Jurnal Manajemen Hutan Tropika, *32*(1), 27–39, January 2026
EISSN: 2089-2063
DOI: 10.7226/jtfm.32.1.27

Scientific Article
ISSN: 2087-0469

Soil CO_2 Emissions in Jakarta Urban Forests: The Role of Canopy Cover Versus Environmental Factors

Ade Irma Elvira[1*], Ibrahim Arif[2], Carla Mariana Nainggolan[1], Destia Puri Prela Renita[1], Nadia Asmawari Putri[1], Mufti Petala Patria[1], Erwin Nurdin[1], Ivan Ivanovich Vasenev[2]

[1]Departement of Biology, Faculty of Mathematics and Natural Sciences, Universitas Indonesia, UI Campus Depok, Pondok Cina, Depok, Indonesia 16424
[2]Russian Timiryazev State Agrarian University, Timiryazevskaya Street dom 49, Moscow, Russian Federation 127434

Received August 11, 2024/Accepted July 10, 2025

Abstract

Increasing carbon dioxide (CO_2) emissions encourages global warming and climate change. Soil can store CO_2 emissions, which are absorbed by vegetation. Studies on the dynamics of soil CO_2 gas emission fluxes with differences in the percentage of vegetation canopy cover in the urban forest ecosystem of the Jakarta Region have never been frequently carried out. This research aims to analyze and compare the dynamics of soil CO_2 gas emission fluxes in the urban forest ecosystem of the Jakarta Region with different percentages of vegetation canopy cover and analyze the relationship between air temperature, soil moisture, soil temperature, and soil acidity (pH) with carbon gas emission fluxes soil dioxide. The research method used is the greenhouse gas capture method, which uses a chamber to measure environmental factors and data analysis using the Kruskal-Wallis test and Spearman correlation. The results showed no significant difference between the percentage of vegetation canopy cover in the urban forest ecosystem and the soil CO_2 gas emissions flux. Environmental factors related to the flux of CO_2 emissions from soil in the urban forest ecosystem of the Jakarta Region are soil moisture and soil pH. Further research is recommended to measure other environmental factors, such as nutrients and soil organic carbon, to obtain more comprehensive research results on the dynamics of soil CO_2gas emission fluxes.

Keywords: *soil CO_2 emissions, ecological factors, urban ecosystem, vegetation canopy cover, greenhouse gas capture method*

**Correspondence author, email*: *ade.irma03@office.ui.ac.id, tel.+6221 786 3436, 786 3437, fax. +6221 727 0012*

Introduction

Climate change is a natural phenomenon due to global warming triggered by increasing concentrations of greenhouse gases in the atmosphere in recent decades. This phenomenon has various negative impacts on the environment, threatens living creatures' lives, and has become the center of attention (Perdinan, 2014). According to the United Nations Framework Convention on Climate Change report, adaptation in social, economic, and technological aspects carried out by developing countries increases vulnerability to the impacts of climate change (United Nations Framework Convention on Climate Change, 2007). The leading cause of climate change is the significant increase in greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), resulting from various development activities in various sectors, which have great potential to trigger global warming (Purwanta, 2009). The city of Jakarta, as a center of economic activity and various industries with high mobility and development, faces potential environmental problems, especially climate change, due to infrastructure development, which continues to increase every year. Research with downscaling projections shows that the Jakarta coastal area experiences a yearly temperature increase of around 0.02 °C to 0.04 °C (Suwarman, 2022). This shows that climate change is an environmental issue that must be immediately addressed by society and the government.

Human activities have caused a significant increase in the concentration of greenhouse gases trapped in the atmosphere, impacting climate change. So, with forest vegetation functioning as a carbon store, the role of forests in reducing emissions becomes crucial for further research (Butarbutar, 2009). Fundamental steps in clearing and planting trees on new land can be done by building urban forests. The existence of urban forests helps expand the CO_2 absorption area to reduce greenhouse gas emissions. Some of them are Srengseng Urban Forest in West Jakarta, Cijantung Urban Forest in East Jakarta, Ciganjur Urban Forest in South Jakarta, and Sukapura Urban Forest in North Jakarta.

Previous studies have shown that CO_2 emission flux from soil is greatly influenced by environmental factors such as soil temperature, soil moisture, pH, and vegetation characteristics (Bond-Lamberty & Thomson, 2010; Guntiñas et al., 2013). In addition, canopy cover density also significantly affects soil respiration intensity through its influence on organic matter input and microclimate (Gao et

Jurnal Manajemen Hutan Tropika, *32*(1), 27–39, January 2026
EISSN: 2089-2063
DOI: 10.7226/jtfm.32.1.27
Scientific Article
ISSN: 2087-0469

al., 2018; Jo et al., 2019). However, specific studies examining the interaction between canopy cover and environmental variables on soil CO_2 emission fluctuations in urban forest areas in tropical regions, especially Jakarta, are still minimal. This study is relevant because the Jakarta urban forest area functions as a green open space and a carbon sink amidst high urbanization pressures. The September–October period was chosen because it reflects the transition from the dry season to the rainy season in the Jakarta area, which, ecologically, according to Sarkar et al. (2024), the transition season affects soil moisture, temperature, and micro-organism activity related to the decomposition and soil respiration processes. Therefore, it is important to understand how fluctuations in these factors impact soil CO_2 emissions in urban forests as part of urban climate mitigation strategies.

Research related to the dynamics of soil CO_2 gas emission fluxes in closed, medium, and open vegetation canopy cover in the Srengseng Urban Forest, Cijantung Urban Forest, Ciganjur Urban Forest, and Sukapura Urban Forest ecosystems has never been carried out. Therefore, this research needs to be carried out because it has a vital role in showing the role of vegetation cover in urban forests in releasing CO_2 gas. This study aims to 1) analyze how vegetation canopy cover density affects the dynamics of soil CO_2 emission fluxes and 2) identify environmental factors–such as soil temperature, air temperature, soil moisture, and soil pH–that most significantly affect soil CO_2 emission fluctuations in five urban forest ecosystems in Jakarta. This research hypothesizes that the flux of CO_2 emissions from soil in open vegetation canopy cover is more significant than in closed vegetation canopy cover. A positive relationship exists between soil temperature, air temperature, soil moisture, and soil pH with soil CO_2 gas emissions fluctuations.

Methods

The location of the research station was determined based on forest areas representing various levels of vegetation canopy cover, namely open, semi-open, and closed, using the Canopeo application on a smartphone (Figure 1). This application is used to photograph the vegetation canopy cover at 30 cm from the surface of the chamber base planted in the ground. The research station was determined by stratified random sampling, dividing the area based on the percentage of canopy cover and selecting representative points.

Measurements were taken at nine points representing three types of canopy cover (open: 0–30%, semi-open: 31–60%, and closed: 61–100%), with three points in each category. The parameters measured included soil temperature, soil pH, soil moisture, and air temperature at the CO_2 gas collection location.

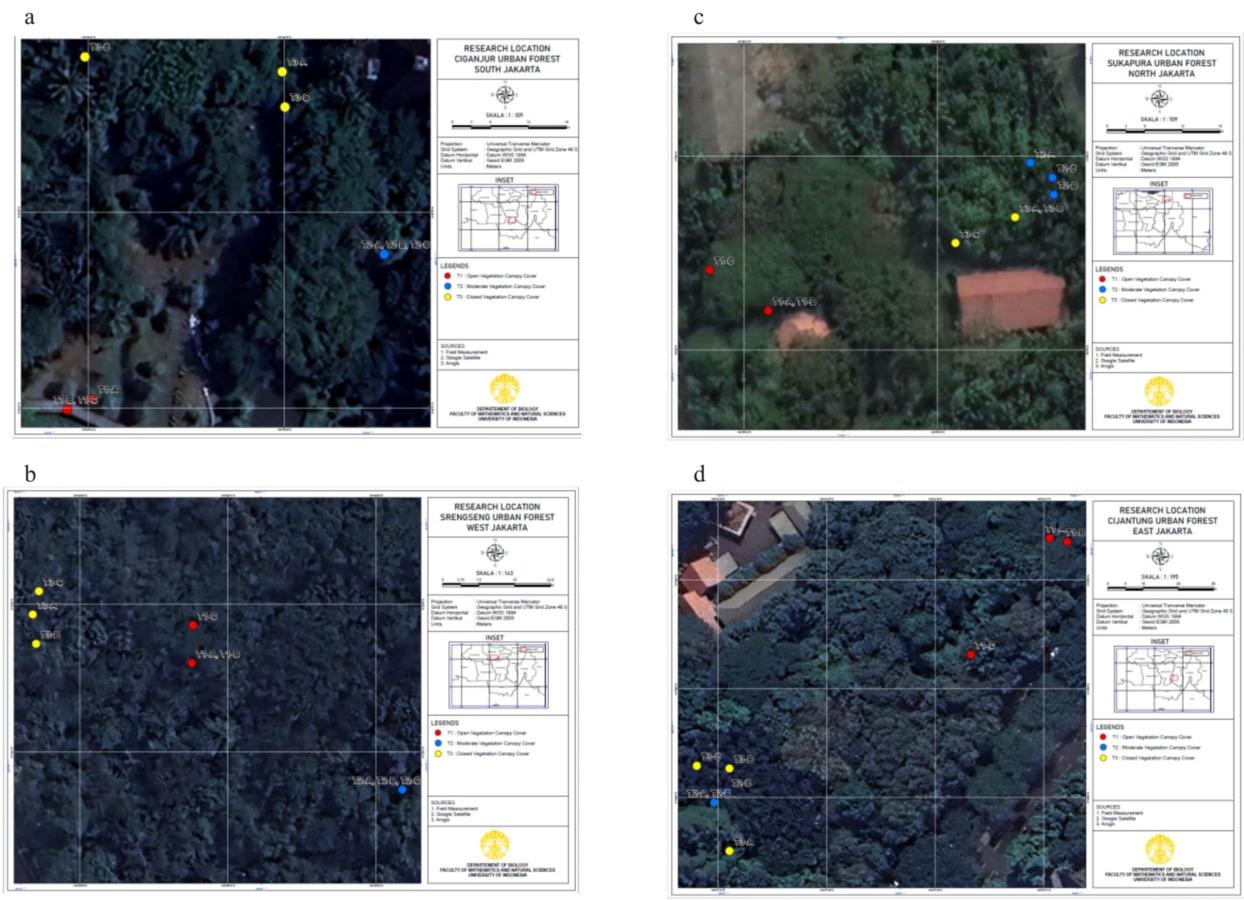

Figure 1 Map of research locations. a) Ciganjur Urban Forest; b) Srengseng Urban Forest; c) Sukapura Urban Forest; d) Cijantung Urban Forest.

The tools used for the measurements include 1) canopeo to measure the percentage of vegetation canopy cover, 2) digital soil analyzer to measure soil temperature, 3) soil pH-moisture meter for soil pH and soil moisture, 4) ThermoPro hygrometer for air temperature, and 5) chamber, stopwatch, camera, and injection for sampling CO_2 gas measured by gas chromatography.

Co_2 gas was collected using the chamber method at 08:00–15:30 Western Indonesian Time for two months, with three repetition points at each location. Sampling was carried out every 10 minutes after the chamber cover was installed. The coordinates of each measurement point were recorded with a timestamp on the smartphone.

The research was carried out in 4 urban forests of the Special Region of Jakarta Province, namely: a) Srengseng Urban Forest, West Jakarta; b) Cijantung Urban Forest, East Jakarta; c) Ciganjur Urban Forest, South Jakarta; and d) Sukapura Urban Forest, North Jakarta.

The research was conducted for six months, namely, from September 2023 to February 2024. Data was collected for two months (September–October 2023) at three research station locations representing urban forest vegetation canopy cover, namely open, semi-open, and closed vegetation canopy cover. Furthermore, three research substations within each research station represent urban forest vegetation canopy cover. Thus, sampling was carried out at 9 location points with coordinates.

The data obtained were analyzed with SPSS 23 using Spearman's rank correlation to measure the relationship between soil CO_2 emission and environmental factors. The results are presented in tabular form and discussed descriptively.

Results

Based on the results of the study conducted in the four forests with different canopy cover, they have varying soil CO_2 gas emission fluxes (Table 1; Figure 2). In the Ciganjur and Sukapura forests, the highest average soil CO_2 emission flux values in open cover were 6.87 g m^{-2} day^{-1} and 3.60 g m^{-2} day^{-1}, while in the Srengseng and Cijanjung forests, the highest average soil CO_2 emission flux values in closed and medium canopies were 4.67 g m^{-2} day^{-1} and 3.60 g m^{-2} day^{-1}. The lowest average soil CO_2 emission flux value was found in the Cijantung forest in closed canopies, 1.99 g m^{-2} day^{-1}.

Environmental factors Overall, the highest average air temperature observation results were in the Ciganjur forest, namely 39.62 °C in open canopy cover, and the lowest

Table 1 Average value of soil CO_2 emission flux in each urban forest

Canopy cover	Average value of soil CO_2 emission flux (g m^{-2} day^{-1})			
	Ciganjur	Srengseng	Sukapura	Cijantung
Open	6.87	3.29	3.60	2.02
Moderate	2.57	3.92	2.68	2.74
Closed	3.21	4.67	2.62	1.99

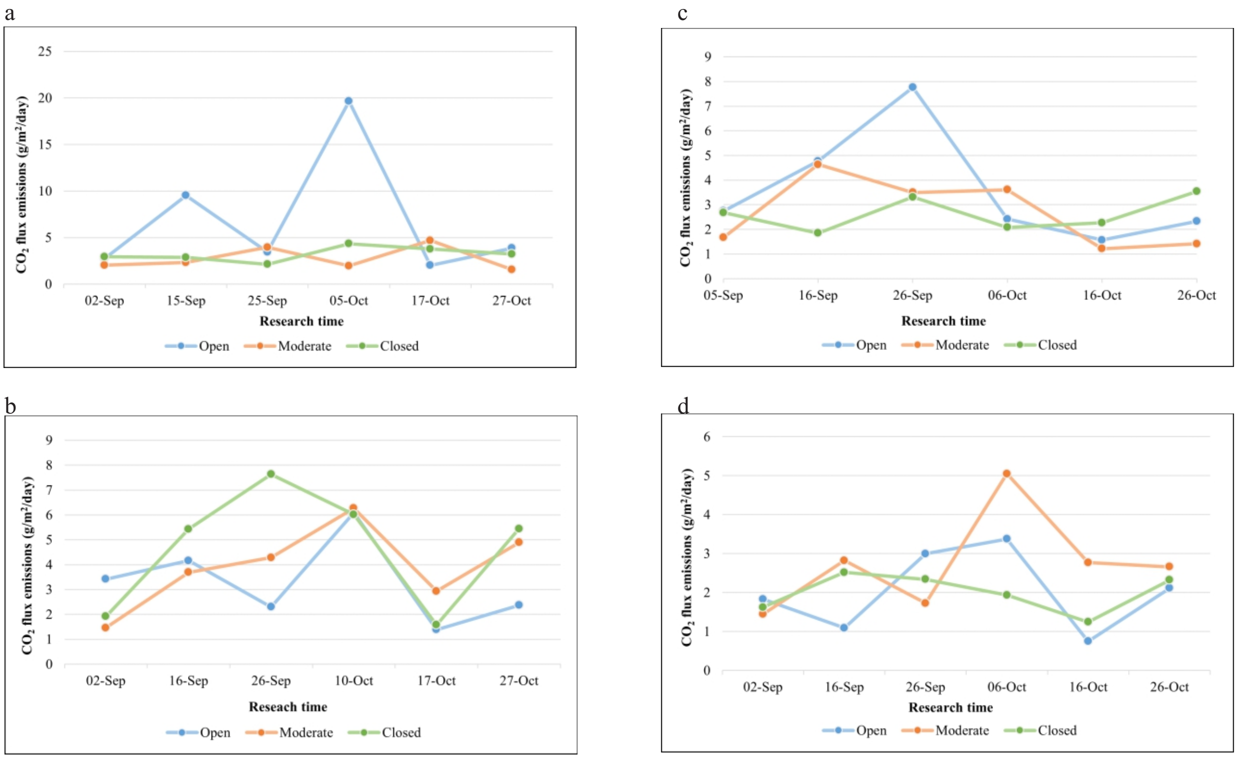

Figure 2 Average value of soil CO_2 emission flux in each urban forest: a) Ciganjur Urban Forest; b) Srengseng Urban Forest; c) Sukapura Urban Forest; and d) Cijantung Urban Forest.

average air temperature was in the Cijantung forest, namely 33.1 °C in closed canopy cover (Table 2; Figure 3).

Air temperature Lowest average air temperature measurements were in the Cijantung forest, namely 33.1 °C in closed canopy cover, and the highest average was in Ciganjur forest, namely 39.6 °C in open canopy cover.

Soil temperature Soil temperature measurements show differences in the average values of the four forests. Where the highest average value is in the Ciganjur forest with a value of 32.80 °C in the open canopy, and the lowest average value is in the closed canopy cover in the Ciganjur forest with a value of 27.40 °C (Table 3; Figure 4).

Soil moisture In general, the soil moisture value in the four urban forests has a range of 11.7–33.2% and is highest in the Ciganjur forest under closed canopy cover (Table 4; Figure 5).

Soil pH Overall, the soil pH recorded in the four urban forests in the Jakarta area tends to have a neutral pH because it is around the pH range of 6.5–7.5 (Table 5; Figure 6).

Correlation Based on the Spearman correlation test results, the correlation significance values between soil CO_2 emission flux, air temperature, and soil temperature were 0.877 and 0.234 (p-value > 0.05) (Table 6). So, it can be interpreted that the soil CO_2 emission flux does not correlate with air temperature or soil temperature. Meanwhile, soil CO_2 emission flux is strongly correlated with soil moisture and pH because it has a significance value of < 0.05.

Table 2 Results of air temperature measurements in each urban forest

Canopy cover	Average value of air temperature (°C)			
	Ciganjur	Srengseng	Sukapura	Cijantung
Open	39.62	33.6	36.4	34.8
Moderate	37.98	33.2	36.0	33.2
Closed	34.33	34.4	34.5	33.1

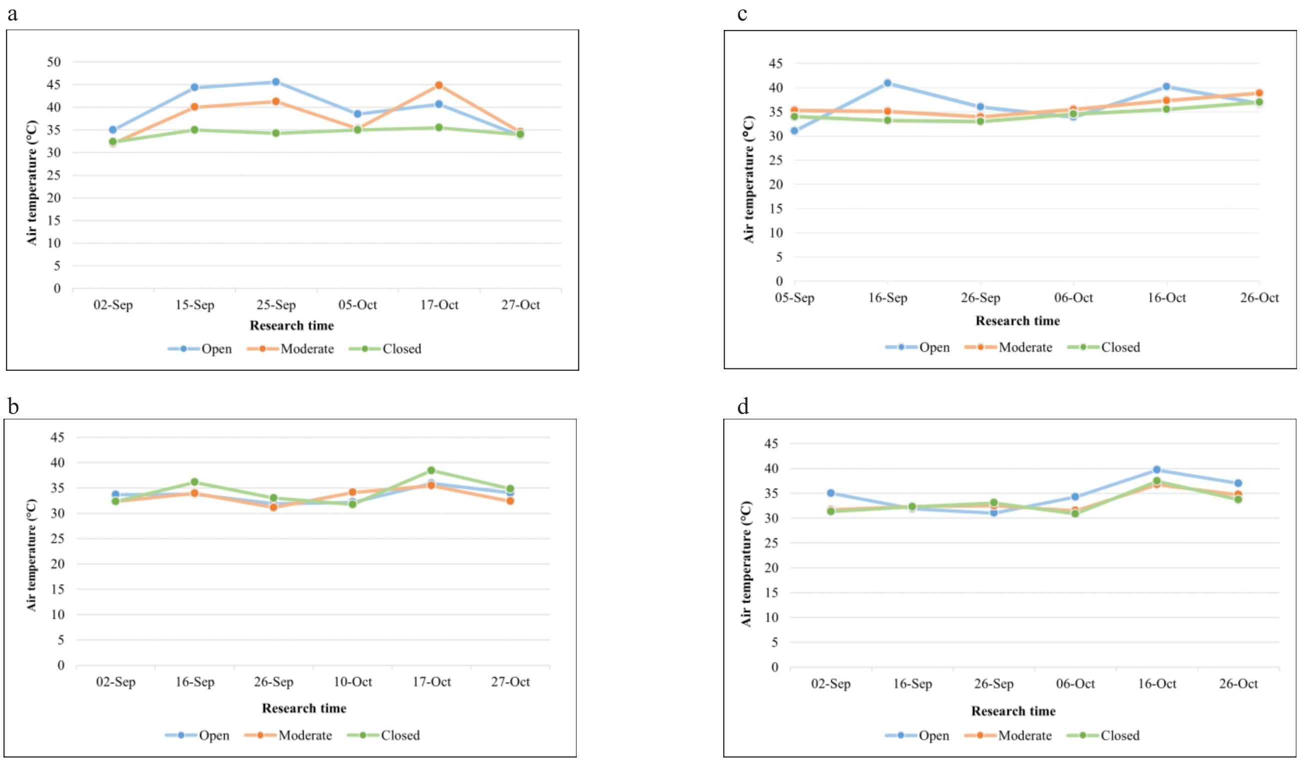

Figure 3 Average value of air temperature measurements in each urban forest: a) Ciganjur Urban Forest; b) Srengseng Urban Forest; c) Sukapura Urban Forest; and d) Cijantung Urban Forest.

Table 3 Results of soil temperature measurements in each urban forest

Canopy cover	Average value of soil temperature (°C)			
	Ciganjur	Srengseng	Sukapura	Cijantung
Open	32.80	30.2	31.9	29.8
Moderate	30.61	28.0	31.3	28.2
Closed	27.40	28.9	30.1	28.1

EISSN: 2089-2063
ISSN: 2087-0469
DOI: 10.7226/jtfm.32.1.27

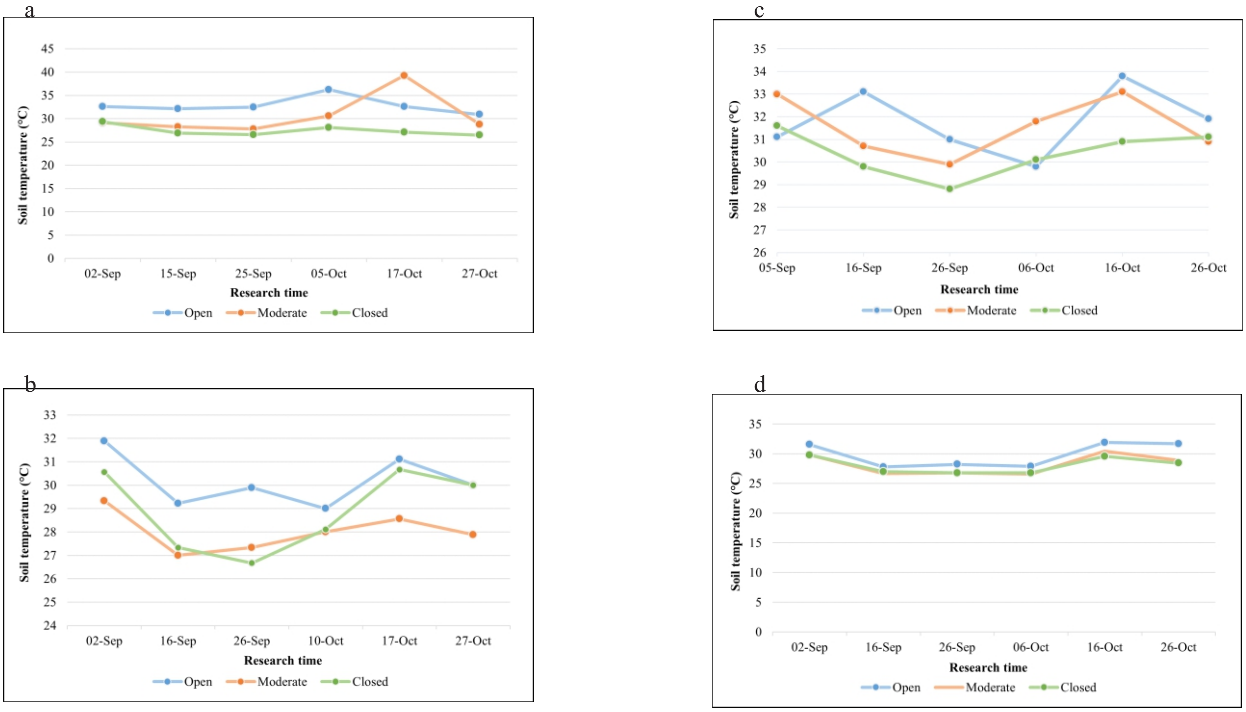

Figure 4 Average value of soil temperature measurements in each urban forest: a) Ciganjur Urban Forest; b) Srengseng Urban Forest; c) Sukapura Urban Forest; and d) Cijantung Urban Forest.

Table 4 Results of soil moisture measurements in each urban forest

Canopy cover	Average value of soil moisture			
	Ciganjur	Srengseng	Sukapura	Cijantung
Open	17.4	18.3	24.6	13.8
Moderate	19.5	18.1	11.7	17.7
Closed	33.2	19.9	11.7	18.8

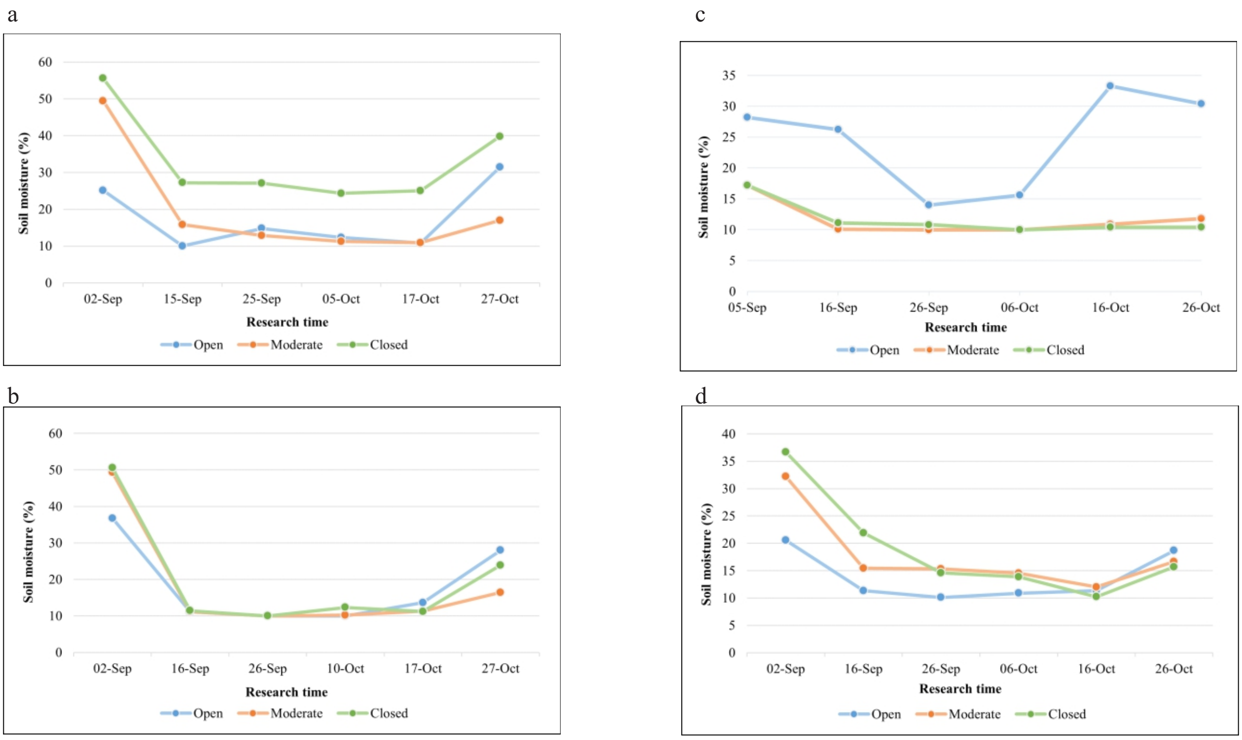

Figure 5 Average value of soil moisture in each urban forest: a) Ciganjur Urban Forest; b) Srengseng Urban Forest; c) Sukapura Urban Forest; and d) Cijantung Urban Forest.

Jurnal Manajemen Hutan Tropika, *32*(1), 27–39, January 2026
EISSN: 2089-2063
DOI: 10.7226/jtfm.32.1.27

Scientific Article
ISSN: 2087-0469

Table 5 Results of soil pH measurements in each urban forest

Canopy cover	Average value of soil moisture			
	Ciganjur	Srengseng	Sukapura	Cijantung
Open	7.0	6.8	6.7	7.0
Moderate	7.0	6.8	7.0	6.9
Closed	6.9	6.9	7.0	6.9

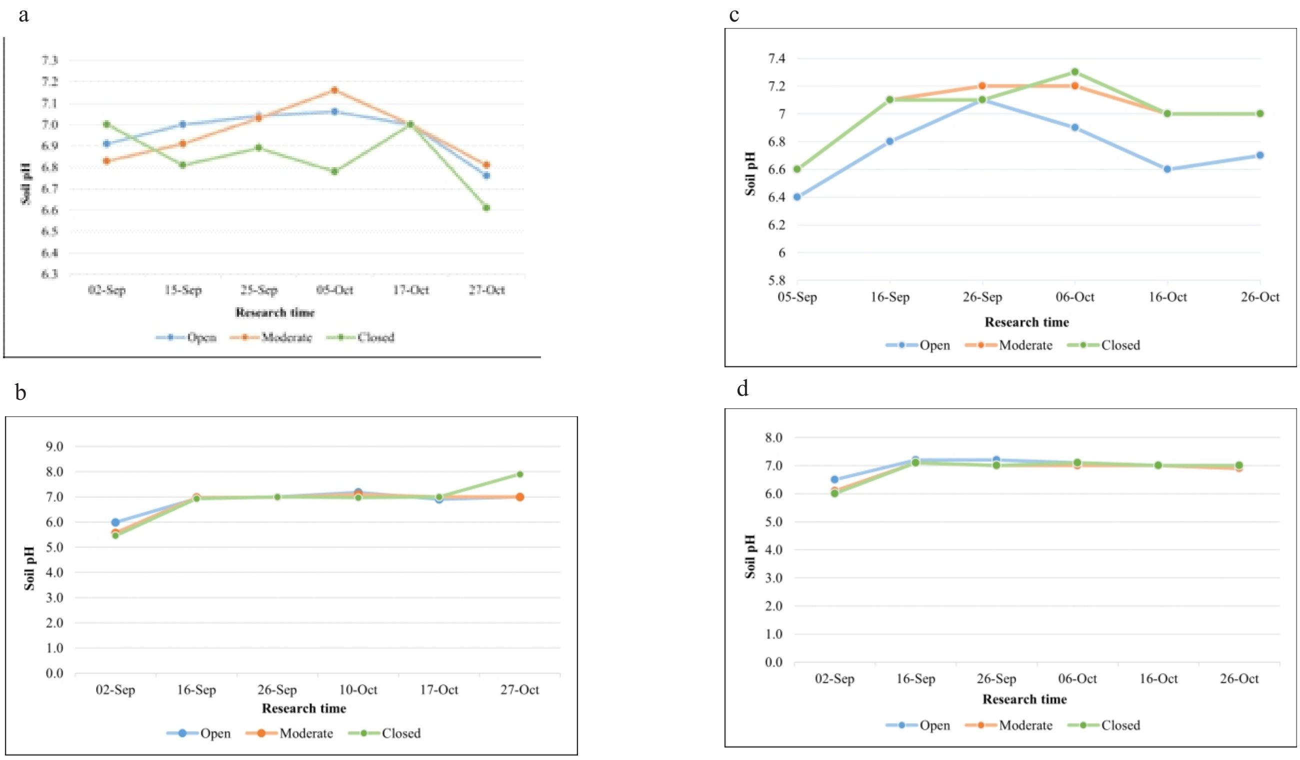

Figure 6 Average value of soil pH in each urban forest: a) Ciganjur Urban Forest; b) Srengseng Urban Forest; c) Sukapura Urban Forest; and d) Cijantung Urban Forest.

Table 5 Correlation of soil CO_2 emission fluxes with environmental parameters with total sample 216

		Air temperature	Soil temperature	Soil moisture	Soil pH
Emission	Correlation coefficient	-0.011	-0.081	0.179^{**}	0.241^{**}
of CO_2	Sig. (2-tailed)	0.877	0.234	0.008	0.000

Discussion

Soil CO_2 emissions fluxes Based on the measurement results in the Ciganjur City Forest, the average value ranking for open vegetation canopy cover was higher than for medium and closed vegetation canopy cover. Meanwhile, the average rank value for closed vegetation canopy cover was greater than for medium vegetation canopy cover. The mean rank value results indicate soil CO_2 gas emission flux variations in each cover category. However, the variation values shown are not large enough to cause significant differences (Irawan & June, 2011; Alhorr et al., 2014; Riyani et al., 2021; Kibet et al., 2022). The results of the highest average CO_2 flux in this open canopy cover are the same as the research conducted by Irawan and June (2011), which was conducted in the forest area in the Lore Lindu National Park, Poso Regency, namely, CO_2 flux in the open canopy with various types of measurements obtained results greater than CO_2 flux in the medium canopy and closed canopy. This is because the soil temperature in the open canopy cover is higher due to the intensity of sunlight entering; the duration of exposure to sunlight will increase the soil temperature below it (Yosep et al., 2017). This increase in soil temperature affects the activity of microorganisms in the rate of metabolism and decomposition of organic matter (Chadirin et al., 2016). In a study conducted by Kartikawati et al. (2017) in tea plantations and fallow land in Cisarua Bogor, the results of soil respiration analysis in tea plantations produced a more significant soil CO_2 emission flux because the number of microorganisms in the soil was more significant than in fallow land. The activity of these microorganisms will produce respiration that generates CO_2, leading to an increase in CO_2 flux. Higher soil temperatures can also increase the stimulation that causes soil respiration to increase (Kartikawati et al., 2017; Man et al., 2021; Amar et al., 2023).

In closed canopy cover, the average flux value produced is higher than moderate canopy cover but not higher than open canopy cover, so it is between the two covers. The flux value at the closed station is relatively high due to the greater vegetation, which causes high root availability. The availability of roots will cause a lot of soil organic carbon through root degradation, which supports nutrient pumping and increases microorganism activity. High carbon concentrations can also be a substrate for microorganisms, which cause faster decomposition, leading to higher emissions of CO_2 from the soil (Kibet et al., 2022). In a study conducted by Kibet et al. (2022), it was explained that the type of vegetation could affect the rate of soil emission in plant roots. Soil CO_2 gas emission flux was higher in agroforestry land than in monoculture plants (corn and sorghum). This is because agroforestry land has the availability of roots that can increase carbon in the soil through root degradation and leaf litter fall, which causes decomposition, so the amount of soil CO_2 gas flux emissions increases. Different vegetation types have different rates of photosynthesis and respiration; this can affect the flux of CO_2 emissions from the soil released through root respiration (Kibet et al., 2022).

The results of measuring the CO_2 emissions from the soil of the Cijantung City Forest showed fluctuations among the three research stations. The high soil emission flux of CO_2 gas at the semi-open vegetation station (3160%) can be explained by several factors. The less dense vegetation canopy cover allows sunlight to directly shine on the soil surface continuously (Putra et al., 2020). This results in an increase in air temperature, soil temperature, decreased soil moisture, and increased microbial activity, all of which contribute to the high soil CO_2 emission flux. Similar results were also observed in the study by Irawan and June (2011) conducted in the Babahaleka Natural Forest, Lore Lindu National Park, Central Sulawesi, that the soil CO_2 emission flux in the closed vegetation canopy cover was lower than the open and semi-open vegetation canopy cover stations. The same thing also happened in the study by Kunnemann et al. (2022) conducted in the Angers-Paris city forest, explaining that the flux in the soil of the city forest was greater than in open land because there was dense tree shade. Additionally, the greater density of vegetation at semi-open canopy cover stations, in comparison to open canopy cover stations, also influences soil CO_2 emission flux. Dense vegetation increases soil respiration directly and provides a source of energy and nutrients for soil microbes (Kibet et al., 2022). Meanwhile, closed vegetation canopy cover stations have low soil CO_2 emission flux due to minimal exposure to sunlight (Irawan & June, 2011). Dense vegetation canopy cover makes the air and soil temperatures cooler and the soil conditions more humid, reducing soil aeration or air circulation processes in it (Chadirin et al., 2016).

The results of the difference test stated that the value of the soil CO_2 emission flux did not differ significantly in various vegetation canopy covers of the Srengseng City Forest. This shows that the soil's CO_2 emission is influenced by differences in vegetation canopy cover and by various environmental factors. These environmental factors include climate conditions, soil temperature, soil moisture, soil organic matter, and soil hydrological conditions (Putra et al., 2020). Based on the measurement results in the Srengseng City Forest, the average value of the soil CO_2 emission flux of the Srengseng City Forest showed the highest to lowest sequence of numbers, namely in closed (4.67 $gCO_2\ m^{-2}\ day^{-1}$), semi-open 3.92 $gCO_2\ m^{-2}\ day^{-1}$), and open vegetation canopy covers (3.29 $gCO_2\ m^{-2}\ day^{-1}$).

Based on research conducted by Putra et al. (2020), the high value of CO_2 emission from the soil was in land with an open canopy. This can be caused by the small layer of plant canopy on the land, which encourages direct solar radiation exposure to the ground surface. Solar radiation to the soil encourages the respiration of plant roots and microorganisms in the soil to release CO_2. However, solar radiation is not directly exposed to the ground surface in forest land with layered plant canopies. Furthermore, a lot of litter is spread on land with layered plant canopies, which act as a barrier to solar radiation in the soil. The results of the study showed that the lowest soil CO_2 emission flux in the open vegetation canopy cover of the Srengseng City Forest could be caused by the presence of a lot of litter in the area so that solar radiation was not directly exposed to the ground surface (Putra et al., 2020).

Based on the results of research conducted by Jamaludin et al. (2020), the value of soil CO_2 gas emission flux is influenced by the plant root system and the presence of trees at the sampling point. In rhizosphere land with plant roots around it, the soil CO_2 emission flux value (429.9 ± 174.1 $mg\ m^{-2}\ h^{-1}$) is higher than in non-rhizosphere land (339.1 ± 170.7 $mg\ m^{-2}\ h^{-1}$). Furthermore, plant roots play a role in releasing CO_2 emissions through the respiration process. Plant roots also release exudates such as carbohydrates and amino acids, encouraging increased respiration in the rhizosphere area. This is by the results of the study that the soil CO_2 emission flux of the Srengseng City Forest in closed vegetation canopy cover (4.67 $gCO_2\ m^{-2}\ day^{-1}$) is higher than that of open vegetation canopy cover (3.29 $gCO_2\ m^{-2}\ day^{-1}$). This is because there is a greater area of plant roots in closed vegetation canopy cover than in open and semi-open vegetation canopy cover, thus determining the increase in soil respiration and the high flux of soil CO_2 emission produced. Furthermore, the activity of soil microorganisms around plant roots also plays an important role in the nutrient cycle, soil formation process, and plant growth (Prayudyaningsih et al., 2015; Jamaludin et al., 2020).

Based on the research results, the value of soil CO_2 gas emission flux at the three research points in Sukapura City Forest fluctuated over time. Although the fluctuation of soil CO_2 emissions was irregular over time, the average value of soil CO_2 emission flux overall during the study showed that soil with open canopy cover had the highest flux (3.60 ± 2.30 $g\ m^{-2}\ day^{-1}$) compared to medium canopy cover (2.68 ± 1.42 $g\ m^{-2}\ day^{-1}$) or closed (2.62 ± 0.68 $g\ m^{-2}\ day^{-1}$). There is no significant difference between soil CO_2 emission flux in open, medium, or closed vegetation canopy cover. The absence of significant differences in soil CO_2 emission flux values in the three types of canopy cover is thought to be due to the abiotic environmental conditions, such as air temperature, soil temperature, soil moisture, and soil pH between the three areas not being much different.

Putra et al. (2020), in their study, stated that plant canopies in forest areas and coffee fields can reduce soil CO_2 emission fluxes because the presence of layered plant canopies on the land can reduce direct sunlight radiation to the soil so that the soil temperature is lower. In addition, blocking exposure to solar radiation on the soil surface can also maintain soil moisture. Therefore, the study results by Putra et al. (2020) show that soil CO_2 emission fluxes in vegetable and rice fields planted with corn have higher values than forest or coffee lands**.**

Meanwhile, the conditions in the Sukapura City Forest differ, as the air and soil temperatures in the open, medium, and closed canopy cover areas show minimal variation. Based on the average data for air temperature and soil temperature, it can be seen that the difference between the lowest and highest temperatures at the three sampling points is 1.9 °C and 1.8 °C. The insignificant temperature difference is because the canopy cover layer in the medium and closed cover areas is not layered. The closed and medium vegetation canopy cover that shades the soil in the research area consists only of leaves from mahogany trees (*Swietenia mahagoni*) arranged at a distance. In addition, *S. mahagoni* trees have medium-sized and narrow leaf morphology so that sunlight can pass through the gaps in the leaves. The arrangement of trees spaced apart also influences how solar radiation enters from various directions, depending on the sun's position, which is not always perpendicular to the ground surface. Meanwhile, regarding soil moisture and pH, the effect of canopy cover cannot be proven because of external factors, namely watering in the soil area with open cover, so that soil moisture in the open area is higher and soil pH tends to be lower.

Air temperature In the Ciganjur City Forest, the calculation of air temperature in each canopy cover has an average that is sequential according to the level of canopy cover, namely, the highest average is in open canopy cover (0–30%), the second highest average is in medium canopy cover (31–60%), and the lowest average is in closed canopy cover (61–100%). The average value obtained is higher in open canopy cover; this is because trees with dense canopies or cover provide shade that reduces the intensity of sunlight reaching the ground, thereby reducing the air temperature and soil temperature below and increasing soil humidity (Kusmana & Yentiana, 2021). The same results were also found in a study conducted by Siagian et al. (2021); the vegetation density at the research location causes less sunlight intensity to be received so that the humidity of the air below is retained because the air temperature is low. As the cover density and tree heterogeneity increase, the level of shade also increases, preventing sunlight from penetrating the area beneath the cover.

Based on the Spearman rank correlation test results between soil CO_2 emission flux and air temperature, a correlation coefficient value of -0.011 and a calculated significance value of 0.877 were obtained. This significance value is greater than the significance value of 0.05, so it can be concluded that there is no correlation between air temperature and soil CO_2 gas emission flux in this study. These results are from research conducted by Jamaludin et al. (2020) on rubber, oil palm, and ginger plantations in Kubu Raya Regency. The study obtained correlation results that did not significantly affect air temperature and soil CO_2 gas emissions. The possibility of results that did not have a significant effect is due to the small range of differences between the lowest and highest temperatures, namely 27–40 °C. However, these results do not match research conducted by Irawan and June (2011) in forests in the Lore Lindu National Park, Poso Regency, namely that air temperature is positively correlated with soil CO_2 gas emissions at each canopy cover with positive correlation values of 0.925, 0.724, and 0.776 (Irawan & June, 2011). The same results were obtained from the research of Riyani et al. (2021) on oil palm plantations in West Kalimantan; an increase in temperature will accelerate the metabolism of micro-organisms in the soil so that the decomposition of organic matter in the soil is faster and produces higher soil CO_2 gas emissions. The study's results showed that the correlation of air temperature had a significant relationship with a positive value ($r = 0.24$; p-value = 0.006).

The average air temperature in the Cijantung City Forest shows that the station with open vegetation and 0–30% canopy cover has a higher value than other stations due to the lack of shade or plant canopy and the high intensity of solar radiation emitted to the ground surface. The heat from solar radiation that reaches the ground surface is radiated back into the atmosphere, which results in an increase in air temperature (Putra et al. 2020). However, when data was collected on September 16 & 26, 2023, the air temperature at the station with open vegetation and low canopy cover was lower than the other two stations because the measurements were taken in the morning at 09:00–10:00, when the intensity of solar radiation had not yet reached its peak. The average air temperature at the three stations increased on October 16, 2023, because the measurements were taken during the day at 11:00–12:30. At this time, the intensity of solar radiation reaches its peak, which directly causes an increase in air temperature at all measurement stations.

This is because the environment of the Cijantung City Forest is influenced by many other variables besides air temperature, such as soil temperature, soil moisture, soil carbon content, and vegetation density. Due to these factors' complexity, air temperature's contribution to soil CO_2 emission fluxes may be insignificant (Chadirin et al., 2016; Wachiye et al., 2020). Air temperature measurements may be carried out over a limited period, which does not cover a wide enough variation to represent natural fluctuations in CO_2 emissions from the soil. A similar thing also happened in the study of Jamaludin et al. (2020) conducted in oil palm plantations in West Kalimantan, stating that air temperature did not have a significant relationship with CO_2 emissions from the soil because the difference between the minimum and maximum temperatures was not too large.

The study results showed that urban forest areas with open canopy cover tend to have higher air temperatures than station points with moderate or closed cover. This occurs because the open canopy cover area is exposed to direct sunlight. In contrast, in areas with mild and closed canopy cover, sunlight is partially blocked by the vegetation canopy so that the air temperature is lower. However, the air temperature during sampling tends to be high, namely in the 31–40.9°C range. The high air temperature occurs because the weather during the study was always sunny, and the exposure to sunlight was quite hot. The absence of a correlation between air temperature and soil CO_2 emission flux can occur because the difference between the lowest and highest air temperatures recorded during sampling is not too far. The same air temperature can have very different soil CO_2 emission flux values even in some conditions. Misbahuddin (2018), in his research on soil CO_2 gas emissions in oil palm plantations, explained that the difference in soil CO_2 gas emission values in the same temperature range is suspected to be due to differences in the sensitivity of soil microbes as one of the main sources of soil CO_2 emissions.

Soil temperature Based on the results of research in Ciganjur Forest, it is known that each canopy cover, in order from open canopy cover to medium canopy cover to closed canopy cover, has an average soil temperature sequence from highest to lowest, namely 32.80 °C, 30.61 °C, and 27.40 °C. Factors that influence soil temperature fluctuations are solar radiation and differences in the percentage of canopy cover. A denser canopy cover will block incoming sunlight, reducing the soil temperature to a lower level (Karyati et al., 2018). Based on the results of calculations using the Spearman correlation that has been carried out, it is known that soil temperature does not correlate with soil CO_2 gas emission flux. Furthermore, a correlation coefficient value of -0.081 and a calculated significance value of 0.234 were obtained. This significance value is greater than the significance value of 0.05. The correlation test results are insignificant because other variables besides soil temperature affect emissions in the Ciganjur City Forest, such as air temperature, soil moisture, vegetation density, and microorganism activity.

The same research results obtained by Arifin et al. (2016) on oil palm plantation land in Riau Province showed the calculated r value (r = 0.04) less than the table r value (r = 0.623), the computed r value approaching zero states that there is no relationship between soil temperature and soil CO_2 gas emissions. Research by Irawan and June (2011) in the forest in Lore Lindu National Park, Poso Regency also showed positive correlation results stating that the amount of soil CO_2 gas emissions is directly proportional to soil temperature, with positive correlation values for each cover, namely 0.468, 0.078, 0.794, and 0.605. Soil temperature is not correlated with soil CO_2 emissions and can be due to fluctuations or minor temperature changes; this also affects the activity of microorganisms that produce CO_2 and the decomposition process of soil organic matter. Generally the optimal rate of microorganism activity at a temperature of 1830 °C will be beneficial (Irawan & June, 2011). Kartikawati et al. (2017) conducted a study in tea plantation areas and fallow land in Bogor Regency, where three research locations with soil temperatures between 1626 °C produced varying soil CO_2 gas emission fluxes. An increase does not always follow an increase in soil temperature in CO_2 emission from the soil, so this non-linear relationship is likely caused by the response of microorganism activity, which results in varying fluxes (Kartikawati et al., 2017).

Another study conducted by Furnando et al. (2014) on oil palm plantations, shrublands, and secondary forests in Riau Province showed different results. A positive relationship exists between soil temperature and soil CO_2 gas emission fluxes in oil palm plantations and shrublands. The difference in correlation results is estimated to occur due to differences in temperature measurement methods, wherein this study, the temperature was measured inside the chamber (Furnando et al., 2014). Soil temperature is one of the factors that determines the activity of soil organisms and the decomposition of soil organic material (Wibowo & Alby, 2020).

Measurements of the average soil temperature in the Cijantung City Forest showed that the station with open vegetation and 0–30% canopy cover had a higher value than other stations due to the lack of shade or plant canopy at the station, which allows solar radiation to directly reach the ground surface with greater intensity and the large intensity of solar radiation emitted to the ground (Irawan & June, 2011; Putra et al., 2020). Soil temperature is greatly influenced by air temperature and the exchange of energy and heat from the soil to the air through the convection process (Chadirin et al., 2016). Therefore, high air temperatures will cause soil temperatures to increase and soil temperature fluctuations to be lower than air temperatures (Wibowo & Alby, 2020).

Similar to air temperature, the absence of correlation between soil temperature and soil CO_2 emission flux can occur because the difference between the lowest and highest soil temperatures in the Sukapura City Forest is not too far. Irawan and June (2011) explained that the absence of correlation between soil temperature and soil CO_2 emission flux in soil with cover could occur because fluctuations or changes in soil temperature are very small, so an increase of soil temperature does not follow the increase in soil CO_2 emission flux. According to Agus et al. (2011) and Amar et al. (2023) as quoted from Putra et al. (2020), the absence of correlation between soil temperature and soil CO_2 emissions indicates that temperature is not a dominant factor influencing soil CO_2 emission flux, especially in tropical ecosystems such as Indonesia.

However, several studies related to the effect of soil temperature on soil CO_2 emission flux in tropical climates also show that soil temperature is positively related to soil CO_2 emissions. The results of this study were obtained by Alhorr et al. (2014) and were conducted in oil palm plantations in West Kalimantan. The results were that soil temperature positively correlated with soil CO_2 emissions by 0.21. The positive correlation between soil temperature and soil CO_2 emissions shows that the higher the air temperature, the higher the soil CO_2 emission flux. The relationship between air temperature and soil CO_2 emission flux is related to the activity of soil microorganisms. Microbial activity increases exponentially at a specific temperature and will decrease at a certain temperature limit, namely 45–50 °C (Luo & Zhou, 2006).

Soil moisture The Spearman rank correlation test results between soil CO_2 gas emission flux and soil moisture obtained a correlation coefficient value of 0.179 and a calculated significance value of 0.008. Furthermore, the significance value is smaller than the significance value of 0.05. Therefore, there is a positive correlation between soil moisture and soil CO_2 gas emission flux. The positive correlation indicates that the increase in CO_2 emission from the soil follows the increase in soil moisture value. Based on research conducted by Yosep et al. (2017) on rubber plantation land in Palangka Raya City, soil moisture has a positive relationship and influence on the emission flux of CO_2 gas from the soil. This is due to the weathering of the results of soil microorganism activity, which is faster, and the population of soil microorganisms, which is increasing with moist soil conditions (Yosep et al., 2017). Based on research conducted by Chadirin et al. (2016), soil moisture has a negative relationship with the emission flux of CO_2 from the soil. Furthermore, rainfall triggers an increase in soil moisture followed by decreased soil CO_2 emission flux. This is because the soil pores are filled with water, so root aeration and respiration are reduced (Putra et al., 2020).

Other environmental factors, such as air temperature, pH, vegetation density, and microorganism activity, can have influences that cause the correlation value of soil moisture to be insignificant in the Ciganjur City Forest. These results are from research conducted by Chadirin et al. (2016): soil CO_2 gas emissions negatively correlate with soil moisture in open peatlands on Padang Island, Riau. Especially when it rains, rainwater wets the land and causes an increase in soil moisture; this is caused by soil pores filled with water so that gas movement is reduced, causing a decrease in soil CO_2 gas emission flux in the soil (Chadirin et al., 2016). Similar research results were also obtained by Kartikawati et al. (2017) in the tea plantation area in Bogor Regency, namely sampling when it rains for a long time, which causes soil moisture to increase and fill the soil pores. This step is followed by a gas diffusion process that is inhibited until anaerobic conditions occur, resulting in a decrease in the respiration capacity of the soil. Although it has a negative trend, soil moisture and CO_2 emission do not correlate because the calculated r value (r = -0.10) is less than the r table (r = 0.226). Yosep et al. (2017) conducted another study on rubber plantation land in Palangka Raya City, which yielded different analysis results. This study found a positive relationship between soil moisture. It has a significant effect on CO_2 emissions from the soil, as well as forest areas with tree cover that cause high humidity. This result can occur because weathering by microorganism activity is faster, and the population of microorganisms increases with moist soil conditions (Yosep et al., 2017).

Measurement of average humidity in the Cijantung City Forest shows that the station with a closed canopy of vegetation (61–100%) has a higher value than other stations. The presence of dense plant canopies or plant shade causes a decrease in the rate of water evaporation from the soil surface because most of the water remains in the soil. This condition allows soil moisture to be stable because water does not evaporate quickly due to being blocked by the shade of the plant canopy (Putra et al., 2020). However, at the time of sampling on October 26, 2023, the humidity value at the open vegetation canopy cover station had a higher value than the other 2 stations due to management interventions carried out by the Cijantung City Forest by watering the station to overcome prolonged dry conditions. This intervention resulted in a temporary increase in soil moisture levels at the station so that it could affect the dynamics of soil moisture in the city forest. The results of the Spearman correlation analysis between soil moisture and soil CO_2 gas emission flux in the Cijantung City Forest showed a negative correlation value and no significant relationship (r = -0.19499). A negative correlation indicates that changes in humidity are inversely proportional to changes in soil CO_2 gas emission flux. These results are in line with the research of Chadirin et al. (2016), and the research results of Winarna and Santoso (2020) stated that a decrease followed the increase in soil moisture due to rainfall in soil CO_2 gas emission flux. This decrease is because the soil pores are filled with water, reducing aeration and root respiration (Putra et al., 2020). In addition, high peat soil moisture causes a low rate of CO_2 emissions from the soil because it reduces oxygen levels and inhibits aerobic microbial activity during the decomposition process (Yahya Surya et al., 2019). Similar to the research results of Chen et al. (2016) conducted in the Beijing City Forest, there was a significant negative correlation between soil water content and soil respiration, where soil water content of more than 0.17 m^3 m^{-3} would reduce soil respiration.

The research results conducted by Irawan and June (2011) stated that soil moisture affects the flux of CO_2 emissions in the soil in open canopy 2, medium canopy 2, and closed canopy 2. Furthermore, there is a negative correlation between soil moisture and soil CO_2 gas emission flux with the respective correlation values (-0.408, -0.541, -0.576). The respiration process in the soil is negatively correlated with the soil water content that determines soil moisture. Furthermore, the soil respiration process in closed vegetation canopy cover is not always high because it can be triggered by high litter and forest vegetation thickness. This causes the decomposition process to take longer and suppresses the availability of energy sources for soil microorganisms (Alhorr et al., 2014). The negative correlation value shows that the increase in soil CO_2 gas emission flux follows the decrease in soil moisture value (Irawan & June, 2011).

The relationship between soil moisture and soil respiration varies greatly and depends on various factors such as soil type, density, and texture, as well as soil microorganism activity. So the effect of soil moisture on soil CO_2 emission flux is very complex (Moyano et al., 2012). Luo and Zhou (2006) explained that soil moisture affects soil CO_2 emission flux by regulating physiological processes of plant roots and soil microorganisms. Soil CO_2 gas emissions reach maximum levels estimated to occur at medium soil moisture (50% of the soil's water-holding capacity). Meanwhile, too dry or wet soil can suppress soil CO_2 emission flux because it can inhibit soil microbial activity. Optimum humidity occurs when the micropore space is mostly filled with water to facilitate soluble substrates and the macropore space is mostly filled with air to facilitate oxygen diffusion (Luo & Zhou, 2006).

Soil pH Based on the Spearman rank correlation test results between soil CO_2 emission flux and soil pH, a correlation coefficient value of 0.241 and a calculated significance value of 0.000 were obtained. The significance value is smaller than the significance value of 0.05, so it can be concluded that there is a positive correlation between soil pH and soil CO_2 gas emission flux in this study. The direction of the positive relationship means that if the soil pH increases, the soil CO_2 emission flux also increases. These results are supported by the results of research by Cuhel et al. (2010), who obtained results in the form of soil with neutral pH having the highest soil CO_2 emission flux value compared to soil with acidic or basic pH. Thus, the direction of the positive relationship in this study cannot be interpreted to mean that the more basic a soil is, the more soil CO_2 emission flux increases, because in this study, the highest soil pH measured was 7.0, classified as neutral pH.

The effect of pH on soil CO_2 emission flux can occur through the activity of microorganisms in the soil. The activity of soil microorganisms depends on the pH value of the soil because pH regulates chemical reactions and various enzymes in microorganisms (Luo & Zhou, 2006). Therefore, the effect of soil pH value on the activity of soil microorganisms can vary depending on the type of microorganism. Thus, the effect of soil pH on soil CO_2 emission flux is not always the same in every condition because various very complex factors influence soil CO_2 emissions.

Conclusion

The density of vegetation canopy cover affects the dynamics of soil CO_2 emission flux. Soil CO_2 emission flux is higher in areas with open vegetation canopy cover, followed by areas with partially closed vegetation canopy cover, and the lowest in areas with closed vegetation canopy cover. Soil moisture and soil pH are the most influential environmental factors on CO_2 emission from the soil. In contrast, air temperature and soil temperature do not significantly correlate with fluctuations in soil CO_2 emission in all types of vegetation canopy cover studied.

Acknowledgment

Thank you for the Research Grant (International Indexed Publication PUTI) Q2 FMIPA UI 2023 by Dr. rer. nat. Mufti Petala Patria, S.Si., M.Sc. entitled "Analysis of Greenhouse Gas Emissions to Assess the Stability of Ecosystem Functions of the University of Indonesia Urban Forest and Other Forests in Jakarta" and thanks to the research team who helped run this research, namely: Drs. Erwin Nurdin, M.Si.; Destia Puri Prela Renita, S.Si.; Nadia Asmawari Putri, S.Si.; Carla Mariana Nainggolan, S.Si.; Ibrahim Arif, S.Si.

References

Agus, F., Hairiah, K., & Mulyani, A. (2011). *Mesuaring carbon stock in peat soils: Practical guidelines*. Bogor: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program and Indonesian Centre for Agricultural Land Resources Research and Development. Retrieved from http://www.worldagroforestry.org/downloads/Publications/PDFs/MN17335.PDF

Alhorr, Y., Eliskandarani, E., Elsarraget, E. (2014). Approaches to reducing carbon dioxide emissions in the built environment: Low carbon cities. *International Journal of Sustainable Built Environment*, *3*(2), 167–178. https://doi.org/10.1016/j.ijsbe.2014.11.003

Amar, G., Mamtimin, A., Wang, Y., Wang, Y. -H., Gao, J. -C., Yang, F., Song, M., Aihaiti, A., Wen, C., & Liu, J. (2023). Factors controlling and variations of CO_2 fluxes during the growing season in Gurbantunggut Desert. *Ecological Indicators*, *154*, Article 110708. https://doi.org/10.1016/j.ecolind.2023.110708

Arifin, L., Irfan, M., Permanasari, I., Annisava A.R., & Arminudin, A. T. (2016). Keanekaragaman serangga pada tumpangsari tanaman pangan sebagai tanaman sela di pertanaman kelapa sawit belum menghasilkan. *Jurnal Agroteknologi*, *7*(1), 33–40. https://doi.org/10.24014/ja.v7i1.2247

Bond-Lamberty, B., & Thomson, A. (2010). Temperature-associated increases in the global soil respiration record. *Nature*, *464*, 579–582. https://doi.org/10.1038/nature08930

Butarbutar, T. (2009). Inovasi manajemen kehutanan untuk solusi perubahan iklim di Indonesia. *Jurnal Analisis Kebijakan Kehutanan*, *6*(2), 121–129.

Chadirin, Y., Saptomo, S. K., Rudiyanto, & Osawa, K. (2016). Lingkungan biofisik dan emisi gas CO_2 lahan gambut untuk produksi biomassa yang berkelanjutan. *Jurnal Ilmu Pertanian Indonesia*, *21*(2), 146–151. https://doi.org/10.18343/jipi.21.2.146

Chen, C., Doherty, M., Coffee, J., Wong, T., & Hellmann, J. (2016). Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas. *Environmental Science & Policy*, *66*, 403–419. https://doi.org/10.1016/j.envsci.2016.05.007

Cuhel, J., Simek, M., Laughlin, R. J., Bru, D., Chèneby, D., Watson, C. J., & Philippot, L. (2010). Insights into the effect of soil pH on N_2O and N_2 emissions and denitrifier community size and activity. *Applied and Environmental Microbiology*, *76*(6), 1870–1878. https://doi.org/10.1128/AEM.02484-09

Fatmah. (2023). The driving factors behind urban communities' carbon emissions in the selected urban villages of Jakarta, Indonesia. *PloS One*, *18*(11), Article e0288396. https://doi.org/10.1371/journal.pone.0288396

Furnando, E., Amri, T. A., & Anita, S. (2014). Studi emisi karbon dioksida dari tiga jenis lahan gambut di Desa Tanjung Leban dan Sepahat, Kecamatan Bukit Batu, Kabupaten Bengkalis. *Jurnal Online Mahasiswa Fakultas Matematika dan Ilmu Pengetahuan Alam Universitas Riau*, *1*(2), 228–236.

Gao, W., Huang, Z., Ye, G., Yue, X., & Chen, Z. (2018). Effects of forest cover types and environmental factors on soil respiration dynamics in a coastal sand dune of subtropical China. *Journal of Forestry Research*, *29*(6), 1645–1655. https://doi.org/10.1007/s11676-017-0565-6

Guntiñas, M. E., Gil-Sotres, F., Leirós, M. C., & Trasar-Cepeda, C. (2013). Sensitivity of soil respiration to moisture and temperature. *Journal of Soil Science and Plant Nutrition*, *13*(2), 445–461. https://doi.org/10.4067/S0718-95162013005000035

Irawan, A. & June, T. (2011). Permukaan tanah di hutan alam Babahaleka Taman Nasional Lore Lindu, Sulawesi Tengah. *Jurnal Agromet*, *25*(1), 1–8.

Jamaludin, Gusmayanti, E., & Anshari, G. Z. (2020). Emisi karbon dioksida (CO_2) dari pertanian skala kecil di lahan gambut. *Jurnal Ilmu Lingkungan*, *18*(3), 582–588. https://doi.org/10.14710/jil.18.3.582-588

Jo, H. -K., Kim, J. -Y, & Park, H. -M. (2019). Carbon reduction and planning strategies for urban parks in Seoul. *Urban Forestry & Urban Greening*, *41*, 48–54. https://doi.org/10.1016/j.ufug.2019.03.009

Kartikawati, R., Suwardi, & Sumawinata, B. (2017). Fluks CO_2 dari andisol pada penggunaan lahan kebun teh dan tanah bera di Desa Tugu Utara Kecamatan Cisarua Kabupaten Bogor. *Buletin Tanah dan Lahan*, *1*(1), 86–92.

Karyati, Putri, R. O., & Syafrudin, M. (2018). Suhu dan kelembaban tanah pada lahan revegetasi pasca tambang di PT Adimitra Baratama Nusantara, Provinsi Kalimantan Timur. *Jurnal AGRIFOR*, *17*(1), 103–114. https://doi.org/10.31293/af.v17i1.3280

Kibet, S., Musafiri, C. M., Kiboi, M., Macharia, J., Ng'etich, O. K., Kosgei, D. K., Mulianga, B., Okoti, M., Zeila, A., & Ngetich, F. K. (2022). Soil greenhouse gas emissions from different land utilization types in Western Kenya. *Frontiers in Soil Science*, *2*, Article 956634. https://doi.org/10.3389/fsoil.2022.956634

Kunnemann, T., Cannavo, P., Guerin, V., & Guenon, R. (2022). Soil CO_2, CH_4 and N_2O fluxes in urban forests, treed and open lawns in Angers, France. *Research Square*. https://doi.org/10.21203/rs.3.rs-2300500/v1

Kusmana, C., & Yentiana, R. A. (2021). Laju dekomposisi serasah daun *Shorea guiso* di Hutan Penelitian Dramaga, Bogor, Jawa Barat. *Jurnal Silvikultur Tropika*, *12*(3), 172–177. https://doi.org/10.29244/j-siltrop.12.3.172-177

Luo, Y & Zhou, X. (2006). *Soil respiration and the environment*. Elsevier.

Man, Z., Che, S., Xie, C., Jiang, R., Liang, A., & Wu, H. (2021). Effect of climate change on CO_2 flux in temperate grassland, subtropical artificial coniferous forest and tropical rain forest ecosystems. *International Journal of Environmental Research and Public Health*, *18*(24), Article 13056. https://doi.org/10.3390/ijerph182413056

Misbahuddin. (2018). Clean water crisis and climate change: Study of clean water resource management in Gunung Kidul. *Jurnal Studi Sosial dan Politik*, *5*(1), 117–132.

Moyano, F. E., Vasilyeva, N. A., Bouckaert, L., Cook, F., Craine, J., Curiel Yuste, J., Don A., Epron, D., Formanek, P., Franzluebbers, A., Ilstedt, U., Kätterer, T., Orchard, V., Reichstein, M., Rey, A., Ruamps, L., Subke, J. -A., Thomsen, I. K., & Chenu, C. (2012). The moisture response of soil heterotrophic respiration: Interaction with soil properties. *Biogeosciences*, *9*(3), 1173–1182. https://doi.org/10.5194/bg-9-1173-2012

Perdinan. (2014). Perubahan iklim dan demokrasi: Ketersediaan dan akses informasi iklim, peranan pemerintah, dan partisipasi masyarakat dalam mendukung implementasi adaptasi perubahan iklim di Indonesia. *Jurnal Hukum Lingkungan*, *1*(1), 109–132. https://doi.org/10.38011/jhli.v1i1.87

Prayudyaningsih, R., Faridah, E., Sumardi, & Sunarminto, B. H. (2015). Dampak fasilitatif tumbuhan legum penutup tanah dan tanaman bermikoriza pada suksesi primer di lahan bekas tambang kapur. *Jurnal Manusia dan Lingkungan*, *22*(3), 310–318. https://doi.org/10.22146/jml.18756

Purwanta, W. 2009. Perhitungan emisi gas rumah kaca (GRK) dari sektor sampah perkotaan di Indonesia. *Jurnal Teknik Lingkungan*, *10*(1), 1–8.

Putra, W. F., Muktamar, Z., & Sudjatmiko, S. (2020). Emisi karbon permukaan tanah pada beberapa penggunaan lahan di daerah tropis (Kabupaten Bengkulu Selatan). *NATURALIS: Jurnal Penelitian Pengelolaan Sumberdaya Alam dan Lingkungan*, *9*(1), 55–65. https://doi.org/10.31186/naturalis.9.1.12231

Riyani, D., Gusmayanti, E., & Pramulya, M. (2021). Dampak pemberian pupuk hayati dan NPK terhadap emisi CO_2 pada perkebunan kelapa sawit di lahan gambut. *Jurnal Ilmu Lingkungan*, *19*(2), 219–226. https://doi.org/10.14710/jil.19.2.219-226

Suwarman, R. (2022). Kajian perubahan iklim di pesisir Jakarta berdasarkan data curah hujan dan temperatur. *Buletin Oseanografi Marina*, *11*(1), 99–110.

Sarkar, S., Das, D. K., Singh, A., Laik, R., Singh, S. K., van Es, H. M., Krishnanf, K., Singh, A. K., Dasa, A., Singh, U., Elansary, H. O., & Mahmoud, E. A. (2024). Seasonal variations in soil characteristics control microbial respiration and carbon use under tree plantations in the middle gangetic region. *Heliyon*, *10*(16), Article e35593. https://doi.org/10.1016/j.heliyon.2024.e35593

Siagian, S. P. S., Susatya, A., & Saprinurdin. (2021). Laju dekomposisi serasah daun *Psychotria malayana* di Hutan Kampus Universitas Bengkulu. *Journal of Global Forest and Environmental Science*, *1*(1), 1–9.

United Nations Framework Convention on Climate Change. (2007). *Climate change: Impacts, vulnerabilities and adaptation in developing countries*. Bonn: UNFCCC Secretariat.

Wachiye, S., Merbold, L., Vesala, T., Rinne, J., Räsänen, M., Leitner, S., & Pellikka, P. (2020). Soil greenhouse

EISSN: 2089-2063 ISSN: 2087-0469
DOI: 10.7226/jtfm.32.1.27

gas emissions under different land-use types in savanna ecosystems of Kenya. *Biogeosciences*, *17*(8), 2149–2167. https://doi.org/10.5194/bg-17-2149-2020

Wibowo, C., & Alby, M. F. (2020). Keanekaragaman dan kelimpahan makrofauna tanah pada tiga tegakan berbeda di Hutan Pendidikan Gunung Walat. *Jurnal Silvikultur Tropika*, *11*(1), 25–31. https://doi.org/10.29244/j-siltrop.11.1.25-31

Winarna, W., & Santoso, H. (2020). Karakteristik emisi CO_2 tanah gambut di bawah tegakan kelapa sawit. *Jurnal Pendidikan Kelapa Sawit*, *28*(1), 41–50. https://doi.org/10.22302/iopri.jur.jpks.v28i1.103

Yahya Surya, M., He, Z., Xia, Y., & Li, L. (2019). Impacts of sea level rise and river discharge on the hydrodynamics characteristics of Jakarta Bay (Indonesia). *Water*, *11*, Article 1384. https://doi.org/10.3390/w11071384

Yosep, Sulistiyanto, Y., & Jaya, A. (2017). Studi fluks karbon dioksida pada berbagai tipe penggunaan di lahan gambut pasang surut dan pedalaman. *Jurnal AGRI PEAT*, *18*(2), 68–81.