Temporal Dynamics of Carbon Dioxide (CO_2) Fluxes In Swamp Paddy Fields Based On Cultivation Age

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Abstract.
Understanding the dynamics of carbon dioxide (CO_2) fluxes in lebak swamp paddy fields is important for assessing carbon cycling under different land-use histories. This study investigated CO_2 fluxes and their relationships with soil environmental properties across different land-use ages in Pelabuhan Dalam Village, Ogan Ilir, South Sumatra. Three land-use ages were evaluated, 0 years, representing uncultivated swamp as the baseline, 6 and 12 years of continuous paddy cultivation. CO_2 fluxes were measured in the field along with soil temperature, soil water content (SWC), electrical conductivity (EC), pH, soil organic carbon (SOC), bulk density, soil porosity, and soil permeability. CO_2 flux showed a nonlinear pattern, with mean values of 1.42 ± 1.29, 5.97 ± 1.29, and 4.27 ± 1.29 for (0, 6, and 12 year) land-use ages, respectively. However, differences among land-use ages were not statistically significant. Among the measured environmental variables, SOC showed a significant relationship with CO_2 flux (R^2 = 0.59, p = 0.015), while bulk density, soil porosity, SWC, soil permeability, pH, and EC were not significantly associated with CO_2 flux ($p > 0.05$). Strong correlations were observed among soil physical properties, particularly between bulk density and soil porosity ($r = -1.00$). These findings indicate that land-use age alone does not directly determine CO_2 flux, while changes in soil characteristics, particularly SOC, are associated with CO_2 dynamics in lebak swamp paddy fields. The findings provide a basis for evaluating soil carbon dynamics and supporting sustainable management of cultivated lebak swamp ecosystems.
Keywords: *CO_2 flux, Paddy field age, Soil organic carbon, and Swamp.*

I. INTRODUCTION

Rice cultivation is an important component of global food production and a significant source of greenhouse gas (GHG) emissions from agricultural ecosystems. Flooded rice fields are particularly relevant to the global carbon cycle because their alternating anaerobic and aerobic conditions regulate carbon transformation and gaseous carbon losses [1]. Carbon dioxide (CO_2) is released primarily through soil and root respiration, microbial decomposition of organic matter, and the mineralization of soil carbon, whereas methane (CH_4) is mainly produced under anaerobic conditions [2]. The magnitude of CO_2 emissions from paddy soils is influenced by a combination of soil physicochemical properties, water availability, organic matter dynamics, and cultivation practices [3], [4]. Quantifying CO_2 fluxes and understanding their environmental controls are therefore essential for evaluating carbon dynamics in wetland agricultural systems.

Lebak swamps are inland freshwater wetlands that are widely distributed across Indonesia and have increasingly been utilized for rice cultivation to support agricultural production. The conversion of swamp areas into paddy fields and their subsequent long-term cultivation can alter soil properties and hydrological conditions, potentially affecting carbon cycling and soil respiration [5]. In these systems, seasonal fluctuations in water levels can periodically shift soil conditions between aerobic and anaerobic states, while repeated cultivation may modify soil organic matter, nutrient availability, bulk density, and other properties that regulate microbial activity [6], [7]. Consequently, the duration of continuous rice cultivation may influence the magnitude and temporal variability of CO_2 fluxes from lebak swamp soils.

Changes in soil physicochemical properties need to be examined alongside land-use duration because the length of cultivation does not directly determine CO_2 fluxes but may alter soil conditions that regulate soil respiration and organic matter decomposition [8]. Soil Organic Carbon (SOC) is an important carbon source for microbial activity and organic matter decomposition; therefore, changes in SOC content may affect substrate availability for soil respiration. Soil temperature regulates microbial activity and decomposition rates,

whereas bulk density and porosity reflect changes in soil structure associated with pore space, aeration, and water movement [9]. In addition, soil texture determines the proportions of sand, silt, and clay, which influence water retention, permeability, aeration, and organic matter stabilization [10]. In paddy soils, flooding, drying, and tillage can alter soil physical and biogeochemical conditions, thereby affecting the carbon cycle [3]. Therefore, examining land-use duration in conjunction with SOC, soil temperature, bulk density, porosity, and soil texture is necessary to determine whether variations in CO_2 fluxes are more closely associated with the duration of land use or with the accompanying changes in soil properties [11].

Although previous studies have documented the effects of agricultural land use and cultivation practices on soil carbon dynamics and GHG emissions, information on the relationship between cultivation age and CO_2 fluxes in tropical lebak swamp paddy fields remains limited [12]. Most studies of GHG emissions from rice cultivation have focused on CH_4, whereas the response of soil CO_2 fluxes to prolonged cultivation in tropical swamp environments has received comparatively less attention [13], [14]. In particular, it remains unclear whether differences in cultivation age are associated with consistent changes in CO_2 fluxes and which soil and environmental variables best explain these variations. Addressing this knowledge gap is important for improving the understanding of carbon cycling in agricultural systems established on tropical freshwater wetlands.

This study investigated the temporal dynamics of soil CO_2 fluxes in lebak swamp paddy fields with different cultivation ages in Pelabuhan Dalam, Ogan Ilir, South Sumatra, Indonesia. The study aimed to compare soil CO_2 fluxes across paddy fields with different cultivation ages, characterize variations in selected soil physicochemical properties associated with cultivation age, and identify the environmental variables regulating soil CO_2 fluxes using linear mixed-effects models. We hypothesized that cultivation age would influence soil CO_2 fluxes through changes in soil physicochemical properties and environmental conditions associated with prolonged rice cultivation.

II. METHODS

Study Site and Experimental Design

The study was conducted in a non-tidal swamp (rawa lebak) ecosystem in August 2026 in the rawa lebak rice field area of Pelabuhan Dalam Village, Pemulutan Subdistrict, Ogan Ilir Regency, South Sumatra (-3.09604, 104.745), which as a whole has a humid tropical climate (Type B) with an average annual temperature of 24°C and an average elevation of 5 meters above sea level (Fig. 1).



Fig. 1. Map of Rice Fields Location for CO_2 Flux Monitoring

Plot Instrumentation and Soil Collars

A space for time substitution (*chronosequence*) approach to evaluate the impact of continuous paddy cultivation on greenhouse gas emissions. Instead of monitoring a single site over a decade, we selected multiple independent sites within the non-tidal swamp ecosystem of Ogan Ilir, South Sumatra. These sites were carefully categorized into three distinct land-use ages based on historical records of cultivation: 0-years (uncultivated swamp as the baseline), 6-years, and 12-years of continuous paddy cultivation. To minimize spatial confounding factors, all selected chronosequence sites were located within the same climatic zone,

shared identical initial soil types (mineral swamp soil), and had similar topographical features prior to agricultural conversion. Therefore, the duration of cultivation (land-use age) is considered the primary driver of the observed differences in soil physicochemical properties and gas fluxes.

Evaluating the impact of continuous paddy cultivation on greenhouse gas (GHG) emissions was carried out by placing soil collars at each land-use age, placing 3 plots as observation points, so that there were a total of 9 observation points. To ensure accurate flux measurements and isolate specific ecosystem activities, permanently fixed circular collars were utilized at each plot. These collars, made from 8-inch-diameter PVC pipes, are installed at a depth of ±10 cm into the soil to create a tight physical seal, preventing gas leakage during sampling (Fig. 2). Flux measurements using the LICOR LI-7810 CH4/CO2/H2O Trace Gas Analyzer integrated with Stevens HydraProb. The LI-COR Smart Chamber has a diameter of: (8 inches, thickness 6 mm, chamber volume: 4244.1 cm^3, ground surface area: 317.8 cm^2 (49.3 $inches^2$) [15].

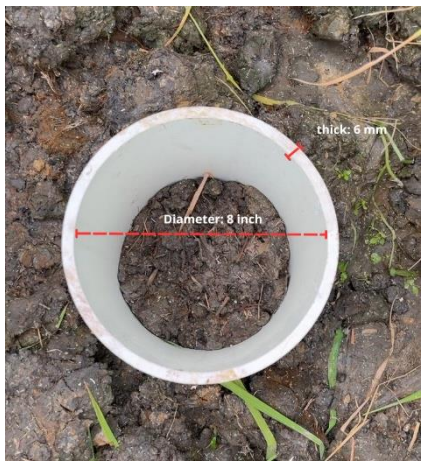


Fig. 2. PVC ring collar (Source: primary research data)

Gas Analysis and Flux Measurement

Carbon Dioxide flux emission was conducted once on August 2026 (Dry seasons). This instrument utilizes Optical Feedback – Cavity Enhanced Absorption Spectroscopy (OF-CEAS) to sample gas concentrations at a frequency of 1 Hz. The analyzer operates at a flow rate of 250 standard cubic centimeters per minute (approximately 0.25 L), resulting in an estimated dead band of 30 seconds based on the following calculation. Each data point was measured four repetition to ensure data consistency, with each measurement lasting 150 seconds, followed by a 20-second post-purge to restore ambient gas conditions before proceeding to the next repetition (Fig. 3).

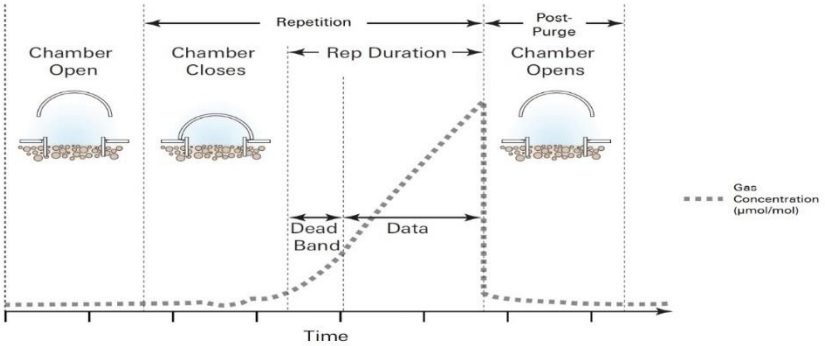


Fig. 3. Schematic diagram of the automated closed-chamber measurement cycle for soil gas flux [15]

The survey measurement cycle

When the Smart Chamber is placed on a soil collar, it will remain open until the measurement is started. When the measurement is started, the bellows pump closes the chamber. Upon closing, the instrument begins logging data, and the dead band starts. The instrument continues to record data for the length of the repetition, and then the chamber opens and pauses for the extra duration. At this point, the measurement cycle is repeated

for the specified number of repetitions or the Smart Chamber is removed from the soil collar and taken to a different collar for a new measurement.

Soil Physicochemical Analysis

To assess the environmental controls on GHG fluxes and understand the sustainability implications of land-use change, key soil physicochemical parameters were measured across all land-use age categories. These included bulk density and porosity (gravimetric method), hydraulic permeability (falling-head permeability test), soil pH (H_2O electrode method), soil organic carbon (Walkley and Black method), and soil texture (hydrometer method). To minimize the impact of physical disturbances on the soil microenvironment, sampling and measurements were conducted only after a sufficient recovery period following any significant field activity were measured across all land-use age categories to assess the environmental controls on GHG fluxes. Soil temperature, soil water content (SWC), electrical conductivity (EC) utilized the Stevens HydraProbe, which connected with LICOR LI-7810. To minimize the impact of physical disturbances between sampling, measurements were performed only after a sufficient recovery period following significant disturbance.

Data Processing and Flux Calculation

To ensure accuracy, a 30-second exclusion period correction at the start and end to avoid measurement instability. This was to cover the dead-band and account for initial pressure changes and fluctuations that may be caused by placing or removing the chamber on the collar, ensuring the headspace air is fully mixed and stable before the regression fit begins.

Then visual inspection of each measurement window was made during the data processing stage to ensure the regression line followed the change in concentration and validate the measurement against the expected direction. This allowed us to identify erroneous fluxes due to chamber leakages or sensor instability and further inspect them in detail.

The measured fluxes were transitioned from raw gas concentrations to mass-based flux densities. To convert the rate of change in gas concentrations into a standardized flux density, SoilFluxPro software (version 5.4.1) was used, which applies the ideal gas law in its mass balance equation.

$$F_C = \left(\frac{PH}{RT}\right)\left(\frac{dC}{dt}\right)$$

Where, FC = carbon dioxide flux (ton ha^{-1} $year^{-1}$), P = atmospheric pressure (Pa), H = chamber height (cm), R = gas constant (8.314 J mol^{-1} K^{-1}), dC/dt = rate of change in CO_2 concentration [16]; [17]).

All statistical analysis were performed in R (version 4.3.3) utilizing differences in CO_2 and CH_4 fluxes between land-use age categories were analyzed using Welch's two-sample t-test to account for potential unequal variances, providing a more robust evaluation for ecological field data. A Pearson correlation test was conducted to determine the relationship between soil properties and CO_2 gas release in swampy rice fields with varying paddy ages. Linear regression analysis was also conducted to determine the extent of the influence of Soil Physicochemicals.

III. RESULT AND DISCUSSION

Differences in CO_2 Flux and Soil Properties Across Land-Use Ages

The results of Welch's t-tests for CO_2 flux, electrical conductivity (EC), and soil water content (SWC) are presented in Fig. 4. CO_2 flux differed significantly among land-use ages. A highly significant difference was observed between the 0-year and 6-year sites, whereas the difference between the 0-year and 12-year sites was significant. In contrast, the difference between the 6-year and 12-year sites was not significant. Mean CO_2 flux increased from 1.42 ± 1.29 at 0 years to 5.97 ± 1.29 at 6 years, representing an increase of 4.55. At 12 years, mean CO_2 flux decreased to 4.27 ± 1.29, a reduction of 1.70 compared with the 6-year site, but remained 2.85 higher than that at the 0-year site. These results indicate that the largest change in CO_2 flux occurred between the 0-year and 6-year sites.

EC showed no significant differences across any of the land-use age comparisons. Mean EC increased from 0.0359 ± 0.0139 dS m^{-1} at 0 years to 0.0466 ± 0.0139 dS m^{-1} at 6 years, corresponding to an increase of 0.0107 dS m^{-1}. At 12 years, mean EC decreased slightly to 0.0416 ± 0.0139 dS m^{-1}, representing a decrease of

0.0050 dS m^{-1} relative to the 6-year site, while remaining 0.0057 dS m^{-1} higher than at the 0-year site. Despite these numerical variations, none of the differences was statistically significant.

SWC differed significantly between the 0-year and 6-year sites and highly significantly between the 0-year and 12-year sites. However, the difference between the 6-year and 12-year sites was not significant. Mean SWC increased from 0.247 ± 0.0494 at 0 years to 0.364 ± 0.0494 at 6 years and 0.416 ± 0.0494 at 12 years. This represented increases of 0.117 and 0.169 between the 0-year site and the 6-year and 12-year sites, respectively. Although SWC increased by a further 0.052 between the 6-year and 12-year sites, this difference was not statistically significant.

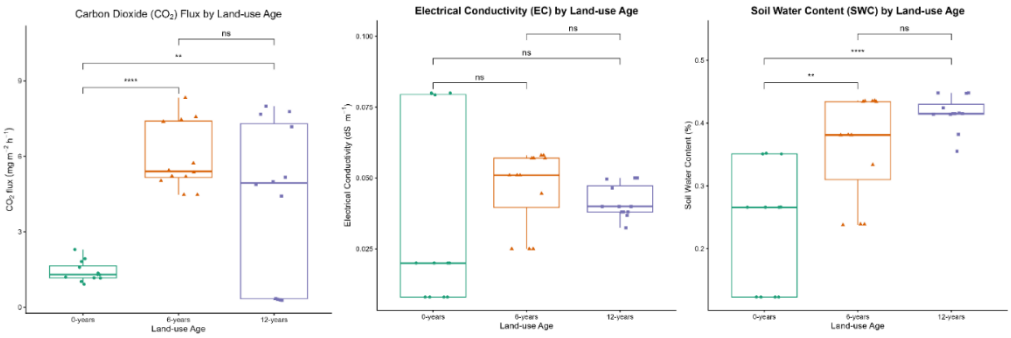


Fig. 4. Results of the Welch's t-test for CO_2 flux, CH_4 flux, EC, and SWC. Asterisks indicate statistical significance ($p < 0.05$, $p < 0.01$, $p < 0.001$, $p < 0.0001$); ns = not significant

Global climate change is the most pressing environmental challenge today, and the agricultural sector and land-use change are major contributors to global greenhouse gas (GHG) emissions [18]. Carbon dioxide (CO2) and methane (CH4) are two major greenhouse gases that contribute significantly to global warming [19], [20]. Rice paddies and wetlands are significant sources of CH4 emissions in tropical regions. Anaerobic conditions due to waterlogging promote methanogenesis by methanogenic archaea in the reductive soil layer, resulting in CH4 flux from the soil to the atmosphere [21], [22]. On the other hand, rice paddies also serve as a source of CO2 through soil respiration and organic matter decomposition, particularly under partially aerobic conditions during low water levels [23]. These two gases collectively contribute to total GHG emissions from rice paddy ecosystems, making their monitoring and quantification crucial. One rice paddy typology in South Sumatra is the lowland swamp.

Periodic flooding follows the tidal patterns of river water and seasonal rainfall, namely dry and rainy seasons. Pelabuhan Dalam Village, Pemulutan District, Ogan Ilir Regency, is an area with stretches of lowland swamps and has long been a location for the development of swamp rice fields by the local community. The uniqueness of this location lies in the presence of rice fields with varying cultivation ages or different printing ages. The existing rice fields range from newly printed rice fields (0 years), medium-aged rice fields (6 years), to rice fields that have been printed and managed for a long time (12 years). These differences in rice field printing ages lead to differences in the physicochemical conditions of the soil, organic matter, and microbial communities, which ultimately affect the amount and pattern of CO2 and CH4 release into the atmosphere [24].

Differences in Soil Physical and Chemical Properties Across Land-Use Ages

As shown in **Fig. 5**, differences among land-use ages were more evident in bulk density and soil porosity than in soil permeability and pH. Mean bulk density increased from 0.821 g cm^{-3} in the 0-year site to 1.046 g cm^{-3} in the 6-year site, before decreasing slightly to 0.994 g cm^{-3} in the 12-year site. Conversely, soil porosity decreased from 69.0% to 60.5%, followed by a slight increase to 62.5%. Significant differences were observed between the 0-year site and both the 6-year and 12-year sites, whereas the differences between the 6-year and 12-year sites were not significant. Soil permeability and pH showed no statistically significant differences among land-use ages, although soil permeability exhibited a numerical decline with increasing land-use age. SOC content increased from 4.12% in the 0-year site to 10.01% in the 6-year site, before declining to 7.89% in the 12-year site.

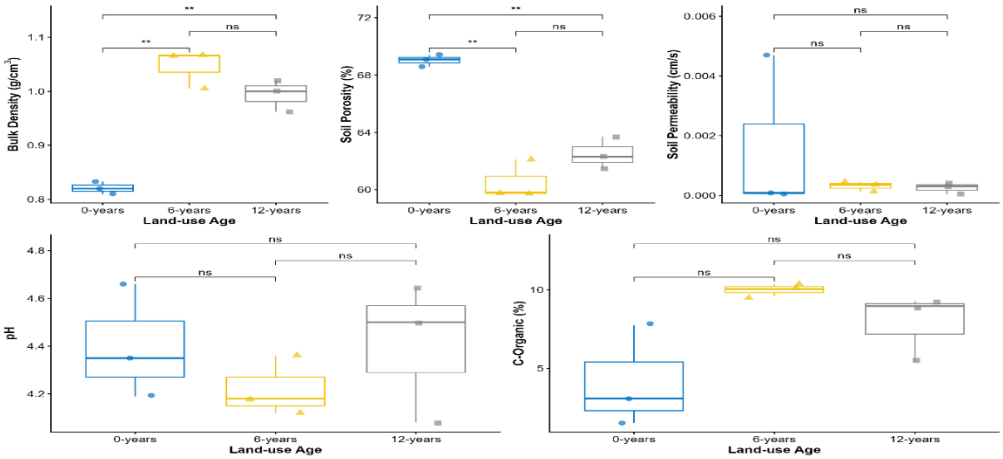


Fig. 5. Results of the Welch's t-test for Bulk Density, Soil Porosity, Soil Permeability, pH, and C-Organik. (* $p < 0.05$; *** $p < 0.001$); ns = not significant.

The study was conducted in the lowland rice fields of Pelabuhan Dalam Village, Pemulutan District, Ogan Ilir Regency, South Sumatra. The study area is a lowland swamp area that has been converted into rice fields and is affected by fluctuations in inundation and groundwater levels. Relatively wet soil conditions can affect the decomposition of organic matter and the activity of soil microorganisms [25]. Based on land use history, the study area consists of rice fields with ages of 0, 6, and 12 years. The 0-year-old land is newly converted into rice fields, while the 6- and 12-year-old land has been used for rice cultivation throughout that period. Differences in land use duration can cause changes in soil characteristics due to cultivation activities, soil processing, and the input and decomposition of crop residues, which can subsequently affect CO_2 flux [26].

Environmental controls of soil CO_2 flux

The results of the linear regression and correlation analyses between CO_2 flux and soil physicochemical properties are presented in Fig. 6. Soil organic carbon (SOC) exhibited a perfect negative correlation with CO_2 flux in the 0-year site (R = −1.00, p = 0.01). However, the relationship was not statistically significant in the 6-year site (R = −0.49, p = 0.67) or the 12-year site (R = 0.95, p = 0.20).

For the other soil properties, bulk density showed correlation coefficients of 0.94, 0.14, and −0.53, while soil porosity showed coefficients of −0.92, −0.16, and 0.52 in the 0-year, 6-year, and 12-year sites, respectively. The correlation coefficients for soil pH were 0.90, 0.80, and 0.91, whereas those for soil permeability were 0.81, 0.99, and 0.57 across the same land-use age groups. Despite the relatively high correlation coefficients observed for some parameters, none of these relationships was statistically significant ($p > 0.05$).

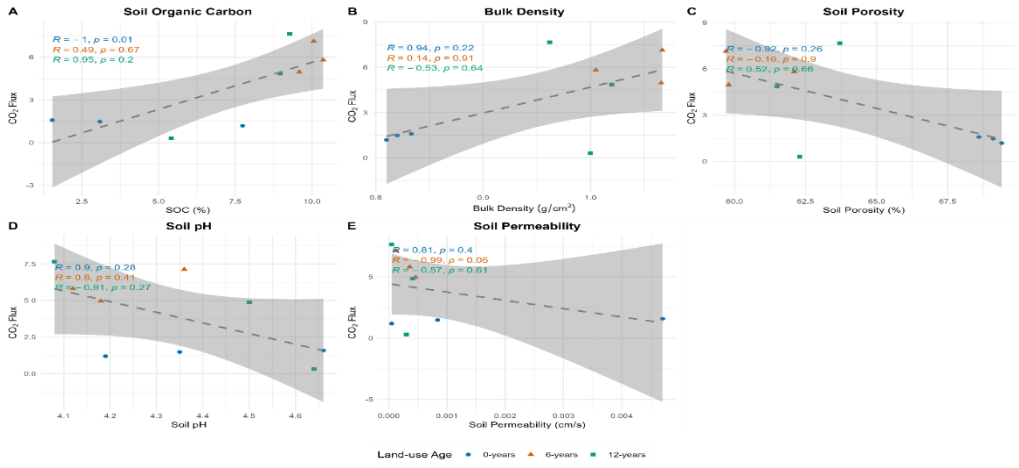


Fig. 6. Linear regression and correlation analysis between soil CO_2 flux and soil physicochemical properties

CO_2 fluxes tended to be lower in 0-year-old land compared to 6-year-old and 12-year-old land. However, the difference between land ages was not significant based on the Tukey test (Table 3). The relatively low CO_2 values in 0-year-old land may be related to soil conditions at the beginning of land clearing. 0-year-old land

has the lowest SOC, lowest soil temperature, lowest bulk density, and highest porosity. These conditions indicate that the soil system in newly cleared land is still different from land that has been managed for several years [27]. Low SOC in 0-year-old land can limit the availability of carbon substrates that can be used by microorganisms for respiration [28]. Furthermore, lower soil temperatures can reduce microbial activity and the rate of organic matter decomposition, resulting in lower CO_2 release from the soil [29]. After 6 years of land use, increased input and accumulation of organic matter from crop residues and cultivation activities can increase carbon availability and soil respiration activity [30], [31]. This is consistent with increased SOC and soil temperature in 6-year-old land, followed by the highest CO_2 flux values.

Effects of Land-Use Age on Soil Physicochemical Properties

The results of the linear regression analysis evaluating the effects of land-use age on soil physicochemical properties are presented in Table 1. Land-use age was significantly associated with soil organic carbon (SOC), which exhibited the highest coefficient of determination ($R^2 = 0.59$, $p = 0.0150$). This indicates that land-use age explained 59% of the variation in SOC. Soil porosity and bulk density had R^2 values of 0.42 and 0.41, respectively, but their relationships with land-use age were not statistically significant ($p = 0.0588$ and $p = 0.0599$, respectively). Similarly, soil pH showed an R^2 of 0.32 ($p = 0.1068$), while soil water content (SWC) and soil permeability each had an R^2 of 0.13 ($p = 0.3308$ and $p = 0.3404$, respectively). Electrical conductivity (EC) exhibited the weakest relationship, with an R^2 of 0.03 ($p = 0.6415$).

Table 1. Effects of land-use age on soil physicochemical properties *(* $p < 0.05$; *** $p < 0.001$); ns = not significant.*

Independent Variable (X)	Regression Equation	R-squared (R2)	P-value
Soil Organic Carbon (%)	$Y = -0.9701 + 0.6619X$	0.59	0.0150*
Bulk Density (g/cm³)	$Y = -12.4532 + 17.1345X$	0.41	0.0599^{ns}
Soil Porosity (%)	$Y = 33.0230 - 0.4551X$	0.42	0.0588^{ns}
Soil Water Content (%)	$Y = 0.5806 + 9.6626X$	0.13	0.3308^{ns}
Soil Permeability (cm/s)	$Y = 4.4364 - 677.0716X$	0.13	0.3404^{ns}
Soil pH	$Y = 35.4773 - 7.2751X$	0.32	0.1068^{ns}
Electrical Conductivity (dS/m)	$Y = 2.9136 + 23.4944X$	0.03	0.6415^{ns}

In 12-year-old fields, CO_2 flux decreased slightly compared to 6-year-old fields, although SOC remained relatively high. This indicates that increasing land age does not linearly increase CO_2 release [32]. CO_2 dynamics are the result of the interaction between carbon availability, temperature, moisture, soil structure, and microbial activity [33]. The most obvious relationship with CO_2 is SOC because organic carbon is the main substrate source for heterotrophic respiration of soil microorganisms [34]. Increased organic carbon availability can provide more material that can be decomposed and converted to CO_2 [35]. Meanwhile, physical parameters such as bulk density and porosity show a tendency towards a relationship with CO_2, but have not yet reached statistical significance. This suggests that the influence of soil physical conditions on CO_2 is likely indirect through changes in aeration, water distribution, and microbial activity [36], [37]. Soil temperature also exhibits an ecologically relevant pattern, as it increases from 0-year-old fields to 6–12-year-old fields. However, based on the presented regression results, this parameter does not appear to be significantly related to CO_2. Therefore, increasing temperature can be used as a supporting explanation, but is not considered a primary controlling factor based on statistical analysis.

Soil Texture Characteristics Across Land-Use Ages

Soil texture characteristics across land-use age groups are presented in Table 2. The sand fraction was highest in the 6-year site (58.40 ± 2.00%), followed by the 0-year site (53.73 ± 1.16%) and the 12-year site (47.73 ± 1.16%). In contrast, the silt fraction was lowest in the 6-year site (12.93 ± 2.08%) and highest in the 12-year site (24.93 ± 3.06%), while the 0-year site had an intermediate value of 20.60 ± 5.13%. The clay fraction was relatively consistent across land-use age groups, ranging from 26.00 ± 4.00% to 28.67 ± 1.15%. The coefficients of variation (CVs) for the soil fractions ranged from 2.16% to 24.90%, with the highest variability observed in the silt fraction of the 0-year site.

Table 2. The effect of soil texture on Land-Use Ages

Land-use Age	Variable	Mean (%)	Standard Deviation	CV (%)
0-years	Sand	53.73	1.16	2.16
	Silt	20.60	5.13	24.90

	Clay	26.00	4.00	15.38
6-years	Sand	58.40	2.00	3.42
	Silt	12.93	2.08	16.08
	Clay	28.67	1.15	4.01
12-years	Sand	47.73	1.16	2.43
	Silt	24.93	3.06	12.27
	Clay	27.33	3.06	11.19

Differences in CO_2 Flux and Soil Properties Across Land-Use Ages

The estimated marginal means (EMMs ± standard errors) and Tukey's post hoc test results for CO_2 flux and soil properties are presented in Table 3. CO_2 flux increased from 1.42 ± 1.29 in the 0-year site to 5.97 ± 1.29 in the 6-year site, before declining to 4.27 ± 1.29 in the 12-year site. However, these differences were not statistically significant among the three land-use age groups. Soil temperature was significantly lower in the 0-year site (30.6 ± 0.187 °C) than in the 6-year (33.4 ± 0.187 °C) and 12-year sites (33.8 ± 0.187 °C). Soil organic carbon (SOC) content increased from 4.12 ± 1.30% in the 0-year site to 10.01 ± 1.30% in the 6-year site, then decreased to 7.89 ± 1.30% in the 12-year site, with a significant difference primarily between the 0-year and 6-year sites. Bulk density was significantly lower in the 0-year site (0.821 ± 0.0159 g cm^{-3}) than in the 6-year (1.046 ± 0.0159 g cm^{-3}) and 12-year sites (0.994 ± 0.0159 g cm^{-3}). Conversely, soil porosity was significantly higher in the 0-year site (69.0 ± 0.601%) than in the 6-year (60.5 ± 0.601%) and 12-year sites (62.5 ± 0.601%).

Soil water content (SWC), electrical conductivity (EC), soil pH, and soil permeability did not differ significantly among the three land-use age groups. Overall, land-use age was associated with significant differences in soil temperature, SOC content, bulk density, and porosity, whereas CO_2 flux and the other measured soil properties showed no statistically significant differences.

Table 3. Estimated marginal means (± SE) and Tukey Grouping of Greenhouse Gas Fluxes and Soil Properties Across Land-Use Ages (α = 0.05)

Variable	0 yr (EMMean ± SE)	6 yr (EMMean ± SE)	12 yr (EMMean ± SE)
CO_2 flux	1.42 ± 1.29 a	5.97 ± 1.29 a	4.27 ± 1.29 a
Soil temperature	30.6 ± 0.187 a	33.4 ± 0.187 b	33.8 ± 0.187 b
SWC	0.247 ± 0.0494 a	0.364 ± 0.0494 a	0.416 ± 0.0494 a
EC	0.0359 ± 0.0139 a	0.0466 ± 0.0139 a	0.0416 ± 0.0139 a
Soil pH	4.38 ± 0.126 a	4.22 ± 0.126 a	4.41 ± 0.126 a
Soil organic C	4.12 ± 1.30 a	10.01 ± 1.30 b	7.89 ± 1.30 ab
Bulk density	0.821 ± 0.0159 a	1.046 ± 0.0159 b	0.994 ± 0.0159 b
Soil porosity	69.0 ± 0.601 b	60.5 ± 0.601 a	62.5 ± 0.601 a
Soil permeability	0.001863 ± 0.000834 a	0.000316 ± 0.000834 a	0.000254 ± 0.000834 a

SOC is a carbon reservoir that provides a substrate for microbial activity and root respiration [38]. As organic carbon content increases, the availability of decomposable organic matter also increases, potentially increasing CO_2 production [34]. The 6-year-old soil had the highest SOC and also exhibited the highest CO_2 flux. However, the relationship was not entirely linear, as the 12-year-old soil had a lower SOC than the 6-year-old soil and also experienced a decrease in CO_2 flux. This suggests that SOC is not the sole factor determining CO_2 flux. Carbon availability, temperature, moisture, aeration, and soil physical conditions can interact to control soil respiration.

Pearson Correlation Matrix of Soil Physicochemical Properties

The Pearson correlation matrix showing the relationships among soil physicochemical properties is presented in Fig. 7. The strongest relationship was observed between bulk density and soil porosity ($r = -1.00$), indicating a perfect negative correlation in the reported data: higher bulk density was associated with lower soil porosity. Bulk density was also strongly positively correlated with soil temperature ($r = 0.89$), whereas soil porosity was strongly negatively correlated with soil temperature ($r = -0.89$). These relationships indicate that higher soil temperatures tended to occur alongside higher bulk density and lower porosity. Together, these correlations highlight the close association among soil temperature, bulk density, and porosity.

In general, positive correlation coefficients indicate that two variables tend to increase or decrease together, whereas negative coefficients indicate an inverse relationship. The magnitude of the coefficient reflects the strength of the linear association, with values closer to +1 or −1 indicating stronger correlations.

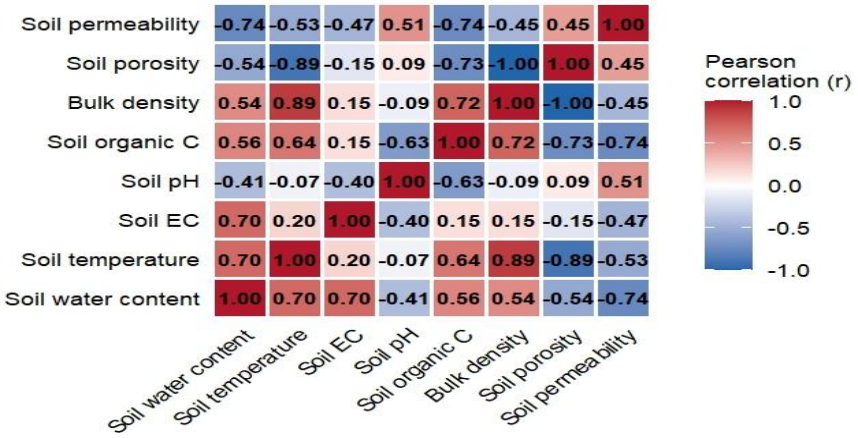


Fig. 7. Pearson correlation matrix among measured soil environmental and physicochemical variables

Correlation results indicate a strong relationship between several soil physical properties. Bulk density and soil porosity had a very strong negative relationship, which is physically consistent with the principle that increasing soil density leads to a reduction in pore space [39]. Bulk density also has a strong positive correlation with soil temperature, while porosity is negatively correlated with soil temperature. This relationship indicates collinearity between soil physical variables. Soils with higher bulk density tend to have lower porosity, which in this dataset is also associated with higher soil temperature [40], [41]. Therefore, changes in one soil physical property can occur simultaneously with changes in other properties.

Differences in soil texture may contribute to this relationship. The 6-year-old soil had the highest sand fraction, while the 12-year-old soil had the lowest sand fraction and the highest silt (Table 2). Textural differences can affect water retention, aeration, permeability, and the protection of organic matter within soil aggregates [10], [42]. Thus, textural characteristics are an important context for understanding the relationship between soil physical properties and CO_2 dynamics.

The increase in CO_2 fluxes in fields managed for 6 and 12 years is inseparable from the increased input and accumulation of organic matter from crop residues and the cultivation activities themselves. This is a highly positive indicator, as it demonstrates that agricultural cultivation practices actively succeed in enhancing Soil Organic Carbon (SOC), which serves as the primary substrate source for the activity of soil-enriching microorganisms. The high SOC content in the cultivated lands (peaking in the 6-year-old fields) proves that the lebak swamp paddy ecosystem is capable of storing essential nutrient reserves.

To realize a more sustainable rice cultivation system, these carbon dynamics can be optimized through the application of site-specific cultivation technologies. Considering that organic carbon availability, temperature, moisture, and soil physical structure interact to control soil respiration, the adoption of precision water management technologies (such as *Alternate Wetting and Drying* or circular water management) can be utilized to maintain a balance between aerobic and anaerobic conditions. Furthermore, organic matter management technologies—such as the application of biofertilizers, biochar, or superior decomposers—can be implemented to stabilize organic carbon within soil aggregates. This technological approach enables farmers to continuously maintain high soil organic carbon levels to support long-term land productivity, while simultaneously controlling the rate of CO_2 emission into the atmosphere without diminishing the intensity of these beneficial agricultural activities.

IV. CONCLUSION

CO_2 flux in lowland swamp rice fields showed distinct patterns based on land use age, with the lowest value at 0 years of age, increasing at 6 years of age, and decreasing again at 12 years of age. However, these

differences were not statistically significant. Among the observed environmental parameters, SOC was significantly associated with CO_2 flux, while bulk density, porosity, SWC, permeability, pH, and EC did not show a significant relationship. The strong relationship between bulk density and porosity suggests a link between soil physical properties that contribute to soil environmental conditions.

Thus, CO_2 flux dynamics are more closely related to changes in soil characteristics, particularly organic carbon availability, rather than the land-use age itself. The implication is that agricultural cultivation activities in lebak swamps play a significant and positive role in enriching organic carbon, which is crucial for the soil health of the ecosystem. These findings open strategic opportunities for the integration of sustainable rice cultivation technologies, such as micro-water management engineering and organic matter stabilization technologies. Through the adoption of these technologies, lebak swamp lands can be managed to preserve organic carbon availability to support high agricultural productivity, thereby realizing climate-smart and environmentally friendly agricultural practices without limiting the sustainability of the community's cultivation activities

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