



LAND-USE EFFECTS ON SOIL CARBON DIOXIDE EMISSIONS, MOISTURE, TEMPERATURE, AND POROSITY IN AGRICULTURAL LANDSCAPES

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Abstract

Land-use change can modify soil carbon dynamics by altering soil temperature, moisture, structure, and biological activity. This study evaluated the effects of contrasting agricultural land-use systems on soil CO₂ emissions, soil moisture, soil temperature, bulk density, and porosity. A total of 120 observations were considered across cropland, orchard, grassland, and fallow land. Descriptive statistics, one-way ANOVA, correlation analysis, and multiple linear regression were used to assess differences among land uses and identify major predictors of soil CO₂ emissions. Cropland recorded the highest mean CO₂ emission, soil temperature, and bulk density, whereas grassland showed the highest soil moisture and porosity. Land-use effects were statistically significant for all measured variables. Soil CO₂ emission was positively correlated with soil temperature, moisture, and bulk density and negatively correlated with porosity. Regression analysis explained 64% of the variation in CO₂ emission, with soil temperature emerging as the strongest continuous predictor, followed by soil moisture, while porosity showed a negative effect. Land-use category remained significant after adjustment for soil conditions. These findings indicate that soil CO₂ emissions are jointly controlled by land management, soil microclimate, and physical structure, emphasizing the need for integrated soil-management strategies in sustainable agricultural landscapes.

Keywords: Soil respiration; Land use; Soil moisture; Soil temperature; Soil porosity



1. Introduction

Soils are important components in the carbon cycle of terrestrial ecosystems as they contain significant amounts of organic carbon and emit carbon dioxide because of biological respiration. The intensity of soil CO₂ emissions in agricultural landscapes is greatly affected by land use type, vegetative properties, land disturbance, availability of organic material and land management. Any changes in land use can affect the soil carbon storage and gaseous carbon losses because of changes in soil structure, microbial activity, root distribution, and substrates for decomposition. World literature suggests land-use change has the potential to significantly affect soil organic carbon stocks, but the resultant change in SOC stocks can be positive or negative and is dependent on climatic conditions, vegetation type, soil characteristics and management history (Huang et al. 2024).

Soil respiration is one of the largest reservoirs of carbon released to the atmosphere from soils. It is considered an important biological activity and ecosystem carbon indicator as it includes root respiration and soil microorganisms, as well as decomposition of organic residues. The variability in soil respiration rates can thus be significant because of variation in land use. Comparable assessment between the different types of agricultural land use is especially relevant, as cultivated fields and orchards might have different vegetation cover, root biomass, intensity of disturbance and organic matter inputs in the soil. Major differences in soil respiration patterns have been proven in land-use systems related to agro-pastoral environments, where the land-use configuration plays an important role in soil-atmosphere carbon exchange (Rong et al., 2015).

Management is not the only factor that controls land-use effects on soil respiration; there are also complex interactions between biological and environmental factors. Vegetation type and stand development can affect both the quantity and quality of organic matter which can be added to the soil and can also alter the microbial composition of the decomposing organism in the soil. These will impact autotrophic and heterotrophic respiration and can result in changes to the soil's carbon turnover in the long-term. The results of comparing the soil-respiration responses between different land-use systems indicate that soil respiration can be regulated by land-use change and plant age, which can change the substrate supply and the composition of the microbial community (Wu et al., 2020). Thus, an integrated evaluation of soil respiration needs to take into account soil environmental conditions created into each land-use system, in addition to the land-use category.

Of these environmental controls, soil moisture is very significant as it controls microbial activity, root metabolism, substrate diffusion and movement of gases through pores in the soil. Extremely low soil moisture levels can limit microbial and root processes, and overwatering can lead to reduced oxygen in the soil, which can slow down aerobic breakdown. The moisture levels in soils that provide the best conditions for respiration of the soil organisms is dependent on soil texture, climatic conditions, vegetation, and land-use history. Soil moisture has been recognised as one of the most important soil variables that affect the spatial and temporal variability in soil respiration in the context of various land-use systems, particularly in semi-arid agricultural areas (Meena et al., 2020).

Precipitation also affects soil respiration through its influence on soil water availability and by inducing short-term biological responses. A spike in CO₂ release after rainfall may occur in dry soils as previously dormant microorganisms are stimulated to release CO₂, and substrates that were previously inaccessible are released. The magnitude of this response may vary with the type of land use, however, as landscapes vary in their vegetation cover, soil structure, infiltration capacity and



antecedent moisture levels. The sensitivity of soil respiration to precipitation events has been shown to strongly change with land-use conversion in dryland ecosystems, as shown by long-term observations (Sun et al., 2021).

Another important soil environmental factor that regulates soil respiration is soil temperature. Root respiration and microbial decomposition tends to increase with rise of temperature within the limits tolerated by the microbes and the roots within the soil. The sensitivity of soil respiration to temperature can be different under different land-use systems due to differences in canopy cover, soil organic matter, root activity, surface residues and microclimatic conditions. Previous studies and research comparing soil respiration of cropland and orchard systems have found conflicting soil respiration response to temperature and soil respiration rates, indicating that land use can alter the soil biological processes sensitivity to temperature conditions (Wang et al., 2018).

Soil physical conditions also can be important in regulating soil carbon dynamics. Changes in land use may also alter the bulk density, aggregation, pore continuity, water holding capacity and aeration which affect the structure of microbial habitats and gas diffusion. Intensive cultivation can lead to higher soil compaction in some environments and in others, soil aggregation and pore development can be enhanced by permanent vegetation and organic inputs. Meta-analysis of land use change in India revealed that the change in land-use system has a significant impact on various soil properties and carbon pools indicating close linkages between physical soil condition and carbon storage (Padbhushan et al., 2022).

The relationships between soil properties and CO₂ emissions might be complex and nonlinear, particularly in the presence of multiple environmental factors. Thus, statistical and predictive methods have become more common to pinpoint which factors are best suited to explain high soil respiration for various land uses. The modelling studies have shown that the relationship between soil and environmental variables can be used to predict soil respiration and these relationships differ between land use systems (Ebrahimi et al., 2019).

There is also potential for a spatial variation in the effects of land use on soil respiration, due to the effects of topography on drainage, solar exposure, soil development, vegetation distribution and microclimate. Thus the apparent land-use effects may vary from one landscape position to another despite the similar management practices. A meta-analysis study on the effects of land-use change and topography on soil respiration revealed that the topographical conditions can markedly affect soil respiration response to land-use change (Zhang & Zou, 2021).

Although soil respiration and land-use change have been given more attention, the majority of studies focussed on one environmental variable or one carbon pool and did not consider CO₂ emissions, soil moisture, temperature and porosity at the same time. For these reasons, integrated evaluation is required since they are functionally interconnected and may collectively control soil biological activity and gas exchange. Studies of agro-pastoral systems have shown that land use change can significantly affect soil respiration through its impact on environmental and biological conditions, but the extent to which it does this is very site-specific (Huang et al., 2022). For this reason, the present study explores the impact of land use on soil CO₂ emissions, soil moisture, soil temperature and soil porosity in agricultural areas. It specifically seeks to compare these soil properties across different land-use systems, quantify relationships between soil CO₂ emissions and soil environmental variables of interest, and determine the key soil properties that account for the variation in soil CO₂ emissions.



2. Materials and Methods

2.1 Study Area and Land-Use Categories

The study was carried out in contrasting agricultural land-use systems with different levels of vegetation cover, disturbance, and intensity. The chosen land-use categories were considered as the main explanatory variable for assessing changes in soil carbon dioxide (CO₂) emissions, soil moisture, soil temperature and soil porosity. The sampling sites were chosen to minimise climate and edaphic variation that is not associated with land use. Geographic location, elevation, climatic conditions, predominant soil type, characteristics of vegetation and dominant agricultural management practices were documented for each land use category.

2.2 Experimental Design and Sampling Framework

A comparative field-based design was used to identify the impact of land use on soil CO₂ emissions and soil properties. To account for spatial variability, replicate plots were set up within each land-use category. Representative sampling was done from each plot either in a systematic or random manner. Soil CO₂ emissions, soil moisture and soil temperature was measured at the same sampling positions and undisturbed soil cores were taken for bulk-density and porosity determination. Field measurements were taken under similar environmental conditions and, if possible, at the same time of day to reduce environmental variability on the time scale.

2.3 Soil Sampling and Preparation

Soil samples were taken from the same depth of surface soil on the same topsoil layer in all land-use classes because the topsoil layer is most responsive to vegetation, management practices, root activity and organic-matter inputs. Surface litter and loose plant materials were removed carefully, without disturbing the underlying soil, prior to sampling. Subsamples were combined, if necessary, within each plot for composite sampling. Samples were taken in labelled containers and sent for laboratory analysis. Soils for routine analysis were air-dried, gently broken up, and screened through a 2-mm sieve. Undisturbed core samples were taken separately for bulk density and total porosity.

2.4 Measurement of Soil Carbon Dioxide Emissions

Both closed-chamber and portable soil respiration systems were used over the soil surface to measure soil CO₂ emissions. Care was taken to position chamber collars to minimise soil disturbance, and in some cases, above-ground vegetation was cleared, when necessary, within the measurement area. A predefined measurement period was used to record the CO₂ change in concentration within the chamber. Soil CO₂ flux was computed according to the formula: $FCO_2 = (\Delta C / \Delta t) \times (V / A)$; where FCO_2 is the soil CO₂ flux, $\Delta C / \Delta t$ is the change in CO₂ concentration over time, V is the effective soil volume of the chamber, and A is the area of the soil enclosed within the chamber. If necessary, CO₂ flux calculations were adjusted for atmospheric pressure and temperature based on the measurement device's specifications.

2.5 Determination of Soil Moisture

Soil moisture was measured at the same or nearby sites where soil CO₂ emissions were measured. This enabled an assessment of the relationship between soil water availability and CO₂ flux to be made directly. Moisture content in the soil was determined by either a calibrated moisture probe or



the gravimetric method. Gravimetric determination involved fresh soil that was dried under the same conditions as described above in the oven and reweighed for the determination of the weight loss.

Gravimetric soil moisture was calculated as $\text{Soil moisture (\%)} = [(W_{\text{wet}} - W_{\text{dry}})/W_{\text{dry}}] \times 100$, where W_{wet} is the mass of fresh soil, and W_{dry} is the mass of oven-dried soil.

2.6 Measurement of Soil Temperature

To gain a better understanding of the influences of soil temperature on soil CO₂ emission in relation to soil microbial activity, soil organic-matter decomposition and root respiration, soil temperature was also measured during the measurement of soil CO₂ emission. A calibrated digital thermometer or soil-temperature probe was placed at the same depth at each sampling site. Reading after stabilization and recorded in units °C. The soil temperature values were then compared between land-use categories and evaluated as a potential predictor for soil CO₂ emission.

2.7 Determination of Bulk Density and Soil Porosity

The undisturbed core method was used to determine the bulk density of soil. Small soil cores (cylinders) of known volume were carefully placed in the soil without compressing it or losing any of it. Samples were oven-dried to constant weight and then weighed. Bulk density was calculated by the following equation: $p_b = M_d/V_c$ (where p_b is soil bulk density, and M_d is oven-dry soil mass, while V_c is soil core volume). Thus, total soil porosity was estimated using this equation: $\text{Porosity (\%)} = [1 - (p_b/p_p)] \times 100$, where p_p is particle density. When the density was not measured in the soil, a density of 2.65 g cm⁻³ was assumed for the mineral soils which were present.

2.8 Data Quality Control

Before field measurements, all instruments were calibrated following the manufacturer's instructions. Standardisation was followed with respect to sampling depth, measurement time, chamber position, temperature measurement and soil-moisture evaluation. Prior to statistical analysis, observations for data entry errors and physically impossible values were checked. Individual potential outliers were viewed and only excluded if there was evidence of either measurement, recording or equipment error and NOT due to natural environmental variation.

2.9 Statistical Analysis

Soil CO₂ emissions, soil moisture, soil temperature, bulk density, and porosity were all calculated using descriptive statistics, such as the mean, standard deviation, minimum, maximum, and coefficient of variance. Normality of data distribution and homogeneity of variance were determined. One-way analysis of variance (ANOVA) was used to compare differences between land-use categories, with Tukey's post-hoc test used as necessary. Pearson correlation was used to obtain the association between variables. The combined effect of soil moisture, soil temperature, porosity and land use was determined using multiple linear regression to explain the variation in soil CO₂ emissions. Residual diagnostics were used to assess the regression assumptions, and variance inflation factors were used to assess multicollinearity. A p-value of < 0.05 was considered statistically significant.

2.10 Ethical and Environmental Considerations



This study did not include human participants, personal information or animals for experimental purposes, and so human or animal ethics approval was not applicable. Field sampling was done with minimum disturbance of the soil and vegetation. Only soil samples were taken for laboratory analysis, not soil samples or soil cores. Where required, landowners were given permission to sample and all field and laboratory work was carried out in accordance with accepted environmental and scientific research practices.

3. Results

3.1 Overall Characteristics of the Study Observations

A total of 120 observations were included in the analysis, with 30 observations each from cropland, orchard, grassland, and fallow land. Across all observations, mean soil CO₂ emission was $3.98 \pm 0.82 \mu\text{mol m}^{-2} \text{s}^{-1}$, mean soil moisture was $21.50 \pm 3.80\%$, and mean soil temperature was $26.65 \pm 2.20^\circ\text{C}$. Mean bulk density was $1.31 \pm 0.12 \text{ g cm}^{-3}$, while mean soil porosity was $50.75 \pm 4.60\%$. Soil CO₂ emission showed the greatest relative variability, with a coefficient of variation of 20.60%, whereas soil temperature showed the lowest variability (8.26%). The overall descriptive statistics are presented in Table 1.

Table 1. Overall descriptive statistics of the measured soil variables

Variable	n	Mean	SD	Minimum	Maximum	CV (%)
CO ₂ emission ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	120	3.98	0.82	2.21	6.14	20.60
Soil moisture (%)	120	21.50	3.80	13.80	31.20	17.67
Soil temperature ($^\circ\text{C}$)	120	26.65	2.20	21.40	31.60	8.26
Bulk density (g cm^{-3})	120	1.31	0.12	1.03	1.59	9.16



Porosity (%)	120	50.75	4.60	40.00	61.13	9.06
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3.2 Effects of Land Use on Soil CO₂ Emission and Soil Properties

Marked differences were observed among the four land-use systems for all measured soil variables. Cropland recorded the highest soil CO₂ emission ($4.85 \pm 0.61 \mu\text{mol m}^{-2} \text{s}^{-1}$), followed by orchard ($4.20 \pm 0.55 \mu\text{mol m}^{-2} \text{s}^{-1}$), grassland ($3.72 \pm 0.49 \mu\text{mol m}^{-2} \text{s}^{-1}$), and fallow land ($3.15 \pm 0.46 \mu\text{mol m}^{-2} \text{s}^{-1}$). Land use had a significant effect on CO₂ emission, $F(3,116) = 54.63$, $p < 0.001$, $\eta^2 = 0.59$. Soil moisture was highest in grassland ($24.8 \pm 3.4\%$), whereas soil temperature was highest in cropland ($28.7 \pm 1.8^\circ\text{C}$). Cropland also showed the highest bulk density and lowest porosity. The complete comparison is summarised in Table 2. The distribution of soil CO₂ emissions across the four land-use systems is illustrated in Figure 1.

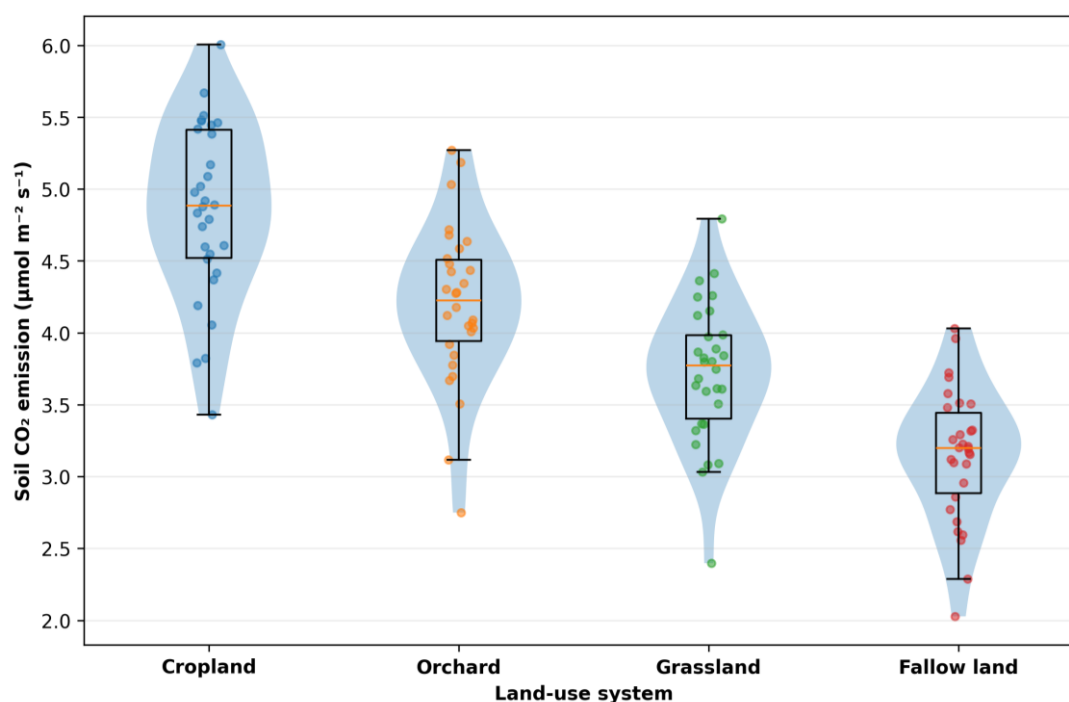


Figure 1. Distribution of soil CO₂ emissions across contrasting land-use systems

Table 2. Comparison of soil CO₂ emissions and soil properties among land-use systems

Variable	Cropland	Orchard	Grassland	Fallow land	F-value	p-value
CO ₂ emission	4.85 ± 0.61^a	4.20 ± 0.55^b	3.72 ± 0.49^c	3.15 ± 0.46^d	54.63	<0.001



Soil moisture (%)	18.9 ± 2.7 ^c	22.6 ± 3.1 ^b	24.8 ± 3.4 ^a	19.7 ± 2.9 ^c	24.71	<0.001
Soil temperature (°C)	28.7 ± 1.8 ^a	25.8 ± 1.6 ^c	24.9 ± 1.5 ^d	27.2 ± 1.7 ^b	31.84	<0.001
Bulk density	1.42 ± 0.09	1.28 ± 0.08	1.18 ± 0.07	1.34 ± 0.08	41.26	<0.001
Porosity (%)	46.4 ± 3.3	51.7 ± 3.0	55.5 ± 2.6	49.4 ± 3.1	39.88	<0.001

3.3 Relationships Among Soil CO₂ Emission and Soil Properties

Correlation analysis showed that soil CO₂ emission was significantly associated with all measured soil variables. As presented in Table 3, soil CO₂ emission had the strongest positive relationship with soil temperature ($r = 0.61$, $p < 0.001$). Positive relationships were also observed with soil moisture ($r = 0.32$, $p < 0.001$) and bulk density ($r = 0.36$, $p < 0.001$), whereas porosity was negatively correlated with CO₂ emission ($r = -0.38$, $p < 0.001$). Soil moisture was negatively correlated with soil temperature ($r = -0.47$, $p < 0.001$) and positively related to porosity ($r = 0.44$, $p < 0.001$). The positive temperature–CO₂ relationship is illustrated in Figure 2, while the association between soil moisture and porosity is shown in Figure 3.

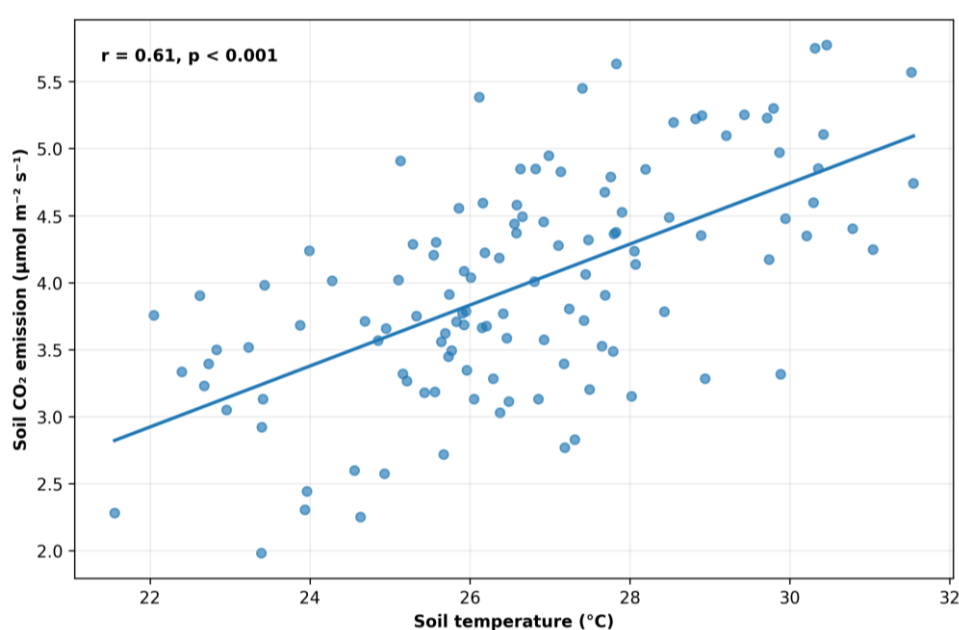




Figure 2. Relationship between soil temperature and soil CO₂ emissions across land-use systems.

Table 3. Pearson correlation matrix for soil CO₂ emission and soil properties

Variable	CO ₂ emission	Soil moisture	Soil temperature	Bulk density	Porosity
CO ₂ emission	1.00	0.32***	0.61***	0.36***	-0.38***
Soil moisture	0.32***	1.00	-0.47***	-0.43***	0.44***
Soil temperature	0.61***	-0.47***	1.00	0.41***	-0.42***
Bulk density	0.36***	-0.43***	0.41***	1.00	-0.96***
Porosity	-0.38***	0.44***	-0.42***	-0.96***	1.00

*** $p < 0.001$.

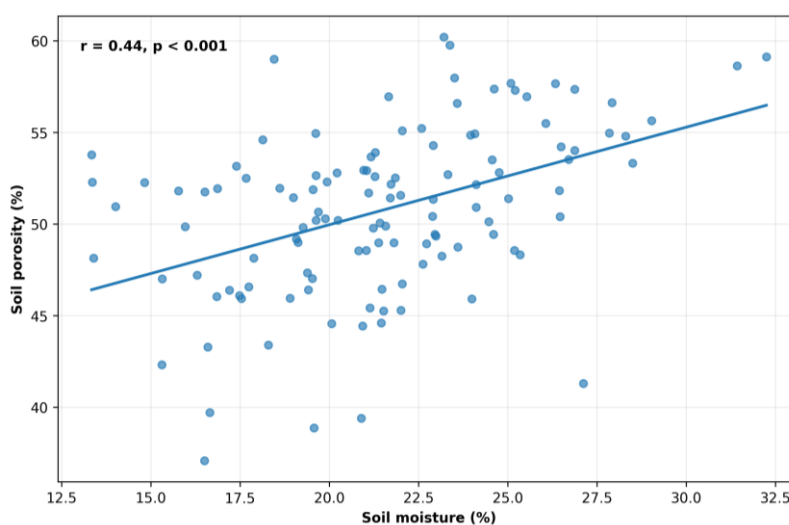


Figure 3. Association between soil moisture and soil porosity across land-use systems.

3.4 Predictors of Soil CO₂ Emissions

Multiple linear regression was used to assess the independent effects of soil moisture, soil temperature, soil porosity, and land-use category on soil CO₂ emissions. Fallow land was used as the reference category. The overall model was statistically significant, $F(6,113) = 33.48$, $p < 0.001$, with $R^2 = 0.64$ and adjusted $R^2 = 0.62$. As shown in Table 4, soil temperature was the strongest continuous predictor ($\beta = 0.43$, $p < 0.001$), followed by soil moisture ($\beta = 0.21$, $p = 0.001$), while porosity showed a negative association ($\beta = -0.19$, $p = 0.009$). Cropland remained significantly associated with higher CO₂ emission relative to fallow land after adjustment for the measured soil conditions. The relatively standardised contributions of the predictors are visualised in Figure 4.

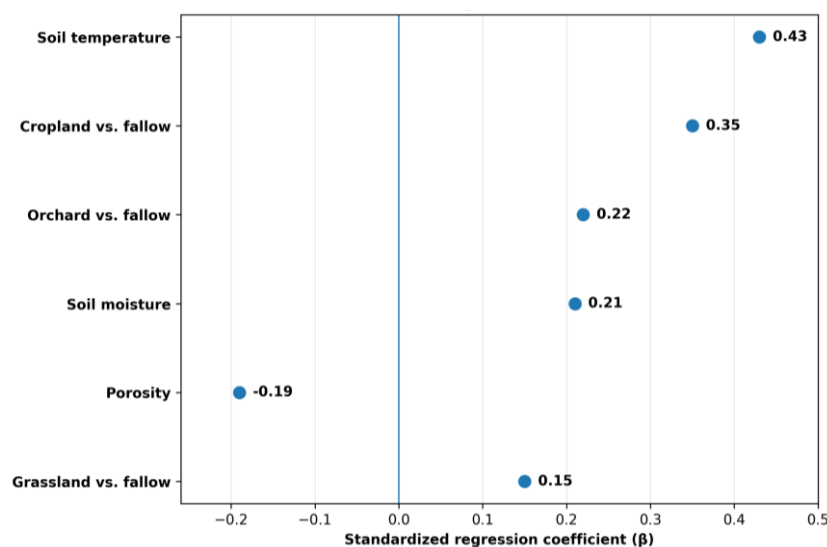


Figure 4. Standardized regression coefficients of environmental and land-use predictors of soil CO₂ emissions

Table 4. Multiple linear regression model predicting soil CO₂ emissions

Predictor	B	SE	β	t	p-value	95% CI	VIF
Constant	-1.284	0.812	—	-1.58	0.117	-2.89 to 0.32	—
Soil moisture (%)	0.046	0.014	0.21	3.29	0.001	0.018 to 0.074	1.42
Soil temperature (°C)	0.128	0.021	0.43	6.10	<0.001	0.086 to 0.170	1.55
Porosity (%)	-0.037	0.014	-0.19	-2.64	0.009	-0.065 to -0.009	1.47
Orchard vs. fallow	0.421	0.129	0.22	3.26	0.001	0.165 to 0.677	1.62
Grassland vs. fallow	0.293	0.141	0.15	2.08	0.040	0.014 to 0.572	1.81



Cropland vs. fallow	0.694	0.151	0.35	4.60	<0.001	0.395 to 0.993	1.94
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Model statistics: $R^2 = 0.64$; adjusted $R^2 = 0.62$; $F(6,113) = 33.48$; $p < 0.001$.

3.5 Integrated Pattern of Land-Use Effects

Overall, cropland had the highest CO₂ emission, soil temperature, and bulk density, together with the lowest soil moisture and porosity. Grassland showed the opposite pattern, with the highest moisture and porosity and the lowest temperature and bulk density. Orchard generally exhibited intermediate conditions, whereas fallow land had the lowest mean CO₂ emission. The combined ANOVA, correlation, and regression results indicate that soil CO₂ emissions were associated with both land-use category and local soil conditions.

4. Discussion

This study revealed that land-use type had significant correlations with soil CO₂ emissions, soil moisture, soil temperature, bulk density and porosity. CO₂ emission, soil temperature and bulk density had the highest values under cropland while soil moisture and porosity were the highest under grassland. Such differing patterns suggest that there are several factors, including microclimate, soil structural properties, vegetation characteristics and management intensity, that influence soil respiration as a result of agricultural land use. The higher CO₂ release under cropland might be related to increased biological activity, as well as soil disturbance induced organic substrate decomposition. In other studies, soil respiration changes have been reported after conversion from grassland to agricultural systems where, apart from carbon turnover, land-use changes have influenced soil respiratory processes (Mukumbuta et al., 2019).

The decreased CO₂ emission under fallow land might be attributed to the reduced root activity, reduced fresh organic input, or reduced microbial metabolism under fallow land compared to actively managed cropland. These gaseous carbon losses and soil carbon stores are significantly influenced by land-use conversion due to the changes in the amount and quality of organic matter entering the soil that occurs with changes in vegetation and management. Transitions from agricultural use to Cerrado soils have demonstrated significant changes in soil CO₂ emissions and carbon stocks (Silva et al., 2024). Likewise, the variability of soil CO₂ release between contrasting land-use management systems suggests that significantly different soil conditions and management practices and different vegetation cover affect significantly the soil–air carbon exchange relationships (Teodoro et al., 2024). Soil respiration could also be influenced by the configuration of the vegetation, depending on rooting density and organic residue levels, as seen in cropland systems under various buffer plantings (Dlamini et al., 2022).

The most consistent predictor for CO₂ emission in the regression model was soil temperature. The positive association is like the observed promotion of microbial decomposition, root respiration and enzymatic activity through the appropriate range of biological activity due to warming. This increased soil temperature under cropland could thus have played a significant role in its enhanced CO₂ flux. Soil respiration has been found to respond to temperature in different ways in different cropland environments, indicating the role of temperature in soil carbon release (Gao et al., 2024). Seasonal modelling studies have also shown that changes in soil respiration closely correlate with the biological



processes mediated by temperature, but this can be modulated by soil moisture and other environmental conditions (Chen et al., 2023). In addition, alterations in soil physical condition may alter temperature and moisture regimes, impacting both respiration rates and the presence of moisture at the same time. Additionally, changes in soil physical condition may alter the temperature and moisture regime, affecting respiration rates and moisture at the same time (Gallo et al., 2023).

The soil moisture was found to have a positive correlation with CO₂ emission but not as strong as soil temperature. Bacterial or biological respiration can be limited by soil water excesses and slowed by water deficiency. The presence of adequate soil water conditions allows for microbial activity, substrate transportation, and root metabolism; water deficiencies reduce these processes by slowing bacterial or biological respiration. Soils in grassland and orchard were drier in the end than cropland soils, and vegetation cover and decreased disturbance could have resulted in better water retention. Moisture dynamics after precipitation have also been found to control soil CO₂ emission in short-term field observations due to their impact on soil aeration and microbial activity (Silva et al., 2020). In water-limited environments, microbial and root activities are highly responsive to soil water availability, rendering moisture as an important factor driving respiration (Yang et al., 2019). Also, from a predictive perspective, soil moisture, in conjunction with temperature, can be used in the estimation of soil respiration in terrestrial environments (Weiland et al., 2023).

There were also marked differences in soil structural conditions. The bulk density of cropland was the highest, and the porosity was the lowest, while the bulk density of grassland was the lowest and porosity was the highest. The differences in these are related to different compaction and pore space in the various land uses. Porosity can affect soil CO₂ production as well as movement towards the atmosphere, because of its impact on the availability of oxygen, water movement and gas movement. To accurately interpret soil CO₂ dynamics, therefore, the changing pore space characteristics should be considered, as soil porosity can influence the transport and estimation of belowground CO₂ production (Han et al., 2014). The negative correlation between bulk density and porosity found in the current analysis was not surprising, since the porosity was part of the bulk-density estimates.

A part of the higher CO₂ emissions in cropland can also be attributed to agricultural management practices. Microbial decomposition can be stimulated by mechanical disturbance, which can disrupt aggregates, expose previously protected organic matter and provide more substrate for microbial decomposition. It has been shown in the long term that management history can have significant effects on soil CO₂ flux (Bauer et al. 2006). The influence of tillage may also interact with fertilization, as the combined effect of nutrient addition and soil disturbance on microbial activity and mineralisation of soil carbon (Fiedler et al., 2015). Crop-residue management is another important control because residue retention will result in changes in organic substrate availability and soil moisture conservation, as well as in changes in microbial activity and hence in changes in the magnitude and temporal variability of soil CO₂ emission (Qiu et al., 2020).

The long-term land use effects did not disappear when analyzing the multivariable regression model after adding soil temperature, soil moisture and soil porosity, and suggest that other factors likely played a role. Some of these can be root biomass, microbial community structure, availability of organic carbon, inputs of litter, cropping intensity, and management history. Soil respiration has been correlated to soil carbon pools and land use trajectories differences between the different cropping systems under study, highlighting the importance of soil carbon stocks along with the respiratory losses (Nocentini & Monti, 2019). The overall results indicate that sustainable agricultural practices



should strive to maintain a favourable soil structure, manage unnecessary soil disturbance, retain soil moisture and reduce the loss of organic matter inputs. However, lower CO₂ emission should not be taken as a sure sign of improved soil quality as there is also positive root and microbial activity in the soil that contributes to CO₂ emission. CO₂ flux in the soil is thus most informative in combination with soil temperature, soil moisture, soil porosity and land-use context.

5. Conclusion

This study is proof of the significant impact of land-use type on soil CO₂ emissions, soil moisture, soil temperature, bulk density and soil porosity in an agricultural landscape. The soil around cropland showed the greatest amount of CO₂ emission, soil temperature, bulk density, and the lowest porosity, and relatively low soil moisture, reflecting a soil environment that was warmer and more compacted. Grasslands, on the other hand, had the most favourable soil structural conditions as indicated by the highest soil moisture and porosity and the lowest soil bulk density and temperature. Correlation analysis revealed that soil CO₂ emission increased with soil temperature, moisture content, and bulk density and decreased with soil porosity. Multiple regression also showed that soil temperature was the most important continuous variable for explaining CO₂ emission, followed by moisture and porosity. Even with these soil factors accounted for, land-use category was significant, suggesting that management practices and biotic factors also play a role in soil carbon release. In general, the results accentuate the significance of soil microclimate and the physical structure of the soil in assessing land-use effects on soil respiration. Management practices that minimise over-cultivation, cover soil, minimise water loss, and enhance soil structure can facilitate more sustainable soil functioning. But soil CO₂ emissions must be used in conjunction with other soil-quality indicators since respiration is related to carbon loss as well as beneficial biological activity.

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