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Variation of soil temperature and moisture in tropical land-uses

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[1]Faculty of Forestry and Tropical Environment, Universitas Mulawarman. Jl. Penajam, Kampus Gunung Kelua, Samarinda 75119, East Kalimantan, Indonesia. Tel.: +62 541-735089, 749068, Fax.: +62-541-735379, ♥email: karyati@fahutan.unmul.ac.id
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Abstract. *Karyati, Syafrudin M, Karmini, Afreliana AM, Wahyuni NS. 2026. Variation of soil temperature and moisture in tropical land-uses. Asian J For 10 (1): r100126. https://doi.org/10.13057/asianjfor/r100126.* Soil temperature and moisture are key microclimatic variables that influence soil processes, plant growth, and ecosystem sustainability. Land-use change and soil depth are among the main factors affecting these dynamics, particularly in tropical urban areas. This study aimed to examine the variations of soil temperature and humidity across different land uses (sengon plantations, shrublands, and residential areas) at varying soil depths (0-10 cm, 20-30 cm, 50-60 cm, and 90-100 cm). Soil temperature and moisture data were collected using an environmental meter over a 30-day observation period. Soil microclimatic conditions in sengon plantations are more favorable, with lower temperatures and higher moisture levels across various soil depths than in shrublands and residential areas. As the soil depth increases, soil temperature decreases, whereas soil moisture increases. Statistical analysis shows significant differences in soil temperature and moisture across land uses and soil depths. The results indicate that sengon plantations create a cooler, moister soil microclimate than shrublands and residential areas across various soil depths, suggesting their potential role to improve soil water retention, reduce heat stress, and support sustainable land management. Incorporating sengon plantations into land-use planning may help enhance soil resilience, agricultural productivity, and local climate adaptation. Information on soil temperature and moisture across various land uses and depths is important for understanding the condition of the plant root zone and can inform fertilization plans, plant growth, and more efficient, sustainable land management.

Keywords: Agroforestry microclimate, soil depth, soil moisture, soil temperature, urban ecosystem

INTRODUCTION

The development, health, and productivity of plants in agricultural cultivation are directly and indirectly affected by environmental factors (Abbas et al. 2025). Climate change has the potential to alter soil temperature and moisture in shrublands, thereby increasing the risk of soil nitrogen loss (Hu et al. 2023). Integrating soil moisture into models of forest microclimate, understory diversity, and tree regeneration is urgently required to improve the accuracy of climate change impact projections (Greiser et al. 2024). The plain site was more climate-sensitive for soil temperature, whereas the mountainous site was more climate-sensitive for soil moisture (Asano et al. 2023).

The reduction in rainfall that occurs when agricultural water demand is high further strains soil moisture conditions and crop development, as decreased actual soil moisture can lead to water loss in river basins (Mammadov et al. 2026). Soil temperature and moisture are key factors in forest ecosystems, as they strongly influence hydrological, biological, and chemical processes and serve as indicators of the recovery of degraded forests (Aytekin and Gökbulak 2020). Vegetation and cloud cover help stabilize soil temperature by minimizing its fluctuations (Shuklina and Voropay 2020). The classification of soil microsites by light or shade exposure has enabled the evaluation of significant differences in soil properties and conditions (Berame et al. 2021). Soil depth considerations and land management practices are necessary to understand their impact on soil health and ecosystem function (Philipp et al. 2025).

The natural regrowth of vegetation after forest fires helps partially reestablish the soil temperature regime (Shuklina and Voropay 2020). Deadwood and forest soils together play a crucial role in climate change mitigation by reducing atmospheric carbon concentrations (Lamichhane and Ghimire 2024). Higher levels of precipitation and soil moisture may cause regions to transition to an opposite regime (Benson and Dirmeyer 2021). Soil temperature plays a key role in reducing soil moisture across vegetation types, and more frequent moisture deficits under climate change may heighten temperature variability (Lozano-Parra et al. 2018). Soil temperature has been demonstrated to be a more precise indicator of the onset of the growing season (Leeper et al. 2020).

Air temperature was strongly correlated with soil temperature across sloping land-use types, with the degree of correlation decreasing with increasing soil depth (Assholihat et al. 2019; Tang et al. 2022). Several chemical properties of soil can be used as attributes for assessing the soil quality index (Leul et al. 2023). The interaction between land use type and soil depth affects the physicochemical properties of the soil, which determine the availability and distribution of soil nutrients required to increase soil productivity and plant growth (Nwosu et al. 2025). Efforts to improve soil quality in land management can conserve ecosystems sustainably in tropical agroecosystems (Saravia-Maldonado et al. 2025).

There is a significant research gap in understanding the simultaneous variation of soil temperature and moisture across different land uses and soil depths in tropical urban environments. Previous studies have shown that soil temperature and moisture are strongly influenced by land use, land cover, plant age, microclimate conditions, slope, and soil depth, with most research conducted in forested areas and other landscapes (Karyati and Ardianto 2016; Karyati et al. 2018, 2019; Assholihat et al. 2019; Cahyaningprastiwi et al. 2021; Tang et al. 2022; Raouj et al. 2023; Rodrigues et al. 2023). Furthermore, comparative data on sengon plantations, shrubland, and residential areas across different depth intervals are limited. The objective of this study was to analyze soil temperatures and higher moisture levels to determine variations in soil temperature and humidity across different land uses (sengon plantations, shrublands, and residential areas) at varying soil depths. We hypothesized that soil temperature and moisture vary significantly among land uses and across soil depths, with surface layers showing greater variability and vegetated land uses exhibiting lower soil temperatures and higher moisture levels than residential areas. Information on variation of soil temperature and moisture is expected to provide depth-specific insights into soil temperature and moisture dynamics across different land uses, serving as a scientific basis for sustainable land-use planning and urban environmental management in tropical regions.

MATERIALS AND METHODS

Study area

This study was conducted on Jl. Abdul Wahab Syahranie 4, Sempaja Barat, North Samarinda District, Samarinda City, East Kalimantan Province, Indonesia (Figure 1). The research area comprised three types of land cover: an 8-year-old sengon plantation, shrublands, and residential areas. The coordinate points for each land cover were as follows: sengon plantation at 0°26'42.2"S and 117°08'41.4"E; shrubland at 0°26'44.9"S and 117°08'39.9"E; and residential area at 0°26'46.0"S and 117°08'40.3"E (Figures 2.A-C). The research was conducted simultaneously at the location and time reported by Karyati et al. (2025a). These sites were selected because they are situated within a contiguous landscape that typifies a tropical urban environment with relatively high population density. The study was carried out over approximately seven months, from November 2024 to May 2025.

Based on the information obtained, rainfall data in Samarinda City over a 10-year period from the Meteorology, Climatology, and Geophysics Agency (BMKG) of Samarinda City as the nearest BMKG, and based on the SKI calculation by Schmidt & Ferguson, Abdul Wahab Syahranie Street 4 is classified as climate type A with a Quotient (Q) value of 5.71%, which is a very wet area with tropical rainforest vegetation. The one-hectare plot of land owned by Mr. Murjani and managed by Mr. Umar Bakri was originally a fruit orchard that grew rambutan, durian, and other crops. This land was converted into a coal-mining area in 2006. Since 2016, the land has been rehabilitated, and sengon trees have been planted with a spacing of 3 m × 3 m (Figure 3.A). The residential areas and shrublands studied are approximately 100 meters from the sengon plantations. Agroecological aspects such as land use history and vegetation structure of the research site located in an urban area influence soil condition, including soil microclimate, biodiversity, and water and nutrient availability, which determine the productivity and sustainability of land management and agroforestry systems.

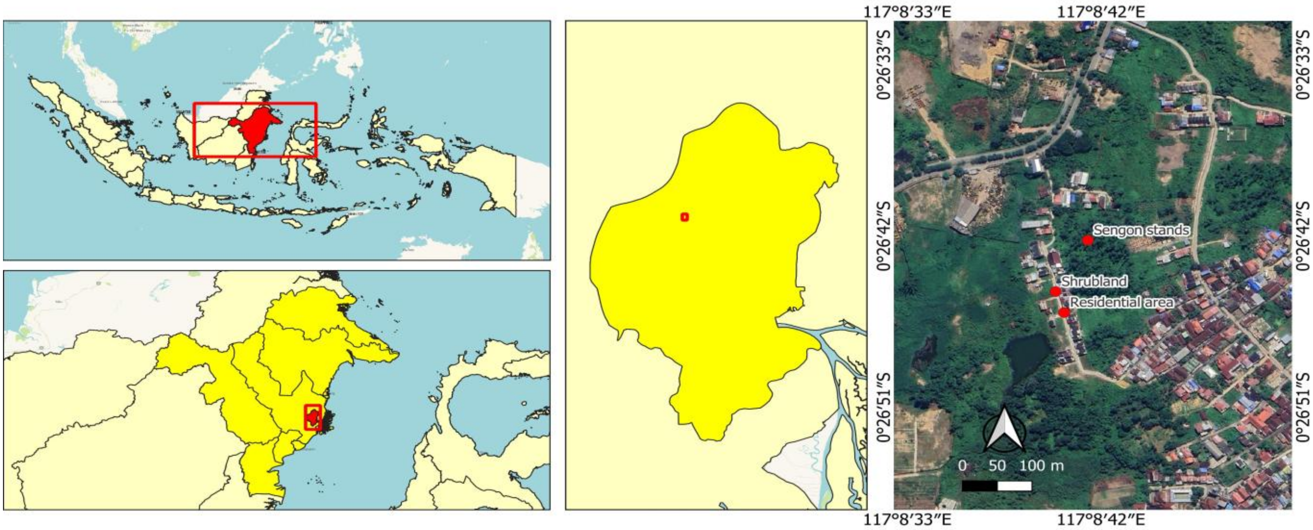

Figure 1. Map of study sites in Samarinda City, East Kalimantan, Indonesia

Figure 2. Soil temperature and humidity measurement points in A. Sengon plantations, B. Shrublands, and C. Residential areas

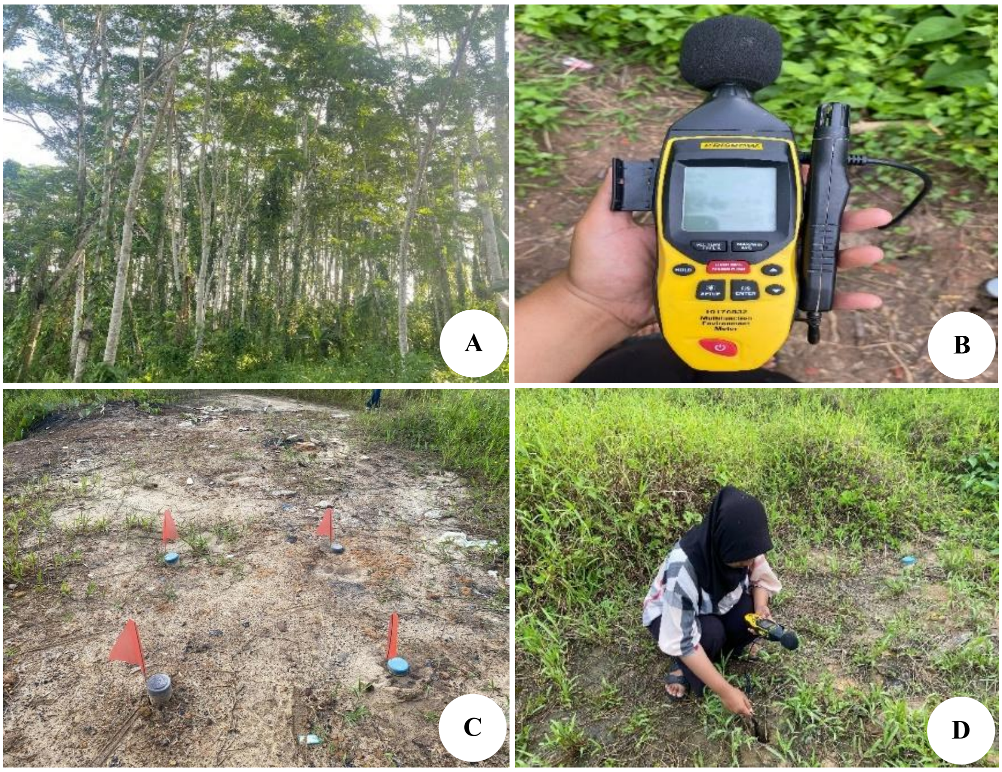

Figure 3. A. Sengon plantation, B. Environmental meter tools, C. Determination of soil temperature and moisture measurement points, and D. Measurement of soil temperature and moisture in shrubland

Procedures

The climatic parameters observed across the three land cover types (sengon plantations, shrublands, and residential areas) included soil temperature and soil moisture. Measurements were conducted using a Krisbow 4-in-1 environmental meter (KW0600291) (Figure 3.B), with precision levels of ±3.5% of the reading, ±2°C for soil temperature, and ±5% for soil moisture. Measurement points for soil temperature and moisture at different depths were selected and determined to represent each land cover type. The distance between measurement points for soil temperature and moisture was 1 m, forming a square (Figure 3.C) to minimize soil variability. Each temperature and depth measurement point is fitted with a PVC pipe and PVC pipe cap (dop/cap). The length of the PVC pipe is adjusted to the corresponding measurement depths: 10 cm, 30 cm, 50 cm, and 100 cm. The PVC pipe caps are used to prevent water accumulation during rainfall, maintain soil temperature and humidity, and maintain consistent water content. At the start of each measurement, the PVC pipes and caps are removed and replaced immediately after the measurement is complete. Data were collected three times a day at each land cover site, namely in the morning (7:00-8:00 AM), afternoon (12:00-1:00 PM), and evening (5:00-6:00 PM) over a 30-day observation period, with each measurement repeated three times at every location point (Figure 3.D). Measurement of soil depth intervals (10 cm, 30 cm, 50 cm, and 100 cm) and measurement times (morning, afternoon, and evening) refer to WMO (2024) and Regulation of the Head of BMKG Number 4 of 2016.

Data analysis

The daily soil temperature and soil moisture were determined using the following equation (Sabaruddin 2012):

$$T = \frac{(2T_{morning} + T_{afternoon} + T_{evening})}{4} \quad RH = \frac{(2RH_{morning} + RH_{afternoon} + RH_{evening})}{4}$$

Where, T: Daily soil temperature (°C), RH: Daily soil moisture (%).

Soil temperature and moisture data obtained from three land-cover types (sengon plantations, shrublands, and residential areas) were analyzed using a combination of descriptive, quantitative, and qualitative methods. A serial test was conducted in this study, covering the Normality test, Homogeneity test, One-Way Anova, post hoc tests of Bonferroni, Kruskal-Wallis One-Way Anova, and its post hoc test. Data analysis was performed using IBM SPSS Statistics 25.

RESULTS AND DISCUSSION

Soil physical properties

The soil texture under the sengon stand land cover consisted of 58.55% sand, 23.83% clay, and 17.62% silt, and was classified as sandy clay loam. In the shrubland area, the soil contained 55.02% sand, 21.30% clay, and 23.68% silt, also categorized as sandy clay loam. Meanwhile, the soil in the open residential area comprised 31.60% sand, 28.90% clay, and 39.50% silt, which falls under the clay loam texture class (Table 1). The texture and pore distribution of the soil indicated variations in its moisture characteristics. Environmental factors and soil properties jointly impact plant characteristics (Indriyani et al. 2011). The soil's physical, chemical, and biological attributes trigger various physiological, biological, and chemical responses that influence the growth, productivity, and quality of plant biomass (Khalil et al. 2015). Air temperature, air humidity, organic matter content, and soil texture are all strongly significant microclimate factors. Clay and loam soils are suitable for abundant plant growth (Berame et al. 2021).

Variations in soil temperature in different land uses and soil depths

The highest mean soil temperature was in the residential area, at 28.872°C, and the lowest was in sengon planting, at only 27.145°C. Meanwhile, the average soil temperature in the shrubland was 28.287°C. Data in Table 2 showed the result of the normality test, stating that the data of soil temperature in different land use have a normal distribution (sig. > 0.05). Distribution of soil temperature data in different land use performed in Figure 4.A. Test of homogeneity of variances accepted hypothesis if data variances are homogeneous (Levene statistic = 1.100, sig. = 0.334 > 0.05). The result of one-way ANOVA showed significance. < 0.05 means that soil temperature is significantly different among land use for sengon planting, shrubland, and residential area. The results of post hoc tests by Bonferroni showed soil temperature was significantly different among different land uses (sig. < 0.05).

Table 1. Soil texture at the different land uses

Land use	Soil fraction (%)			Texture class
	Sand	Clay	Dust	
Sengon plantations	58.55	23.83	17.62	Sandy Clay Loam
Shrublands	55.02	21.30	23.68	Sandy Clay Loam
Residential areas	31.60	28.90	39.50	Clay Loam

Table 2. The result of data analysis on land use and soil temperature

Land use	Tests of normality				
	Kolmogorov-Smirnov			Shapiro-Wilk	
	Statistic	df	Sig.	Statistic	Sig.
Sengon planting	0.056	120	0.200*	0.993	0.849
Shrubland	0.055	120	0.200*	0.993	0.829
Residential area	0.061	120	0.200*	0.986	0.244

Soil temperature	ANOVA				
	Sum of squares	df	Mean square	F	Sig.
Between groups	185.080	2	92.540	106.812	0.000
Within groups	309.299	357	0.866		
Total	494.380	359			

Multiple comparisons	Post hoc tests of Bonferroni				
Land use	Mean difference (I-J)	Std. error	Sig.	95% confidence interval	
				Lower bound	Upper bound
(I) Sengon planting (J) Shrubland	-1.1417*	0.1202	0.000	-1.431	-0.853
(I) Sengon planting (J) Residential area	-1.7267*	0.1202	0.000	-2.016	-1.438
(I) Shrubland (J) Residential area	-0.5850*	0.1202	0.000	-0.874	-0.296

Note: *: This is a lower bound of the true significance, a: Lilliefors significance correction, the mean difference is significant at the 0.05 level

The temperature variation among the three land covers was attributed to differences in vegetation type, which influenced the amount of sunlight penetrating the soil. Areas with vegetation cover, such as sengon stands, exhibited lower soil temperatures than areas with sparse canopy cover, as the vegetation canopy naturally reduced the amount of solar radiation reaching the soil surface. The results revealed that the lowest soil temperature was observed under sengon plantations, followed by shrubland and residential areas (Figures 5.A-D). In this study, the soil temperature beneath 8-year-old sengon stands ranged from 25.0°C to 29.3°C. After land improvement efforts, the suitability of sengon plantations improved to a moderately suitable level, with water availability, terrain, root conditions, and rock exposure remaining as limiting factors (Talenta et al. 2023). This indicates that tree cover, such as sengon plantations, plays an important role in lowering soil temperature through canopy shading effects.

The type of land cover significantly affects soil temperature distribution. Areas with dense vegetation (such as sengon stands) have lower soil temperatures than open land. The highest temperatures are found in open residential areas, followed by shrubland. The lowest temperatures are found in sengon stands, as shown in Figure 6. These differences demonstrate that denser vegetation cover leads to lower soil temperatures because less solar radiation reaches the soil surface. Based on these study findings, it can be concluded that land use for sengon planting is better than land use for shrubland and residential areas in terms of temperature, because sengon planting can reduce soil temperature. Teramage et al. (2023) revealed the significant effects of both land use types and agro-climate on the depth distribution of bulk density, Na, K, Cu, and electrical conductivity, reflecting their influences on the paths associated with bio-geo-recycling processes in Sidama Region, Ethiopia.

The means of soil temperature were 28.719°C, 28.324°C, 27.932°C, and 27.429°C in soil depths of 0-10 cm, 20-30 cm, 50-60 cm, and 90-100 cm, respectively. The deeper the soil, the lower the soil temperature. Based on the result of the normality test (Table 3), the data on soil temperature in different soil depths have a normal distribution (sig. > 0.05). Figure 4.B showed distribution of soil moisture data in different soil depths. According to the result test of homogeneity of variances is known if data variance is homogenic (Levene statistic = 0.002, sig. = 1.000 > 0.05). The result of one-way ANOVA showed significance. 0.000 < 0.05, it means that soil temperature is very significantly different among different soil depths of 0-10 cm, 20-30 cm, 50-60 cm, and 90-100 cm. Other findings were the results of post hoc tests by Bonferroni, which showed soil temperature was significantly different on soil depth between 0-10 cm and 50-60 cm, between 0-10 cm and 90-100 cm, and between 20-30 cm and 90-100 cm (sig. 0.005 < 0.05). Meanwhile, soil temperature is significantly different between 50-60 cm and 90-100 cm. However, there is no difference in soil moisture at depths of 0-10 cm and 20-30 cm, and at 20-30 cm and 50-60 cm. According to Ran et al. (2020), soil temperatures at varying depths within the soil profile are crucial agro-meteorological indicators, essential for ecological modeling and precision agricultural practices.

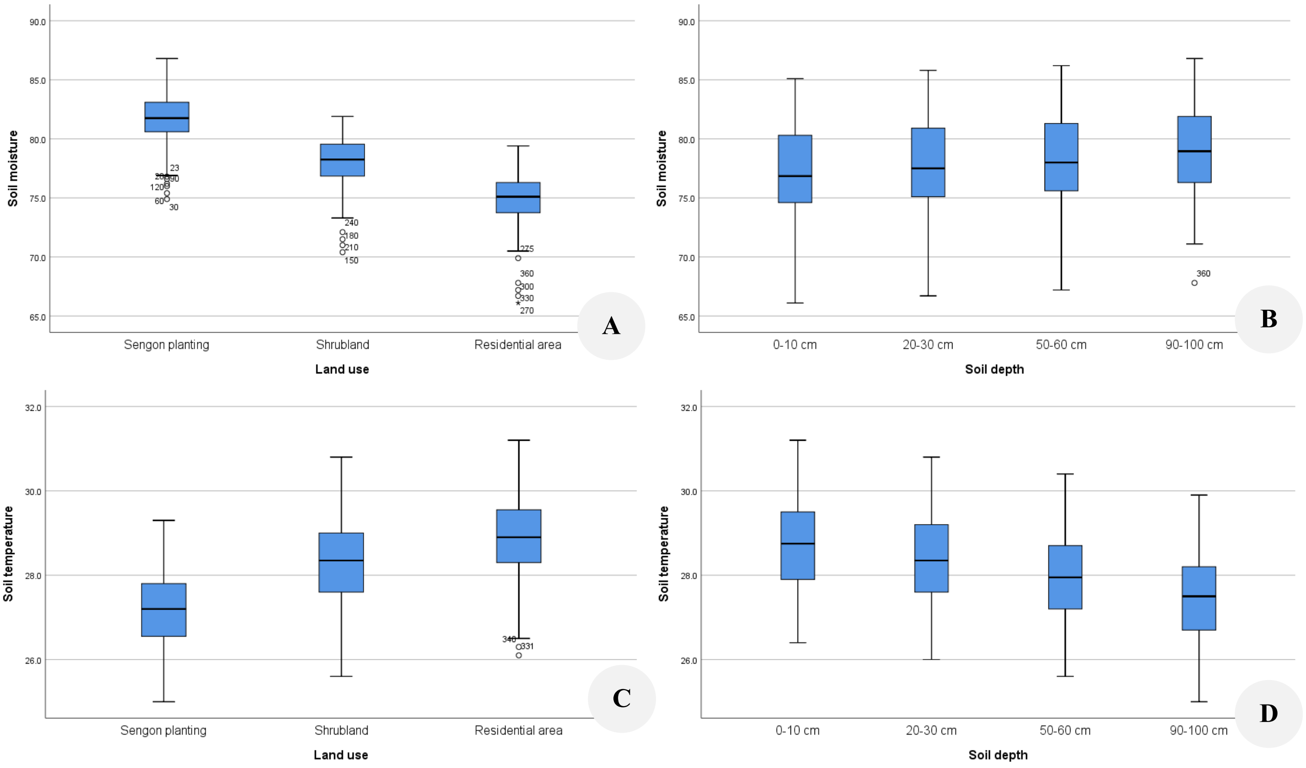

Figure 4. Data distribution: A. Land use and soil moisture, B. Soil depth and soil moisture, C. Land use and soil temperature, and D. Soil depth and soil temperature

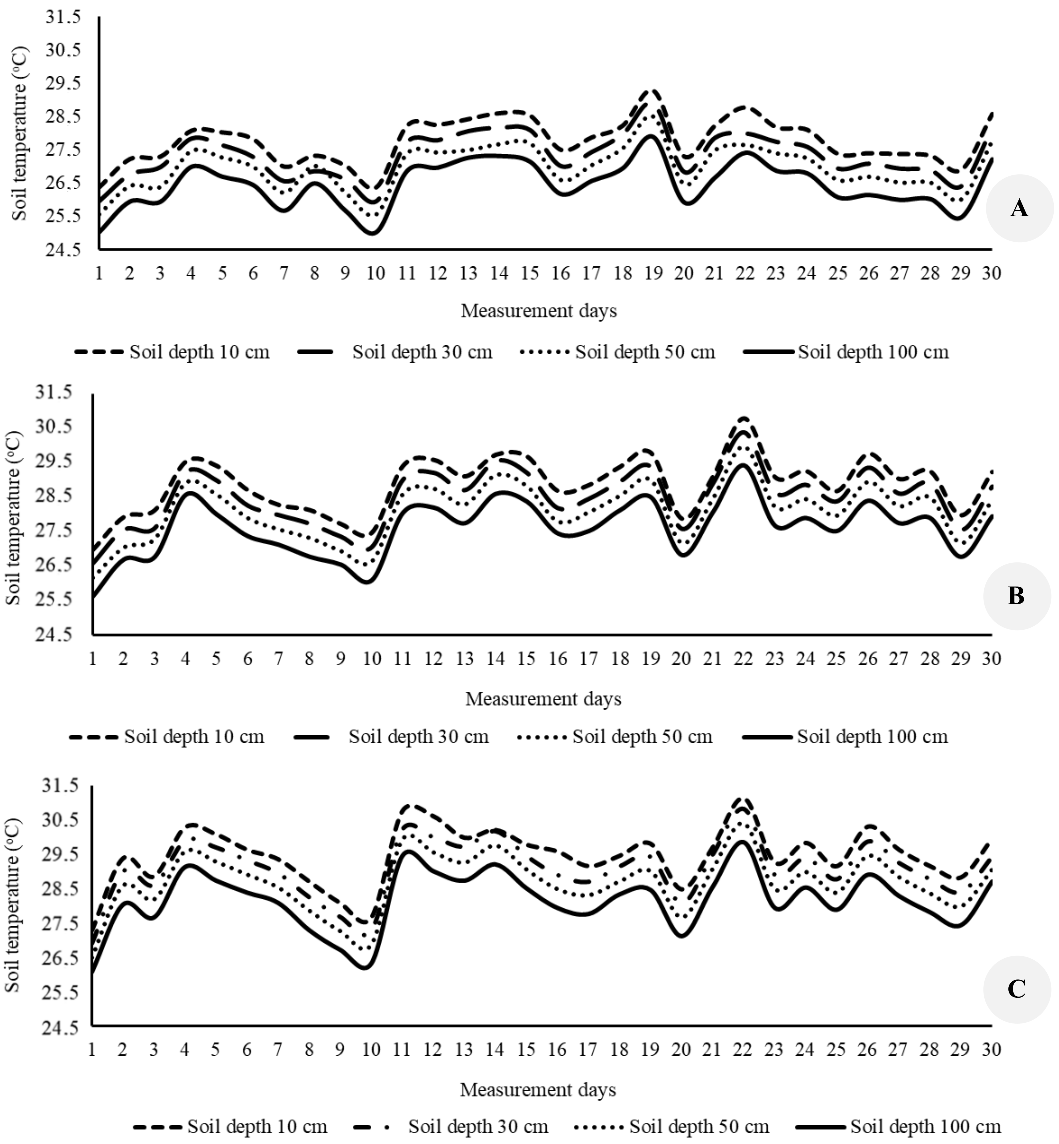

Figure 5. Daily soil temperature across different land covers and depths. A. Sengon plantations, B. Shrublands, and C. Residential areas

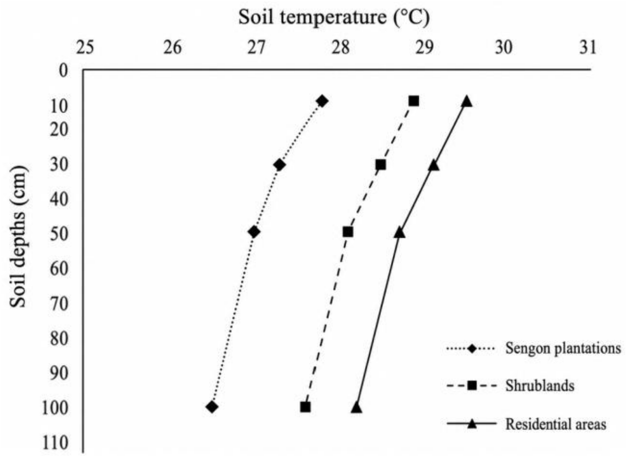

Figure 6. Soil temperature profiles on different land uses

Soil temperature decreased with increasing depth, with the average temperatures at 50 cm and 100 cm lower than those at 10 cm and 30 cm (Figure 7.A-D). This phenomenon is likely related to the darker color of the soil at 10 cm and 30 cm depths, which enhances heat absorption, whereas the lighter-colored soil layers at 50 cm and 100 cm depths have lower heat-absorption capacity. Alterations in soil characteristics may occur if forest cover is replaced by herbaceous vegetation due to global warming (Aytekin and Gökbulak 2020). The interaction between air temperature and soil temperature can trigger changes in weather and climate, particularly in open areas (Ariyanto et al. 2021). However, with increasing soil depth, changes in soil temperature become less significant as the soil temperature approaches the average annual air temperature (Mukhtar et al. 2017).

Soil temperature decreases with depth in all land cover types. Various tree species exhibit disparate patterns of soil temperature regulation at both 5 cm and 15 cm depths

(Raouj et al. 2023). The average soil temperature at various depths within the forest was lower compared to that in areas outside the forest (Karyati et al. 2018). Variations in soil temperature and moisture properties are affected by both topographic position and soil depth (Cahyaningprastiwi et al. 2021). Future soil temperatures are expected to rise year-round, with greater increases in the plains than in the mountainous region (Asano et al. 2023).

Variations in soil moisture in different land uses and soil depths

Soil moisture variations were observed over 30 measurement days under three land cover types: sengon plantations, shrublands, and residential areas. Overall, soil moisture fluctuated throughout the observation period. Mean of soil moisture in land use for sengon planting (81.614%), shrubland (77.986%), and residential area (74.781%). The result of the normality test showed that the data of soil moisture for land use for sengon planting, shrubland, and residential area do not normally distribute (sig. < 0.05) as shown in Table 4. The distribution of soil moisture data in different land uses is shown in Figure 4.C. The result of the Kruskal-Wallis test showed that soil moisture was significantly different among the lands used for sengon planting, shrubland, and residential area (statistic = 233.545, df = 2, asymp. sig 0.000 < 0.005). The result of the post hoct test showed that soil moisture in the residential area is very significantly different from that in shrubland and sengon planting, meanwhile, soil moisture in the shrubland area is very significantly different from that in land for sengon planting (adj. sig. 0.000). Soil moisture in the sengon planting area (284.63) is better than that in shrubland. Soil moisture in the shrubland (177.47) is better than that in the residential area (79.40).

Table 3. The result of data analysis on soil depths and soil temperature

Soil depth	Tests of normality				
	Kolmogorov-Smirnov			Shapiro-Wilk	
	Statistic	df	Sig.	Statistic	Sig.
0-10 cm	0.084	90	0.152	0.983	0.291
20-30 cm	0.082	90	0.181	0.985	0.389
50-60 cm	0.079	90	0.200*	0.986	0.457
90-100 cm	0.079	90	0.200*	0.988	0.558

Soil temperature	ANOVA				
	Sum of squares	df	Mean square	F	Sig.
Between groups	82.074	3	27.358	23.622	0.000
Within groups	412.306	356	1.158		
Total	494.380	359			

Multiple comparisons	Post hoc tests of Bonferroni				
Soil depth	Mean difference (I-J)	Std. error	Sig.	95% confidence interval	
				Lower bound	Upper bound
(I) 0-10 cm (J) 20-30 cm	0.3944	0.1604	0.087	-0.031	0.820
(I) 0-10 cm (J) 50-60 cm	0.7867*	0.1604	0.000	0.361	1.212
(I) 0-10 cm (J) 90-100 cm	1.2900*	0.1604	0.000	0.864	1.716
(I) 20-30 cm (J) 50-60 cm	0.3922	0.1604	0.090	-0.033	0.818
(I) 20-30 cm (J) 90-100 cm	0.8956*	0.1604	0.000	0.470	1.321
(I) 50-60 cm (J) 90-100 cm	0.5033*	0.1604	0.011	0.078	0.929

Note: *: This is a lower bound of the true significance, a: Lilliefors significance correction, the mean difference is significant at the 0.05 level

Table 4. The result of data analysis on land use and soil moisture

Land use	Tests of normality				
	Kolmogorov-Smirnov			Shapiro-Wilk	
	Statistic	df	Sig.	Statistic	Sig.
Sengon planting	0.097	120	0.008	0.963	0.291
Shrubland	0.075	120	0.097	0.946	0.389
Residential area	0.096	120	0.009	0.925	0.457

Pairwise comparison	Post hoc tests of Kruskal Wallis One Way Anova				
	Test statistic	Std. error	Std. test statistic	Sig.	Adj. sig.
Residential area-Shrubland	98.075	13.434	7.300	0.000	0.000
Residential area-Sengon planting	205.238	13.434	15.277	0.000	0.000
Shrubland-Sengon planting	107.162	13.434	7.977	0.000	0.000

Note: *: This is a lower bound of the true significance, a: Lilliefors significance correction, the mean difference is significant at the 0.05 level

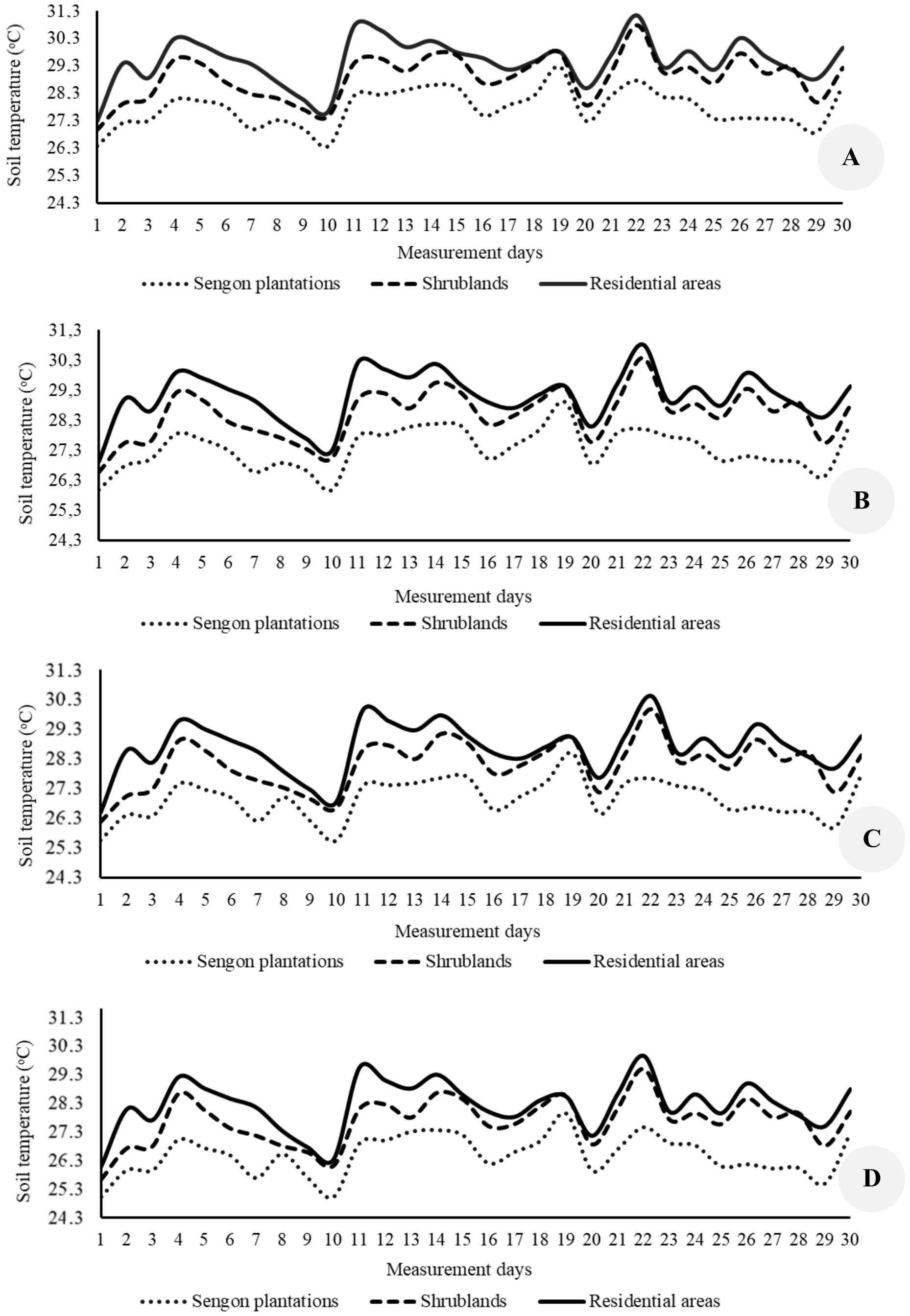

Figure 7. Daily soil temperature at A. 10 cm depth, B. 30 cm depth, C. 50 cm depth, and D. 100 cm depth

The highest soil moisture was consistently recorded under sengon plantations, followed by shrublands, while residential areas showed the lowest values (Figure 8.A-D). These results indicate that denser vegetation cover helps retain higher soil moisture compared to open or built-up areas. Mulching moderate's fluctuations in soil temperature, while drip irrigation combined with mulch maintains a consistent soil moisture profile near field capacity (Rodrigues et al. 2023). Plant growth dynamics contribute to variations in soil moisture profiles, while vegetation degradation alters soil temperature (Yang et al. 2019). Species distribution is closely linked to altitude and soil properties, with increasing abundance and distinct shifts in vegetation and soil characteristics along the altitudinal gradient (Bhatt et al. 2024).

Soil moisture increases with soil depth under all land cover types. The highest soil moisture is found under sengon plantations, followed by shrublands, while the open residential area has the lowest values. This indicates that denser vegetation helps maintain higher soil moisture by reducing evaporation and improving water retention in deeper layers (Figure 8). The results show that the soil texture in sengon plantations and shrublands is sandy clay loam, which tends to have greater moisture content than the soil in residential areas, which has a clay loam texture (Table 1) across several measured soil depths. Although the water retention capacity of sandy clay loam soil is lower than that of clay loam, sandy loam soil has good drainage and aeration due to the presence of fairly dense sand particles, which result in a high ability to maintain soil moisture. In general, sandy clay loam soil is easier to cultivate and has better drainage, while clay loam soil can retain water more effectively but is prone to compaction or waterlogging. Both are good soil textures for plant growth because they retain moisture and prevent rapid drying.

Soil moisture levels increased with elevation, but the rate of change varied with elevation due to factors such as aspect and topographic position (Lu et al. 2025). Different combinations of forestry and crops lead to variations in soil temperature and moisture. In deeper soil layers, however, soil temperature tends to decrease while soil moisture increases (Yang et al. 2019). Means of soil moisture in soil depths of 0-10 cm, 20-30 cm, 50-60 cm, and 90-100 cm were 77.237%, 77.830%, 78.417%, and 79.024%, respectively. The result of the normality test indicated that the soil moisture data across different soil depths are normally distributed, based on the significance (sig. > 0.05) (Table 5). Figure 4.D illustrates the distribution of soil moisture data in different soil depths. Test of homogeneity of variances accepted hypothesis if data variances are homogeneous (Levene statistic = 0.011, sig. = 0.998). The result of one-way ANOVA showed significance. 0.006 < 0.05 means that soil moisture is significantly different among soil depths of 0-10 cm, 20-30 cm, 50-60 cm, and 90-100 cm. The results of post hoc tests by Bonferroni showed soil moisture was significantly different between soil depths of 0-10 cm and 90-100 cm (sig. 0.005 < 0.05), there was no difference in soil moisture in other multiple comparisons.

Soil moisture increased with depth, with average moisture content at 50 cm and 100 cm depths being higher than at 10 cm and 30 cm depths (Figures 9.A-C and 10). This pattern is influenced by temperature variations across soil depths. Higher soil temperatures tend to reduce soil moisture, whereas lower soil temperatures lead to higher moisture retention. Temperature shows a direct relationship with soil resistance, while soil moisture shows an inverse relationship, with higher moisture content reducing resistance. Similarly, soil pH is positively correlated with resistance, as lower pH is associated with decreased resistance (Sukamta et al. 2020). As soil moisture levels decreased, soil temperature increased. However, this effect was weaker under tree canopies than in grasslands, where higher moisture and shading reduced maximum temperature and daily fluctuation (Lozano-Parra et al. 2018).

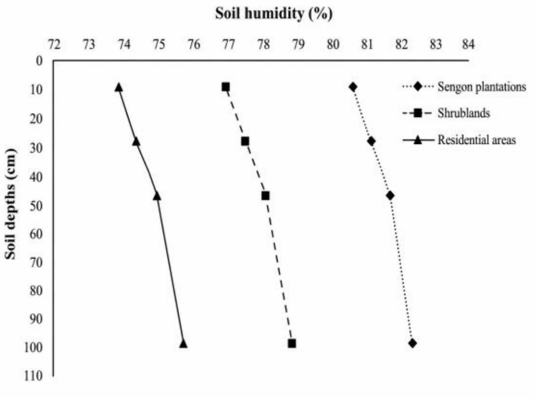

Figure 8. Soil moisture profiles on different land uses

Table 5. The result of data analysis on soil depths and soil moisture

Soil depth	**Tests of normality**				
	Kolmogorov-Smirnov			**Shapiro-Wilk**	
	Statistic	**df**	**Sig.**	**Statistic**	**Sig.**
0-10 cm	0.067	90	0.200*	0.986	0.447
20-30 cm	0.063	90	0.200*	0.987	0.515
50-60 cm	0.058	90	0.200*	0.986	0.475
90-100 cm	0.056	90	0.200*	0.987	0.546

Soil moisture	**ANOVA**				
	Sum of squares	**df**	**Mean square**	**F**	**Sig.**
Between groups	159.319	3	53.106	4.214	0.006
Within groups	4485.929	356	12.601		
Total	4645.249	359			

Multiple comparisons	**Post hoc tests of Bonferroni**				
Soil depth	**Mean difference (I-J)**	**Std. error**	**Sig.**	**95% confidence interval**	
				Lower bound	**Upper bound**
(I) 0-10 cm (J) 20-30 cm	-0.5933	0.5292	1.000	-1.997	0.811
(I) 0-10 cm (J) 50-60 cm	-1.1800	0.5292	0.158	-2.584	0.224
(I) 0-10 cm (J) 90-100 cm	-1.7878*	0.5292	0.005**	-3.192	-0.384
(I) 20-30 cm (J) 50-60 cm	-0.5867	0.5292	1.000	-1.991	0.817
(I) 20-30 cm (J) 90-100 cm	-1.1944	0.5292	0.148	-2.598	0.209
(I) 50-60 cm (J) 90-100 cm	-0.6078	0.5292	1.000	-2.012	0.796

Note: *: This is a lower bound of the true significance, a: Lilliefors significance correction, the mean difference is significant at the 0.05 level

Differences in soil temperature and humidity in different land uses and soil depths

Soil temperature varied depending on land use, soil depth, and time of observation. At all depths, soil temperature was lowest in the sengon plantation, intermediate in the shrubland, and highest in the residential areas. Temperatures increased diurnally from morning (7:00-8:00 am) to midday (12:00-1:00 pm) and decreased slightly in the late afternoon (5:00-6:00 pm) (Figures 11.A-D). Increasing soil depth resulted in lower, more stable temperatures, indicating reduced sensitivity to short-term atmospheric fluctuations. The results showed that land use and soil depth strongly influenced soil temperature, with residential areas and surface layers experiencing higher and more variable temperatures, whereas vegetated land uses and deeper soils maintained cooler, more stable thermal conditions.

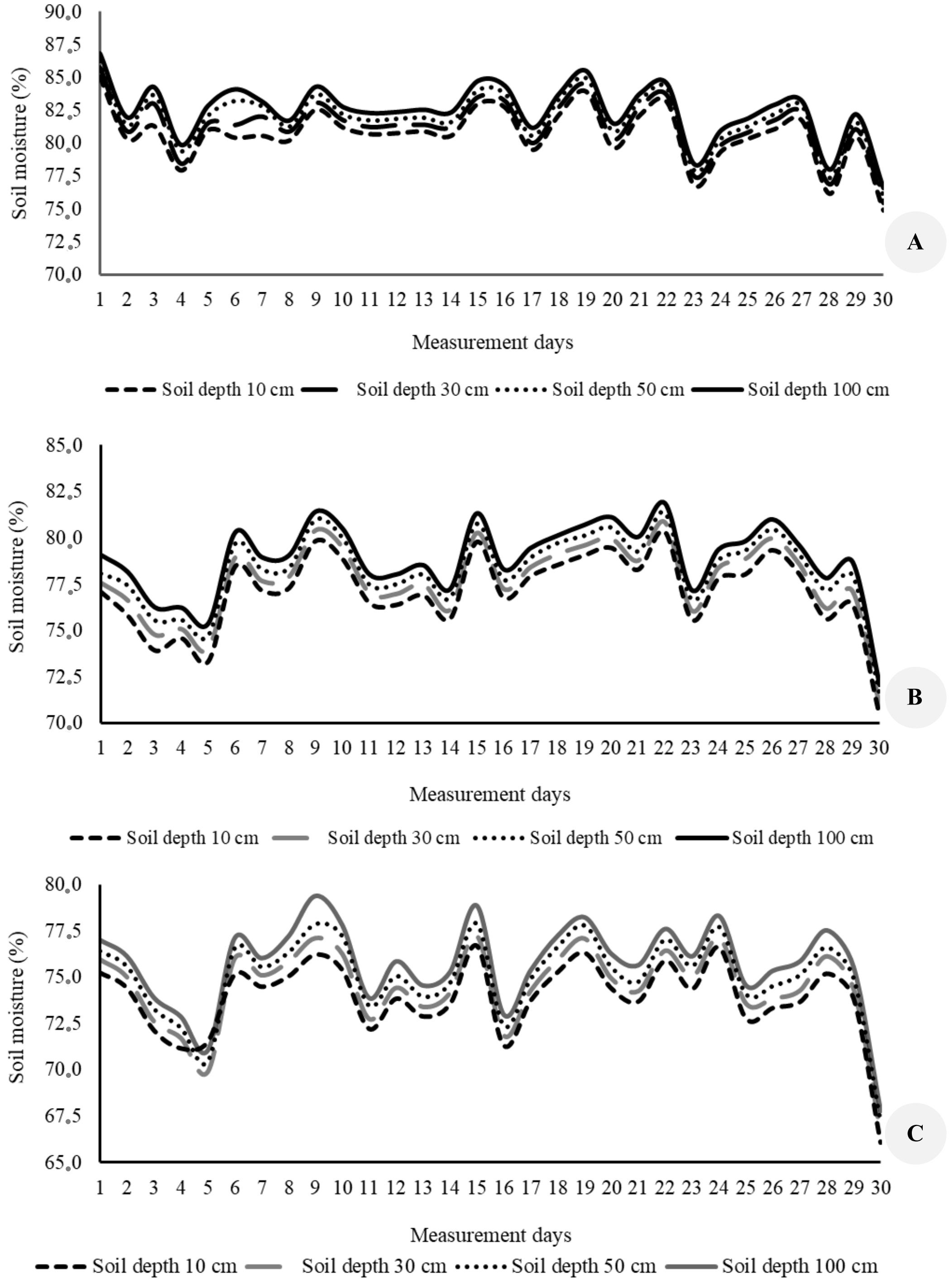

Figure 9. Daily soil moisture on different land covers with different depths: A. Sengon plantations, B. Shrublands, and C. Residential areas

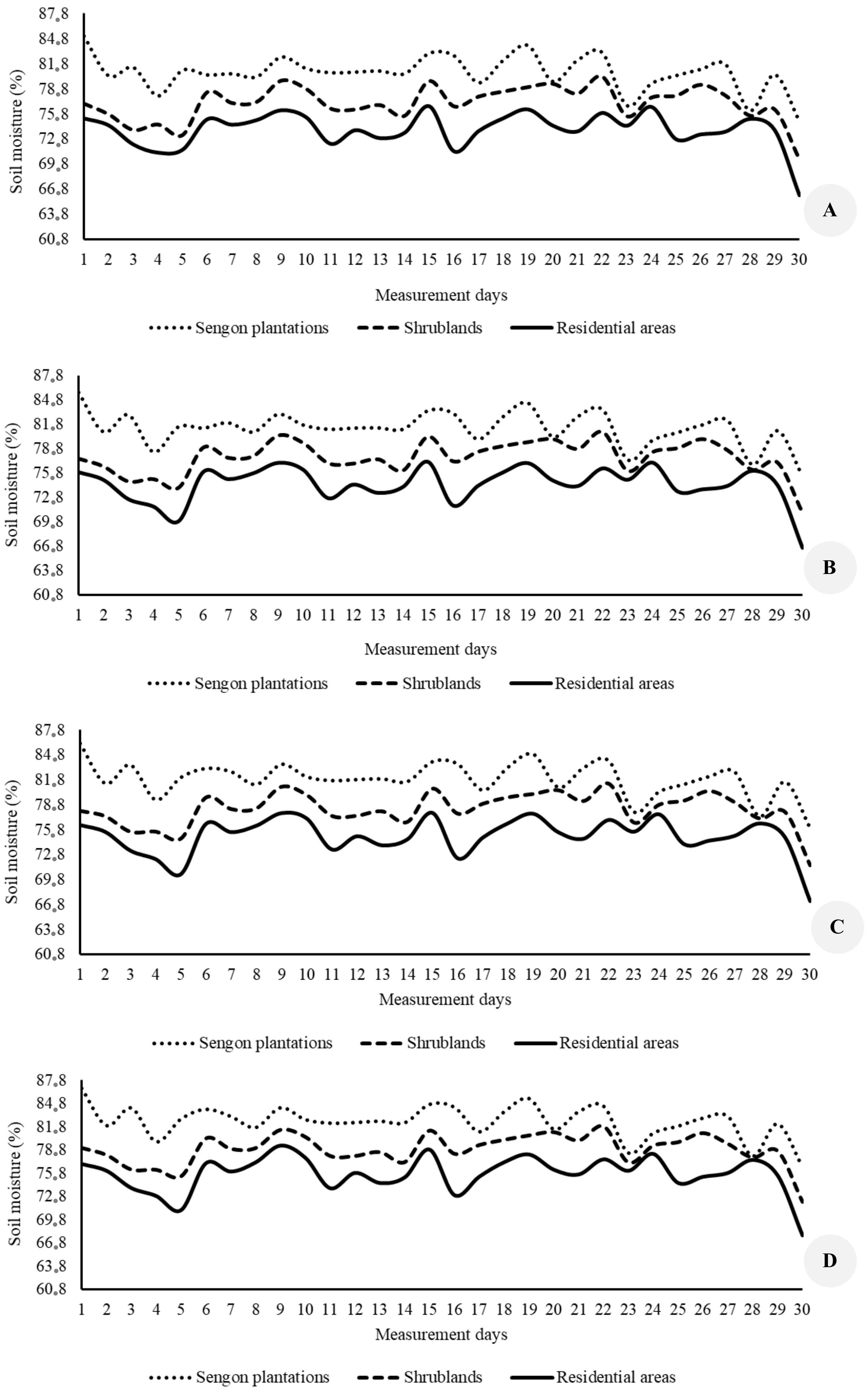

Figure 10. Daily soil moisture at A. 10 cm depth, B. 30 cm depth, C. 50 cm depth, and D. 100 cm depth

Soil moisture in the tropical urban area displayed marked variation across land-use types, soil depths, and times of observation. Sengon plantations consistently exhibit the highest soil moisture levels at all depths, with shrubland exhibiting the next-highest levels (Figures 12.A-D). Conversely, residential areas have been found to have the lowest soil moisture levels. This pattern suggests that vegetation cover and minimal land disturbance enhance soil water retention. Diurnally, soil moisture levels peaked in the morning, then declined at midday and recovered slightly in the late afternoon. The most pronounced decline in soil moisture levels was recorded in residential areas. The increase in soil depth has been shown to reduce temporal variability, suggesting that deeper soil layers are less affected by surface evaporation and solar radiation. The study indicated that changes in land use and urban development have a substantial impact on soil moisture availability, particularly in surface soils. In contrast, vegetated areas have been found to offer greater stability of soil water in tropical urban environments. The trends in temperature and soil moisture fluctuations in sengon plantations, shrublands, and residential areas were similar to those of air temperature and humidity in the area. The eight-year-old sengon plantations provided the most favourable microclimatic conditions, with lower light intensity and temperature than in shrublands and residential areas (Karyati et al. 2025a). Planting shade trees with dense and wide canopies can improve thermal comfort in urban areas (Mulyadi et al. 2025).

The soil moisture was lowest in the residential area (74.781%), medium in shrubland (77.860%), and highest in sengon planting (81.614%). Land used for sengon planting has the highest soil moisture, indicating that sengon planting has the greatest water-absorbing capacity compared to residential areas and shrubland. Differences in soil temperature and moisture are clearly visible across different land-cover or dominant-vegetation types. Locations with higher vegetation density have lower light intensity and temperature than locations with less vegetation cover. Several environmental factors that influence microclimate variation within an area are vegetation cover, light intensity, and local weather conditions (Karyati et al. 2025b). Tree canopies can reduce light intensity and air temperature and increase air humidity in vegetated areas. Variations in air temperature and humidity affect variations in soil temperature and humidity. Plants that grow in soil with unsuitable temperatures will experience obstacles to their growth (Karyati 2022). In addition to the reciprocal influence between climate elements, fluctuations in climate elements are also influenced by other environmental factors (Karyati 2019).

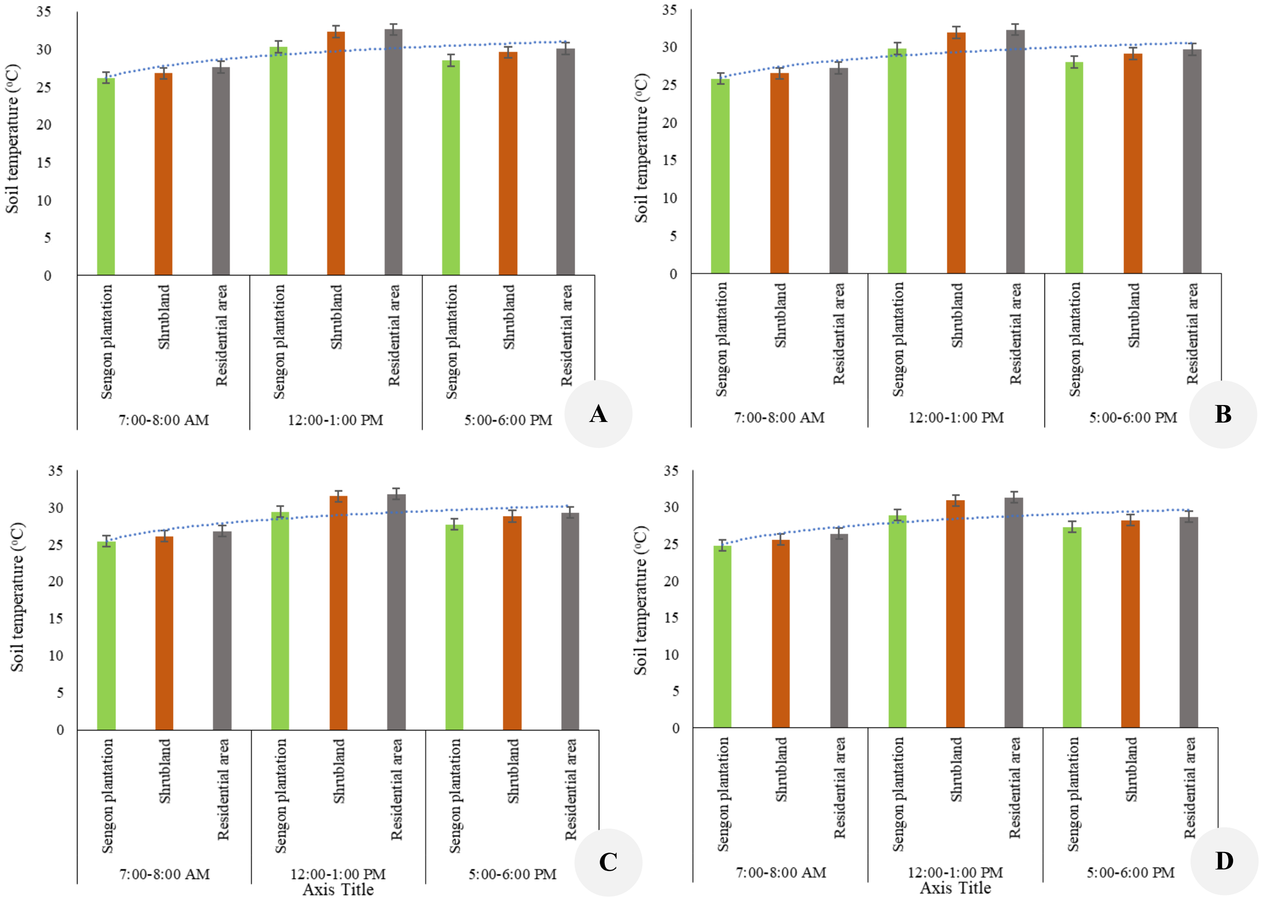

Figure 11. Soil temperature at different land uses based on measurement time: A. 10 cm depth, B. 30 cm depth, C. 50 cm depth, and D. 100 cm depth

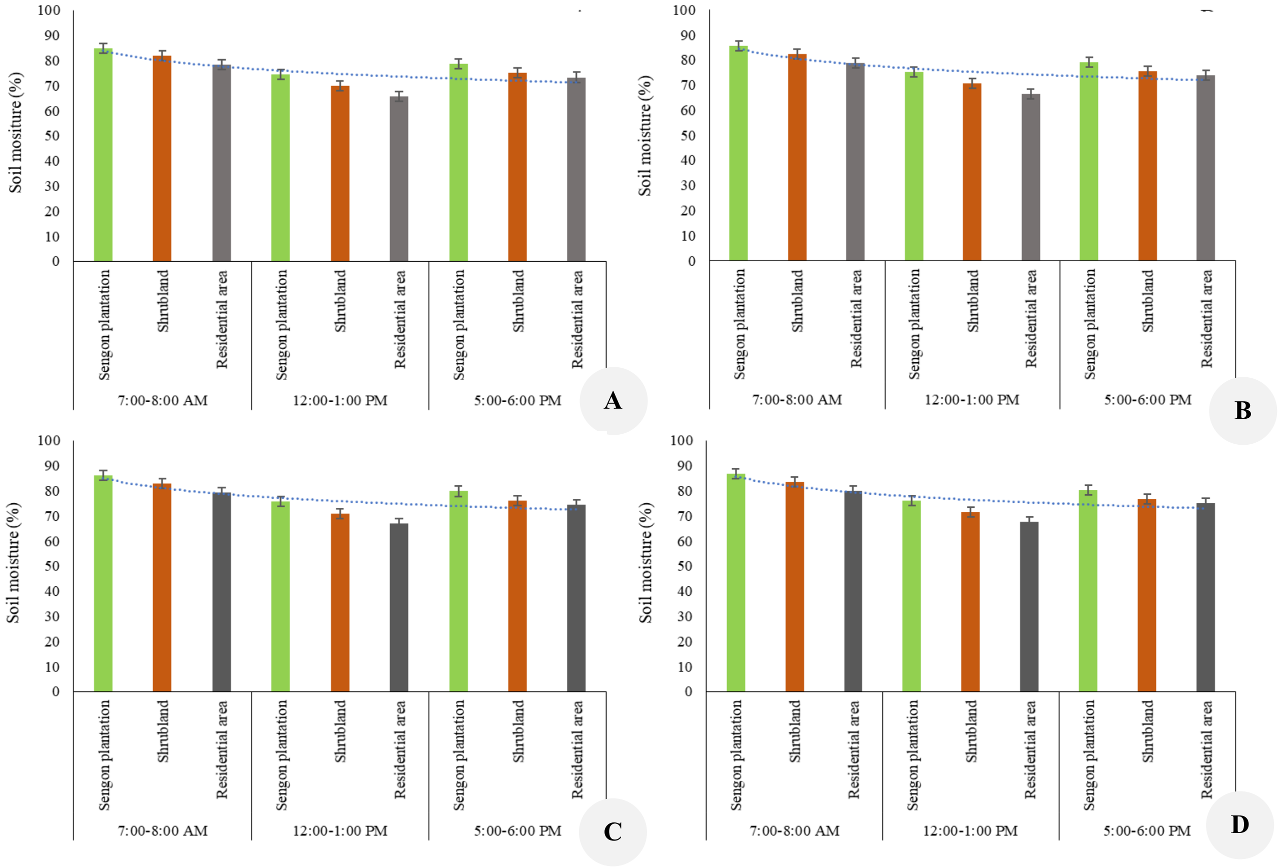

Figure 12. Soil moisture at different land uses based on measurement time: A. 10 cm depth, B. 30 cm depth, C. 50 cm depth, and D. 100 cm depth

The averages of soil moisture were 77.237%, 77.830%, 78.417% and 79.024% in soil depths of 0-10 cm, 20-30 cm, 50-60 cm and 90-100 cm, respectively. The deeper the soil, the lower the soil temperature and the higher soil moisture. The results of Li et al. (2024) study in the United States of America showed a strong and positive relationship was observed between soil moisture at depths of 10 and 20 cm (r = 0.84), while the relationship between soil moisture at depths of 10 and 40 cm was moderate (r = 0.52). Ran et al. (2020) explained that precipitation alters the soil water content, which in turn affects the soil's heat capacity. As soil moisture levels increase, the soil heat capacity also rises, leading to reduced fluctuations in soil temperature. In addition, the Tang et al. study (2022) in China's loess hilly region found that the air temperature and humidity are the main factors affecting how the soil moisture changed in the 0–60 cm soil layer of soybean sloping fields and grasslands in the normal precipitation year (2014) and the dry year (2015). Meanwhile, the main factors driving changes in soil moisture in the maize terraced field were humidity and wind speed in China's loess hilly region.

Soil temperature and moisture levels varied significantly across different land uses and soil depths in East Kalimantan. Forests and well-developed revegetation areas have the coolest, most humid soils due to their dense canopy cover and reduced exposure to direct sunlight. In contrast, residential and open areas experience warmer, drier conditions due to limited vegetation and greater exposure to the sunlight. Agroforestry systems maintained intermediate microclimates due to partial shading. Across all land uses, soil temperature decreased, and moisture increased with depth, reflecting reduced evaporation and greater moisture retention in deeper layers. Overall, vegetation structure is the primary factor that regulates the soil microclimate in tropical urban landscapes. Soil temperature and soil moisture in several types of land use and soil depth in East Kalimantan are shown in Table 6.

Plant age greatly affects soil temperature and moisture at a certain soil depth. Soil temperature at a depth of 30 cm (29.4°C) under the shade of 1-year-old sengon trees combined with beans was higher (Karyati et al. 2019) than soil temperature at the same depth under 8-year-old sengon trees (27.3°C) in this study. Conversely, soil moisture at a depth of 30 cm under a combination of 1-year-old sengon trees and beans was lower (77.8%) (Karyati et al. 2019) than under 8-year-old sengon trees (81.3%). This is because young sengon trees have sparser and narrower canopies than older sengon trees. The intensity of light reaching under the canopy of younger sengon trees was greater than that reaching under the canopy of older sengon trees. The intensity of light increases air temperature and reduces humidity under the tree canopy. The increase in air temperature under the canopy is followed by increases in soil temperature at different depths. However, the increase is slower in deeper soil than in shallower soil. In line with this, the decrease in air humidity will also be followed by a decrease in soil moisture at different depths.

Table 6. Soil temperature and soil moisture in several types of land use and soil depth in East Kalimantan, Indonesia

Location	Land use	Soil depth (cm)	Soil temperature (°C)	Soil moisture (%)	Source
Samarinda City	Young secondary forest	5	27.6	78.5	Assholihat et al. (2019)
		10	27.4	78.8	
		20	27.0	79.1	
		30	26.9	79.4	
	Residential area	5	27.5	76.4	
		10	27.4	78.5	
		20	27.0	79.3	
		30	26.8	80.2	
	Open area	5	27.6	69.2	
		10	27.4	69.6	
		20	27.0	70.3	
		30	26.9	70.8	
Sejati Park, Samarinda	Peaks	5, 10, and 20	27.8-30.0	72.8-90.0	Cahyaningprastiwi et al. (2021)
	Slopes	5, 10, and 20	27.6-30.4	64.9-89.7	
	Valleys	5, 10, and 20	28.6-31.4	67.0-88.7	
Education Forest, Faculty Forestry, Universitas Mulawarman, Samarinda	Forest	5	25.6-27.4		Karyati and Ardianto (2016)
		10	25.8-27.2		
		20	24.0-25.0		
		30	24.1-24.9		
	Open area	5	27.9-31.9		
		10	28.2-31.5		
		20	27.0-28.1		
		30	27.0-28.2		
PT Adimitra Baratama Nusantara, East Kalimantan	Revegetation 3 years	10	27.7	81.3	Karyati et al. (2018)
		20	26.6	81.5	
	Revegetation 4 years	10	27.2	82.9	
		20	26.1	83.2	
	Revegetation 5 years	10	27.0	85.8	
		20	25.9	85.9	
	Revegetation 6 years	10	26.4	86.0	
		20	25.3	86.1	
	Revegetation 7 years	10	26.1	87.8	
		20	24.9	88.0	
	Secondary forest	10	25.9	90.0	
		20	24.8	90.2	
Education Forest, Faculty Forestry, Universitas Mulawarman, Samarinda	Sengon - long beans	5	29.6	77.5	Karyati et al. (2019)
		10	29.6	77.5	
		20	29.4	77.7	
		30	29.4	77.8	
	Jabon - bean	5	29.6	76.7	
		10	29.4	77.4	
		20	29.4	77.4	
		30	29.3	77.8	
Samarinda City	Sengon planting	0-10	27.8	80.7	This study (2025)
		20-30	27.3	81.3	
		50-60	27.0	81.9	
		90-100	26.5	82.5	
	Shrubland	0-10	28.9	77.1	
		20-30	28.5	77.7	
		50-60	28.1	78.3	
		90-100	27.0	78.9	
	Residential area	0-10	29.5	73.9	
		20-30	29.1	74.4	
		50-60	28.7	75.0	
		90-100	28.2	75.7	

The average soil temperature at a depth of 30 cm in the residential area in this study was 29.1°C higher than the average soil temperature in residential areas at the same depth (26.8°C) reported by Assholihat et al. (2019). Meanwhile, soil moisture in this study was 74.4% lower than soil moisture in residential areas at a depth of 30 cm, which was 80.2% (Assholihat et al. 2019). This is thought to be due to the influence of different microclimates. The residential area Assholihat et al. (2019) conducted their research is located on the outskirts of Samarinda City, with a lower population density than the location of this study. A more beautiful environment with relatively low population density will support a more comfortable microclimate, with lower air and soil temperatures and higher air and soil humidity than residential environments located near urban centers, where this study was conducted.

Temperature and humidity patterns in residential buildings exhibit a reciprocal relationship, whereby occupants' water use can increase indoor air humidity (Zhou et al. 2019). The surface cooling effects of urban and peri-urban green spaces are influenced not only by land cover and vegetation characteristics but also by soil texture, which serves as an indicator of water availability through its storage capacity and unsaturated hydraulic conductivity (Stumpe et al. 2023). In addition to their potential to reduce surface runoff and soil erosion, sengon and jabon (Sarminah et al. 2021), and sengon and peanut (Sarminah et al. 2018) also contribute to improving the microclimate both above and below the soil surface. Under future warmer conditions, the limitation of forest temperature buffering by soil–water will become more prevalent and likely lead to changes in understory communities (Greiser et al. 2024). Forest soils accumulate large amounts of organic matter, which makes them essential for long-term carbon storage (Lamichhane and Ghimire 2024).

The study provides important data on soil temperature and moisture variations across different land uses in Samarinda City. These findings can help urban planners and environmental managers understand current microclimate conditions and identify areas vulnerable to heat and moisture imbalance. In the long term, the results support sustainable urban development and land-use planning by promoting vegetation-based designs that regulate soil temperature and moisture. This contributes to improved urban resilience, ecological balance, and climate adaptation strategies in tropical cities.

In conclusion, different land cover and soil depth influence soil microclimate, particularly temperature and moisture conditions. Land use type influences soil microclimate, with soil temperatures in areas with denser vegetation cover, such as agroforestry, more stable and soil moisture higher than in areas with denser shrubs or more open residential areas. This confirms the role of vegetation in maintaining thermal balance and water availability in the soil, which influences land fertility and productivity. This study recommends that planning and spatial planning in tropical urban areas prioritize plantings that combine trees and understory plants to moderate soil conditions. Further research on plant species that can improve soil temperature and moisture in urban areas is needed. However, this study has limitations, including the limited scope of the study area and observation period, as well as the potential influence of other factors, such as rainfall and human activities, that have not been fully analyzed. The practical implication of this finding is that agricultural land-use planning in tropical urban areas needs to consider the extent and type of vegetation cover, especially agroforestry systems and green spaces, to maintain soil quality, increase water retention, and reduce increase in soil temperature due to changes in land use and land cover.

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