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Spatial Characterization of NDVI-Based Vegetation Density in Smallholder Coffee Plantation on Mount Kawi's Southern Slopes

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Abstract. *Indonesia's coffee cultivation covers 1.25 million hectares, predominantly managed by smallholders (98.14%). Malang Regency, a key production area in East Java, experienced a sharp yield decline from 29,728 tonnes (2021) to 14,151 tonnes (2022). This study investigates smallholder plantations in the Kletek sub-watershed, emphasising the role of shade vegetation in coffee growth. Shade density critically influences productivity and ecological resilience. To support sustainable management, vegetation cover is assessed via remote sensing using the Normalised Difference Vegetation Index (NDVI), enabling spatial analysis of canopy structure. This research aims to analyse the types of coffee shade trees on smallholder coffee farms. NDVI is used to distinguish differences in land cover, including coffee shade. The study employed a land survey using the grid method with 30 observation points. Spatial analysis involves spectral transformation of Sentinel-2A Harmonised imagery, while statistical analysis uses correlation tests. Smallholder coffee farms in the Kletek Sub-watershed feature shade plants such as lamtoro, mahogany, and banana trees. NDVI values across these plantations ranged from moderate (0.4–0.5) to very high (>0.6) vegetation density, showing a strong correlation with land cover conditions (r = 0.80). This confirms NDVI as an effective remote sensing tool for assessing shade vegetation, significantly influencing coffee productivity and ecological resilience. The findings support NDVI-based monitoring for precision agriculture and adaptive management, with scalable applications in sustainable land-use planning, agroforestry optimisation, and climate-resilient coffee cultivation in regions such as Malang Regency, where production has declined.*
Keywords: *normalised difference vegetation index; shade crops; smallholder coffee plantations; vegetation density.*

Type of the Paper: Regular Article.

1. Introduction

Coffee is a high-value plantation commodity in Indonesia, contributing substantially to the country's non-oil and gas foreign exchange revenues. In 2020, national coffee cultivation covered approximately 1.25 million hectares, with smallholder plantations (PR) dominating at 98.14%, while large-scale estates (PB) accounted for only 1.86% [1]. This positions Indonesia as the fourth-largest coffee bean producer globally, after Brazil, Vietnam, and Colombia [2]. East Java ranks among Indonesia's leading coffee-producing provinces, yielding approximately 45,914 tonnes of coffee beans annually across 89,219 hectares, reflecting its substantial role in the national coffee

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sector [3]. Malang Regency is a key coffee-producing area within East Java, ranking among the top three highest-yielding regencies, after Jember and Banyuwangi Regencies [4,5]. One prominent cultivation area is the southern slopes of Mount Kawi, specifically the Kletek sub-watershed, characterized by smallholder robusta coffee plantations.

Land issues in smallholder coffee plantations involve highly diverse management practices, including crop composition, which can lead to reduced coffee production due to competition for water, nutrients, and sunlight [6]. To address this, two cultivation methods are considered: coffee with shade trees and without shade trees (monoculture). Shade cultivation protects plants from direct sunlight, reduces heat stress, controls weeds, and maintains soil moisture [7,8]. However, excessive shade can limit the sunlight coffee plants require [9,10]. Monoculture provides higher productivity but requires intensive management with additional fertiliser; otherwise, soil nutrient depletion can reduce yields. In this region, coffee is generally cultivated under a shade system using trees such as lamtoro, pine, mahogany, and banana [11,12]. Therefore, assessing shade density in smallholder coffee gardens is essential for optimising plantation management, particularly in determining shade tree composition to enhance coffee productivity.

One way to determine differences in canopy management is by examining vegetation density in coffee plantations. Vegetation density can be efficiently analysed using remote sensing through spectral transformation methods, expressed as vegetation indices [13]. A vegetation index quantifies greenness by processing digital brightness values from several satellite sensor channels [14]. A widely used index for analysing vegetation density is the Normalised Difference Vegetation Index (NDVI), which exploits the reflection of light waves from leaves [15]. Vegetation greenness in a given area is measured on a scale from -1 to 1, calculated by comparing reflectance at red (R) and near-infrared (NIR) wavelengths [16].

This study investigates the composition of shade tree species within smallholder coffee agro-ecosystems and examines the correlation between vegetation density and coffee land cover using the Normalized Difference Vegetation Index (NDVI) derived from remote sensing data. The relationship between NDVI and shade conditions can inform the management of shade density in smallholder coffee plantations.

2. Materials and Methods

2.1. Research Location

The study was conducted within the Kletek Sub-Watershed, on the southern flank of Mount Kawi, East Java, encompassing the districts of Wonosari, Ngajum, and Sumberpucung in Malang Regency. Land cover analysis, composition, and measurement of vegetation diversity in coffee plantations were conducted from September to November 2024. The Kletek Sub-Watershed area has numerous coffee plantations, particularly managed by local communities, covering

approximately 17,845.97 hectares. Research sites were located at elevations ranging from 274 to 2,029 meters above sea level, with central geographic coordinates of 8°03'55" South and 112°30'54" East. A spatial representation of the study area is shown in Fig. 1.

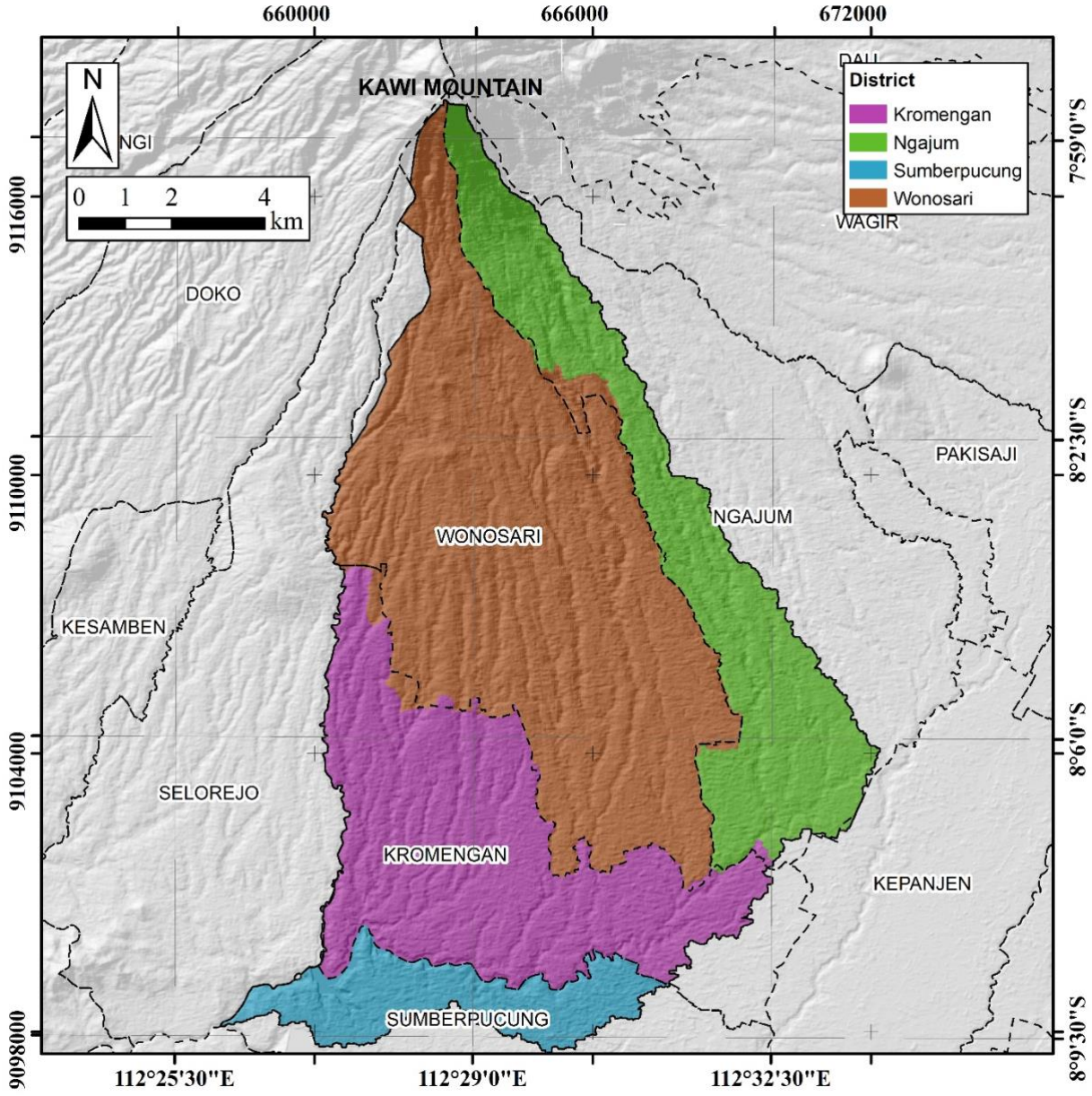

Fig. 1. Map of research location on the southern slopes of Mount Kawi, Malang Regency

2.2. Research Design

The study involved a land survey using the free grid method at a semi-detailed scale (1:50,000). Sampling locations were selected through a stratified random sampling approach to ensure representative coverage across predefined strata within the study area. The strata are defined based on similar land characteristics, focusing on smallholder coffee plantations. Validation was conducted using 30 sample points spread across land units, considering differences in topography, slope, curvature, geology, and vegetation characteristics [17]. The land unit map is presented in Fig. 2.

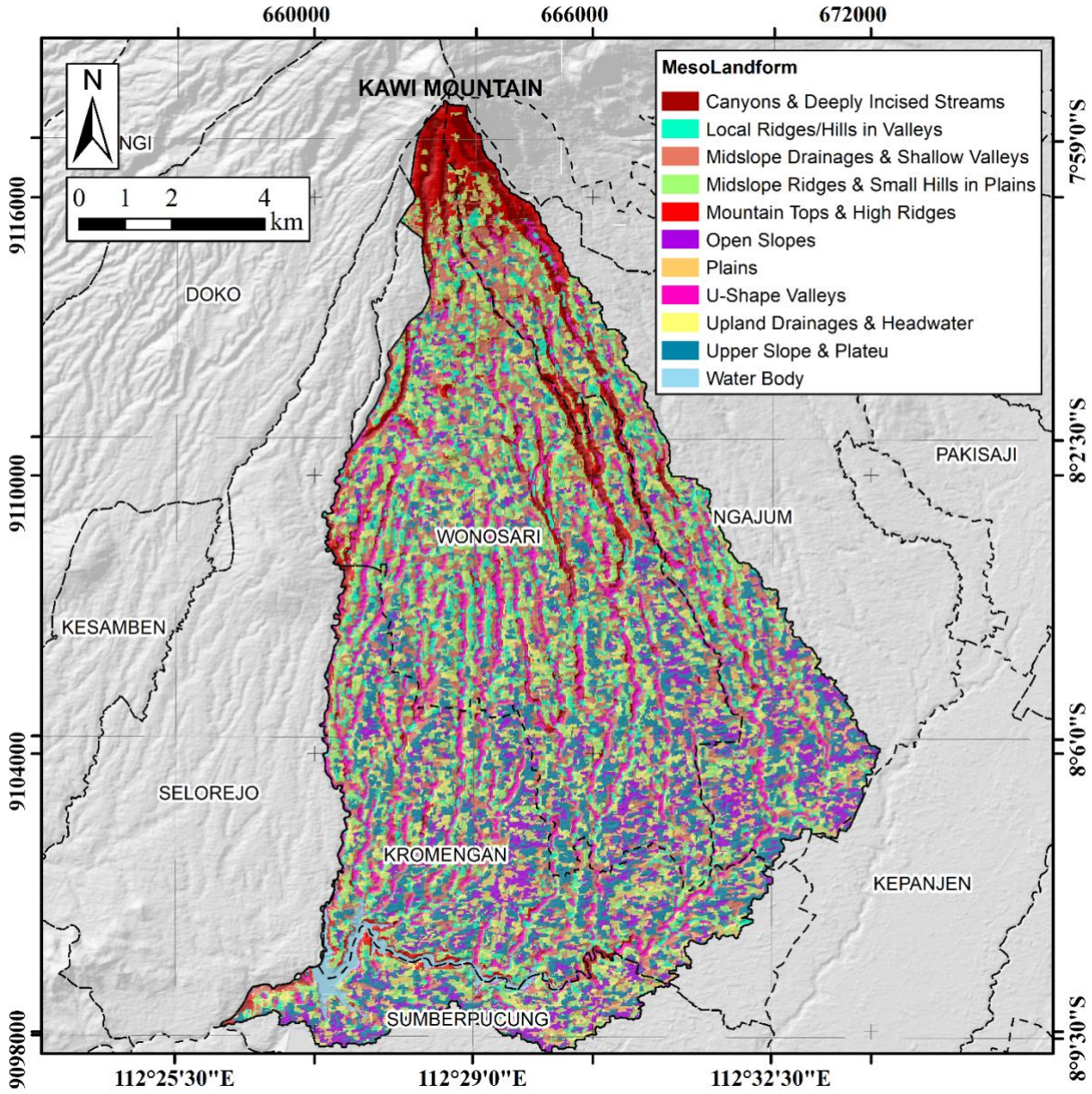

Fig. 2. Map of research plots based on mesolandform characteristics

2.3. Integration of Remote Sensing and Geographic Information Systems

Remote sensing analysis was conducted using Sentinel-2A Harmonised imagery through vegetation index transformation. NDVI is one of the most widely used vegetation indices for monitoring vegetation cover over the past two decades, converts reflectance data from near infrared (NIR) and red wavelengths [18]. The Normalised Difference Vegetation Index (NDVI) is evaluated using Equation 1, which quantitatively represents its computational framework [19].

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

The Normalized Difference Vegetation Index (NDVI) describes plants' greenness and is used to classify vegetation in an area. By transforming digital number data from Sentinel-2A images reflected by plants, vegetation density in smallholder coffee plantations in the Kletek sub-

watershed can be determined [20]. NDVI values correspond to six vegetation cover classes (Table 1).

Field vegetation density was assessed by identifying plant composition and quantifying individuals within 10 × 10 m sampling plots. Vegetation density was classified using the King Ma method, which calculates the highest (Xt) and lowest (Xr) observed values and divides them into a predetermined number of classes (n). For statistical analysis and streamlined data grouping, vegetation density classes were defined on a scale from 10 (absence of vegetation cover) to 100 (complex canopy density). NDVI interval classification was further refined based on these vegetation density groupings, as proposed by Sholikah et al. [17].

Table 1. Intervals and classes of NDVI and actual vegetation density

No	Interval of NDVI	Class of vegetation density	Actual density score	Description
1	<0.03	Non coverage	10	No covered land
2	0.03-0.2	Very low vegetation cover	20	Lamtoro (<5 trees/100 m^2)
3	0.2-0.4	Low vegetation cover	40	Lamtoro (5-10 trees/100 m^2)
4	0.4-0.5	Moderate vegetation cover	60	Lamtoro (>10 trees/100 m^2)
5	0.5-0.6	High vegetation cover	80	Lamtoro, banana, taro, chilli
6	>0.6	Very high vegetation cover	100	Lamtoro, mahogany, banana, chilli, taro

Source: Actual classification results based on research location conditions in 2024

2.4. Statistical Analysis

Statistical analysis was conducted using Microsoft Excel 2020, including a correlation test between NDVI values and field-measured vegetation density. The correlation test aims to determine the degree of relationship between variables, expressed as a correlation coefficient (r) [13]. Field data consisted of vegetation information from coffee plantations at each sampling point, including types and quantities of vegetation within 10×10 m plots [21].

3. Results and Discussion

3.1. Types of Coffee Shade Trees

Field surveys were systematically conducted to quantify vegetation density by directly observing shade tree species and their counts at designated observation points. Of the 30 surveyed locations, one site had no shade trees or vegetation. Sites with high vegetation density exhibited a diverse assemblage of shade-providing species, including *Pinus* spp., *Leucaena leucocephala* (lamtoro), *Swietenia macrophylla* (mahogany), *Musa* spp. (banana), *Durio zibethinus* (durian), and *Colocasia esculenta* (taro), with varying population densities. Conversely, sites with low vegetation density contained only a few shade-providing species, sparsely distributed across the area.

As illustrated in Fig. 3, observed vegetation density is classified as very high, characterised by three shade tree species, especially lamtoro, mahogany, and banana, with intercrops of chilli and taro. High vegetation density includes two shade trees, lamtoro and banana, and two intercrops, chilli and taro. Moderate vegetation density features lamtoro (>10 trees/100m^2). Low vegetation density consists of lamtoro (5-10 trees/100m^2), while very low vegetation cover consists of lamtoro (<5 trees/100m^2). Areas without vegetation cover (Fig. 3d) comprise vacant land or post-harvest plots of seasonal crops left untouched. Open land can accelerate land degradation and reduce land productivity [22]. Very high canopy closure is characterised by tall, dense shade trees such as pine and lamtoro.

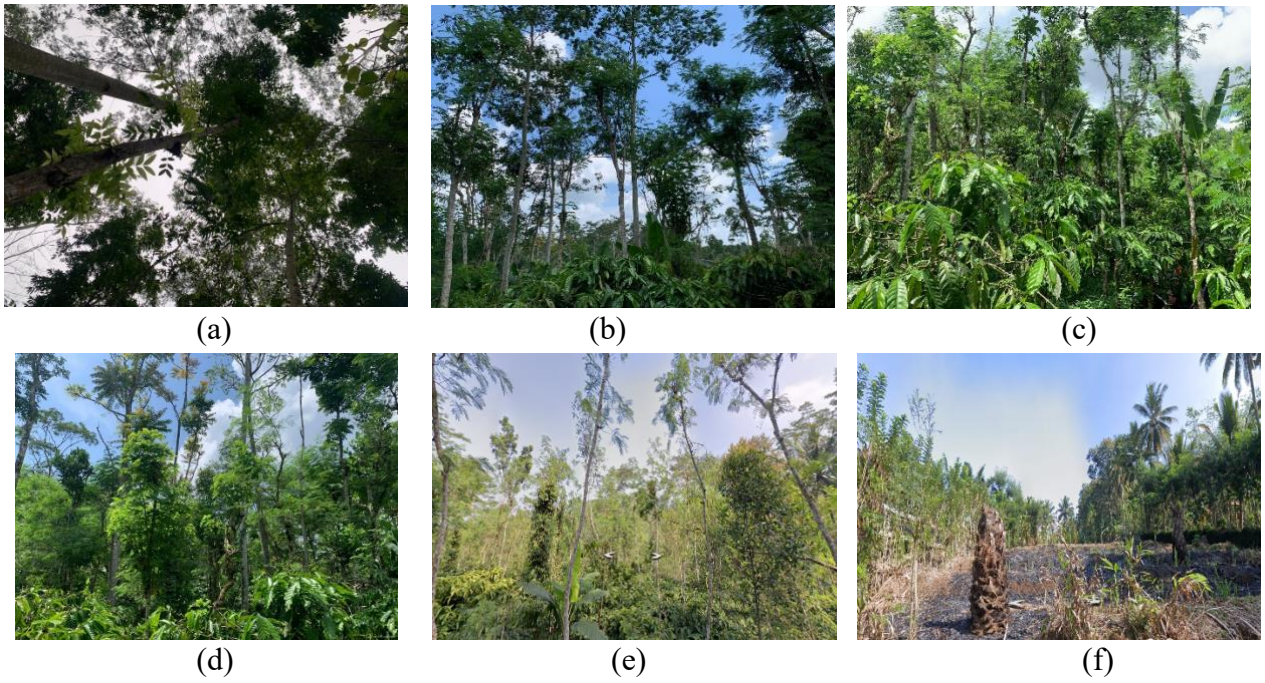

Fig. 3. Actual vegetation density (a) very high cover (b) high cover (c) moderate cover (d) low cover (e) very low cover (f) no covered land

3.2. Distribution of Normalised Different Vegetation Index

The Normalised Difference Vegetation Index (NDVI) is a spectral metric derived from remote sensing data, primarily from satellites, used to determine the presence and condition of live green vegetation within a study area. Vegetation indices such as NDVI are extensively utilised to monitor, analyse, and map spatial and temporal dynamics in vegetation structure across diverse landscapes [23]. Among various thematic layers, NDVI performs the best results for vegetation analysis in urban environments [24], coffee production [13], and plant biomass assessment [25]. The Normalised Difference Vegetation Index (NDVI) is a reliable tool for analysing vegetation cover in coffee plantations by detecting variations in shade tree density [26,27]. The distribution of NDVI in smallholder coffee plantations in the Kletek sub-watershed is shown in Fig. 4.

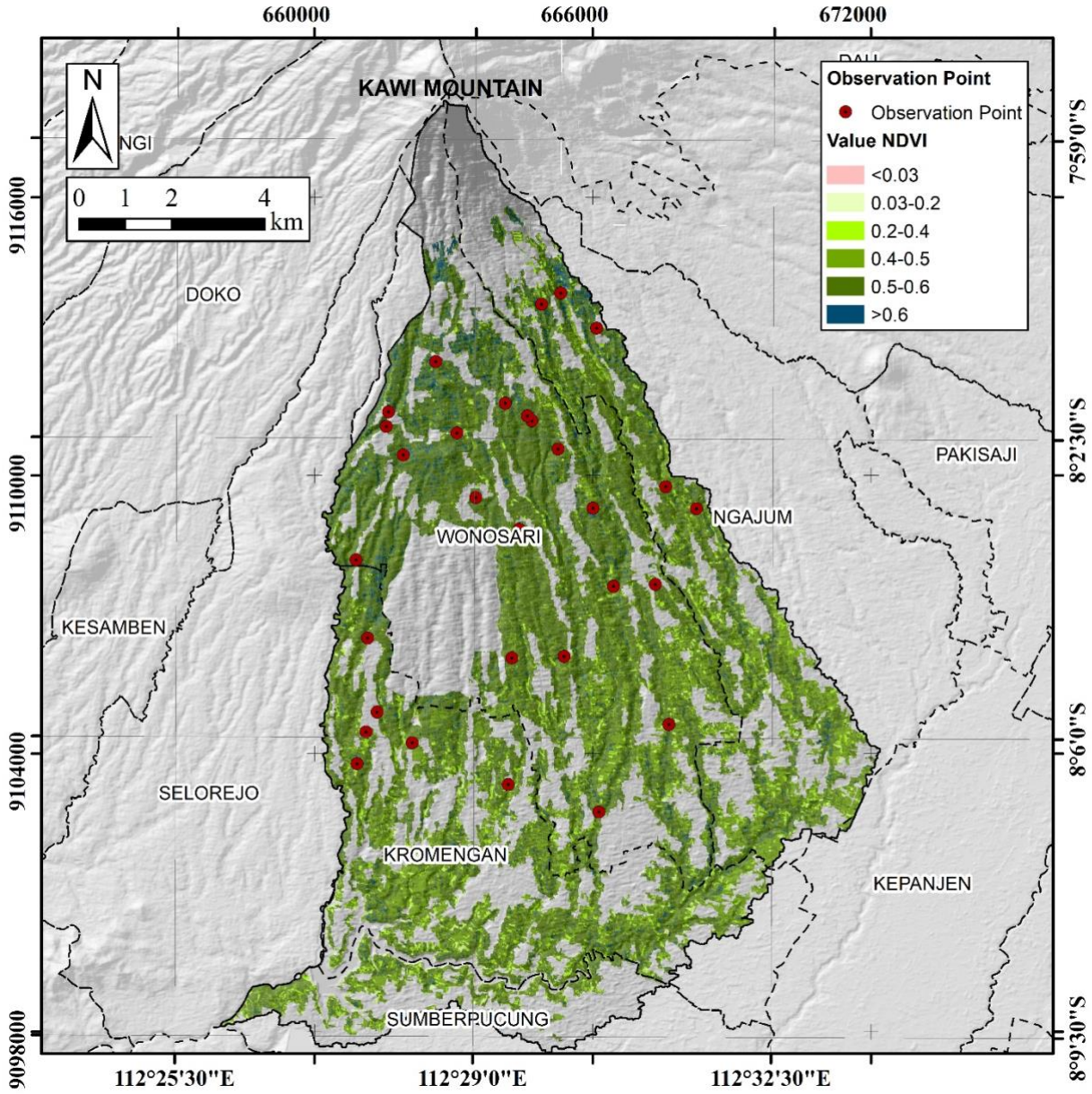

Fig. 4. NDVI distribution map of smallholder coffee plantations on the southern slopes of Mount Kawi

Based on vegetation index transformation in the Kletek Sub-Watershed area, NDVI values ranged from -0.10 to 0.71 and were classified into six classes (Table 1). The NDVI values reflect diverse vegetation density patterns corresponding to land use types, including water bodies, open land, gardens, coffee–sengon–pine agroforestry systems, dry fields, rice fields, and built-up areas. NDVI values for smallholder coffee plantations in Fig. 4 range from 0.4 to 0.6, corresponding to moderate to high vegetation density. A comparison of field-measured vegetation density and NDVI results is presented in Table 2.

Table 2. Comparison of actual vegetation density and NDVI analysis results

Validation Point	NDVI Value	Actual Vegetation Density	Score Vegetation Actual Density
1	0.58	High vegetation cover	80
2	0.58	High vegetation cover	80

Validation Point	NDVI Value	Actual Vegetation Density	Score Vegetation Actual Density
3	0.53	Very high vegetation cover	100
4	0.56	High vegetation cover	80
5	0.57	High vegetation cover	80
6	0.53	Low vegetation cover	40
7	0.57	High vegetation cover	80
8	0.56	High vegetation cover	80
9	0.54	High vegetation cover	80
10	0.63	Moderate vegetation cover	60
11	0.46	High vegetation cover	80
12	0.60	High vegetation cover	80
13	0.31	Very low vegetation cover	20
14	0.53	Moderate vegetation cover	60
15	0.61	Moderate vegetation cover	60
16	0.48	Moderate vegetation cover	60
17	0.58	High vegetation cover	80
18	0.56	Moderate vegetation cover	60
19	0.62	High vegetation cover	80
20	0.52	High vegetation cover	80
21	0.49	Low vegetation cover	40
22	0.56	Moderate vegetation cover	60
23	0.16	Non coverage	10
24	0.58	Moderate vegetation cover	60
25	0.44	Low vegetation cover	40
26	0.56	High vegetation cover	80
27	0.03	Non coverage	10
28	0.49	Moderate vegetation cover	60
29	0.49	Low vegetation cover	40
30	0.39	Low vegetation cover	40

Based on the NDVI values in Table 2, shade tree density in coffee plantations is relatively moderate vegetation cover (26.67%) and high vegetation cover (43.33%). The highest NDVI value observed was 0.63, indicating very high vegetation density (>0.6). Elevated NDVI values are positively correlated with increased canopy density of shade trees, indicating a higher vegetative cover associated with shaded cultivation practices [28]. Shade trees with high coffee plant density dominate the distribution of observation points, indicating that coffee farmers in this area employ intercropping systems in their cultivation practices.

3.3. The relationship between NDVI and actual vegetation density

NDVI values represent vegetation density conditions in the Kletek sub-watershed. The correlation between the Normalised Difference Vegetation Index (NDVI) and vegetation density within coffee plantations is a critical parameter for monitoring and managing agricultural landscapes. This relationship facilitates the assessment of canopy cover dynamics and supports data-driven decision-making in sustainable land-use planning. Correlation test results between NDVI and actual vegetation density in smallholder coffee plantations are presented in Fig. 5.

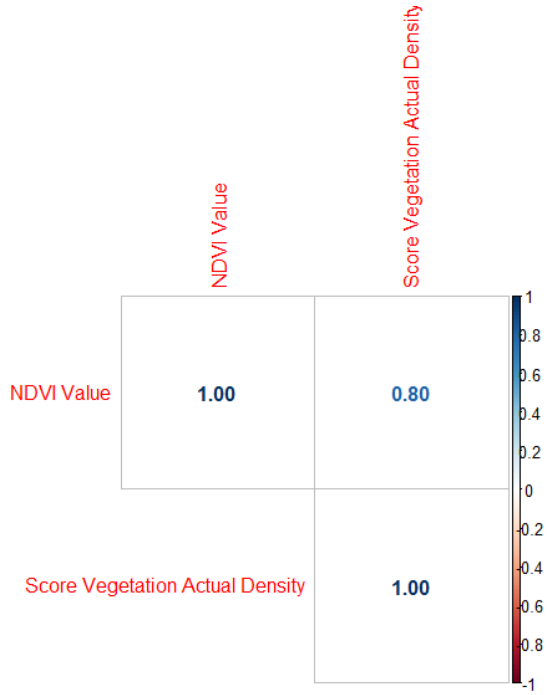

Fig. 5. Results of the correlation test between NDVI and actual vegetation density in smallholder coffee plantations

A statistically significant correlation (r = 0.80) was observed between the Normalised Difference Vegetation Index (NDVI) and coffee canopy cover condition, indicating a strong positive association. This supports the use of NDVI as a reliable proxy for assessing vegetation density in smallholder coffee plantations within the Kletek sub-watershed. Compared to previous studies, our correlation value aligns with findings by dos Santos et al. [29], who used drone-derived NDVI to map vegetation structure in agroforestry systems, although their focus was on spatial mapping rather than direct canopy quantification. Our study extends this application by demonstrating a robust statistical relationship between NDVI and field-measured canopy cover, reinforcing NDVI's utility for fine-scale vegetation monitoring.

In contrast, Arafat et al. [30] applied NDVI to infer soil moisture availability, highlighting its sensitivity to vegetation stress rather than structural canopy attributes. While our study does not directly assess soil moisture, the strong NDVI–canopy correlation suggests potential for integrating NDVI-based vegetation metrics with hydrological indicators in future research. Similarly, Imanda et al. [31] explored the relationship between vegetation density and biodiversity, showing that higher canopy density correlates with greater species richness. Our findings align with this ecological perspective, as denser canopy cover—reflected in higher NDVI values—may also indicate more complex habitat structures. Furthermore, the role of native vegetation in coffee agroecosystems is emphasized by Alvarez-Alvarez et al., Manson et al., Valencia et al. [32–34], underscoring the importance of managing shade composition and planting arrangements. Our results support this by demonstrating that NDVI can capture variations in canopy structure

influenced by such management practices. Ultimately, integrating NDVI into routine monitoring can enhance both yield optimization and biodiversity conservation, contributing to sustainable coffee production, as advocated by Koutouleas et al., Nesper et al. [35,36].

4. Conclusions

Smallholder coffee plantations on the southern slopes of Mount Kawi, Malang Regency, are characterised by shade tree management, predominantly using lamtoro trees. Canopy cover reaches very high density, comprising lamtoro, mahogany, and banana, followed by intercrops such as chilli and taro. High-density areas include lamtoro and banana as canopy plants, with chilli and taro as intercrops. Correlation analysis between NDVI values and actual vegetation density indicates a strong relationship (r=0.75), with high NDVI values indicating high vegetation density in actual conditions. Coffee cultivation should consider planting systems, including the composition and spacing of shade trees, to optimize production.

Abbreviations

No data or condition applies in this context.

Data availability statement

Supporting data for this study can be provided upon request.

CRediT authorship contribution statement

Dinna Hadi Sholikah: Conceptualisation, Methodology, Validation, Writing-original draft, Visualisation. **Nabilla Putry Maharani:** Writing – original draft, Visualisation. **Daljit Singh Karam:** Writing and Reviewing. **Ramadhani Mahendra Kusuma**: Funding acquisition, Investigation. **Dewi Shasa Bella**: Data curation, Formal analysis. **Yoga Gregorius Sembiring**: Data curation, Formal analysis. **Fitri Wijayanti:** Project administration. **Soemarno:** Supervision, Validation.

Declaration of Competing Interest

The authors declare that no financial conflicts of interest or personal affiliations are known to have influenced the conduct, analysis, or presentation of the research detailed in this manuscript.

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