, K.H.: The metabolic quotient for CO2 (qCO2) as a specific activity parameter to assess the effects of environmental conditions, such as ph, on the microbial biomass of forest soils. Soil Biol. Biochem. **25**, 393–395 (1993). https://doi.org/10.1016/0038-0717(93)90140-7
31. Jenkinson, D.S., Powlson, D.S.: The effects of biocidal treatments on metabolism in soil—V: a method for measuring soil biomass. Soil Biol. Biochem. **8**, 209–213 (1976). https://doi.org/10.1016/0038-0717(76)90005-5
32. Islam, K.R., Weil, R.R.: Microwave irradiation of soil for routine measurement of microbial biomass carbon. Biol. Fertil. Soils **27**, 408–416 (1998). https://doi.org/10.1007/s003740050451
33. Mendonça, E., Matos, E.: Matéria Orgânica do Solo: Métodos de Análises (2017)
34. Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S.: Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol. Biochem. **17**, 837–842 (1985). https://doi.org/10.1016/0038-0717(85)90144-0
35. Vance, E.D., Brookes, P.C., Jenkinson, D.S.: An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. **19**, 703–707 (1987). https://doi.org/10.1016/0038-0717(87)90052-6
36. Sparling, G.P., West, A.W.: A direct extraction method to estimate soil microbial C: calibration in situ using microbial respiration and 14C labelled cells. Soil Biol. Biochem. **20**, 337–343 (1988). https://doi.org/10.1016/0038-0717(88)90014-4
37. van Raij, B., Quaggio, J.A., da Silva, N.M.: Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion-exchange resin procedure. Communications in soil science and plant analysis (USA) (1986)
38. R Core Team: R A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. - References - Scientific Research Publishing (2021). https://www.scirp.org/(S(czeh2tfqw2orz553k1w0r45))/reference/referencespapers.aspx?referenceid=3131254
39. Johannes, A., Matter, A., Schulin, R., Weisskopf, P., Baveye, P.C., Boivin, P.: Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? Geoderma **302**, 14–21 (2017). https://doi.org/10.1016/j.geoderma.2017.04.021

40. Cotrufo, M.F.: Recalcitrance: an inherent relative attribute of plant litter describing its potential decomposability. Apresentado em 2014 AGU Fall Meeting dezembro 16 (2014)
41. Ellerbrock, R.H., Gerke, H.H.: Explaining soil organic matter composition based on associations between OM and polyvalent cations. J. Plant Nutr. Soil Sci. **181**, 721–736 (2018). https://doi.org/10.1002/jpln.201800093
42. Rowley, M.C., Grand, S., Verrecchia, É.P.: Calcium-mediated stabilisation of soil organic carbon. Biogeochemistry **137**(1–2), 27–49 (2017). https://doi.org/10.1007/s10533-017-0410-1
43. Allison, S.D.: Modeling adaptation of carbon use efficiency in microbial communities. Front. Microbiol. **5**, 571 (2014)
44. Hendrix, P.F., Parmelee, R.W., Crossley, D.A., Coleman, D.C., Odum, E.P., Groffman, P.M.: Detritus food webs in conventional and no-tillage agroecosystems. Bioscience **36**, 374–380 (1986). https://doi.org/10.2307/1310259
45. Boni, T.S., Pereira, E.I.P., Santos, A.A., Cassiolato, A.M.R., Maltoni, K.L.: Biomass residues improve soil chemical and biological properties reestablishing native species in an exposed subsoil in Brazilian Cerrado. PLoS ONE **17**, e0270215 (2022). https://doi.org/10.1371/journal.pone.0270215
46. Powlson, D.S., Jenkinson, D.S.: A comparison of the organic matter, biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct-drilled soils. J. Agric. Sci. **97**, 713–721 (1981). https://doi.org/10.1017/s0021859600037084
47. Witzgall, K., et al.: Particulate organic matter as a functional soil component for persistent soil organic carbon. Nat Commun. **12**, 4115 (2021). https://doi.org/10.1038/s41467-021-24192-8
48. Lavallee, J.M., Soong, J.L., Cotrufo, M.F.: Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. Glob. Change Biol. **26**, 261–273 (2020). https://doi.org/10.1111/gcb.14859
49. Liang, B.C., et al.: Revisiting no-till's impact on soil organic carbon storage in Canada. Soil Tillage Res. **198**, 104529 (2020). https://doi.org/10.1016/j.still.2019.104529
50. Högberg, M.N., Skyllberg, U., Högberg, P., Knicker, H.: Does ectomycorrhiza have a universal key role in the formation of soil organic matter in boreal forests? Soil Biol. Biochem. **140**, 107635 (2020). https://doi.org/10.1016/j.soilbio.2019.107635
51. Wan, D., et al.: Effects of long-term fertilization on calcium-associated soil organic carbon: Implications for C sequestration in agricultural soils. Sci. Total Environ. **772**, 145037 (2021). https://doi.org/10.1016/j.scitotenv.2021.145037