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Basal soil respiration in land use and cover systems in a caatinga enclaves moist forest

Respiração basal edáfica em sistemas de uso e cobertura da terra em um Brejo de Altitude

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Highlights

Different forms of land use and management interfere with soil respiration.
CO_2 emissions are higher at night than during the day.
Soil temperature and moisture influence the carbon dynamics and cycle.
Systems with greater human intervention release more CO_2 into the atmosphere.
Natural vegetation areas function as CO_2 receptors and wells.

Abstract

Deforestation and the disorderly exploitation of natural resources for agricultural expansion occurred at an accelerated pace in the Brejo microregion of the state of Paraíba, Brazil, which resulted in abandonment and erosion of the soil in a large part of the region. In view of this scenario, the present study was undertaken to investigate the soil respiration in systems involving different forms of land use and cover in *caatinga* enclaves moist forests (*Brejo de Altitude* areas). The study was conducted in four land use and cover systems, namely, pasture, mandala agriculture, agroforestry system, and forest. Microbial activity was estimated by quantifying the carbon dioxide (CO_2) released in the soil respiration process, from the soil surface, and captured by KOH solution. Soil temperature (°C) and water content (%) were monitored simultaneously with the analysis of soil respiration. The forms of land use and cover have a direct effect on the metabolic activity of soil organisms, and climatic factors such as soil temperature and moisture influence the dynamics of organic matter decomposition and, consequently, the release of CO_2. The production of CO_2 is higher at night than during the day, regardless of the analyzed systems. Among the evaluated areas, the forest showed the lowest CO_2 emissions, so it was considered a CO_2 receptor in contrast to the pasture area, which functioned as a CO_2 emitter. Management techniques that reduce surface temperature and increase organic matter should be prioritized to promote soil biota.

Key words: Bioindicator. Carbon. Climate changes. Management. Soil organisms. Temperature.

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Resumo

O desmatamento e a exploração desordenada dos recursos naturais visando à expansão agropecuária aconteceram de forma acelerada na Microrregião do Brejo do Estado da Paraíba, o que resultou no desgaste e abandono do solo em grande parte da região. Diante desse contexto, objetivou-se avaliar a respiração edáfica em sistemas sob diferentes formas de uso e cobertura da terra em áreas de Brejo de Altitude. O estudo foi conduzido em quatro sistemas de uso e cobertura da terra, sendo eles: pastagem, mandala agrícola, sistema agroflorestal (SAF) e floresta. A atividade microbiana foi estimada pela quantificação do dióxido de carbono (CO_2) desprendido no processo de respiração edáfica, a partir da superfície do solo, e capturado por solução de KOH. Simultaneamente à análise da respiração edáfica, foram monitorados a temperatura (°C) e o conteúdo de água do solo (%). As formas de uso e cobertura da terra têm efeito direto sobre a atividade metabólica dos organismos edáficos e os fatores climáticos, a exemplo da temperatura e umidade do solo, influenciam na dinâmica de decomposição da matéria orgânica e, consequentemente, na liberação de CO_2. A produção de CO_2 é maior no período noturno em relação ao diurno, independente dos sistemas analisados. Dentre as áreas avaliadas, a floresta foi a que apresentou menores emissões de CO_2, sendo considerada, portanto, como um receptor de CO_2 em contraposição a área de pastagem que funcionou como um emissor de CO_2. Técnicas de manejo que reduzem a temperatura superficial e aumenta o teor de matéria orgânica devem ser priorizadas para a promoção da biota do solo.
Palavras-chave: Bioindicador. Carbono. Manejo. Mudanças climáticas. Organismos edáficos. Temperatura.

The concentration of greenhouse gases (GHG) in the atmosphere has increased significantly since the beginning of the industrial revolution. This increase has been associated mainly with anthropogenic emissions, particularly those related to the change in land use (Pais et al., 2020). Among the GHGs, CO_2 is the most produced by man, and the conversion of natural vegetation areas for agricultural expansion has caused alterations that directly affect the carbon dynamics and cycle, leading to profound environmental and climatic changes (Simon et al., 2019). Because agricultural systems are particularly vulnerable to climate change, attempts to achieve higher crop yields through a more efficient use of resources while minimizing environmental impacts have become urgent and necessary (Pais et al., 2020).

The increasing soil degradation has promoted the adoption of agricultural management techniques that combine agricultural production with conservation of the soil environment (J. H. C. S. Silva et al., 2021). In this respect, systems that integrate natural vegetation and ecosystems transformed by humans are efficient for the production of goods and services, besides acting as a potential carbon sink for the atmosphere by storing a greater amount of carbon in the soil (Nogueira et al., 2020). These systems that integrate different components ensure the recovery of degraded areas and the of potentiation land use. Therefore, they have become increasingly frequent, warranting technical-scientific knowledge to ensure their socio-economic and environmental viability (Stieven et al., 2020).

There is a dearth of research in the mesoregion of Agreste da Paraíba on the selection of indicators of chemical, physical, and biological changes in the soil in areas under different forms of use and cover, with soil under natural vegetation being adopted as a reference. Nonetheless, studies of this nature are important, as they provide relevant information about the quality of the soil environment and the sustainability of organic farming systems (G. F. da Silva et al., 2015). From this perspective, soil respiration, i.e., the biological oxidation of organic matter to CO_2 by microorganisms, occupies a crucial position in the carbon cycle in terrestrial ecosystems and is one of the most used parameters to quantify microbiological activity in the soil. Additionally, it may be used as a bioindicator of changes in soil carbon dynamics in areas whose cover has undergone changes (Valentini et al., 2015).

The *caatinga* enclaves moist forests (*Brejos de Altitude*) of northeastern Brazil are areas that exhibit distinct microclimates relative to their climatic region of insertion the semi-arid, which renders this region an area of great faunal and floristic biodiversity (Barbosa et al., 2004). However, in the Brejo microregion of the state of Paraíba, the disorderly exploitation of natural resources and deforestation for agricultural expansion occurred at an accelerated pace, which resulted in abandonment and erosion of the soil in a large part of the region. In view of this scenario, the present study was developed to evaluate the soil respiration in systems under different forms of land use and cover in *caatinga* enclaves moist forests.

The study was carried out in four land occupation systems located at the Center for Human, Social, and Agrarian Sciences at the Federal University of Paraíba (UFPB), Campus III, in Bananeiras - PB, Brazil. The municipality of Bananeiras occupies a territory of 258 km² and is located in the Agreste mesoregion (more specifically, in the Brejo microregion), at an altitude of approximately 526 m. The climate of the region is classified as rainy, hot, and humid tropical (Köppen classification) (Alvares et al., 2013) and is characterized by temperatures ranging from 18 to 27 °C and average annual precipitation of 1,200 to 1,500 mm. Rainfall occurs from fall to winter, concentrated in the months of March to August. The soil of the region is classified as a dystric Oxisol (*Latossolo amarelo distrófico*) (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 1999).

Land use and cover systems are described below:

Pasture – Area composed of unidentified exotic and native grasses; dominant herbaceous plants, such as *Ipomoea asarifolia* (Desr.) Roem. & Schult.; sparse trees, mostly jackfruit (*Artocarpus heterophyllus* Lam.); and small shrubs. The area has a little more than 1.2 ha and does not receive many cultivation treatments, except for the entry of machines to plow and harrow the soil once a year. There was an attempt to recover the area with *Panicum maximum* grass; however, the area was quickly infested by weeds, where sheep periodically forage.

Mandala agriculture – Organic production system in a circular format, in an area of approximately 0.4 ha that was established around 17 years ago, comprising fruit trees such as papaya and banana; annual crops (maize, cassava, common bean, and squash); vegetables (lettuce, chives, carrots, beets, cabbage, coriander, bell pepper); medicinal and aromatic plants (basil, mint); and unconventional food plants (“taioba” [*Xanthosoma sagittifolium*]). There is often a considerable contribution of organic matter from crop residues from the system itself and manure from small ruminants. On the other hand, the area is managed without many technical criteria. The system is weeded frequently and irrigated daily with hoses and sprinklers; there is no systematic use of mulch on the beds, and much of the soil is exposed and/or dominated by invasive plants, such as sedge (*Cyperus* sp.).

Agroforestry system – An area of about 0.7 ha, implemented approximately 16 years ago, where gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) is the main plant and coffee (*Coffea* spp.) is a secondary plant in the inter-row space as it requires shade, a characteristic of understory species. The soil in the area has a thin layer (3-5 cm) of leaf litter, consisting mainly of the biomass of gliricidia and some isolated jackfruit trees. In the coffee plantations, the soil was topdressed with goat/sheep manure and single superphosphate. The system was initially drip-irrigated until the coffee plantation was firm and well-established. The cultivation practices performed in the area are: selective weeding, gliricidia pruning, and coffee harvesting.

Forest – A remnant of open ombrophilous forest that has approximately 35.5 ha and is considered an important ecotonal fragment of *caatinga* enclaves moist forests that harbors important autochthonous species representing the plant typology of great phytogenetic and ecological relevance for the protection of the local fauna and flora. Among the species that occur in the area are the *Hymenaea courbaril* L., *Talisia esculenta* (Cambess.) Radlk., *Eschweilera ovata* (Cambess.) Mart. ex Miers, and *Licania* sp. The soil in the area is covered by a thick layer of plant litter. There are no signs of human intervention at the site, suggesting that the area is in a good state of conservation.

Soil respiration was monitored between the 26th-27th days of December/2019 and January and February/2020, during the dry season in the region. To quantify the carbon dioxide released in each system, the method proposed by Grisi (1978) was followed, whereby the CO_2 released from the soil is captured by a solution of potassium hydroxide (KOH, 0.5N) and then quantified by titration with hydrochloric acid (HCl, 0.1 N), using phenolphthalein and methyl orange as indicators, both at 1% concentration (Morita & Assumpção, 2007). In the capture of CO_2, the containers holding 10 mL of KOH solution remained in the field covered individually by an inverted bucket for 12 h for each period: daytime (05h00 to 17h00) and nighttime (17h00 to 05h00). Two control samples were also used for each area, both of which remained closed throughout the process to avoid exchanges, undergoing the titration process at the end. The buckets had a diameter of 29.8 cm and a height of 36.5 cm, covering an area of 697.46 cm^2 (Figure 1). To prevent gas exchange, the bucket rim was buried in the ground. The absorbed CO_2 was determined according to the method proposed by Gomes et al. (2022).

For each land use system, three transects were set out with an area of approximately 2.5 m^2, spaced at least 25 m apart. Each transect had three sampling points (n = 9 sampling points per system). Climatic data such as precipitation and average temperature in the municipality during the entire experimental period were obtained by consulting the database of the Instituto Nacional de Meteorologia [INMET] (2021). Accumulated precipitation and average temperature were approximately 45 mm and 24.7 ± 2 °C, respectively.

Soil temperature was measured at a depth of 10 cm in each transect using a stick-on thermometer (TE-400, Instrutherm®). Assuming that the soil temperature remains practically stable (25 ± 1 °C) between the systems throughout the nocturnal period (observation based on preliminary tests), we decided to measure the soil temperature weekly at noon (12h00). This time was chosen because this is the moment when the incidence of ultraviolet radiation on the earth's surface is highest, which makes it possible to assess the influence of the land cover (provided by the plant canopy) on the average temperature and thermal amplitude in the evaluated systems.

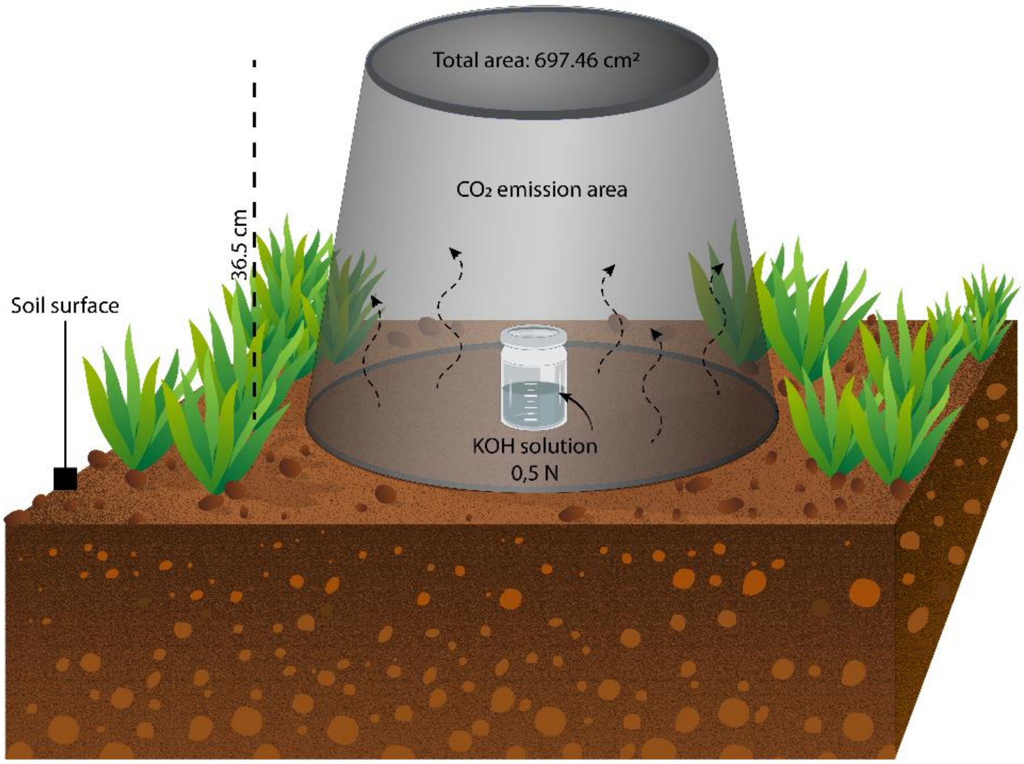

Figure 1. Schematic of the method used to capture the CO_2 released from the soil.

The soil moisture content was measured simultaneously with surface temperature analysis. Soil moisture was measured by collecting simple soil samples at a depth of 0-10 cm in each transect. The samples were taken to the laboratory to be weighed on 0.0001-g precision scales, then packed in aluminum capsules and oven-dried at 105 ± 1 °C for 24 h. The soil moisture content was calculated by the following equation:

$$M\% = \left(\frac{Ww - Dw}{Dw}\right).100,$$

where M%: soil moisture percentage; Ww: wet weight (g); Dw: dry weight (g).

The experiment was laid out in a completely randomized design with nine replicates per treatment (areas), following a 4 × 2 factorial arrangement (system × period of the day). The Shapiro-Wilk and Bartlett tests were used to evaluate the normality of data and homogeneity of variances, respectively. In case the hypothesis of equality between treatments was rejected, Tukey's test ($p \leq 0.05$) was applied to analyze the difference between the means. Statistical analysis was performed using R statistical software version 3.4.1.

There were significant effects of the system × period interaction as well as of the factors in isolation. According to the field-based respirometry study, the release of CO_2 by the soil is significantly higher during the night period in all land use systems evaluated (Figure 2). The CO_2 means found in each system reveal an absence of statistical differences between treatments at nighttime, with an emitted amount ranging between 129.2 and 143.3 mg m^{-2} h^{-1}. However, within the daytime period, the greatest release of soil CO_2 occurred in the pasture use system (113.8 mg m^{-2} h^{-1}), followed by mandala agriculture (93.9 mg m^{-2} h^{-1}), agroforestry (84 mg m^{-2} h^{-1}), and forest (74.9 mg m^{-2} h^{-1}) (Figure 2). This difference in the concentration of daytime CO_2 between the systems can be attributed to inherent characteristics of the soil in each area and the form of use or management adopted, which, associated with environmental stimuli such as moisture and surface temperature, influence the metabolic processes of soil organisms (Gomes et al., 2022).

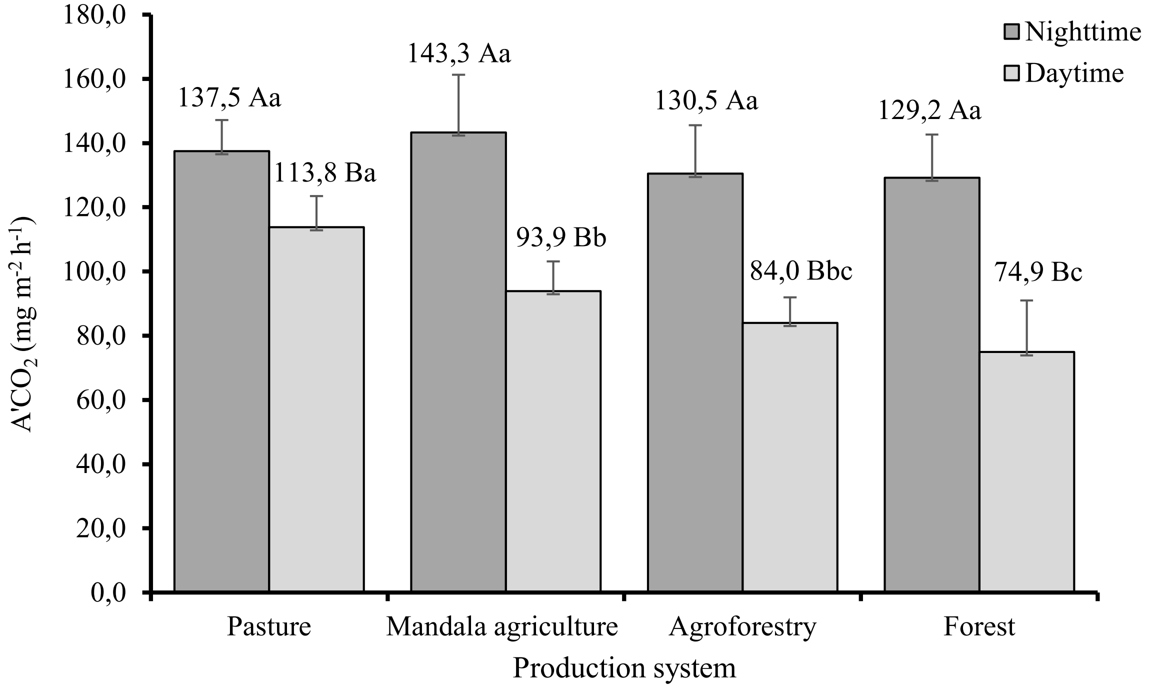

Figure 2. Daytime and nighttime soil respiration in land use and management systems. Uppercase letters compare periods of the day for each land use system, while lowercase letters compare land use systems for each period. Means followed by the same letter do not differ from each other at $p \leq 0.05$ probability by Tukey's test.

The balance between the input and output of carbon (C) from the soil has strong influences on atmospheric CO_2 concentrations, and the form of land occupation and management can affect this natural process by modifying the flow of CO_2 from the soil to the atmosphere (emission) or from the atmosphere to the ground (sequestration). Thus, there is a growing interest in promoting C sequestration in agricultural soils as a way to mitigate the increasing CO_2 levels in the atmosphere (Santos, 2019). The more C is stored in the soil in the form of organic matter, the more life there is in the soil, the greater the retention of moisture, and the more nutrients are available to the plants.

Surface-temperature frequency distributions were significantly different between the land use and cover systems (Figure 3A). Temperatures in the forest use system were mild, with a median of 26.3 °C (Figure 3A). In the agroforestry and mandala agriculture systems, the median temperature was 29.7 and 33.4 °C, respectively. On the other hand, the pasture use system showed the highest median soil temperature, of 36.3 °C (equivalent to 1.3 times the value observed in the forest) and minimum and maximum temperatures of 35 and 37.5 °C, respectively. As for soil moisture percentage (Figure 3B), the highest amplitudes were observed in the pasture use system, which ranged between 0.23 and 17.46%. The median values for soil water content (%) in each system were as follows, in ascending order: pasture (0.99%), mandala (3.51%), agroforestry (3.95%), and forest (4 .95%) (Figure 3B).

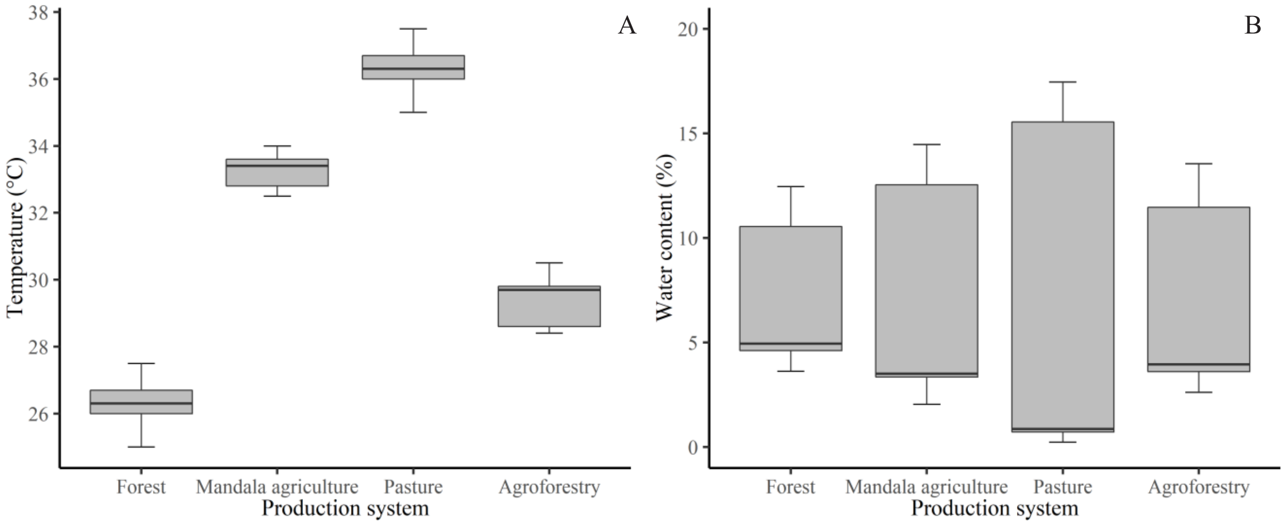

Figure 3. Frequency distribution of soil temperature (°C; A) and water content (%; B). The narrowest portion within each box represents the median; box notch boundaries indicate the median confidence interval; lower and upper bounds of the box show the lower and upper quartiles, respectively; vertical bars represent the maximum and minimum values.

Greater release of soil CO_2 occurred in the systems whose soils showed higher temperature and moistures values. These results corroborate those found by Araujo et al. (2016), according to whom more anthropized areas, without ground cover, allow a greater incidence of ultraviolet radiation, increasing microbiological activity and, consequently, the release of soil CO_2. As stated by the authors, the microbial activity responsible for the production of CO_2 is controlled by the temperature and water content in the soil, and if the temperature is not within the favorable physiological limits of the soil microorganisms, microbial activity can be interrupted. In soils with little or no ground cover, the surface temperature can reach ≥ 50 °C, depending on the region, reducing the availability of water for organisms and altering the soil carbon dynamics (Giovanetti et al., 2019).

The present findings provide crucial information for research on the management and conservation of tropical soils and may allow us to infer that the forms of land use and occupation induce changes in the quality of the soil environment, which may have repercussions on the establishment of populations or communities and their processes (J. H. C. S. Silva et al., 2021). This knowledge can stimulate the use of management techniques to support the recovery of modified areas and the insertion of more sustainable production systems, aiming at mitigating global warming.

Land use and cover systems have a direct effect on the metabolic activity of soil organisms. Environmental stimuli, such as soil temperature and moisture, influence the dynamics of organic matter decomposition and, consequently, the release of CO_2. Among the analyzed areas, the forest showed the lowest CO_2 emissions. As such, it was considered a CO_2 receptor, in contrast to the pasture area, which functioned as a CO_2 emitter. Management techniques that reduce surface temperature and increase organic matter content should be prioritized to promote soil biota. Further studies in this line of research, investigating other land use and cover systems, are encouraged.

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