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Impacts of forest management zones on termite attack frequency, intensity, and diversity in Wera Nature Tourism Park, Indonesia

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Abstract. *Zulkaidhah, Rukmi, Wahyuni D, Hapid A, Hamka. 2026. Impacts of forest management zones on termite attack frequency, intensity, and diversity in Wera Nature Tourism Park, Indonesia. Biodiversitas 27 (4): d270407. https://doi.org/10.13057/biodiv/d270407.* Forest management zoning may influence termite attack patterns and the composition of termite taxa associated with attacked vegetation. This study evaluated the effects of management zones and vegetation growth stages on termite attack frequency, attack intensity, and diversity patterns in Wera Nature Tourism Park (WNTP), Central Sulawesi, Indonesia. Field surveys were conducted using nested vegetation plots established across three management zones. Termite sampling was restricted to plants showing visible signs of attack within the vegetation plots, and specimens were identified primarily on the basis of morphological characteristics, especially soldier morphology. Attack frequency and intensity were analyzed using two-way ANOVA, whereas termite community structure was described using Shannon diversity, Margalef richness, Pielou evenness, and relative dominance indices. Both management zone and vegetation growth stage significantly affected termite attack frequency and attack intensity ($p<0.001$), with trees showing the highest vulnerability. The utilization zone had the highest attack intensity (27.07%), whereas the protection zone had the lowest (11.00%). A total of eight termite taxa representing five genera were recorded from attacked vegetation across the three management zones. Most taxa were identified to species level, whereas two taxa (*Bulbitermes* sp. and *Odontotermes* sp.) remained at genus level because available diagnostic characters were insufficient for reliable species-level identification. Diversity and richness of termite taxa associated with attacked vegetation were highest in the protection zone and lowest in the utilization zone. *Nasutitermes matangensis* was the most dominant and widely distributed taxon across zones. Because environmental drivers were not measured directly, the observed zonation effects should be interpreted as statistically supported associations rather than confirmed mechanisms. These findings highlight the value of zoning-based termite monitoring for adaptive forest conservation and sustainable ecotourism management in WNTP.

Keywords: Attacked vegetation, forest management zoning, termite attack intensity, termite taxa diversity, Wera Nature Tourism Park

INTRODUCTION

Termites are a fundamental component of tropical forest ecosystems, acting as major decomposers that drive nutrient cycling, soil formation, and energy flow. By fragmenting and processing lignocellulosic material, they contribute substantially to deadwood decomposition, soil structure, and overall ecosystem functioning (Jouquet et al. 2011; Garg et al. 2023; Zulkaidhah et al. 2025). However, termites may also become economically and ecologically important pests when ecosystem balance is disrupted, particularly where disturbance alters microclimate, resource availability, and host susceptibility (Ashton et al. 2019; Vishaka et al. 2022; Madonsela and Magagula 2024). This dual role as ecosystem engineers and potential pests makes termites a useful biological group for evaluating forest condition and management outcomes (Jones and Eggleton 2000; Indrayani et al. 2024).

In addition to their taxonomic diversity, termites are often evaluated through functional classifications, such as feeding groups or lifeways, because these provide a mechanistic link between community composition and ecosystem processes (Liu et al. 2022; Jiang et al. 2024). Previous studies have shown that termite assemblages respond sensitively to habitat disturbance, with changes in richness, dominance, and functional structure reflecting broader shifts in habitat quality, decomposition pathways, and forest resilience (Kimber and Eggleton 2018; Ashton et al. 2019; Heriza et al. 2021; Zulkaidhah et al. 2021, 2025). Across tropical landscapes in Southeast Asia, disturbed habitats are commonly associated with simplified termite assemblages and greater dominance by disturbance-tolerant taxa (Kimber and Eggleton 2018; Ashton et al. 2019; Heriza et al. 2021). These patterns highlight the value of termites as indicators of ecological change and the importance of monitoring their activity under varying environmental and management conditions (Subekti et al. 2018; Heriza et al. 2021).

In managed forest parks and conservation-based ecotourism areas, zoning systems often create gradients of human activity, vegetation disturbance, and habitat modification. These zonation-related differences may influence termite attack patterns by altering host condition, microclimate, and resource availability, while also shaping the diversity and dominance structure of termite taxa. Therefore, management zonation provides a useful ecological framework for examining how disturbance-related variation affects termite-vegetation interactions in protected landscapes. Wera Nature Tourism Park (WNTP) in Central Sulawesi, Indonesia, is a conservation-based ecotourism area managed through a zonation system consisting of utilization, rehabilitation, and protection zones, each characterized by different levels of management intensity and human activity. This zonation provides a valuable framework for examining how management-related disturbance gradients shape termite attack patterns and termite assemblages. Nevertheless, empirical information on termite occurrence, attack dynamics, and community attributes across management zones in WNTP remains limited. This lack of evidence restricts efforts to understand how forest management zoning influences both the ecological role of termites and their potential impacts on vegetation within a nature-based tourism landscape.

Such information is particularly important because disturbances associated with land clearing, selective logging, trail development, and tourism infrastructure can alter canopy cover, soil temperature, soil moisture, and deadwood availability, all of which may affect termite habitat suitability and host vulnerability (De Azevedo et al. 2021; Heriza et al. 2021; Wu et al. 2024). In more disturbed zones, woody debris accumulation and vegetation stress may increase termite activity and the likelihood of attack (Luke et al. 2014). Conversely, less disturbed zones may support higher termite diversity and a more balanced community structure under more stable environmental conditions. For ecotourism forest management, understanding these zonation-related patterns is essential not only because termites support important ecosystem processes, but also because termite attacks may affect vegetation health, visitor experience, and the condition of wooden facilities.

Therefore, this study examined how forest management zonation in WNTP influences: (i) termite attack frequency and intensity on vegetation; and (ii) the diversity and dominance structure of termite taxa associated with attacked vegetation across vegetation growth stages. We expected that more disturbed zones would show higher attack levels but lower termite diversity than less disturbed zones. By linking termite attack dynamics with community attributes under different management zones, this study provides a zonation-based perspective that is relevant for adaptive monitoring in conservation-based ecotourism areas. The findings are expected to strengthen understanding of termite-forest interactions under different management intensities and to support integrated, zone-specific strategies for forest conservation and sustainable ecotourism management in WNTP.

MATERIALS AND METHODS

Study area

This study was conducted in Wera Nature Tourism Park (WNTP), West Dolo Subdistrict, Sigi District, Central Sulawesi, Indonesia (Figure 1). The study site is situated at approximately 325 m asl and is classified as secondary forest under a type F climate (slightly dry). Field observations focused on termite attacks on plants at different growth stages. The observations considered two main objects: natural vegetation within the sampling plots (sapling, pole, and tree levels), including both termite-attacked and unattacked plants, and biotic and abiotic factors potentially associated with plant damage other than that caused by termites (Gathorne-Hardy et al. 2001; Subekti et al. 2018; Zulkaidhah et al. 2021).

Procedures

Sampling design

Vegetation data were collected using one observation plot measuring 20 m × 100 m in each management zone, resulting in a total of three main plots across the study area. Each main plot was subdivided into five 20 m × 20 m subplots, giving a total of 15 subplots. Each management zone was therefore represented by one main plot, with the five subplots serving as repeated sampling units within the zone; accordingly, zonation effects in this study should be interpreted as within-site associations rather than fully replicated landscape-level treatment effects.

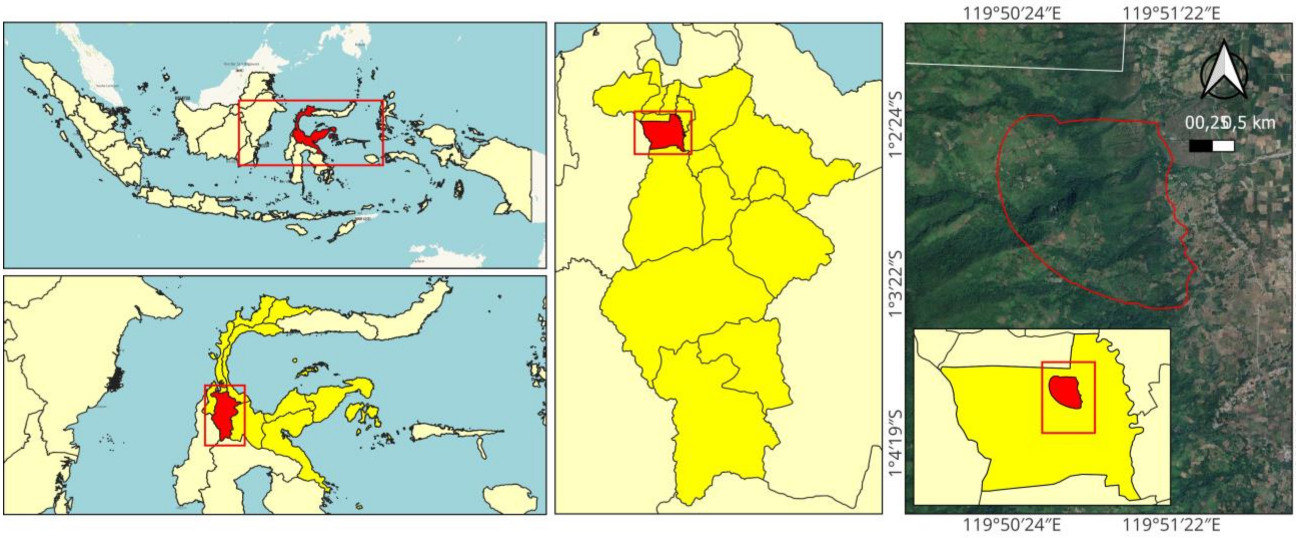

Figure 1. Research location at Wera Nature Tourism Park (WNTP), West Dolo Subdistrict, Sigi District, Central Sulawesi, Indonesia

A nested sampling design was applied within each subplot, consisting of 20 m × 20 m plots for trees (diameter at breast height (dbh) ≥20 cm), 10 m × 10 m plots for poles (10 cm ≤ dbh < 20 cm), and 5 m × 5 m plots for saplings (2 cm ≤ dbh < 10 cm). Plots were established systematically within each zone to represent the dominant vegetation conditions. All plant species within the plots were identified in the field. Specimens that could not be identified directly were photographed or collected and later identified at Herbarium Celebense, Tadulako University, Palu.

Termite sampling and identification

Termite sampling was restricted to plants showing visible signs of termite attack within the established vegetation plots. Each attacked plant was inspected directly by examining damaged bark, mud galleries, infested wood surfaces, and accessible nesting or foraging structures associated with the attacked plant. Termites encountered during inspection were collected manually using forceps and preserved in 70% alcohol.

Identification was based primarily on soldier morphology because the soldier caste provides the most reliable diagnostic characters in standard termite keys. Workers associated with the same colony were also recorded when present, but species determination relied mainly on soldier characters. Specimens were identified using regional taxonomic references, including Termites of Peninsular Malaysia by Tho (1992) and The Termites of Sabah by Thapa (1982). Identification was conducted to species level when diagnostic characters were sufficient and to genus level when species-level confirmation was not possible (Subekti et al. 2018; Zulkaidhah et al. 2021). Voucher specimens were preserved in the Forestry Sciences Laboratory, Faculty of Forestry, Universitas Tadulako. Because termite sampling was limited to attacked vegetation, this study did not apply standardized habitat-wide termite survey methods such as belt transects, soil monoliths, or wood baits. Therefore, the termite diversity indices presented here describe only termite taxa associated with attacked vegetation and do not represent the full termite assemblage potentially present in the broader habitat.

Attack assessment

Termite attack frequency was calculated as the percentage of attacked plants relative to the total number of plants observed in each plot and growth stage. Attack intensity was calculated using a weighted damage score based on severity classes ranging from 0 to 4, based on predefined criteria (Table 1).

Data analysis

Attack frequency

Attack frequency (F) was calculated as follows:

$$F = \frac{Xa}{Xt} x\ 100\%$$

Where: F : Attack frequency (%), Xa : Number of plants attacked by termites, Xt : Total number of plants observed.

Attack intensity

Attack intensity (AI) was calculated using the following weighted formula:

$$AI = \frac{(n1x1)+(n2x2)+(n3x3+(n4x4)}{Nx4} x\ 100\%$$

Where: AI: Attack Intensity, n1: Number of Plants Lightly Attacked (score 1), n2: Number of Plants Moderately Attacked (score 2), n3: Number of Plants Heavily attacked (score 3), n4: Number of Plants Severely attacked/dead (score 4), N: Total Affected Plants.

Based on the intensity value of the attack, the overall condition of plants at various stages of growth in Wera Nature Tourism Park due to termite attacks can be determined using the criteria in Table 2.

Margalef index (DMg)

Termite community structure was quantified using complementary diversity indices. Taxa richness was assessed using the Margalef index (DMg), calculated using the following formula:

$$D_{Mg} = \frac{S-1}{\ln (N)}$$

Where: S: The total number of taxa recorded, N: The total number of individuals in the sample (Magurran 1988).

Table 1. Scoring criteria for termite attack severity across vegetation growth stages

Plant conditions at various growth stages	Score
No visible evidence of termite attack.	0
Light attack, with damage limited to the bark and wood, affecting approximately one-quarter of the stem height.	1
Moderate attack, with more extensive damage to the bark and wood, affecting approximately half of the stem height.	2
Severe attack, with substantial bark and wood damage, affecting approximately three-quarters of the stem height.	3
Very severe attack or plant mortality, where most plant parts are damaged, bark and wood are extensively destroyed, and the plant exhibits symptoms such as drying and leaf loss.	4

Table 2. Classification of plant condition based on termite attack intensity

Attack intensity (%)	Plant condition
0 - 1	Not attacked
>1 - 25	Light damage
>25 - 50	Moderately damaged
>50 - 75	Heavily damaged
>75 - 100	Very seriously damaged/dead

Shannon-Wiener diversity index (H′)

Taxa diversity was quantified using the Shannon-Wiener diversity index (H′), calculated as:

$$H' = -\sum_{i=1}^{S} p_i \ln(p_i)$$

Where, S is the total number of taxa, p_i is the proportion of individuals belonging to the *i*-th taxon, calculated as $p_i = \frac{n_i}{N}$,; n_i is the number of individuals of taxon *i*, and N is the total number of individuals across all taxa (Magurran 1988).

Pielou's Evenness Index (E)

Taxa evenness was calculated using Pielou's evenness index (E), expressed as:

$$E = \frac{H'}{\ln(S)}$$

Where: H′: The Shannon Wiener diversity index, S: The total number of taxa recorded (Magurran 1988).

Relative dominance of termite taxa

Relative dominance of termite taxa was calculated as the proportion of individuals of a given taxon to the total number of individuals collected across all management zones. This was expressed as a percentage using the following formula:

$$RD_i = \frac{n_i}{N} x100\%$$

Where: RD_i is the relative dominance of taxon i (%), n_i is the number of individuals of taxon i, and N is the total number of individuals of all termite taxa collected from attacked vegetation. This metric describes the proportional contribution of each taxon to the overall termite assemblage associated with attacked vegetation (Magurran 1988).

Statistical analysis

Differences in termite attack frequency and attack intensity among management zones and vegetation growth stages were analyzed using a two-way analysis of variance (two-way ANOVA), with management zone (utilization, rehabilitation, protection) and growth stage (tree, pole, sapling) treated as fixed factors. Interaction effects between zone and growth stage were also tested. Prior to analysis, data were examined for normality using the Shapiro Wilk test and for homogeneity of variances using Levene's test. When necessary, percentage data were arcsine square root transformed to meet ANOVA assumptions. Post hoc comparisons were conducted using Tukey's HSD test at a significance level of $\alpha = 0.05$. Statistical analyses were performed using IBM SPSS Statistics 30.0.

RESULTS AND DISCUSSION

Frequency and intensity of termite attacks

Management zone and vegetation growth stage significantly affected both termite attack frequency and attack intensity (Table 3; $p<0.001$). Tukey's HSD test further showed significant differences among zones and among growth stages (Table 4). The utilization zone had the highest mean attack intensity (27.07%), followed by the rehabilitation zone, whereas the protection zone had the lowest value (11.00%). Across vegetation growth stages, trees consistently showed the highest attack frequency (48.47%) and attack intensity (38.80%), followed by poles and saplings. These results indicate that both disturbance-related zoning and plant growth stage are important predictors of termite attack patterns in WNTP.

Diversity and dominance structure of termite taxa associated with attacked vegetation

A total of eight termite taxa were recorded from attacked vegetation across the three management zones, representing five genera: *Bulbitermes*, *Macrotermes*, *Microcerotermes*, *Nasutitermes*, and *Odontotermes* (Table 5). Most taxa were identified to species level, including *Macrotermes gilvus* (Hagen, 1858), *Nasutitermes matangensis* (Haviland, 1898), *Nasutitermes havilandi* (Desneux, 1904), *Microcerotermes crassus* Snyder, 1934, *Microcerotermes serrula* (Desneux 1904), and *Bulbitermes sarawakensis* (Haviland, 1898), whereas two taxa, *Bulbitermes* sp. and *Odontotermes* sp., remained at genus level because available diagnostic characters were insufficient for reliable species-level identification. Taxon composition also varied among management zones, with three taxa recorded in the utilization zone, four in the rehabilitation zone, and six in the protection zone. Details of termite taxa in the three zones can be seen in Table 5.

Morphology of termite taxa found in Wera Nature Tourism Park is based on the identification results as follows:

Bulbitermes sarawakensis was recognized by the soldier head capsule, which is distinctly constricted behind the antennal sockets, and by the well-developed forward-projecting nasus. These characters clearly separate *Bulbitermes* from closely related nasute genera (Figure 2.A). *Bulbitermes* sp. showed the general nasute body form, with a rounded to pear-shaped head capsule and a distinct nasus. It was assigned to *Bulbitermes* based on head shape and antennal characters, but species-level identification was not emphasized here because the available characters were insufficiently diagnostic for more confident separation in the present material (Figure 2.B).

Macrotermes gilvus was identified by its relatively large soldier caste, elongated head capsule, and characteristic robust symmetrical mandibles (Figure 2.C). The combination of large body size and typical Macrotermitine soldier morphology distinguished this species from the other taxa recorded in the study.

Table 3. Summary of two-way ANOVA for termite attack frequency and intensity

Parameter	Source of variation	F-value	p-value
Frequency	Zone	12.20	<0.001
	Growth stage	198.64	<0.001
Intensity	Zone	37.76	<0.001
	Growth stage	195.01	<0.001

Table 4. Mean termite attack frequency and intensity across management zones and vegetation growth stages, with Tukey's HSD groupings

Zone	Growth stage	Average frequency (%)	Average intensity (%)	Plant condition
	Saplings	7.80	5.70	Not attacked
Utilization	Poles	21.70	20.80	Lightly damaged
	Trees	57.40	54.70	Moderately damaged
Averages		28.9 a	27.07 a	Moderately damaged
	Saplings	2.10	0.50	Not attacked
Rehabilitation	Poles	26.70	17.80	Lightly damaged
	Trees	51.50	29.70	Moderately damaged
Averages		28.4 a	16.00 c	Lightly damaged
	Saplings	2.40	0.70	Not attacked
Protection	Poles	16.50	7.10	Lightly damaged
	Trees	36.50	25.20	Moderately damaged
Averages		18.4 b	11.00 b	Lightly damaged
	Saplings	4.10 c	2.93 c	
Growth stage mean	Poles	21.63 b	14.80 b	
	Trees	48.47 a	38.80 a	

Note: Different superscript letters (a, b, c) within the same column (zone means and growth stage means) indicate significant differences according to Tukey's Honestly Significant Difference (HSD) test at α = 0.05

Table 5. Termite taxa associated with attacked vegetation in three management zones of Wera Nature Tourism Park

Zone	Termite taxa
Utilization	*Macrotermes gilvus* (Hagen, 1858) *Nasutitermes matangensis* (Haviland, 1898) *Odontotermes* sp.
Rehabilitation	*Bulbitermes* sp. *Microcerotermes crassus* (Snyder, 1934) *Nasutitermes havilandi* (Desneux, 1904) *Nasutitermes matangensis* (Haviland, 1898)
Protection	*Bulbitermes sarawakensis* (Haviland, 1898) *Bulbitermes* sp. *Microcerotermes crassus* (Snyder, 1934) *Microcerotermes serrula* (Desneux (1904) *Nasutitermes matangensis* (Haviland, 1898) *Odontotermes* sp.

Microcerotermes crassus was recognized by its rectangular to sub-rectangular soldier head capsule and well-developed serrated mandibles. Head shape, mandibular form, and general body size were the main characters used to distinguish it from other taxa (Figure 2.D).

Microcerotermes serrula was distinguished from *M. crassus* by its relatively narrower and more elongated head capsule, together with the characteristic serrated mandibles typical of *Microcerotermes* (Figure 2.E). Identification relied mainly on differences in head proportions and mandibular characters.

Nasutitermes havilandi was identified by its rounded to slightly oval soldier head capsule and relatively slender, elongated nasus. Antennal segmentation and nasus shape were important characters for distinguishing it from other *Nasutitermes* species (Figure 2.F).

Nasutitermes matangensis was recognized by its broader and more robust head capsule and a shorter, stouter nasus than that of *N. havilandi* (Figure 2.G). Differences in head capsule shape, nasus form, and antennal segmentation were used as the main diagnostic features.

Odontotermes sp. was recognized by its robust Macrotermitine soldier morphology, including a broad head capsule and strongly developed mandibles (Figure 2.H). However, the available diagnostic characters were insufficient for reliable species-level identification, so it was retained at genus level.

Diversity index of termite taxa associated with attacked vegetation

The diversity of termite taxa associated with attacked vegetation in Three Management Zones of Wera Nature Tourism Park is presented in Table 6. The diversity indices of termite taxa associated with attacked vegetation across the three management zones are presented in Table 6. The protection zone showed the highest Shannon diversity (H′ = 1.73) and Margalef richness (DMg = 1.44), followed by the rehabilitation zone (H′ = 1.32; DMg = 0.66), whereas the utilization zone had the lowest values (H′ = 1.08; DMg = 0.80). Evenness values were consistently high across zones (E = 0.95-0.98), indicating a relatively even distribution of individuals among taxa within each zone. These results suggest that termite taxa associated with attacked vegetation were more diverse and richer in the protection zone than in the more disturbed zones. However, these values are descriptive only and represent termite taxa collected from attacked vegetation rather than the overall termite assemblage present in Wera Nature Tourism Park. No inferential statistical tests were conducted to compare diversity indices among zones. The protection zone showed the highest taxon richness, whereas the utilization and rehabilitation zones had lower richness values. Evenness values remained high across all zones (0.95-0.98), indicating a relatively even distribution of termite taxa associated with attacked vegetation.

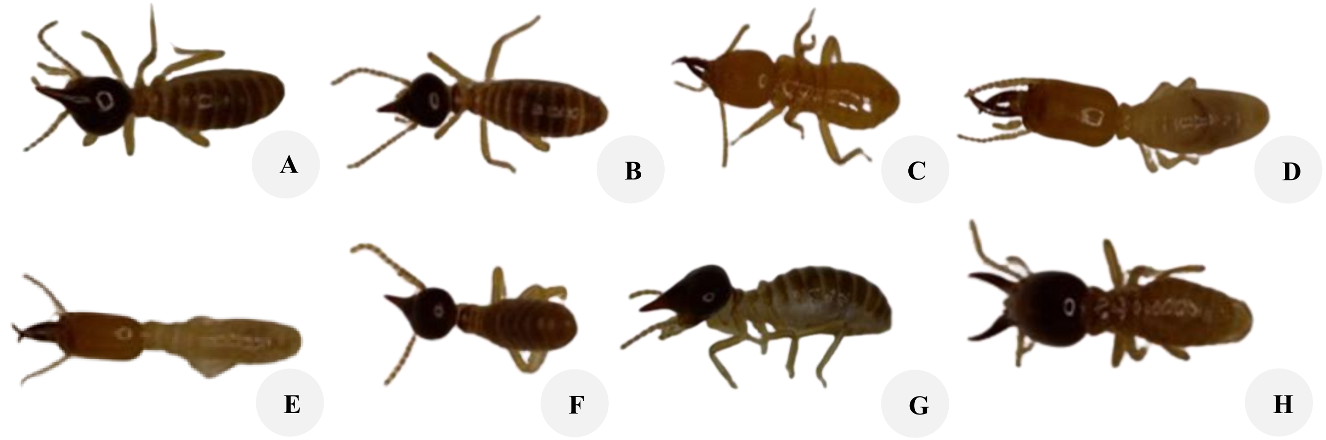

Figure 2. Morphology of termite taxa found in Wera Nature Tourism Park. A. *Bulbitermes sarawakensis*, B. *Bulbitermes* sp., C. *Macrotermes gilvus*, D. *Microcerotermes crassus*, E. *Microcerotermes serrula*, F. *Nasutitermes havilandi*, G. *Nasutitermes matangensis*, H. *Odontotermes* sp.

Table 6. Diversity of termite taxa associated with attacked vegetation in three management zones of Wera Nature Tourism Park

Zone	S	H'	DMG	E	Dominant taxa
Utilization	3	1.08	0.80	0.98	*Macrotermes gilvus*
Rehabilitation	4	1.32	0.66	**0.95**	*Nasutitermes matangensis*
Protection	6	1.73	1.44	0.97	*Bulbitermes sarawakensis*

Note: S: number of taxa, H': Shannon Index, DMg: Margalef Index, E: Evenness Index

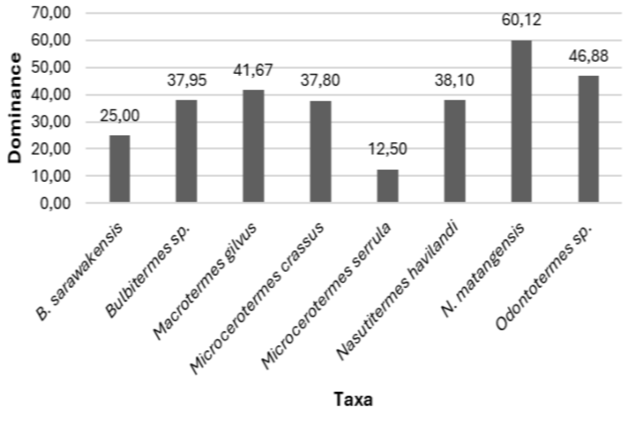

Figure 3. Relative dominance (%) of termite taxa in Wera Nature Tourism Park

Termite taxa dominance

The results of the dominance analysis of termite taxa in all zones observed in Wera Nature Tourism Park can be seen in Figure 3. *M. serrula* is the least dominant taxon at 12.50%, whereas *N. matangensis* showed the highest dominance (60.12%) across zones. The dominance analysis showed that *N. matangensis* had the highest relative dominance across the three management zones, whereas *M. serrula* had the lowest (Figure 3). In addition, *N. matangensis* was the only taxon consistently recorded in all zones, indicating a broad distribution in WNTP.

Discussion

The present study shows that forest management zoning is associated with significant differences in termite attack frequency, attack intensity, and the diversity of termite taxa collected from attacked vegetation in WNTP. The lower taxon richness observed in the utilization and rehabilitation zones may be associated with greater human activity and habitat disturbance in these areas. This interpretation is consistent with previous studies showing that termite richness is generally higher in natural and less-disturbed forests than in heavily disturbed habitats (Zulkaidhah et al. 2025). Physical disturbance may reduce habitat complexity and alter environmental conditions that support a broader range of termite taxa. In contrast, the protection zone, which is subject to lower disturbance, may provide more stable habitat conditions for maintaining higher termite taxon richness. Although the protection zone showed a slightly lower evenness value than the other zones, evenness remained high overall, suggesting that termite taxa were still relatively evenly distributed across zones rather than being strongly dominated by a single taxon (Mugerwa 2015). However, because environmental variables were not measured directly in this study, these explanations should be interpreted cautiously.

More disturbed zones tended to show higher attack intensity, whereas the less disturbed protection zone supported higher diversity and richness of termite taxa associated with attacked plants (Gillison et al. 2003; Griffiths et al. 2019; Kremen 2020). These patterns suggest that disturbance gradients created by zoning may influence both host vulnerability and termite assemblage structure. This pattern is consistent with previous studies showing that termite assemblages respond strongly to habitat disturbance, with disturbed environments often characterized by simplified communities and greater dominance of disturbance-tolerant taxa (Jouquet et al. 2018; Ashton et al. 2019; Fernandes et al. 2023; Ferreira et al. 2025). In WNTP, the utilization zone showed the highest attack intensity but comparatively lower diversity, whereas the protection zone maintained higher taxon richness and Shannon diversity. This contrast suggests that more intensive management and human activity may be associated with conditions that increase termite attack on vegetation while reducing the diversity of taxa associated with attacked plants (Silué et al. 2022). From a management perspective, these results indicate that zoning can be ecologically informative for identifying areas with greater potential termite impact.

These interpretations should remain cautious because environmental variables such as canopy cover, temperature, humidity, soil properties, and deadwood volume were not quantified directly in the present study. Therefore, zoning should be viewed as a management-related disturbance proxy rather than a direct ecological mechanism. The observed patterns are statistically supported associations that warrant further testing with direct habitat measurements. The higher attack intensity recorded in the utilization zone may be associated with greater vegetation stress, more frequent habitat modification, or higher availability of suitable woody material for termite foraging. Conversely, the higher diversity and richness observed in the protection zone may reflect more stable habitat conditions and a broader range of microhabitats. However, because these environmental drivers were not measured directly, such explanations remain inferential. Future studies should combine vegetation-based termite surveys with measurements of microclimate, deadwood availability, and habitat structure to clarify the mechanisms underlying zonation-related differences.

The dominance of *N. matangensis* across zones may reflect broad ecological tolerance and flexible use of woody resources, which are traits often associated with successful termite taxa in disturbed habitats (do Sacramento et al. 2020; Thorne et al. 2025). Its occurrence in all management zones suggests that this taxon can persist under a range of habitat conditions in WNTP. Nevertheless, this explanation remains inferential because the study did not measure colony traits, resource quality, or microhabitat conditions directly. Future studies should test these mechanisms using environmental and behavioral data. The observed patterns have practical implications for conservation-based ecotourism management in WNTP. In zones with higher attack intensity, especially the utilization zone, regular monitoring of termite attack on vegetation may help identify areas where disturbance-related habitat change is linked to elevated termite activity (Griffiths et al. 2019; Seibold et al. 2021; Falconí-López et al. 2024). Such monitoring could support early management responses, including vegetation maintenance, reduction of unmanaged woody debris in high-use areas, and protection of wooden facilities. In contrast, the protection zone appears important for maintaining a richer assemblage of termite taxa associated with attacked vegetation, reinforcing the value of low-disturbance management for conserving ecological complexity. Overall, the findings support zoning-based termite monitoring as part of adaptive forest conservation and sustainable ecotourism management in WNTP.

In conclusion, forest management zoning and vegetation growth stage were significantly associated with termite attack frequency and attack intensity in Wera Nature Tourism Park, Central Sulawesi. Trees were more vulnerable to termite attack than poles and saplings, and the utilization zone showed the highest attack intensity, whereas the protection zone supported the highest diversity of termite taxa associated with attacked vegetation. These findings suggest that zoning-based forest management is closely linked to variation in termite attack patterns and termite assemblage structure in WNTP. However, because environmental drivers were not measured directly, the ecological mechanisms underlying these patterns remain inferential. Future studies should incorporate direct measurements of habitat and microenvironmental conditions to support more targeted termite monitoring and zone-specific conservation management in conservation-based ecotourism areas.

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