https://doi.org/10.1590/1678-4499.20250280

SOIL AND PLANT NUTRITION
Article

Assessment of soil respiration and microbial indicators under different land-use systems in the Mantaro Valley, Peru

Fredy Fernando Rivas Yupanqui[1], Giuliana Shelly Lizana Flores[2]*, Mara Cristina Pêssoa da Cruz[2]

1. Universidad Nacional del Centro del Peru – Agronomía – Huancayo, Junin, Peru.
2. Universidade Estadual Paulista – Faculdade de Ciências Agrárias e Veterinárias – Jaboticabal (SP), Brazil.

Received: Jan. 12, 2026 | **Accepted:** July 13, 2026

Section Editor: Hector Valenzuela

***Corresponding author:** shelly.lizana@unesp.br

How to cite: Yupanqui, F. F. R., Flores, G. S. L. and Cruz, M. C. P. (2026). Assessment of soil respiration and microbial indicators under different land-use systems in the Mantaro Valley, Peru. Bragantia, 85, e20250280. https://doi.org/10.1590/1678-4499.20250280

ABSTRACT: Land-use intensification alters soil carbon dynamics and edaphic microbial activity, thereby affecting soil quality and functionality in inter-Andean agroecosystems. The aim of this study was to analyze soil basal respiration, and its relationship with microbial indices under different land-use systems in soils of the Mantaro Valley, Peru. Four land-use systems were evaluated: forest, pasture, fallow, and cropland systems. Soil samples were evaluated collected at a depth of 0–20 cm, and oxidizable carbon, microbial biomass, permanganate-oxidizable carbon, basal respiration, metabolic quotient, microbial quotient, and basal respiration normalized by oxidizable carbon were determined. Results showed differences among land-use systems. Forest and pasture systems exhibited higher contents of oxidizable carbon, microbial biomass, and active carbon, associated with greater biological activity and soil functional stability. The cropland system showed lower carbon and microbial biomass value, and higher metabolic quotient values, indicating reduced microbial efficiency and increased physiological stress. Basal respiration normalized evidenced greater carbon mineralization in fallow and cropland systems. Correlation analyses showed that soil respiration responded differentially according to land-use system and the functional status of soil carbon. Less disturbed systems promoted carbon conservation and microbial metabolic efficiency, suggesting greater sustainability for inter-Andean agroecosystems due to their sensitivity to changes in carbon quality, whereas the fallow system reflected recovery processes in which microbial biomass and metabolic efficiency appeared to be undergoing restructuring.

Key words: soil CO_2 emissions, soil biological indicators, oxidizable carbon, microbial quotient, organic matter.

INTRODUCTION

Land-use intensification in agroecosystems of the inter-Andean valleys of Peru has led to a substantial decline in soil productive capacity, negatively affecting their potential fertility and the livelihoods of smallholder farming communities in this region of Peru (Fonte et al. 2012). Several factors threaten the sustainability of agriculture due to dramatic and rapid changes in land use, such as agricultural system intensification and deforestation (Tovar et al. 2013). Soil management practices have a direct and indirect influence on the composition, diversity, and activity of soil microbial communities, which in turn could have important impacts in crop productivity (Köhl et al. 2014).

Soil respiration is one of the main processes controlling the carbon balance of terrestrial ecosystems. Total soil CO_2 emissions constitute one of the largest carbon (C) fluxes in the global cycle. This respiration releases 80.4 Pg CO_2 annually (1 petagram, Pg = 10^{15} g), which is 10 times greater than the combined contribution of deforestation and fossil fuel combustion. Therefore, small changes in the amount of CO_2 released from the soil impact atmospheric concentrations (Shi et al. 2012). Monastersky (2013) reported that atmospheric C concentrations have increased exponentially from approximately 275–285 to 400 ppm. This significant rise in greenhouse gas concentrations is mainly associated with anthropogenic emissions, particularly those related to land-use change (Pais et al. 2020). Since agricultural systems are particularly vulnerable to climate change, it is imperative to achieve higher crop yields through more efficient resource use while minimizing environmental impacts (Pais et al. 2020).

CC BY

Soil CO_2 release is a critical factor in the ecosystem carbon balance and represents one of the most significant challenges in the C cycle. However, soil C pool dynamics can be altered by factors such as climate change, land use (Muñoz-Rojas et al. 2015), and soil management practices (Luo et al. 2010). Soil C storage depends on organic inputs, soil organic matter (SOM) decomposition rates, texture, and climate (Johnston et al. 2009). This indicates a close relationship between CO_2 evolution through respiration, and the carbon forms present in the soil, the latter being a fundamental component of crop productivity.

Soil microbial activity depends on the availability of energy, carbon, and nutrients; consequently, there is special interest in identifying microbial food sources, specifically active carbon, which acts as a potential driver of microbial performance (Blazier and Liechty 2016). This active organic matter represents 10 to 20% of the SOM and consists of the microorganisms responsible for decomposing the organic fraction (the labile fraction) and resynthesizing substances that yield metabolic products such as mucilages, gum, acids, enzymes, extracellular polysaccharides, and CO_2. Several factors influence microbial activity, including land use, vegetative cover, management practices, and the quality of plant residues entering the system (Delgado 2015). Furthermore, CO_2 evolution rates vary across ecosystems, such as forests, grasslands, tundra, and ecoregions (Zhong et al. 2016). A critical factor intensely influencing microbial populations is soil tillage, which can increase activity by 20 to 30 times. This is due to changes in gas and water fluxes through pore spaces (Delgado 2015), which modify soil microbial activity.

The Mantaro Valley, one of Peru's most extensive inter-Andean valleys, is characterized by a diverse mosaic of land-use systems, including agriculture, forestry, grasslands, and fallow areas. Within this productive matrix, agricultural systems, particularly maize cultivation, are of paramount importance to the local economy. These land-use types may exert distinct influences on soil carbon dynamics and microbial activity due to variations in organic residue inputs, soil disturbance, vegetative cover, and management practices, all of which modulate C transformation and stabilization processes.

Soil CO_2 emission, used as an indicator of soil basal respiration (SBR), reflects the metabolic activity of microbial communities responsible for organic matter decomposition. Conversely, normalized basal respiration by oxidizable carbon (BRCox), defined as soil basal respiration per unit of oxidizable carbon (Cox), is an index that expresses microbial activity relative to the available substrate. Similarly, indicators such as microbial biomass carbon (MBC) allow for estimating the size and potential activity of the microbial community, while Cox represents a relatively stable pool of soil organic carbon. Furthermore, permanganate oxidizable carbon (POXc) constitutes an active fraction of organic carbon that is readily available to microorganisms and sensitive to changes in soil management. Other derived indices, such as the microbial metabolic quotient (qCO_2), provide information on microbial metabolic efficiency, whereas the microbial quotient (qMic), the ratio between MBC and total soil organic carbon, indicates carbon availability and use efficiency for microorganisms.

Although numerous studies have evaluated soil respiration responses to various environmental factors, research analyzing how different land uses influence soil CO_2 emissions and their relationship with microbiological indicators remains limited, particularly within the inter-Andean valley ecosystems of Peru.

This study evaluated soil respiration in relation to microbial indices across four land-use systems in the Mantaro Valley: forest, comprising pine species (*Pinus radiata*, *Pinus pinea*, and *Pinus ayacahuite*) and eucalyptus (*Eucalyptus globulus* and *Eucalyptus gunnii*); cropland, featuring artichoke cultivation (*Cynara cardunculus* var. *Criolla*); pasture, consisting of an association of oat (*Avena sativa*), ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*), and alfalfa (*Medicago sativa*); and fallow, represented by an agricultural resting area with spontaneous vegetation, including *Taraxacum officinale*, *Oxalis latifolia*, and *Verbena officinalis*.

The research hypotheses posit that grassland and forest systems exhibit higher MBC and SBR levels, driven by minimal soil disturbance, continuous high organic matter inputs (litterfall and roots), and permanent vegetative cover. Conversely, because cropland systems undergo intensive soil disturbance (tillage) that oxidizes organic matter and releases larger amounts of CO_2, this system is expected to show lower carbon use efficiency, as reflected by higher BRCox values. Furthermore, reduced soil carbon availability, coupled with lower microbial metabolic efficiency, results in higher metabolic quotient (qCO_2) values, indicating greater physiological stress for microorganisms, particularly in fallow and cropland systems. Therefore, the objective of this study was to evaluate the impact of different land-use systems on soil respiration and its relationship with microbial indices in the Mantaro Valley, Peru.

MATERIALS AND METHODS

Study area

The study was conducted at the experimental area of the Universidad Nacional del Centro del Perú, El Mantaro Agricultural Experiment Station, located in the Mantaro district, Jauja province, Junín department (an inter-Andean valley in Peru) (Fig. 1). The site is situated at 3,221 m above sea level (asl), and the soil is taxonomically classified as Inceptisols, with Ustorthents, and Haplustepts as the primary soil groups. Soil sampling was carried out during January and February 2023. The climate in the Jauja province is classified as temperate, characterized by moderate rainfall and a moderate thermal amplitude. The mean annual maximum and minimum temperatures are 19.4 and 5°C, respectively. The mean annual cumulative precipitation is 757.8 mm. The highest rainfall occurs from October to March, whereas the lowest is recorded between April and September. Following the rainy season, meteorological frosts typically begin in April and subside in September, reaching their peak intensity and frequency in June and July. The temperature drop is more pronounced at night and during the early morning hours before dawn, under clear skies or low cloud cover (SENAMHI 2021). The soil moisture regime is ustic (limited moisture, yet available during part of the growing season).

The study evaluated four land-use systems: forestry, pasture, fallow, and cropland. Their physical and chemical attributes are presented in Table 1, while their description and history are shown in Table 2.

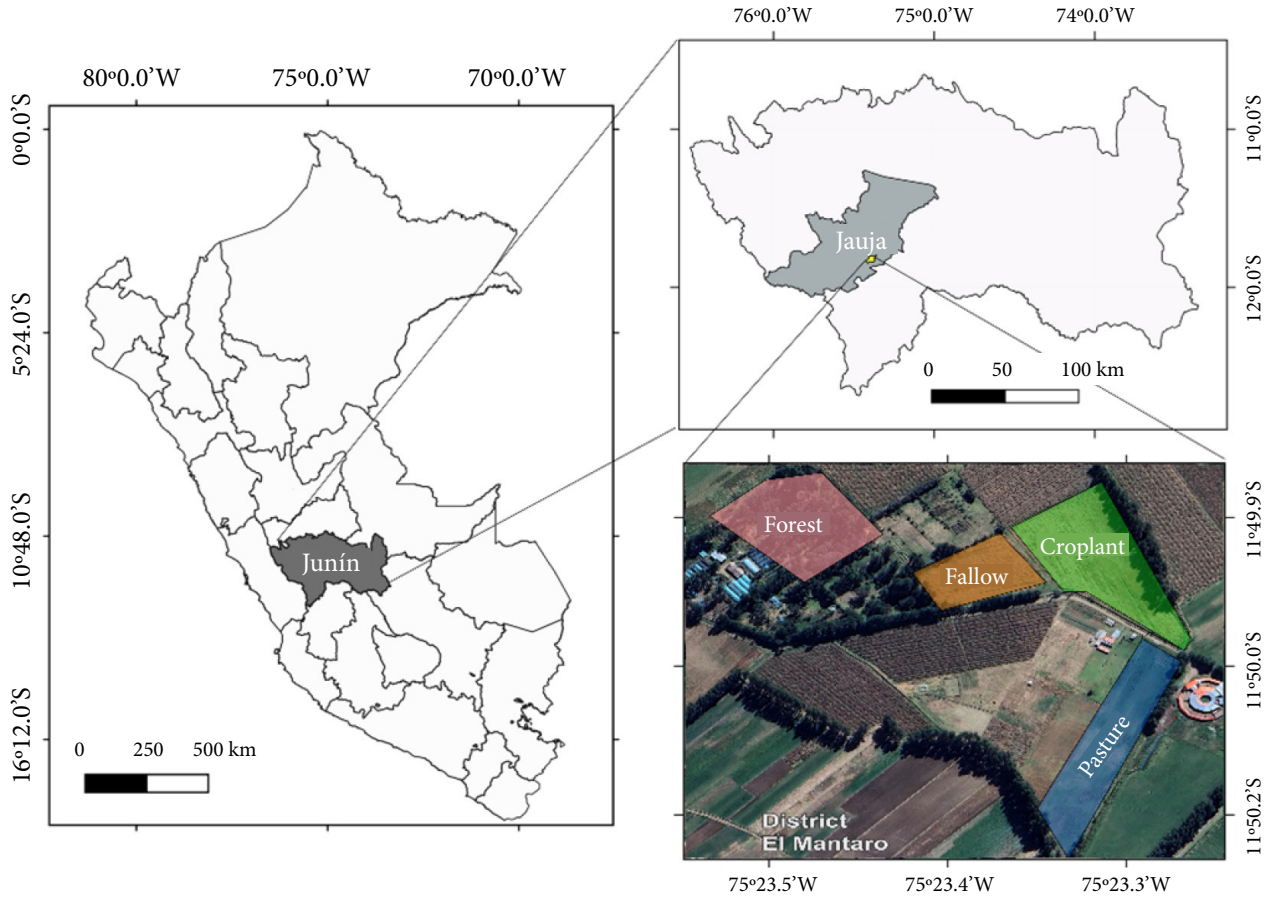


Figure 1. Geographic location of the land-use systems in the El Mantaro distric, Junín, Peru. The following land-use systems are delimited: forest, pasture, fallow, and cropland.

CC BY

Table 1. Soil properties according to the land-use system.

Soil properties		Forest	Pasture	Fallow	Cropland
pHH2O (1:1)		5.88	6.93	7.47	6.76
CE (1:1)	$dS \cdot m^{-1}$	0.10	0.35	0.20	0.50
$CaCO_3$	(%)	0.00	0.19	10.02	0.00
OM	(%)	5.00	4.13	3.33	2.80
P	$(mg \cdot kg^{-1})$	13.4	14.6	21.2	29.7
Sand	(%)	42	38	74	38
Silt		35	27	17	39
Clay		23	35	9	23
Texture class		Loam	Clay loam	Sandy loam	Loam
CEC	$cmolc \cdot kg^{-1}$	15.52	17.60	9.28	14.24
Ca^{2+}		10.40	13.80	7.23	10.86
Mg^{2+}		2.62	3.07	1.78	2.30
K^+		0.25	0.28	0.15	0.26
Na^+		0.11	0.16	0.11	0.12
$Al^{3+}+H^+$		0.05	0.00	0.00	0.00

OM: organic matter, analyzed at the Soil Microbiology Laboratory, Faculty of Agronomy, Universidad Nacional del Centro del Perú.

Table 2. Description and land-use history of the studied systems.

Land-use system	Description of the area
Forest	Located at 11°49'54.2" S and 75°23'31.78" W, this area covers 0.79 ha and hosts pine species (*Pinus radiata*, *P. ponderosa*, and *P. patula*) and eucalyptus (*Eucalytus globulus* Labill). The site consists of a forest plantation over 50 years old, with no record of soluble fertilizer application. The soil has a loamy texture with a moderately acidic pH of 5.88, 5% soil organic matter, and 13.4 $mg \cdot kg^{-1}$ extractable P.
Pasture	The grassland area, spanning 1.30 ha, has been under continuous grazing management for over 20 years. Located at 11°50'03.48" S and 75°23'21.14" W, the site is covered by a mix of grasses and forages, including oat (*Avena sativa*), ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*), and alfalfa (*Medicago sativa*). The soil is classified as clay loam, with a pH of 6.93, 4.13% soil organic matter, and 14.6 $mg \cdot kg^{-1}$ extractable P.
Fallow	Located at 11°49'56.72" S and 75°23'25.54" W, this 0.76-ha area has been under fallow for one growing season. It features spontaneous species such as dandelion (*Taraxacum officinale*), *Oxalis latifolia*, and *Verbena officinalis*. The soil is characterized by a sandy loam texture, a pH of 7.47, 3.33% soil organic matter, and an extractable P concentration of 21.2 $mg \cdot ha^{-1}$. This area was previously under maize cultivation (*Zea mays* L.) two years ago, receiving a fertilization of 120 $kg \cdot ha^{-1}$ N, 80 $kg \cdot ha^{-1}$ P_2O_5, and 60 $kg \cdot ha^{-1}$ K_2O.
Cropland	Located at 11°49'56.15" S and 75°23'21.44" W, this 1.65-ha cropland has been under no till management for over 15 years, with a crop rotation of maize, potato, and artichoke (*Cynara cardunculus* var. Criolla) planted in late October with a spacing of 0.8 m between rows and 0.7 m between plants. The soil has a loamy texture, a pH of 6.76, 2.80% soil organic matter, and 29.7 $mg \cdot kg^{-1}$ extractable P. Fertilization during the rainy season consisted of 220 $kg \cdot ha^{-1}$ N, 360 $kg \cdot ha^{-1}$ K_2O, and 270 $kg \cdot ha^{-1}$ P_2O_5, supplemented by a basal application of 5 $t \cdot ha^{-1}$ of a cattle-poultry manure mixture. Glyphosate was applied for weed control (*e.g.*, goosefoot, ryegrass, and barnyard grass).

Sampling and site description

Three experimental plots (20 × 20 m) were established for each land-use system: forest, pasture, fallow, and cropland. Soil samples were collected from five positions within each plot (the four corners and the center). At each position, four subsamples were taken, resulting in a total of 20 subsamples per plot (5 positions × 4 subsamples). These were thoroughly mixed and homogenized to form one composite sample per plot, yielding three replicates (n = 3) per land-use system. Soil was sampled at a depth of 0–20 cm in January 2023 using a soil auger. This depth was selected due to the higher concentration of organic matter and biological activity typically found in the upper soil layers (Madejón et al. 2007, Payán et al. 2009). Prior to sampling, the litter layer and plant debris were carefully removed.

The samples were transported in large plastic bags, sieved through a 4-mm mesh, and stored at 4°C at their field moisture levels until microbiological analyses were performed within 20 days of sampling. Prior to these analyses, plant debris and roots were carefully removed. The remaining soil was air-dried at room temperature for 120 h; for the determination of easily oxidizable carbon and physicochemical analyses, these samples were sieved through a 2-mm mesh.

Soil analyses

Oxidizable carbon (Cox) was determined using the Walkley-Black method (Nelson and Sommers 1996) through acid-dichromate wet oxidation (Fontana and Campos 2017).

SBR was determined according to Jenkinson and Powlson (1976). Briefly, 100 g of soil were placed in a 500-mL airtight glass jar, with soil moisture adjusted to 70% of field capacity. Samples were incubated in the dark at 28°C for 72 h. The CO_2 released during incubation was trapped in an internal vial containing 20 mL of 0.2 mol·L^{-1} NaOH. At the end of the incubation period, the NaOH solution was quantitatively transferred to an Erlenmeyer flask, in which 2 mL of 0.5 mol·L^{-1} $BaCl_2$ were added. The excess hydroxide was then back-titrated with 0.2 N HCl using phenolphthalein as an indicator.

Total soil microbial activity was reflected by SBR, which was determined as the C-CO_2 release rate under controlled conditions and expressed per unit of soil mass (mg C-CO_2·kg^{-1}·h^{-1}). Additionally, the BRCox was calculated as the ratio of SBR to oxidizable carbon content (mg C-CO_2·kg^{-1} Cox·h^{-1}) (Emran et al. 2025). This index expresses microbial activity relative to substrate availability, thereby eliminating the confounding effects of varying soil organic carbon (SOC) levels across the four land-use systems (Tian et al. 2016).

Soil MBC was determined using the chloroform fumigation-extraction method according to Vance et al. (1987). Briefly, the same soil samples used for SBR analysis served as non-fumigated (NF) controls immediately after a five-day incubation period. Three additional replicates were pre-incubated under identical conditions; on the third day, these samples were fumigated (F) at room temperature for 48 h in a desiccator containing 20 mL of ethanol-free chloroform. The NF controls were maintained at 28°C. Following fumigation, microbial C was extracted from all samples using 50 mL of 0.5 mol·L^{-1} K_2SO_4. Organic C was quantified via the potassium dichromate oxidation method (Jenkinson and Powlson 1976) followed by titration. The MBC content was calculated as the difference between the C extracted from F and NF samples, using a conversion factor (*kEC*) of 0.35 (Joergensen 1996).

The microbial metabolic quotient (qCO_2) (mg C-CO_2·g^{-1} MBC·h^{-1}) was determined as the ratio of the basal CO_2 evolution rate to the MBC (Anderson and Domsch 1985).

The microbial quotient (qMic) was calculated as the ratio of MBC to total soil organic carbon, according to Anderson and Domsch (1985).

Permanganate-oxidizable carbon (POXc) analysis was performed according to Weil et al. (2003). Briefly, 2.5 g of air-dried soil were weighed into 50-mL centrifuge tubes, followed by the addition of 18 mL of deionized water and 2 mL of 0.2 M $KMnO_4$ solution. The mixture was shaken for 2 min at 240 oscillations per minute, and allowed to settle for 10 min. Subsequently, a 0.5-mL aliquot of the supernatant was diluted with 49.5 mL of deionized water. The absorbance was measured at 550-nm using a ultraviolet-visible spectrophotometer.

Statistical analysis

Quantitative data were tested for normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively. The data, adjusted to three replicates per land-use system, were subjected to one-way analysis of variance (ANOVA). When significant differences were detected, Tukey's honestly significant difference (HSD) test was performed at a 5% significance level ($p < 0.05$) to identify statistical differences in soil respiration related variables among the land-use systems.

Additionally, correlation analyses were performed between soil respiration data and the indicators of different carbon forms. Pearson's correlation coefficient was used to determine the strength and direction of the association between each variable and SBR. Data processing and statistical analyses were conducted using R software (version 4.3.0) within the RStudio environment.

CC BY

RESULTS AND DISCUSSION

Forest plantations, such as *Pinus* spp., developed in a moderately acidic soil (pH 5.88), which falls within the expected range for coniferous dominated systems (Table 1). Conversely, soils from cropland and pasture systems exhibited near neutral pH values (6.76 and 6.93, respectively). The fallow system showed a slightly alkaline reaction (pH 7.47), possibly associated with the $CaCO_3$ content (10.02%), suggesting the influence of parent material and base accumulation on soil reaction.

Soils under forestry use exhibited the highest SOM content (50 $g \cdot kg^{-1}$), followed by pasture (41.3 $g \cdot kg^{-1}$) and cropland (28 $g \cdot kg^{-1}$) systems (Table 1). These differences indicate a greater carbon accumulation in less disturbed systems, likely associated with higher organic residue inputs, reduced soil disturbance, and enhanced physical protection of SOM. Such elevated SOM content may also contribute to improving edaphic properties, including aggregate stability, moisture retention, pH buffering capacity, and nutrient availability. Furthermore, the location at 3,221 m above sea level (asl), with an average annual precipitation of 757.8 mm and a mean annual temperature of 12°C, likely favored low organic matter decomposition rates, a key factor in its maintenance.

The forest soil recorded an extremely low exchangeable acidity ($Al^{3+}+H^{+}$) of 0.05 $cmol_c \cdot kg^{-1}$, indicating an absence of aluminum toxicity, a general characteristic of soils in this valley. Additionally, it exhibited a cation exchange capacity (CEC) of 15.52 $cmol_c \cdot kg^{-1}$, with Ca^{2+} as the dominant cation in the exchange complex, occupying 67% of the exchange sites. The cropland system showed a CEC of 14.24 $cmol_c \cdot kg^{-1}$, with Ca^{2+} occupying 76% of the exchange sites. The base saturation reflects how nutrient status contributes to potential soil fertility. In this sense, all four land-use systems presented very high base saturation levels, suggesting low leaching rates.

Oxidizable organic carbon

Cox content was significantly higher in forest soils, which may be attributed to ecological factors and soil carbon dynamics. Continuous and substantial surface inputs of plant residues (leaves, branches, roots, and litter), rich in structural compounds such as lignin, favor carbon accumulation in the topsoil and promote humic substance synthesis over mineralization processes (Tavares and Nahas 2014), thereby supporting Cox maintenance. As a low disturbance system, carbon in these soils exhibits greater stability and protection against degradation. Additionally, intense microbial immobilization constitutes a key process in transforming labile carbon into more recalcitrant forms, facilitating long-term storage (Gayan et al. 2023).

The Cox values observed in the pasture (14.13 $g \cdot kg^{-1}$) suggest that carbon accumulation in this system depends not only on aboveground biomass inputs but also on mechanisms associated with belowground carbon. The high turnover of fine roots, root exudates, and organic inputs from grazing (cattle and sheep manure and urine), combined with animal induced soil compaction, may significantly contribute to sustaining soil carbon stocks (Ordoñez et al. 2020). Additionally, carbon derived from grasses may exhibit greater physical protection within soil aggregates, favoring its stabilization against oxidative processes (Singhal et al. 2026). This behavior might also reflect active microbial dynamics promoting SOM turnover and transformation, coupled with the effects of reduced soil disturbance, a condition that favors carbon conservation. Together, these mechanisms indicate that pasture systems can sustain carbon accumulation and stabilization processes that are functionally comparable to those observed in forestry systems (Rui et al. 2022).

Conversely, the lower Cox content in the cropland system (7.73 $g \cdot kg^{-1}$) (Table 3) is likely associated with continuous soil disturbances from management practices, which lead to higher SOM decomposition rates. Meanwhile, in the fallow system, one year of rest appears to have been insufficient to establish carbon stocks comparable to those of less disturbed systems. This evidence suggests that carbon recovery is a long-term process.

Compared to the forest system, the other land uses showed decreases in Cox of 72.8, 65.7, and 49.7% for cropland, fallow, and pasture, respectively. Nonetheless, the 20.7% increase observed in the fallow soil relative to the cropland soil, though not significant, may indicate an initial trend of soil carbon recovery, with potential implications for fertility in inter-Andean valley conditions.

Soil basal respiration

SBR varied between 1.90 and 3.36 mg C-CO_2·kg^{-1}·h^{-1}, with CO_2 evolution values similar to those reported by Pinto et al. (2022), and Comeau et al. (2023). The highest CO_2 release rates were observed in pasture and forest systems compared to the other land uses (Table 3), evidencing an intensification of microbial activity. This intensification could be attributed to a sustained flux of labile organic matter, which likely promoted the metabolic dynamics of heterotrophic microorganisms and their subsequent activation in decomposition and nutrient cycling (Azevedo et al. 2024). Such behavior is consistent with the higher MBC, Cox, and POXc contents observed in both systems, suggesting enhanced organic matter transformation dynamics. However, the higher SBR recorded in the pasture, despite lower Cox and MBC contents compared to the forest system, indicates that respiration rates may not depend solely on the size of the carbon pool, but also on substrate quality and availability, particularly within the more active carbon fractions.

Table 3. Soil basal respiration and other microbial variables across different land-use systems in the Mantaro Valley, Junín, Peru.

Microbiological		Land-use systems							
variable		Forest		Pasture		Fallow		Cropland	
Cox	(g·kg^{-1})	28.40 ± 1.6	a	14.13 ± 0.9	b	9.33 ± 0.9	c	7.73 ± 0.9	c
SBR	(mg C-CO_2·kg^{-1} h^{-1})	2.85 ± 0.5	ab	3.36 ± 0.1	a	2.45 ± 0.1	bc	1.90 ± 0.1	c
MBC	(mg·kg^{-1} C)	251.56 ± 6.1	a	214.61 ± 5.0	b	147.73 ± 25.0	c	86.60 ± 11.6	c
POXc	(mg·kg^{-1})	1,272.78 ± 38.9	a	936.09 ± 48.4	b	450.68 ± 23.2	c	339.54 ± 17.2	d
qCO_2	(mg C-CO_2·g^{-1} MBC·h^{-1})	11.37 ± 2.4	b	15.68 ± 0.5	ab	16.81 ± 2.3	ab	22.32 ± 4.7	a
qMic	(%)	0.89 ± 0.1	b	1.52 ± 0.1	a	1.58 ± 0.2	a	1.12 ± 0.1	b

a, b, c, and d: not significantly different according to Tukey's test ($p \leq 0.05$); Cox: oxidizable carbon; SBR: soil basal respiration; MBC: microbial biomass carbon; POXc: permanganate-oxidizable carbon; qCO_2: metabolic quotient; qMic: microbial quotient.

In contrast, the lower CO_2 evolution in the cropland system coincided with reduced Cox, MBC, and POXc contents, which may reflect lower substrate availability and less favorable conditions for sustaining significant microbial activity. Furthermore, the higher qCO_2 observed in this system could indicate lower metabolic efficiency or higher microbial maintenance costs compared to less disturbed systems.

Permanganate-oxidizable carbon

POXc contents ranged from 339.54 to 1,272.78 mg·kg^{-1}, values comparable to those reported by Culman et al. (2012) across various edaphoclimatic scenarios. The higher POXc levels in forest and pasture systems are influenced by SOM content, which is determined by the quantity and quality of biomass inputs (Mandal et al. 2011). These levels are also closely associated with the deposition of plant species, influencing soil biota quality, which in turn depends on management factors involving forest species or grasses. This indicator responds to management changes, such as the addition of organic amendments (Wang et al. 2021) and cultural practices including tillage, crop rotation, and cover cropping (Jagadamma et al. 2019). Furthermore, POXc is more sensitive to tillage treatments and correlates more closely with other soil quality indicators, such as microbial biomass, basal respiration, and aggregate stability, than with Cox (Culman et al. 2012).

SOM plays a crucial role in maintaining and enhancing soil quality (Lal 2016). Complementarily, the proper management of this component contributes to strengthening key soil functions, including nutrient cycling, aggregate stability, water retention, aeration, drainage, cation exchange, and biodiversity (Weil and Magdoff 2004). These results confirm that agricultural land use involving a maize-potato-artichoke rotation with low organic matter input can lead to a decrease in POXc contents. Since POXc is considered an indicator of the labile SOC fraction and is highly sensitive to management induced changes (Bongiorno et al. 2019), it serves as a critical tool for identifying changes associated with land use.

Microbial biomass carbon

MBC was significantly higher in forest (251.56 mg·kg^{-1} C) and pasture (214.61 mg·kg^{-1} C) systems compared to fallow (147.73 mg·kg^{-1} C), and cropland (86.60 mg·kg^{-1} C) (Table 3), suggesting that less disturbed land uses favor a larger microbial biomass. As the living fraction of SOM, the microbial biomass constitutes an important reservoir of nutrients such as N and P and serves as a sensitive indicator of early changes in soil conditions (Marinari et al. 2006). The higher MBC contents in forest and pasture systems are likely associated with greater organic carbon inputs from plant residues and root biomass, alongside lower disturbance levels, conditions that sustain higher substrate availability for microbial growth. The correspondence with higher MBC, Cox, and POXc values suggests that these systems not only sequester more carbon but also maintain a biologically active fraction. This pattern is consistent with Silva et al. (2012) and Zhang et al. (2016), who also reported higher microbial biomass in systems with greater vegetative cover and minimal disturbance. In contrast, the lower microbial biomass in the cropland system may be associated with intensive management and lower organic residue inputs, which can restrict both the size and potential activity of the microbial community. The fallow system exhibited an intermediate value (147.73 mg·kg^{-1} C), potentially indicating a partial biological recovery, although still below that of less disturbed systems.

These results also concur with Tiwari et al. (2019), who observed higher microbial biomass values in forest systems and lower values in cropland systems. Although the values reported by those authors for the forest system (768.25 mg·kg^{-1} C) were higher than those found in the present study, such differences may be associated with edaphoclimatic variations, plant composition, and site-specific management conditions.

Microbial metabolic quotient

The microbial metabolic quotient describes microbial energy-use efficiency and allows for measuring the efficiency of microbial biomass in Cox utilization; furthermore, it serves as an indicator of soil stress or disturbance (Liptzin et al. 2022). It varies according to the composition and physiological state of microbial communities, substrate availability, and abiotic factors such as pH, texture, temperature, and organic carbon (Anderson and Domsch 1985). The cropland system (22.32 mg C-CO_2·g^{-1} MBC·h^{-1}) appeared to be subject to greater stress, under unfavorable conditions in which microorganisms require more maintenance energy to sustain biomass, resulting in higher C release as CO_2. These findings concur with Anderson and Domsch (1985), who reported the highest values for agricultural soils in younger plots. In contrast, the forestry system recorded the lowest qCO_2 (11.37 mg C-CO_2·g^{-1} MBC·h^{-1}), suggesting mature and stable ecosystems in which microorganisms require less energy for biomass maintenance and a larger fraction of carbon is incorporated into microbial tissues (Insam and Domsch 1988).

Research consistently interprets high qCO_2 values as indicating higher respiration per unit of microbial biomass and lower microbial carbon-use efficiency, which are associated with stress or nutrient imbalance. It should be noted that no fixed critical value exists; however, a value of 2 mg C-CO_2·g^{-1} MBC·h^{-1} is widely accepted for various soils. Therefore, the values found in this study are driven by land-use systems, climate, soil type, and management characteristics. Nevertheless, Clayton et al. (2021) considers 0.5–2-mg C-CO_2·g^{-1} MBC·h^{-1} to be the normal range. The qCO_2 values obtained in this study (11.37 mg C-CO_2·g^{-1} MBC·h^{-1} for forest and 22.32 mg C-CO_2·g^{-1} MBC·h^{-1} for cropland) greatly exceed these reported normal ranges.

Microbial quotient

The microbial quotient expressed as the ratio of MBC to Cox ranged from 0.89 to 1.58% (Table 3). This index serves as an indicator of the proportion of organic carbon immobilized within the microbial biomass, reflecting the conversion efficiency of organic carbon into living biomass and, potentially, carbon availability for microorganisms (Anderson 1994). Furthermore, it reflects the assimilation of Cox by microorganisms and their maintenance respiration (Cao et al. 2021).

The higher qMic values in pasture (1.52%) and fallow (1.58%) systems suggest a greater proportion of organic carbon associated with the active microbial biomass, which may indicate higher relative carbon-use efficiency by microorganisms. In the pasture system, this pattern could be linked to an increased availability of readily utilizable substrates derived from root turnover and exudates. In the fallow system, this behavior may reflect an initial biological recovery response following the reduction in soil disturbance, although this interpretation would require further evaluation.

In contrast, the lower qMic in the forest system (0.89%), despite its higher Cox and MBC contents, suggests that a greater proportion of carbon is stored in pools less associated with living biomass or in relatively more stabilized forms. This highlights that high carbon contents do not necessarily imply higher proportions of active microbial carbon. This finding provides a complementary dimension to the interpretation of the forestry system, emphasizing carbon stabilization processes in addition to accumulation.

Although high qMic values have been associated with improved soil quality and greater microbial carbon-use efficiency (Pardo-Plaza et al. 2019), the values observed in this study were below the thresholds proposed by Anderson (2003) for agricultural and forest systems. These discrepancies may be attributed to specific soil types, climatic conditions, and management characteristics.

Normalized basal respiration

SBR was higher in pasture (3.36 mg C-CO_2·kg^{-1}·h^{-1}) and forest (2.85 mg C-CO_2·kg^{-1}·h^{-1}) systems, evidencing greater overall microbial activity compared to fallow and cropland. However, BRCox is an index that expresses microbial activity relative to substrate availability (Emran et al. 2025). The forest system exhibited the lowest BRCox value (175.17 mg C-CO_2·kg^{-1} Cox·h^{-1}), while the fallow and cropland systems recorded significantly higher values (Table 4).

Table 4. Soil basal respiration and normalized basal respiration across different land-use systems.

Land use	SBR (mg C-CO_2·kg^{-1}·h^{-1})		BRCox (mg C-CO_2·kg^{-1} Cox·h^{-1})	
Forest	2.85 ± 0.5	ab	175.17 ± 29.95	b
Pasture	3.36 ± 0.1	a	238.32 ± 6.59	b
Fallow	2.45 ± 0.1	bc	263.20 ± 21.87	a
Cropland	1.90 ± 0.1	c	248.09 ± 37.62	ab

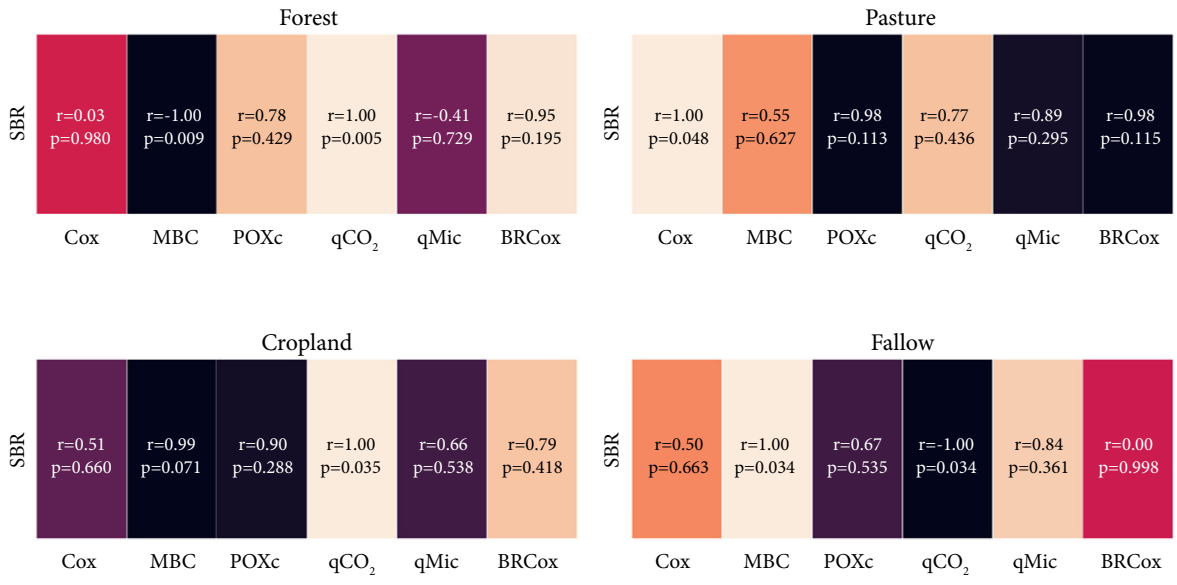
a, b, c, and d: not significantly different according to Tukey's test ($p \leq 0.05$); SBR: soil basal respiration; BRCox: normalized basal respiration (basal respiration normalized by oxidizable carbon).

The SBR values for the forest system indicate high microbial activity, while the lower BRCox suggests more efficient carbon use. Under these conditions, carbon is more stable and protected from oxidative processes, indicating a more balanced and sustainable system. Conversely, in the cropland system, SBR tends to be much lower, whereas BRCox is higher, indicating low microbial activity but rapid consumption of available carbon. This system likely experiences microbial stress and lower stability, with a clear trend toward carbon degradation.

These results evidence that SBR and BRCox respond differently to land use. While forest and pasture systems exhibit higher total microbial activity, cropland and fallow systems show a greater mineralization intensity of labile carbon. These latter systems also demonstrate lower carbon-use efficiency and potential soil degradation processes. In summary, forest and pasture systems tend to better conserve carbon, whereas cropland and fallow systems lose it more rapidly through oxidative processes.

From a functional perspective, the strong positive association between SBR and qCO_2 in the cropland system (Fig. 2) suggests an increase in microbial respiration relative to biomass, indicating lower metabolic efficiency within the microbial system. This is common in intensive agricultural systems, in which frequent disturbances may favor microbial communities with higher maintenance energy expenditures (Ghorbani et al. 2023). In contrast, the negative relationship between SBR and MBC indicates that higher microbial biomass levels do not necessarily translate into higher respiration, potentially reflecting more efficient communities or limiting conditions for metabolic activity (Feketeová et al. 2021). The negative trend with Cox and POXc reinforces the idea that available carbon is not being efficiently incorporated into microbial metabolism.

CC BY



SBR: soil basal respiration; Cox: oxidizable carbon; MBC: microbial biomass carbon; POXc: permanganate-oxidizable carbon; qCO_2: metabolic quotient; qMic: microbial quotient; BRCox: basal respiration normalized by oxidizable carbon.

Figure 2. Pearson's correlation between soil basal respiration and selected soil microbial properties across the four land-use systems (forest, pasture, cropland, and fallow).

This suggests a decoupling between microbial biomass and respiratory activity, possibly associated with stress induced by disturbances such as tillage, fertilization, or intensive management. These results are consistent with previous studies (Ghorbani et al. 2023, Li et al. 2024) reporting that qCO_2 serves as a sensitive indicator of changes in soil biological quality.

The forest system exhibits a highly structured, active, dynamic, and non-degraded behavior, and microbial respiration is not controlled by the total carbon quantity but by labile carbon, specifically carbon quality. The negative relationship between microbial biomass and respiration indicates efficient carbon use, reflecting a stable and low-disturbance ecosystem. Furthermore, the strong association with qCO_2 confirms that respiration variability responds primarily to changes in metabolic efficiency rather than carbon availability (Li et al. 2024, Babur et al. 2025).

In the pasture system, respiration depends on total organic carbon (Cox) but decreases with labile carbon (POXc). This suggests that SBR is primarily associated with total organic carbon, which acts as an energy source for microorganisms, promoting C mineralization and, consequently, increasing CO_2 release. This pattern may indicate the occurrence of labile fraction depletion or enhanced carbon stabilization. Furthermore, the increase in qCO_2 suggests some metabolic inefficiency, though to a lesser extent than in the cropland system. Therefore, this system maintains biological activity but shows signs of available carbon limitation and moderate efficiency (Fig. 2).

In the fallow system, SBR exhibited contrasting relationships with the evaluated biological attributes. Microbial activity appears to be more closely controlled by microbial biomass than by total organic carbon, reflecting a system in a process of recovery or stabilization. The inverse relationship with qCO_2 indicates higher carbon-use efficiency, possibly associated with microbial communities adapted to lower disturbance conditions (Ashraf et al. 2022). This system seems to favor greater microbial metabolic efficiency, although without a consistent relationship with soil carbon fractions.

These results align with the conceptual framework of Anderson (2003) and Ashraf et al (2022), in which qCO_2 acts as an indicator of metabolic stress and carbon-use efficiency (Table 5). The positive relationship between qCO_2 and SBR in forest and cropland systems suggests microbial communities with higher energetic expenditure per unit of biomass, typically associated with disturbance conditions or lower substrate quality. In contrast, the negative relationship between MBC and SBR in these systems indicates that increases in microbial biomass do not necessarily translate into higher respiratory efficiency. This reinforces the hypothesis of a decoupling between microbial size and activity under resource-limiting conditions (Qu et al. 2023). In the pasture system, the positive association between Cox and SBR reflects a more conserved system, in which organic carbon availability directly drives microbial activity.

Table 5. Summary of acronyms, key functions, and references of soil quality indicators discussed in the manuscript.

Acronym	Full name	Description/Function	Reference
MBC	Microbial biomass carbon	Represents the living fraction of soil organic matter; considered a sensitive indicator of soil quality.	Vance et al. (1987) and Nannipieri et al. (2017)
SBR	Soil basal respiration	The rate of CO_2 evolution produced by microorganisms utilizing organic substrates naturally present in the soil. It evaluates the metabolic activity of the soil microbiota.	Anderson and Domsch (1985)
BRCox	Basal respiration normalized by oxidizable carbon	An index relating soil basal respiration (SBR) to the oxidizable organic carbon (Cox) content. It indicates the relative intensity of carbon mineralization and biological activity associated with soil organic pools.	Anderson and Domsch (1985) and Emran et al. (2025)
POXc	Permanganate-oxidizable carbon	The labile fraction of soil organic carbon susceptible to oxidation by a dilute potassium permanganate solution; a sensitive indicator of soil quality and management-induced changes.	Weil et al. (2003) and Culman et al. (2012)
qCO_2	Metabolic quotient	The amount of CO_2 released per unit of microbial biomass carbon; represents an index of the metabolic efficiency of the soil microbial community.	Anderson and Domsch (1985)
qMIc	Microbial quotient	The ratio of microbial biomass carbon (MBC) to total soil organic carbon (SOC). It serves as a sensitive indicator of changes in organic matter and soil quality.	Sparling (1992)

In terms of ecological and management implications, the four systems represent contrasting states of soil functional stability. The forest system exhibits highly regulated metabolic control but remains potentially sensitive to changes in carbon quality; the cropland system evidences signs of microbial stress and lower ecological efficiency, consistent with anthropogenic disturbances; the pasture system suggests a transition toward a more balanced state, with greater coupling between available carbon and biological activity; while the fallow system reflects recovery processes in which microbial biomass and metabolic efficiency begin to restructure. These results reinforce the paradigm that SBR, in interaction with MBC and qCO_2, constitutes a robust indicator of soil functional status, allowing for the discrimination between degraded, transitioning, and stable systems (Ashraf et al. 2022).

Comparing SBR values between cropland and forest systems in an inter-Andean valley in Peru (Mantaro) and those reported for humid tropical regions reveals that SBR in tropical environments can be two to four times higher. In cropland systems, tropical environments exhibit values ranging from 2.08 to 4.16 mg $C\text{-}CO_2 \cdot kg^{-1} \cdot h^{-1}$, whereas the inter-Andean valley recorded 1.90 mg $C\text{-}CO_2 \cdot kg^{-1} \cdot h^{-1}$. Similarly, in forest systems, tropical values range from 1.45 to 6.54 mg $C\text{-}CO_2 \cdot kg^{-1} \cdot h^{-1}$, compared to 2.85 mg $C\text{-}CO_2 \cdot kg^{-1} \cdot h^{-1}$ in the inter-Andean valley. These patterns are particularly significant in high-Andean ecosystems, in which low temperatures, high altitude, limited water availability, and reduced organic residue input may constrain microbial metabolic activity. Consequently, these factors slow down decomposition processes and organic matter transformation compared to warmer tropical agroecosystems. In this context, land-use changes can exert substantial effects on soil carbon dynamics and stability, highlighting the imperative to integrate local environmental conditions into the design of sustainable management strategies.

CONCLUSION

The results demonstrated that forest and pasture systems promote processes associated with higher microbial activity, carbon transformation, and soil functional stability, whereas the cropland system exhibits lower microbial carbon-use efficiency. These findings consolidate soil respiration, microbial biomass, and active carbon as sensitive indicators for monitoring soil health and guiding management strategies aimed at the sustainability of inter-Andean agroecosystems. Land-use changes modify the ecological mechanisms regulating carbon processing, turnover, and stabilization potential, highlighting the importance of microbiological and respiratory indicators in assessing soil quality.

CC BY

From a management perspective, practices should be oriented toward minimizing soil disturbance, increasing organic inputs, and promoting longer fallow periods to enhance the recovery of soil biological functions.

Since similar processes may operate in other valleys undergoing agricultural intensification, future research should further explore the temporal dynamics of soils under extended fallow periods, integrating enzymatic activities and climatic variables to better understand the mechanisms controlling soil carbon resilience and recovery.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

AUTHORS' CONTRIBUTION

Conceptualization: Yupanqui, F. F. R. and Flores G. S. L. **Methodology:** Yupanqui, F. F. R. **Resources:** Yupanqui, F. F. R. **Investigation:** Yupanqui, F. F. R., Flores G. S. L. and Cruz M. C. P. **Data curation:** Yupanqui, F. F. R., Flores G. S. L. and Cruz M. C. P. **Supervision:** Yupanqui, F. F. R. **Writing – original draft:** Yupanqui, F. F. R., Flores G. S. L. and Cruz M. C. P. **Writing – review and editing**: Yupanqui, F. F. R., Flores G. S. L. and Cruz M. C. P. **Final approval:** Flores G. S. L.

FUNDING

This research was funded by the ExFEDU Program of the Universidad Nacional del Centro del Perú (UNCP). No grant or project number was assigned.

ACKNOWLEDGMENTS

The authors sincerely thank the Universidad Nacional del Centro del Perú and the Laboratorio de Microbiología de Suelos, Facultad de Agronomia, for their institutional and technical support during this research.

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

The authors declare that no artificial intelligence (AI) tools were used for data analysis, interpretation, discussion, or writing of this manuscript.

REFERENCES

Anderson, T. H. (1994). Physiological analysis of microbial communities in soil: applications and limitations. In K. D. Ritz and K. E. Giller (Eds.). Beyond the biomass (p. 67-76). London: British Society of Soil Science.

Anderson, T. H. (2003). Microbial eco-physiological indicators to assess soil quality. Agriculture, Ecosystems and Environment, 98, 285-293. https://doi.org/10.1016/S0167-8809(03)00088-4

Anderson, T. H. and Domsch, K. H. (1985). Determination of ecophysiological maintenance carbon requirements of soil microorganisms in a dormant state. Biology and Fertility of Soils, 1, 81-89. https://doi.org/10.1007/BF00255134

Ashraf, M. N., Waqas, M. A. and Rahman, S. (2022). Microbial metabolic quotient is a dynamic indicator of soil health: trends, implications and perspectives. Eurasian Soil Science, 55, 1794-1803. https://doi.org/10.1134/S1064229322700119

Azevedo, G. A., Silva, T. B., Vilar, F. C. R., Sousa Junior, A. D. O., Lobato, L. M., Lobato, G. M., Costa, C. A. A., Azevedo, J. R., Vieira Neto, G. F., Silva, H. M. S., Santos, C. A. F. and Silva, R. F. (2024). Qualidade do solo em sistemas de produção de hortaliças orgânico e convencional no norte maranhense. Recima21, 5, e565164. https://doi.org/10.47820/recima21.v5i6.5164

Babur, E., Ozlu, E. and Uslu, O. S. (2025). Soil respiration, microbial biomass, and stoichiometry within riparian buffers and adjacent land use. Scientific Reports, 15, 40445. https://doi.org/10.1038/s41598-025-23152-2

Blazier, M. A. and Liechty, H. O. (2016). Assessment of labile organic carbon in soil using sequential fumigation incubation procedures. Journal of Visualized Experiments, 116, e54614. https://doi.org/10.3791/54614

Bongiorno, G., Bünemann, E. K., Oguejiofor, C. U., Meier, J., Gort, G., Comans, R., Mäder, P., Brusaard, L. and de Goede, R. (2019). Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecological Indicators, 99, 38-50. https://doi.org/10.1016/j.ecolind.2018.12.008

Cao, R., Yang, W., Chang, C., Wang, Z., Wang, Q., Jiang, Y., Li, H. and Tan, B. (2021). Soil microbial biomass carbon and freeze-thaw cycles drive seasonal changes in soil microbial quotient along a steep altitudinal gradient. Journal of Geophysical Research: Biogeosciences, 126, e2021JG006325. https://doi.org/10.1029/2021JG006325

Clayton, J., Lemanski, K. and Bonkowski, M. (2021). Shifts in soil microbial stoichiometry and metabolic quotient provide evidence for a critical tipping point at 1% soil organic carbon in an agricultural post-mining chronosequence. Biology and Fertility of Soils, 57, 435-446. https://doi.org/10.1007/s00374-020-01532-2

Comeau, L. P., MacKinley, K., Unc, A. and Vallotton, J. (2023). Ex situ soil respiration assessment using minimally disturbed microcosms and dried–sieved soils; comparison of methods to assess soil health. Canadian Journal of Soil Science, 103, 143-151. https://doi.org/10.1139/cjss-2021-0143

Culman, S. W., Snapp, S. S., Freeman, M. A., Schipanski, M. E., Beniston, J., Lal, R., Drinkwater, L. E., Franzluebbers, A. J., Glover, J. D., Grandey, A. S., Lee, J., Six, J., Mauel, J. E., Mirsky, S. B., Spargo, J. T. and Wander, M. M. (2012). Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Science Society of America Journal, 76, 494-504. https://doi.org/10.2136/sssaj2011.0286

Delgado, J. R. M. (2015). La actividad microbiana: un indicador integral de la calidad del suelo. Luna Azul, 1-6. Available at: https://revistasojs.ucaldas.edu.co/index.php/lunazul/article/view/1503. Accessed on: Aug 10, 2026.

Emran, M., Alfaro-Leranoz, A., Martí-Dalmau, C. and Badía-Villas, D. (2025). Glomalin-related soil protein as an indicator of changes generated by prescribed burning of scrubland in the Central Pyrenees: A ten-year study. Geoderma Regional, 44, e01039. https://doi.org/10.1016/j.geodrs.2025.e01039

Feketeová, Z., Hrabovský, A. and Šimkovic, I. (2021). Microbial features indicating the recovery of soil ecosystem strongly affected by mining and ore processing. International Journal of Environmental Research and Public Health, 18, 3240. https://doi.org/10.3390/ijerph18063240

Fontana, A. and Campos, D. V. B. (2017). Carbono orgânico. In P. C. Teixeira, G. K. Donagemma, A. Fontana and W. G. Teixeira (Eds.). Manual de métodos de análise de solos (p. 360-365). Brasília, DF: Embrapa Solos. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1107196/1/Pt3Cap1Carbonoorganico.pdf

Fonte, S. J., Vanek, S. J., Oyarzun, P., Parsa, S., Quintero, D. C., Rao, I. M. and Lavelle, P. (2012). Pathways to agroecological intensification of soil fertility management by smallholder farmers in the Andean highlands. Advances in Agronomy, 116, 125-184. https://doi.org/10.1016/B978-0-12-394277-7.00004-X

Gayan, A., Borah, P., Nath, D. and Kataki, R. (2023). Soil microbial diversity, soil health and agricultural sustainability. Sustainable Agriculture and the Environment, 107-126. https://doi.org/10.1016/B978-0-323-90500-8.00006-3

Ghorbani, M., Amirahmadi, E., Konvalina, P., Moudrý, J., Kopecký, M. and Hoang, T. N. (2023). Carbon pool dynamic and soil microbial respiration affected by land use alteration: a case study in humid subtropical area. Land, 12, 459. https://doi.org/10.3390/land12020459

Insam, H. and Domsch, K. H. (1988). Relationship between soil organic carbon and microbial biomass on chronosequences of reclamation sites. Microbial Ecology, 15, 177-188. https://doi.org/10.1007/BF02011711

Jagadamma, S., Essington, M. E., Xu, S. and Yin, X. (2019). Total and active soil organic carbon from long-term agricultural management practices in West Tennessee. Agricultural & Environmental Letters, 4, 180062. https://doi.org/10.2134/ael2018.11.0062

Jenkinson, D. S. and Powlson, D. S. (1976). The effects of biocidal treatments on metabolism in soil - I. Fumigation with chloroform. Soil Biology and Biochemistry, 8, 167-177. https://doi.org/10.1016/0038-0717(76)90001-8

Joergensen, R. G. (1996). The fumigation-extraction method to estimate soil microbial biomass: calibration of the kEC value. Soil Biology and Biochemistry, 28, 25-31. https://doi.org/10.1016/0038-0717(95)00102-6

Johnston, A. E., Poulton, P. R. and Coleman, K. (2009). Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. Advances in Agronomy, 101, 1-57. https://doi.org/10.1016/S0065-2113(08)00801-8

Köhl, L., Oehl, F. and van der Heijden, M. G. (2014). Agricultural practices indirectly influence plant productivity and ecosystem services through effects on soil biota. Ecological Applications, 24, 1842-1853. https://doi.org/10.1890/13-1821.1

Lal, R. (2016). Soil health and carbon management. Food Energy Security, 5, 212-222. https://doi.org/10.1002/fes3.96

Li, P., Zhang, Y., Li, C., Chen, Z., Ying, D., Tian, S., Zhao, G., Ye, D., Cheng, C., Wu, C., Zhang, L., Jiao, J. and Hu, F. (2024). Assessing the alteration of soil quality under long-term fertilization management in farmland soil: Integrating a minimum data set and developing new biological indicators. Agronomy, 14, 1552. https://doi.org/10.3390/agronomy14071552

Liptzin, D. L., Norris, C. E., Cappellazzi, S. B., Bean, G. M., Cope, M., Greub, K. L. H., Rieke, E. L., Tracy, P. W., Aberle, E., Ashworth, A. J., Bañuelos Tavarez, O., Bary, A. I., Baumhardt, R. L., Borbón Gracia, A., Brainard, D. C., Brennan, J. R., Briones Reyes, D., Bruhjell, D., Carlyle, C. N., Crawford, J. J. W., Creech, C. F., Culman, S. W., Deen, B., Dell, C. J., Derner, J. D., Ducey, T. F., Duiker, S. W., Dyck, M. F., Ellert, B. H., Entz, M. H., Espinosa Solorio, A., Fonte, S. J., Fonteyne, S., Fortuna, A. M., Foster, J. L., Fultz, L. M., Gamble, A. V., Geddes, C. M., Griffin-LaHue, D., Grove, J. H., Hamilton, S. K., Hao, X., Hayden, Z. D., Honsdorf, N., Howe, J. A., Ippolito, J. A., Johnson, G. A., Kautz, M. A., Kitchen, N. R., Kumar, S., Kurtz, K. S. M., Larney, F. J., Lewis, K. L., Liebman, M., Lopez Ramirez, A., Machado, S., Maharjan, B., Martinez Gamiño, M. A., May, W. E., McClaran, M. P., McDaniel, M. D., Millar, N., Mitchell, J. P., Moore, A. D., Moore, P. A. Jr., Mora Gutiérrez, M., Nelson, K. A., Omondi, E. C., Osborne, S. L., Osorio Alcalá, L., Owens, P., Pena-Yewtukhiw, E. M., Poffenbarger, H. J., Ponce Lira, B., Reeve, J. R., Reinbott, T. M., Reiter, M. S., Ritchey, E. L., Roozeboom, K. L., Rui, Y., Sadeghpour, A., Sainju, U. M., Sanford, G. R., Schillinger, W. F., Schindelbeck, R. R., Schipanski, M. E., Schlegel, A. J., Scow, K. M., Sherrod, L. A., Shober, A. L., Sidhu, S. S., Solís Moya, E., St Luce, M., Strock, J. S., Suyker, A. E., Sykes, V. R., Tao, H., Trujillo Campos, A., Van Eerd, L. L., Van Es, H., Verhulst, N., Vyn, T. J., Wang, Y., Watts, D. B., Wright, D. L., Zhang, T., Morgan, C. L. S. and Honeycutt, C. W. (2022). An evaluation of carbon indicators of soil health in long-term agricultural experiments. Soil Biology and Biochemistry, 172, 108708. https://doi.org/10.1016/j.soilbio.2022.108708

Luo, Z. K., Wang, E. L. and Sun, Q. J. (2010). Soil carbon change and its response to agricultural practices in australian agroecosystems: a review and synthesis. Geoderma, 155, 211-223. https://doi.org/10.1016/j.geoderma.2009.12.012

Madejón, E., Moreno E., Murillo, J. M. and Pelegrín, F. (2007). Soil biochemical response to long-term conservation tillage under semi-arid Mediterranean conditions. Soil and Tillage Research, 94, 346-352. https://doi.org/10.1016/j.still.2006.08.010

Mandal, U. K., Yadav, S. K., Sharma, K. L., Varadharajan, R. and Venkanna, K. (2011). Estimating permanganate-oxidizable active carbon as quick indicator for assessing soil quality under different land-use system of rainfed Alfisols. Indian Journal of Agricultural Sciences, 81, 927-931. https://www.researchgate.net/publication/287463659_Estimating_permanganate-oxidizable_active_carbon_as_quick_indicator_for_assessing_soil_quality_under_different_land-use_system_of_rainfed_Alfisols#fullTextFileContent

Marinari, S., Mancinelli, R., Campiglia, E. and Grego, S. (2006). Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. Ecological Indicators, 6, 701-711. https://doi.org/10.1016/j.ecolind.2005.08.029

Monastersky, R. (2013). Global carbon dioxide levels near worrisome milestone: concentrations of greenhouse gas will soon surpass 400 parts per million at sentinel spot. Nature, 497, 13-14. https://doi.org/10.1038/497013a

Muñoz-Rojas, M., Jordán, A., Zavala, L. M., Rosa, D., Abd-Elmabod, S. K. and Anaya-Romero, M. (2015). Impact of land use and land cover changes on organic carbon stocks in Mediterranean soils (1956-2007). Land Degradation and Development, 26, 168-179. https://doi.org/10.1002/ldr.2194

Nannipieri, P., Ascher, J., Ceccherini, M. T., Landi, L., Pietramellara, G. and Renella, G. (2017). Microbial diversity and soil functions. European Journal of Soil Science, 68, 12-26. https://doi.org/10.1111/ejss.4_12398

Nelson, D. W. and Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston and M. E. Sumner (Eds.). Methods of soil analysis. Part 3. Chemical methods (p. 961-1010). Madison: Wiley. https://doi.org/10.2136/sssabookser5.3.c34

Ordoñez, M., Olaya, J., Galicia, L. and Figueroa, A. (2020). Soil carbon dynamics under pastures in Andean socio-ecosystems of Colombia. Agronomy, 10, 507. https://doi.org/10.3390/agronomy10040507

Pais, I. P., Reboredo, F. H., Ramalho, J. C., Pessoa, M. F., Lidon, F. C. and Silva, M. M. (2020). Potential impacts of climate change on agriculture – A review. Emirates Journal of Food and Agriculture, 32, 397-407. https://doi.org/10.9755/ejfa.2020.v32.i6.2111

Pardo-Plaza, Y. J., Paolini Gómez, J. E. and Cantero-Guevara, M. E. (2019). Biomasa microbiana y respiración basal del suelo bajo sistemas agroforestales con cultivos de café. Revista U.D.C.A Actualidad & Divulgación Científica, 22. https://doi.org/10.31910/rudca.v22.n1.2019.1144

Payán, F., Jones, D. L., Beer, J. and Harmand, J. M. (2009). Soil characteristics below Erythrina poeppigiana in organic and conventional Costa Rican coffee plantations. Agroforestry Systems, 76, 81-93. https://doi.org/10.1007/s10457-008-9201-y

Pinto, L. A. S. R., Lima, S. S., Silva, C. F., Mota Gonçalves, R. G., Sousa Morais, I., Ferreira, R., Silva Junior, W. F., Torres, J. L. R. and Pereira, M. G. (2022). Soil quality indicators in conventional and conservation tillage systems in the Brazilian Cerrado. Environmental Earth Sciences, 81, 306. https://doi.org/10.1007/s12665-022-10426-5

Qu, R., Liu, G., Yue, M., Wang, G., Peng, C., Wang, K. and Gao, X. (2023). Soil temperature, microbial biomass and enzyme activity are the critical factors affecting soil respiration in different soil layers in Ziwuling Mountains, China. Frontiers in Microbiology, 14, 1105723. https://doi.org/10.3389/fmicb.2023.1105723

Rui, Y., Jackson, R. D., Cotrufo, M. F., Sanford, G. R., Spiesman, B. J., Deiss, L., Culman, S. W., Liang, C. and Ruark, M. D. (2022). Persistent soil carbon enhanced in Mollisols by well-managed grasslands but not annual grain or dairy forage cropping systems. Proceedings of the National Academy of Sciences, 119, e2118931119. https://doi.org/10.1073/pnas.2118931119

[SENAMHI] Servicio Nacional de Meteorología e Hidrología del Perú. (2021). Climas del Perú: mapa de clasificación climática nacional. Peru: SENAMHI. Available at: https://www.senamhi.gob.pe/load/file/01404SENA-4.pdf. Accessed on: Aug 10, 2026.

Shi, X. H., Zhang, X. P., Yang, X. M., Drury, C. F., McLaughlin, N. B., Liang, A. Z., Fan, R. Q. and Jia, S. X. (2012). Contribution of winter soil respiration to annual soil CO_2 emission in a Mollisol under different tillage practices in northeast China. Global Biogeochemical Cycles, 26. https://doi.org/10.1029/2011GB004054

Silva, C. F. D., Pereira, M. G., Miguel, D. L., Feitora, J. C. F., Loss, A., Menezes, C. E. G. and Silva, E. M. R. D. (2012). Carbono orgânico total, biomassa microbiana e atividade enzimática do solo de áreas agrícolas, florestais e pastagem no médio Vale do Paraíba do Sul (RJ). Revista Brasileira de Ciência do solo, 36, 1680-1689. https://doi.org/10.1590/S0100-06832012000600002

Singhal, V. K., Ghosh, A., Singh, A. K., Singh, Y., Misra, S., Singh, S. K. and Debnath, S. (2026). Grasses improve soil multifunctionality by strengthening aggregate-carbon-enzyme linkage in semi-arid degraded land. Agriculture, Ecosystems & Environment, 399, 110167. https://doi.org/10.1016/j.agee.2025.110167

Sparling, G. P. (1992). Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. Soil Research, 30, 195-207. https://doi.org/10.1071/SR9920195

Tavares, R. L. and Nahas, E. (2014). Humic fractions of forest, pasture and maize crop soils resulting from microbial activity. Brazilian Journal of Microbiology, 45, 963-969. https://doi.org/10.1590/S1517-83822014000300028

Tian, Q., He, H., Cheng, W., Bai, Z., Wang, Y. and Zhang, X. (2016). Factors controlling soil organic carbon stability along a temperate forest altitudinal gradient. Scientific Reports, 6, 18783. https://doi.org/10.1038/srep18783

Tiwari, S., Singh, C., Boudh, S., Rai, P. K., Kumar, V., Gupta, V. K. and Singh, J. S. (2019). Land use change: A key ecological disturbance declines soil microbial biomass in dry tropical uplands. Journal of Environmental Management, 242, 1-10. https://doi.org/10.1016/j.jenvman.2019.04.052

Tovar, C., Seijmonsbergen, A. C. and Duivenvoorden, J. F. (2013). Monitoring land use and land cover change in mountain regions: an example in the Jalca grasslands of the Peruvian Andes. Landscape and Urban Planning, 112, 40-49. https://doi.org/10.1016/j.landurbplan.2012.12.003

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

Wang, Y., Dong, J., Zheng, X., Zhang, J., Zhou, P., Song, X., Song, W. and Wang, S. (2021). Wheat straw and biochar effect on soil carbon fractions, enzyme activities, and nutrients in a tobacco field. Canadian Journal of Soil Science, 101, 353-364. https://doi.org/10.1139/cjss-2019-0092

Weil, R. R. and Magdoff, F. (2004). Significance of soil organic matter to soil quality and health. In F. Magdoff and R. R. Weil (Eds.). Soil organic matter in sustainable agriculture (p. 1-43). Boca Raton: CRC Press. https://doi.org/10.1201/9780203496374.ch1

Weil, R. R., Islam, K. R., Stine, M. A., Gruver, J. B. and Samson-Liebig, S. E. (2003). Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. American Journal of Alternative Agriculture, 18, 3-17. https://doi.org/10.1079/AJAA200228

Zhang, B., Gao, Q., Xu, S., Ma, L. and Tian, C. (2016). Long-term effect of residue returns and fertilization on microbial biomass and community composition of a clay loam soil. Journal of Agricultural Science, 154, 1051-1061. https://doi.org/10.1017/S0021859615001008

Zhong, Z. M., Shen, Z. X. and Fu, G. (2016). Response of soil respiration to experimental warming in a highland barley of the Tibet. Springer Plus, 5, 137. https://doi.org/10.1186/s40064-016-1761-0