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EXPLORING THE RELATIONSHIP BETWEEN VEGETATION DIVERSITY AND SOIL FERTILITY IN A TROPICAL FOREST ECOSYSTEM OF SOUTHEAST SULAWESI

SUMMARY

Many studies have investigated the relationship between vegetation density and soil quality. However, the influence of vegetation diversity on soil fertility is still not documented. This study evaluated the relationship between vegetation diversity and soil fertility in a tropical forest ecosystem located in Southeast Celebes. An ecological survey was conducted using the quadrat method at three forest sites in different toposequences, including upper, middle, and lower. Three indicators were selected to describe the vegetation diversity, namely richness, evenness, and heterogeneity. Soil fertility was evaluated by six parameters, including soil acidity, organic carbon, total nitrogen, available phosphorus, available potassium, and cation exchange capacity. We used correlation analysis to examine the relationship between the two variables. Nineteen species were recorded from the field observation. The highest species abundance was noted in the lower forest. This site was also superior in richness, heterogeneity, and evenness. Soil fertility among sites was relatively similar, with low values for all parameters. There was no significant correlation between vegetation diversity and soil fertility. Further investigation is still required to verify this finding in other ecosystems.

Keywords: soil quality, plant biodiversity, soil organic matter, toposequence

INTRODUCTION

Understanding the interaction between soil and plant is necessary to support sustainable ecosystem management. Soil naturally supplies water and nutrients for plant growth and development (FAO, 2022; Huntley, 2023). Inversely, the plant has the potential to improve soil fertility by providing organic matter through litter fall (Giweta, 2020; Alam *et al*., 2022; Xu *et al.,* 2022). When

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the litter is decomposed, nutrients will be released into the soil (Krishna and Mohan 2017; Liu *et al.,* 2022). This process is generally known as the close nutrient cycle and becomes one of the specific attributes in tropical forest ecosystems.

Several studies have investigated the soil and plant interactions, wherein higher plant density will improve soil fertility (Ndabamenye *et al.,* 2013; Brauner-Otto, 2014; Duan *et al.,* 2019). It can happen because there is a high accumulation of organic matter from litter. Besides containing several nutrients, the dense litter can also maintain soil moisture (Deutsch *et al.,* 2010). It indirectly influences soil organism activity that makes meaningful contributions to the biogeochemical cycle (Chen *et al.,* 2020). However, the interaction between soil and plant in the tropics still has many interesting questions that require further investigation. One of them is the significant effect of vegetation diversity on soil fertility.

Vegetation diversity is an important indicator of environmental stability in tropical forest ecosystems (Majeed *et al.,* 2022; Suyanto *et al.,* 2022). This indicator is also used to assess the resilience of ecosystems to natural disturbances, such as pests and diseases, wind damage, wildfire, etc (Cantarello *et al.,* 2017). Previous studies also reported that higher diversity described better environmental capability for facilitating life cycle (Isbell *et al.,* 2011; Souza *et al.,* 2014; Asselin *et al.,* 2019; Lindner *et al.,* 2019; Sanyé-Mengual *et al.,* 2023). In other words, vegetation diversity should also affect soil fertility, as soil is the major component of the ecosystem.

However, most empirical findings discussing the relationship between vegetation diversity and soil fertility are still dominated by studies in temperate ecosystems, while similar studies on tropical forests are relatively limited and have not been comprehensively integrated (Prober and Wiehl 2012; Li *et al.,* 2018; Chen *et al.,* 2020; Xie *et al.,* 2021). Tropical ecosystems have distinctive biogeochemical characteristics, such as pronounced phosphorus limitation, high nutrient recycling rates, and highly intense weathering. There is no adequate information to support this claim in the tropical forest ecosystem. Meanwhile, previous studies in tropical ecosystems have only focused on the relationship between vegetation density and soil fertility (Song *et al.,* 2013; Dibala *et al.,* 2021; Tokozwayo *et al.,* 2021).

To date, empirical evidence specifically examining soil fertility variations along the vegetation diversity gradient in tropical forest ecosystems remains limited. This limitation hinders a deeper understanding of the extent to which biodiversity itself plays a role in shaping soil nutrient dynamics, independent of the influence of vegetation structure alone. Therefore, this study aims to analyze patterns of soil fertility change along the vegetation diversity gradient in tropical forest ecosystems. By directly testing the relationship between vegetation diversity and various indicators of soil fertility in a tropical context, this study contributes to enriching the existing ecological framework by providing region-based evidence on the feedback mechanisms between biodiversity and soil. The result is expected to provide a deeper understanding of the ecological relationship between the diversity of vegetation and soil fertility dynamics as the primary component of a forest ecosystem.

MATERIAL AND METHODS

This study was undertaken in a tropical forest ecosystem located at Moramo Education Estate (Figure 1). It is a special-purpose area managed by Universitas Halu Oleo in Southeast Sulawesi. The site has a geographic position in E4°6'30"-4°7'30" and S122°35'0"-122°35'30". Moramo Education Estate is a natural ecosystem consisting of three land cover types, including forest (70%), shrub (20%), and savanna (10%) (Alam *et al.,* 2022). Altitude varies from 25 to 137 m above sea level—topography dominated by a hilly area with a slope level of 8−15%. The mean daily temperature reaches 27.6°C, with a minimum of 23.1°C and a maximum of 32.2°C. Annual rainfall is 3,179.70 mm year^{-1} with air humidity of 81%. Dry periods occur from September to October.

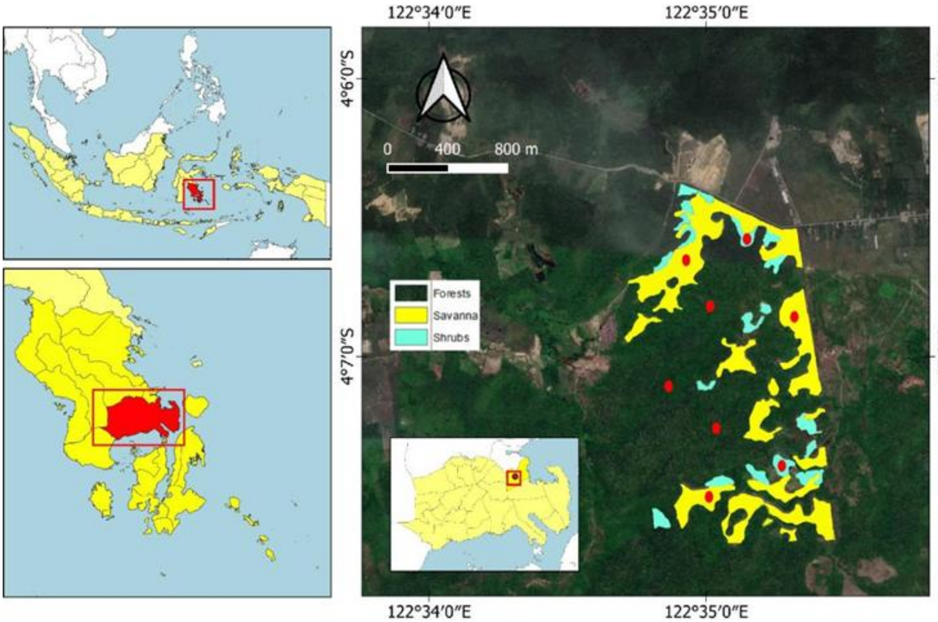

Figure 1. Study site of Moramo Education Estate in Southeast Sulawesi. Red circles indicate sampling locations for vegetation and soil survey (Source: Alam *et al.,* 2022).

An ecological survey was carried out using the quadrat method at three forest sites in different toposequences, including upper, middle, and lower (Alam *et al.,* 2020). We used a sampling plot of 20×20 m to facilitate the measurement process (Grussu *et al.,* 2016). The number of plots in each toposequence was five units. These plots were placed systematically with a distance between plots of 50 m (Sadono *et al.,* 2020). Data collection in each plot was divided into two stages, namely vegetation inventory and soil sampling.

We conducted a vegetation inventory using a nested method, wherein each plot was divided into four subplots with a specific size and objective: 1×1 m (understorey), 2×2 m (seedlings), 5×5 m (saplings), 10×10 m (poles), and 20×20 m (trees) (Rambey *et al.*, 2021). However, the life stage of vegetation in this site was only in poles and trees; thus, there were only two subplots in every sampling plot. Several parameters were recorded from the vegetation inventory, including species name, density, and diameter (Nugroho *et al.*, 2022a). The diameter was measured at 1.3 m above ground using a diameter tape.

In parallel, we took soil samples from three different positions in every plot at the depths of 0−10 cm, 11−20 cm, and 21−30 cm (Nugroho *et al.*, 2022b). Afterward, these samples were composited and brought to the laboratory for quality analysis. We used six parameters to quantify the soil fertility, namely soil acidity (pH), organic carbon (SOC), total nitrogen (TN), available phosphorus (AvP), exchangeable potassium (ExK), and cation exchange capacity (CEC) (Alam *et al.*, 2022). Soil pH was determined using a pH meter, while SOC was quantified using the Walkley−Black method. TN was analyzed using the Kjeldahl method. The ammonium acetate (NH_4OAc) 1 M, pH 7.0 extraction was applied to determine ExK, while AvP was enumerated using the Bray method. We used the ammonium acetate method to quantify the CEC. The soil analysis protocol was conducted following the guidance of soil analysis published by Estefan *et al.*, (2013).

We conducted descriptive analysis to identify the vegetation structure in each toposequence. First, data from the vegetation inventory were analyzed to calculate species density, species dominance, and frequency distribution. The generated values were then utilized to compute relative abundance, dominance, and frequency from every species (Matatula *et al.*, 2021). Then, the importance value index was calculated by summing up these three indicators. It is an essential parameter to recognize the strategic position of species in each toposequence (Yuliana *et al.*, 2019).

The diversity of vegetation from every toposequence was evaluated using three indicators, including richness, heterogeneity, and evenness (Wirabuana *et al.*, 2021). We used the Margalef Index to determine vegetation richness (Singh, 2020), while the Shannon-Wiener Index was applied to quantify the vegetation heterogeneity (Li *et al.*, 2018). The evenness level of vegetation was assessed using the Pielou-Evenness Index (Nugroho *et al.*, 2022a). Furthermore, the analysis of Spearman correlation was applied to examine the relationship between vegetation diversity and soil fertility for each parameter (Alam *et al.*, 2020).

RESULTS AND DISCUSSION

Vegetation diversity patterns along the toposequence

Nineteen species were recorded from the forest inventory (Table 1). Most species had a life stage in the pole, although some species also existed at the tree level. The highest species abundance was found in LF (15), followed by UF (7) and MF (5). Interestingly, the number of species in every life stage was relatively different (Figure 2), although LF showed the highest species abundance at each phase. Among the observed species, *Castanopsis buruana* was the only one that appeared at every site (Table 1).

Table 1. Importance value index of every species in different forest sites

No.	Species	Upper Forest (UF)		Middle Forest (MF)		Lower Forest (LF)	
		Poles	Trees	Poles	Trees	Poles	Trees
1	*Castanopsis buruana*	58.51	190.92	126.48	300	43.84	117.51
2	*Xanthophylum sp.*	-	109.08	-	-	-	-
3	*Lasjia hildebrandi*	47.52	-	55.23	-	-	-
4	*Palmaceae sp*	21.41	-	56.61	-	-	-
5	*Barringtonia reticulate*	24.07	-	-	-	13.8	
6	*Syzygium subglauca*	52.41	-	32.26	-	-	-
7	*Cleistanthus sumatranus*	96.08	-	-	-	20.94	-
8	*Syzygium sp.*	-	-	29.41		23.06	-
9	*Santiria laevigata*	-	-	-	-	-	83.97
10	*Dillenia serrata*	-	-	-	-	23.49	98.53
11	*Vitex cofassus*	-	-	-	-	18.53	-
12	*Lagerstroemia speciosa*	-	-	-	-	19.09	-
13	*Gardenia sp.*	-	-	-	-	13.8	-
14	*Guensia cinnamomea*	-	-	-	-	22.98	-
15	*Fagrarea fragrans*	-	-	-	-	13.8	-
16	*Nauclea orientalis*	-	-	-	-	34.59	-
17	*Hibiscus tiliaceus*	-	-	-	-	13.8	-
18	*Colona scabra*	-	-	-	-	25.36	-
19	*Ficus fistulosa*	-	-	-	-	12.9	-
	Important value index	300	300	300	300	300	300

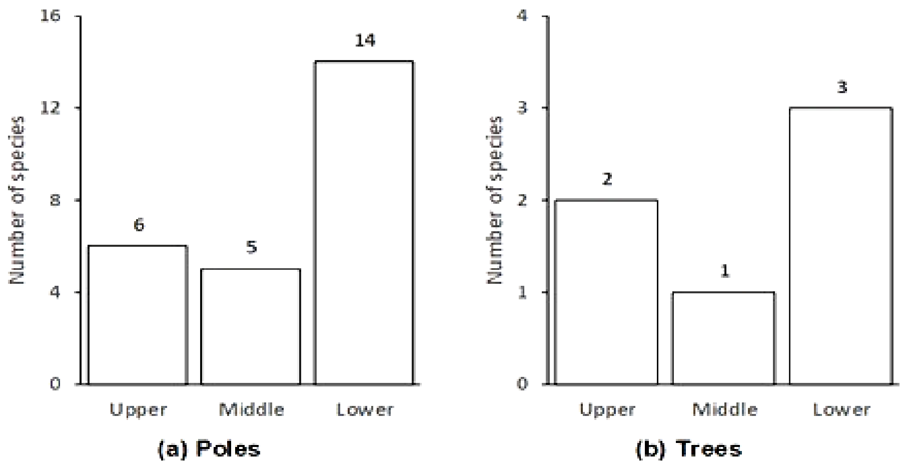

Figure 2. Number of species in every life stage at different forest sites

Our study reported that vegetation diversity among toposequences varied relatively, with the lower forest demonstrating the highest richness (4.08), heterogeneity (2.52), and evenness (0.93) (Figure 3). This could be attributed to the lower forest having the highest species abundance among sites (Table 1). In addition, the species distribution in this site exhibited a better proportion of important value index than the upper and middle forests, particularly at the pole stage.

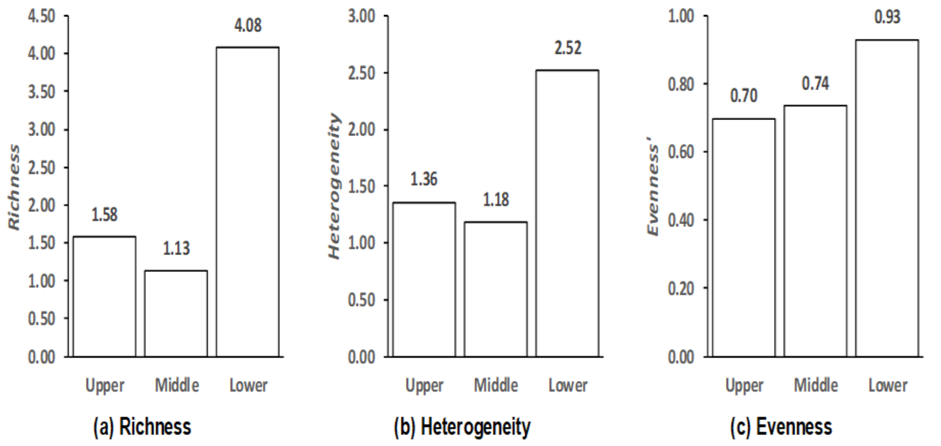

Figure 3. Plant diversity among forest sites based on richness, heterogeneity, and evenness

Soil fertility characteristics

Soil properties among sites generally had high acidity with a pH of lower than 5.0 (Table 2). Most sites also had low organic carbon content (<2.0%), except for the upper forest, which had moderate levels. Meanwhile, other parameters such as total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity were classified as low concentrations. This trend was consistently found in all sites.

Table 2. Soil fertility in different forest sites

Soil attributes	Symbol	Unit	Upper	Middle	Lower
pH H_2O	pH	-	4.4	4.5	4.4
Organic carbon	SOC	%	2.19	1.38	1.43
Total nitrogen	TN	%	0.18	0.14	0.14
Available phosphorus	AvP	ppm	6.72	3.66	4.94
Exchangeable potassium	ExK	cmol(+) kg^{-1}	0.32	0.29	0.3
Cation exchange capacity	CEC	cmol(+) kg^{-1}	15.54	11.46	12.63

Vegetation diversity–soil fertility correlation

The correlation analysis between vegetation diversity indicators and soil fertility parameters shows that there is no statistically significant relationship between the two variables (Table 3). All correlation values have a p-value greater than 0.05, indicating that vegetation diversity is not significantly related to the observed soil fertility parameters. However, the relationship between vegetation diversity indicators and soil pH showed a moderate negative correlation.

Table 3. Correlation results between vegetation diversity and soil fertility

	Richness	**Heterogeneity**	**Evenness**
pH	-0.655	-0.618	-0.601
	(0.546)	*(0.576)*	*(0.590)*
SOC	-0.275	-0.320	-0.341
	(0.823)	*(0.792)*	*(0.778)*
TN	-0.327	-0.372	-0.392
	(0.788)	*(0.757)*	*(0.743)*
AvP	0.096	0.048	0.026
	(0.939)	*(0.969)*	*(0.983)*
ExK	0.000	-0.048	-0.070
	(1.000)	*(0.970)*	*(0.956)*
CEC	-0.051	-0.099	-0.121
	(0.967)	*(0.937)*	*(0.923)*

Note: The number inside the breakers indicates

DISCUSSION

The dominance of *Castanopsis buruana* in all locations indicates that this species has a good ability to adapt to environmental conditions in the study area. This is reflected in the high importance value index (IVI) values, especially at the tree level in all observation locations. These high IVI values indicate that *C. buruana* plays a significant role in shaping the structure of the vegetation community and contributes significantly to the ecological dynamics of the forest in the study area.

The interaction between biotic and abiotic factors, such as soil, climate, vegetation, and topography, naturally influences vegetation dynamics in a tropical forest ecosystem. This process generates a high variation of vegetation at the microsite level, like toposequences. Hussain *et al.*, (2012) explained that the vegetation condition in forest ecosystems was principally assessed using three biodiversity indicators, such as richness, heterogeneity, and evenness. According to the richness value, the vegetation dynamics of tropical forests could be classified into three levels, including disturbed (<2.0), semi-disturbed (2.0−5.0), and integrated (>5.0). Our results indicated that the vegetation of the upper and middle forest had a disturbed condition, while the lower forest was semi-disturbed.

Hussain *et al.,* (2012) also classified the heterogeneity of vegetation into three statuses, namely poor (<2.0), moderate (2.0−3.0), and good (>3.0). Meanwhile, the species evenness was stratified into three stages, i.e., unbalanced (<0.5), semi-balanced (0.5−0.8), and balanced (>0.8). Referring to our results, the upper and middle forests had relatively poor heterogeneity with semi-balanced species distribution. In contrast, the lower forest showed moderate heterogeneity and balanced species evenness. Our findings were also similar to Suyanto *et al.*, (2022), who reported that tropical forest ecosystems in lowland areas had relatively low−moderate diversity with semi-balanced species distribution. It could happen since most species in tropical forests naturally live in groups and have a habitat preference (Purwaningsih, 2004; Hadi *et al.,* 2019; Sari *et al.*, 2019).

The soil fertility characteristics observed in this study showed generally low nutrient levels across the study sites. The soils were strongly acidic, with pH values below 5.0, and most nutrient parameters such as soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and cation exchange capacity were classified as low. These conditions are typical for highly weathered tropical soils where intensive rainfall and leaching processes reduce nutrient availability (Purwanto and Alam 2020; Basak *et al.*, 2022; Liu *et al.*, 2024).

Interestingly, we reported there was no significant correlation between the vegetation diversity and soil fertility in the study site for all parameters, although there was a moderate correlation between diversity indicators and soil acidity (Table 3). This outcome was in contrast to other previous studies in temperate forests, which reported a significant influence of plant diversity and soil fertility (Prober and Wiehl 2012; Li *et al.,* 2018; Chen *et al.,* 2020; Xie *et al.,* 2021). Several factors may influence this different finding. One of them is related to the species composition between the two forest ecosystems. In general, tropical forests had substantially more abundance of species than temperate forests since they had humid conditions with full sun intensity. This condition is suitable for plant species to establish and grow. In contrast, the temperate forest had more extreme conditions, particularly related to temperature and sunlight. The number of species in a temperate forest is relatively lower than in a tropical forest. Thereby, the increase in plant diversity in temperate forests may provide a faster impact on soil fertility than tropical forests.

Forest fires also occurred frequently in this site, which decreased the litter accumulation as input for improving soil fertility. This observation is consistent with AlKhayri and Khan (2024), who reported that forest fires can influence soil fertility by altering organic matter inputs and nutrient cycling in the soil. It typically happened in the dry season, wherein the monthly precipitation was substantially lower than in the wet season. Meanwhile, during the rainy season, the root systems of vegetation can minimize runoff and maintain soil fertility in forest sites. It also possibly means there is no significant correlation between vegetation diversity and soil fertility across the toposequence.

Furthermore, there are also other factors that affect soil fertility in the tropics, such as topography, climate, and natural disturbance. Topography is highly related to the risk of runoff and erosion that can leach topsoil (Zhao *et al.,* 2022; Supandi *et al.,* 2023; Zhou *et al.,* 2023). Meanwhile, climate condition determines the rate of decomposition since they correlate with soil temperature and moisture (Wang *et al.,* 2016; Krishna and Mohan 2017; Petraglia *et al.,* 2019). Natural disturbance can also affect soil fertility since it can change vegetation dynamics aboveground (Maynard *et al.,* 2014; Guo *et al.,* 2019; Cornejo *et al.,* 2023). Our study also found that vegetation diversity in the majority of sites had a disturbance condition based on the range of species richness (Table 1).

CONCLUSIONS

This study concluded that there was no significant relationship between vegetation diversity and soil fertility in the tropical forest ecosystem in the study area. Although vegetation diversity varied among sites, soil fertility indicators remained relatively similar, suggesting that soil nutrient status may be influenced more strongly by inherent edaphic and topographic factors than by vegetation diversity alone. From a forest management perspective, these findings indicate that increasing vegetation diversity does not necessarily lead to immediate improvements in soil fertility. Therefore, sustainable forest management in tropical ecosystems should integrate biodiversity conservation with careful consideration of soil physicochemical properties and landscape characteristics. While vegetation diversity remains essential for maintaining ecosystem resilience and other ecological functions, it may not directly predict soil fertility conditions.

This study is limited by the relatively small sample size and the use of correlation analysis, which may not fully capture complex multivariate interactions among ecological variables. Future research should include broader spatial gradients, larger datasets, and more comprehensive analytical approaches, such as multivariate or long-term studies to better understand biodiversity–soil feedback mechanisms in tropical forest ecosystems.

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