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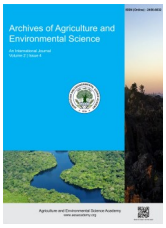

ORIGINAL RESEARCH ARTICLE

Assessing assisted natural succession for tropical rainforest rehabilitation: Evidence from Gunung Halimun Salak National Park, Indonesia

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ABSTRACT

Rehabilitation zone – a tropical rainforest ecosystem in Gunung Halimun Salak National Park (GHSNP) which had been degraded and restored by reforestation as an approach of assisted natural succession (ANS) to accelerate natural succession (NS) for ecosystem recovery. This study aimed to examine the ecological attributes (vegetation density or cover, carbon storage, and soil properties) in areas that have been rehabilitated through the ANS approach via reintroduction of tree species, and to compare these attributes with those found in natural forest areas (core zone) resulted by NS process. Vegetation density or cover based on NDVI, carbon storage, and soil properties of the tropical rainforest in rehabilitation zone were relatively lower than in the core zone as reference ecosystem. Core zone of the national park conserving biodiversity and their habitat with original and natural attributes without human interferences. NDVI value of tropical rainforest in the rehabilitation zone of GHSNP was relatively lower than in the core zone, namely 0.76 and 0.89, respectively. The ANS approach through revegetation on degraded forested areas (rehabilitation zone) affected positively toward the pathway of ecological succession and stimulated forest recovery, particularly on vegetation density and carbon storage. Vegetation density based on NDVI value was positively correlated with other parameters, including soil organic matter, soil C-organic, soil porosity, and soil respiration. Moreover, vegetation density or cover was also positively correlated with carbon storage, particularly in above ground carbon storage. Besides, vegetation density based on NDVI value showed inverse relationship with the soil bulk density and temperature.

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INTRODUCTION

In the year 2020, deforestation in Indonesia was estimated at approximately 116,900 ha, with Java Island accounting for around 34 ha (Ardiyanto *et al.*, 2022). During 2021 – 2022, Indonesia experienced an average deforestation rate of approximately 104,032.5 ha per year, which the highest losses occurring in forested areas, amounting to 73,130.1 ha annually (BPS, 2024). According to Giri *et al.* (2023), the remaining forested area in Java constitutes only about 24%, equivalent to ± 128,297 km^2. These facts highlight the pressures to the tropical rainforest still potentially exist and may lead to forest degradation and deforestation. Gunung Halimun Salak National Park (GHSNP) is the most extensive of tropical montane rainforest conservation area remaining in Java, Indonesia (Qodri *et al.*, 2020; Irawan *et al.*, 2023). Topographically, it lies at altitude of 500 – 2,200 m asl (Peggie & Harmonis, 2014; Wasis *et al.*, 2024). Like many forests around the world, forest ecosystems in GHSNP face potential threats from degradation and deforestation. Natural succession (NS) refers to the progressive changes

that occur within an ecosystem over time following disturbances, including the alteration of ecosystem attributes, such as species structure and composition, biodiversity, soil properties, and ecological processes (Poorter *et al.*, 2023). Succession also involves shifts in microclimate conditions, evolving from the simplest to the most complex states as the ecosystem develops. NS is a successional process that occurs naturally in the ecosystem recovery after the perturbation. As a natural recovery mechanism in disturbed ecosystems, ecological succession provides a fundamental basis for restoration or rehabilitation efforts. However, Huebner *et al.* (2022) suggested that the natural successional processes can probably take many decades. Therefore, it requires intervention by humans to accelerate ecological succession as a natural process, then hereafter we called as "assisted natural succession" (ANS).

Forest restoration or rehabilitation is a critical step to address the ecological issues of forest ecosystems. This study aimed to examine the ecological attributes (vegetation cover, carbon storage, and soil properties) in areas that have been restored (rehabilitated) through the ANS approach via reintroduction of tree species within tropical rainforest ecosystem of GHSNP, and to compared these attributes with those found in natural forest areas which were the result of the NS process. Accordingly, this study tried to reveal the potential of ANS approach by reintroduction or replanting of tree species as a prospective strategy for ecological restoration (rehabilitation).

MATERIALS AND METHODS

Plot establishment and soil sampling

The GHSNP area comprises diverse natural forested ecosystems, including low land rainforest, sub-montane and montane rainforest (Istomo *et al.*, 2024). As a national park in Indonesia, GHSNP consisted of several management zones. One of them was a rehabilitation zone – an area belonging to the national park which had experienced a perturbation, then being restored or rehabilitated by human interference primarily via reforestation to assist and accelerate the NS process as ecological recovery mechanism. Besides, remnants of natural tropical rainforest persisted in their original condition and ecological function without human interventions. The pristine forest types were primarily located within the core zone of GHSNP. Research plots were established with purposive sampling in the rehabilitation zone (± 910 m asl) for representing disturbed-forested areas with ANS process, and the core zone (± 1,300 m asl) as a reference ecosystem (undisturbed tropical rainforest ecosystem in natural state, including the NS process) (Figure 1). According to (Kusmana *et al.*, 2022), both our research locations are categorized as lower rainforest ecosystem (0 – 1,000 m asl) and middle rainforest ecosystem (1,000 – 3,000 m asl), respectively. The 50x50 m square single plot with 15 repetitions were established in each study location. In addition, there were 1x1 m subplots with 3 repetitions within the main plot (Figure 2). Soil samples were taken in 1x1 m subplot with 5 sampling points.

Normalize Difference Vegetation Index (NDVI) analysis

Vegetation index represents the greenness value of vegetation, derived from processing digital signal data based on brightness values from multiple satellite sensor data channels (Zaitunah *et al.*, 2021; Gašparović *et al.*, 2023). It consists of various algorithms, and the most widely used for vegetation monitoring is the Normalized Difference Vegetation Index (NDVI). Due to its high sensitivity to chlorophyll – related photosynthetic activity, NDVI serves as an effective indicator for vegetation classification (Wang *et al.*, 2023), such as on vegetation density or cover. We employed Sentinel-2A imagery data with Band-4 (Red) and Band-8 (NIR) for spatial data processing. The use of multispectral data from Sentinel-2A satellites has several benefits, such as offering high temporal resolution with rich spectral information (Rapinel *et al.*, 2019; Zhang *et al.*, 2022). It is widely used as an approach to estimate various vegetation parameters (Meyer *et al.*, 2019), including the vegetation index. In addition, Sentinel imagery data can be applied across various fields, including environmental monitoring, spatial planning, water management, forestry, carbon assessment, natural resource management, and global agricultural assessment (Gunawansa *et al.*, 2022; Sulton *et al.*, 2023). All spatial and NDVI data analysis were processed by using QGIS 3.34. The NDVI value was calculated with the following formula (Armita *et al.*, 2022):

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where, NDVI = Normalized Difference Vegetation Index, NIR = Infrared Band (Band-8), Red = Red Band (Band-4)

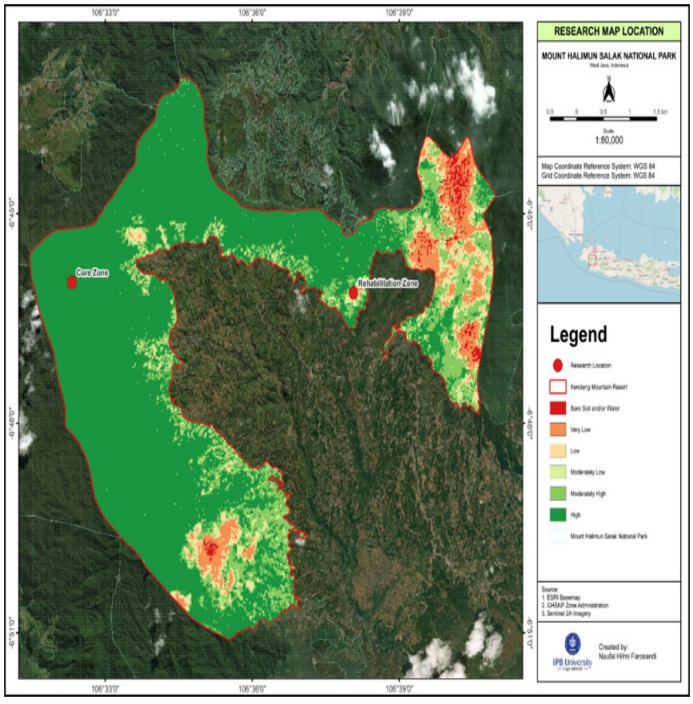

Figure 1. *NDVI value distribution in research location.*

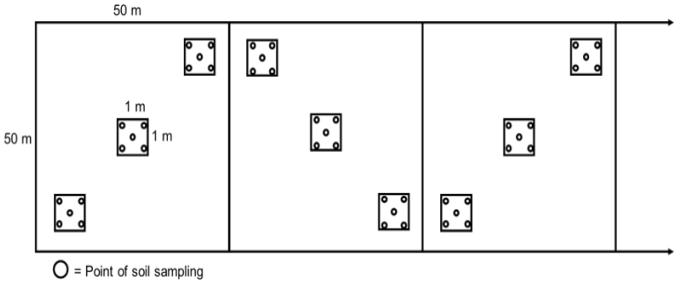

Figure 2. *Observation and soil sampling plot design.*

Soil properties analysis

Soil temperature (STp) was measured by using soil thermometer in the 1 × 1 m subplot with 5 repetitions (Figure 2). The undisturbed soil sample was used in analyzing soil bulk density (SBD) and soil porosity (SPr). Meanwhile, the composite soil sample was used in analyzing soil organic matter (SOM), soil C-organic (SCO), and soil respiration (SRs). The SOM and SCO were measured by using a spectrophotometry method, whereas the SRs was determined following the procedure outlined by Wasis *et al.* (2024). Besides, the SBD and SPr were estimated by gravimetry method (Rusdiana *et al.*, 2024; Toková *et al.*, 2020).

Estimation of above ground and below ground carbon storage

The above ground biomass refers to all living organisms dominated by vegetation that occupies the soil surface, including stems, branches, bark, seeds, and leaves (Indriyani *et al.*, 2024), which has ability on carbon storage. In this study, above ground carbon storage (AGC) referred to vegetation that occupied the ground (habitat), was estimated through non-destructive method by using the following regression formula (Mosa *et al.*, 2024):

$$Y = 100.83\ X + 31.259$$

Where, Y = Carbon storage (concentration) (ton/ha) and X = Normalize Difference Vegetation Index (NDVI). Moreover, below ground carbon storage (BGC) represented carbon storage in the forest floor (forest soil), was estimated by using the following formula (BSN, 2011):

$$Cs = Ds \times BD \times C\text{-}org.$$

$$Cs = Ct \times 100$$

Where, Cs = Soil carbon content or carbon content in the soil sample (g/cm^2); Ds = Depth of soil sample (cm); BD = Bulk density (g/cm^3); C-org. = Soil C-organic content (%); and 100 = Conversion factor of g/cm^2 to ton/ha.

Data analysis

Microsoft Excel and R-Studio were used for data processing and statistical analysis. The Pearson Correlation Test was used to analyze relationship between variables, including vegetation density or cover (NDVI value), soil organic matter (SOM), soil C-org. (SCO), above and below ground carbon storage (AGC and BGC), soil bulk density (SBD), soil porosity (SPr), and soil respiration (SRs). The coefficient of Pearson (r) quantifies both direction and strength of the liner relationship between two variables. A positive value of r indicates that the variables tend to have unidirectional relations, whereas a negative value signifies the inverse relation between variables. The r value ranges from -1 to +1. Values closer to either -1 or +1 indicate a stronger correlation between variables. Conversely, value near 0 suggests a weak or negligible relationship between variables (Papageorgiou, 2022).

RESULTS AND DISCUSSION

Vegetation cover and carbon storage

The NDVI is a widely used vegetation index that quantifies the plant greenness, serving as a reliable indicator for estimating land cover, vegetation density, and temporal changes in vegetation dynamics (Hartoyo *et al.*, 2021; Khairunnisa *et al.*, 2024). Our study revealed that the NDVI value of tropical rainforest in the rehabilitation zone of GHSNP was relatively lower than in the core zone, namely 0.76 and 0.89, respectively (Table 2; Figure 1). This finding indicated that the vegetation density and land cover of tropical rainforest ecosystem in the core zone were greater than the rehabilitation zone. Higher NDVI values in general reflect denser and healthier vegetation, whereas lower values suggested sparse or degraded vegetation cover. The high vegetation density also suggested not only an abundance of tree stands, but also a greater potential of biomass accumulation within ecosystems. According to Aquino *et al.* (2018) the rehabilitation zone demonstrated a moderately high for vegetation density or cover (0.6 < NDVI ≤ 0.8). Conversely, the core zone reflected a substantially higher vegetation cover density (0.8 < NDVI ≤ 1) (Table 1). The rehabilitation zone of GHSNP constituted a tropical rainforest ecosystem that had been subjected to ecological disturbances, leading to a reduction in both vegetation abundance and plant biodiversity. These changes directly affected vegetation density and canopy cover in the forest ecosystem. To accelerate ecological succession or natural succession (NS) and promote ecosystem recovery, forest restoration or rehabilitation efforts were implemented through reforestation. Reforestation was essentially a form of forest ecosystem rehabilitation, with its primary step being revegetation, particularly through reintroduction (replanting) of tree species, especially native tree species. Technically, reintroduction tree species in degraded tropical rainforests might provide several benefits: 1) Accelerating natural succession (NS) trajectories by enhancing migration, ecesis, invasion of plant species and development of canopy cover that might affect habitat reactions, 2) Promoting soil nutrient cycling through litter production, which was essential for soil organic matter and soil biota activity, and 3) Fostering land cover establishment, which was critical for soil and water conservation within ecosystems.

An NDVI value of 0.76 in the rehabilitation zone (moderately high for vegetation density or cover) reflected an ongoing re-

Table 1. The vegetation cover density based on NDVI value (Aquino *et al.*, 2018).

S. No.	Class	NDVI Value Criterion
1	Bare soil and/or water	NDVI ≤ 0
2	Very low	0 < NDVI ≤ 0.2
3	Low	0.2 < NDVI ≤ 0.4
4	Moderately low	0.4 < NDVI ≤ 0.6
5	Moderately high	0.6 < NDVI ≤ 0.8
6	High	0.8 < NDVI ≤ 1

Table 2. The average of vegetation cover (based on NDVI value) and carbon storage estimation in areas with natural succession and assisted natural succession process in GHSNP.

Parameter	Units	Tropical Rainforest Ecosystem in	
		Core Zone	Rehabilitation Zone
		NS[a]	ANS[b]
Vegetation density or cover (NDVI)	-	0.89	0.76
Above ground carbon storage (AGC)	ton/ha	120.59	107.87
Below ground carbon storage (BGC)	ton/ha	10,568.85	9,024.90
Total carbon storage	**ton/ha**	**10,689.44**	**9,132.77**

[(a)]Area with Natural Succession Process; [(b)]Area with Assisted Natural Succession Process.

covery process of natural succession (NS) supported by human intervention. This condition suggested that ANS approach through revegetation could potentially encourage and accelerate the path of ecological succession and ecosystem recovery, both in ecosystem components and functions. Relying solely on natural succession process (NS) to restore disturbed forest ecosystems required a long time, relatively. Therefore, assisted natural succession (ANS) offered promising alternatives for accelerating the ecological recovery. In addition, the ANS approach through the revegetation by using tree species on degraded forested areas (rehabilitation zone) affected positively toward carbon storage (sequestration). Indriyani *et al.* (2024) stated that carbon sequestration through photosynthesis by plants which can synthesize CO_2 from atmosphere to carbohydrate then accumulate into biomass, can be considered as a nature-based solution (NBS) in solving climate change.

Carbon might be found in various forms, such as living organisms, especially in the plant biomass, soil organic matter, and CO_2 in atmosphere. Harris *et al.* (2021) and Satdichanh *et al.* (2023) estimated that tropical forests may contribute around 30% for the total carbon sink globally, where about 40% of carbon storage is dominated in the form of carbon soil and plant biomass. Overall, the total carbon storage estimation of tropical rainforest in the core zone GHSNP (10,689.44 ton/ha) was relatively higher than in the rehabilitation zone (9,132.77 ton/ha). It was also in line with the above and below ground carbon storage in both zones. This condition was likely caused by disparity in vegetation density, as indicated by dissimilarity in NDVI value. Moreover, below ground carbon storage (BGC) was found to be greater than above ground carbon storage (AGC) in tropical rainforest of GHSNP in both zones. The findings demonstrated that forest soils, particularly in tropical rain forests, possess substantial potential for carbon storage. Moinet *et al.* (2023) and Sun *et al.* (2024) outlined that globally, soil carbon is relatively much greater than the amount of vegetation and atmospheric carbon. Furthermore, soil plays a significant role mainly as carbon reservoir in terrestrial ecosystem, which is three times larger than atmospheric reservoir, and four times greater than biotic reservoir (Chanlabut & Nahok, 2023; Naorem *et al.*, 2022).

Soil characteristics

Table 3 presented the soil properties across several parameters at the research site. Only soil bulk density (SBD) and soil temperature (STp) of tropical rainforest ecosystem in the rehabilitation zone were relatively higher than those in the core zone. High bulk density was presumed to affect the soil organism's existence and activities. These phenomena were associated with lower vegetation density and cover in this zone. Low vegetation density and canopy cover in the rehabilitation zone created greater openness, allowing more solar radiation to reach forest floor and thereby increasing soil temperature (STr) that might affect soil biota. Thomson (2022) stated that vegetation cover can strongly influence soil temperature, which plays a role as a thermal insulator. Besides, soil temperature is driven by several factors, such as soil moisture, soil color, and soil texture. In addition, bulk density also might impact on the soil porosity (SPr). Basically, SPr could influence soil aeration and drainage, which were important to advocate for living of soil organisms. Bulk density is essential soil parameter on understanding and analyzing the soil properties, either physically, chemically, or biologically (Panagos *et al.*, 2024; Topa *et al.*, 2021). Soil respiration (SRs) can be a parameter that has great potential as an indicator of soil ecosystem metabolism or soil biological activities (Bhaduri *et al.*, 2022; Lima *et al.*, 2021). SRs of tropical rainforest in rehabilitation zone was relatively lower than core zone, which indicated that soil metabolism as form of soil organism's activities of tropical rainforest in rehabilitation zone was relatively lower than core zone. Furthermore, the increase of soil respiration may indicate the raising of soil microbial activities, such as decomposition of soil organic matter that is important for increasing soil nutrients, like soil nitrogen (Thomson, 2022), as well as soil C-organic.

Table 3. Soil characteristics in area with natural succession and assisted natural succession process in GHSNP.

Parameters	Unit	Tropical Rainforest Ecosystem in	
		Core Zone	Rehabilitation Zone
		NS[a]	ANS[b]
Soil organic matter (SOM)	%	28.47	16.09
Soil C-org. (SCO)	%	16.52	9.34
Soil bulk density (SBD)	g/cm^3	0.32	0.48
Soil porosity (SPr)	%	87.83	81.79
Soil temperature (STp)	°C	19.03	21.85
Soil respiration (SRs)	mgCO_2/100g soil/day	60.99	39.50

[(a)]Area with Natural Succession Process; [(b)]Area with Assisted Natural Succession Process.

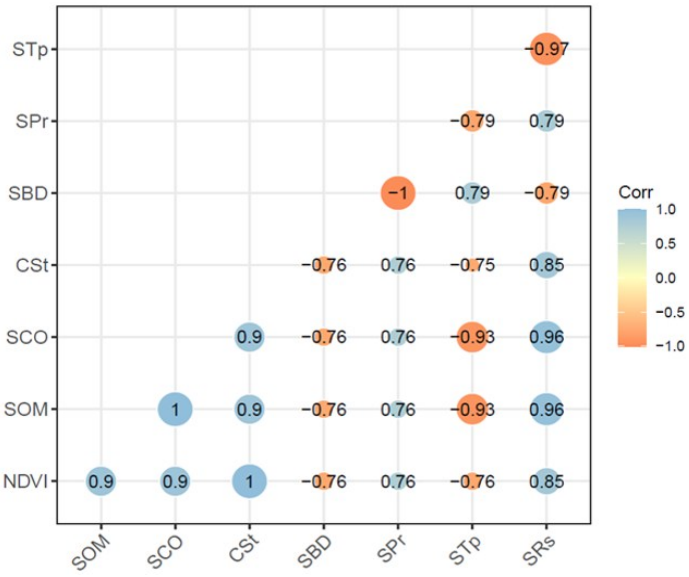

Figure 3. *Correlation matrix of ecological parameters. Normalize Difference Vegetation Index (NDVI), soil organic matter (SOM), soil C-organic (SOC), total carbon storage (CSt), soil bulk density (SBD), soil porosity (SPr), soil temperature (STp), and soil respiration (SRs).*

On other hand, soil organic matter (SOM) and soil C-organic (SCO) content of tropical rainforest in core zone was relatively higher than rehabilitation zone. In general, SCO content of tropical rainforest both in rehabilitation and core zone of GHSNP was categorized at a very high level. Hardjowigeno (2010) stated that for mineral soil with > 5.00 % of C-org. content is included in the very high category. Kotroczó & Fekete (2020) stated that litter can influence to soil biological activities, soil organic matter, as well as soil C-organic. SCO content may indicate the carbon content of the soil (Sagiarti *et al.*, 2020). In addition, SCO is not only an important component of soil which can determine soil quality, yet it plays a crucial role toward soil carbon sequestration as well as the global carbon cycle (Wu *et al.*, 2022). The core zone in GHSNP constituted an undisturbed natural forest shaped by the natural succession (NS), and distinguished by complex vegetation composition and structure, as well as elevated levels of biodiversity. Those conditions might impact litter production in this area that was potentially higher than rehabilitation zone. However, assisted natural succession (ANS) implementation by planting of tree species (reforestation) in rehabilitation zone was potentially able to stimulate the presence of ecological functions in degraded forested areas, such as function of biodiversity, nutrient cycles, and soil improvement. (Satdichanh *et al.*, 2023) suggested that reforestation or restoration practices can increase plant diversity and other ecological functions, such as enhance organic carbon sequestration.

Correlation of vegetation cover, carbon storage, and soil characteristics

Figure 3 served the correlogram of Pearson correlation test that indicated the variables relationship. This study revealed that vegetation density or cover based on NDVI value had a strong and positive correlation with other variables, such as soil organic matter (SOM), soil C-organic (SCO), soil porosity (SPr), and soil respiration (SRs), where the r value was almost reached to +1, respectively. Moreover, NDVI also positively correlated with total carbon storage (CSt). Forested ecosystems including tropical rain forests, largely dominated by tree species, typically exhibited vegetation composition and structures that play a pivotal role in regulating capacity of these systems to sequester carbon, primarily through the physiological process of photosynthesis. The result of photosynthesis was then placed into above and/or belowground biomass. Hawkins *et al.* (2023) suggested that plants can deliver an estimated 35 – 80% of the carbon fixed from photosynthesis to belowground, particularly for root growth and metabolism, as well as for mycorrhizae, and other soil organisms. Besides, Paul *et al.* (2022) stated that plants also can transfer around 10% of annual photosynthesis into aboveground litter form. Moreover, vegetation density or cover (NDVI) value showed inverse correlation with the soil bulk density (SBD) and soil temperature (STr). These indicated that the increment of soil bulk density might obstruct the growth of roots, because of soil compaction. Soil bulk density and porosity are the most frequently used as soil indicators on soil compactness and may determine air and water movement in soil (Panagos *et al.*, 2024). Hence, these soil properties were able to be limited factors for the growth of plants and other soil organisms. The assisted natural succession (ANS) approach, implemented through tree planting as a form of reforestation in degraded forest ecosystems, represented a promising alternative strategy for the forest restoration. Apart from being able to encourage the development of forest composition and structure, this method had the potential to stimulate and catalyze the development of soil biota via litter input, which played a pivotal role in enhancing soil properties and function, and thereby accelerating habitat recovery.

Conclusion

The rehabilitation zone in GHSNP was a degraded tropical rainforest area within the national park that had been restored by reforestation as an assisted natural succession (ASN) approach to accelerate ecological succession for forest recovery. This study concluded that in general, the ecological attributes of tropical rainforest in the rehabilitation zone in GHSNP included vegetation cover density based on NDVI value, carbon storage, and soil properties (organic matter, C-org., porosity, and soil respiration) were relatively lower than the core zone. Nonetheless, ANS approach through the reforestation of degraded forested areas (rehabilitation zone) had a potential and positive effect toward the pathway of ecological succession and accelerating the forest recovery. Vegetation density or cover (NDVI) had a strong and positive correlation with other variables, such as soil C-organic, porosity and soil respiration. Conversely, vegetation density or cover based on NDVI value showed inverse correlation with the soil bulk density and temperature.

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DECLARATIONS

Authors contribution statement: Conceptualization, methodology: B.W.; Software, validation: B.W., R.S.N., and N.H.F.; Investigation: W.M.; Data curation: B.W., R.S.N., N.H.F.; Writing-original draft preparation: B.W.; Writing-review and editing: B.W., R.S.N., N.H.F., S.H.G.; Supervision: B.W. All authors have read and agreed to the published version of the manuscript.

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Ethics approval: This study was conducted in view of the institutional ethical guidelines and does not harm the human participants.

Consent for publication: All co-authors gave their consent to publish this paper in AAES.

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