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Ground-dwelling insects as bioindicators of ecosystem health in South Sulawesi, Indonesia

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Abstract. *Sadapotto A, Budiaman, Mutmainnah N, Prastiyo A. 2025. Ground-dwelling insects as bioindicators of ecosystem health in South Sulawesi, Indonesia. Asian J For 9: 211-220.* The sugar palm (*Arenga pinnata*) and pine (*Pinus merkusii*) stands serve as vital ecological and socio-economic landscapes, supporting biodiversity, community livelihoods, and education. Ground-dwelling insects play a role as bioindicator agents in ecosystem health and quality. This study examined the diversity and ecological role of ground-dwelling insects in sugar palm and pine stands at the Universitas Hasanuddin Education Forest, South Sulawesi, Indonesia. Sampling was conducted from October to December 2023 using pitfall traps across sugar palm and pine stands. The data were analyzed using diversity indices, t-tests, and Principal Component Analysis (PCA). A total of 989 individuals were recorded in the sugar palm stand and 889 in the pine stand. The independent t-test results revealed that diversity, richness, and evenness indices were significantly ($p<0.05$) higher in sugar palm stands. These results are consistent with the mean values, where sugar palm habitats exhibited greater diversity (2.56±0.12), richness (4.29±0.19), and evenness (0.75±0.03) compared to pine stands. Light intensity emerged as the dominant factor, contributing 87.489% of the variation, highlighting its strong impact on insect distribution and activity, particularly for light-sensitive groups such as ants. The most dominant species overall was the funnel ant (*Aphaenogaster laevior*), comprising 57.43% of individuals in pine and 17.10% in sugar palm habitats. These results emphasize the importance of habitat structure and microclimate in shaping insect communities and guiding conservation strategies.

Keywords: Bioindicator taxa, land-use gradient, pitfall trap, Shannon index, soil insect

INTRODUCTION

Insects, as one of the most abundant and diverse animal groups, contribute to ecosystem balance and are often used as indicators of environmental quality. Ground-dwelling insects are reliable bioindicators due to their high sensitivity to microhabitat changes, such as shifts in temperature, moisture, and soil conditions. Their roles in nutrient cycling, decomposition, and food web dynamics make them effective for assessing ecosystem health and environmental disturbances. Indonesia is rich in the diversity of living things, including insects (Buchory et al. 2018). High diversity in morphological, physiological, and behavioral characteristics of insects according to the surrounding environment (Schroeder et al. 2018). Insects are widespread, occurring in diverse habitats ranging from mountains and forests to agricultural fields and urban areas. However, insects have a positive role because they not only have ecological but also aesthetic value and function as a means of education (Chowdhury et al. 2023). The diversity and abundance of insects in a habitat reflect the unique characteristics and environmental conditions compared to other insect habitats (Dianzinga et al. 2020).

Some ground-dwelling insects also play roles as parasites of other organisms. Examples of ground-dwelling insects that act as parasites include Staphylinidae and Carabidae, with species such as *Pterostichus melanarius* (Shelton et al. 1983). This group of insects has a very valuable role, especially in decomposing organic soil material (Jankielsohn 2018). The life of ground-dwelling insects is greatly influenced by their habitat and dependence on environmental factors (Menta and Remelli 2020). Ground-dwelling insects play a vital role in maintaining soil ecosystem functions and supporting plant health through processes such as nutrient cycling, decomposition, and soil aeration (Feng et al. 2023). A recent study by Hasin and Booncher (2020) also showed changes in soil arthropod communities in response to agroecosystem type in Thailand, confirming the role of insects as bioindicators in tropical landscapes. Ground-dwelling insects have essential values in ecology, endemism, conservation, aesthetics, education, and economics (Gonçalves et al. 2021). The diversity of insects has a tremendous potential role and must be preserved so that they do not become extinct (Prastiyo et al. 2023) and do not experience a decrease in the diversity of their species.

One of the plants that has the potential to be developed into a commodity of economic value and is easily found in several areas in Sulawesi is the sugar palm (*Arenga pinnata*) plant. The sugar palm plant in Indonesia is widely used as a raw material for brown sugar (Amzu et al. 2020). The sugar palm plant in the South Sulawesi region, especially in the research location, is located in Rompegading Village, Maros District, with an area of almost 50 ha. This area is also one of the centers of water

sources upstream that are utilized by the village community.

The sugar palm stand is not far from the pine (*Pinus merkusii*) forest stand located in the Universitas Hasanuddin (Unhas) Educational Forest, where this plant is a superior type that has been often planted in reforestation and greening activities by the Indonesian government through the Ministry of Forestry since the 1960s. The selection of pine species is based on several factors, such as the availability of sufficient seeds, their rapid growth, and their ability to grow on marginal lands (Schroeder et al. 2018). Widespread pine planting has proven successful in forming pine forests that contribute to state foreign exchange and community welfare in Java and other areas (Pasaribu et al. 2021). The Unhas Educational Forest has a pine forest area of 60 ha. This area needs to evaluate the condition of its ecosystem, especially the diversity of ground-dwelling insects, as a form of reforestation and land restoration. The role of ground-dwelling insects as bioindicators of ecosystem health (Rainio and Niemelä 2003; Maleque et al. 2006) is essential to both environmental and economic buffers. This research is expected to provide data and information. It can be used as a reference in managing the sustainability of the Unhas Educational Forest area to support biodiversity and maintain a sustainable ecosystem balance. The purpose of this study was to examine the distribution of ground-dwelling insects and their roles in sugar palm and pine stands in the Unhas Educational Forest, Maros District, South Sulawesi, Indonesia.

MATERIALS AND METHODS

Site location

The research was conducted in the Unhas Educational Forest, located in Bengo-Bengo, Maros District, South Sulawesi, Indonesia (Figure 1). This secondary forest lies approximately 65 kilometers from the main Universitas Hasanuddin campus in Makassar and can be reached in about two hours by road. Geographically, the Unhas Educational Forest is situated in a topographically varied landscape, ranging from gently sloping areas to mountainous terrain, with elevations between 300 and 800 meters above sea level (m asl). The two primary research sites within this forest are the sugar palm stand (4°59′41.3″ S, 119°45′44.6″ E) and the pine stand (4°58′8.9″ S, 119°46′34.9″ E). Vegetation under sugar palm stands is dominated by pioneer shrubs such as *Melastoma malabathricum*, *Clidemia hirta*, *Chromolaena odorata*, and *Lantana camara*, along with grasses like *Ageratum conyzoides*, *Axonopus compressus*, *Cyperus rotundus*, and *Imperata cylindrica*, ferns (*Adiantum* spp.), wild bananas (*Musa acuminata*), rattans (*Calamus* spp.), orchids (Orchidaceae), and tree species such as *Diospyros celebica* and *Mangifera indica* add to the structural and floristic diversity of the understory. Whereas in pine stands, several vegetation species are present, such as *M. malabathricum*, *C. rotundus*, *A. compressus*, Orchidaceae, *Swietenia macrophylla*, and *Acacia* sp.. The sugar palm site lies at approximately 442 m asl, while the pine site is at around 542 m asl. These two areas are important economic zones for the local community, serving as sources of brown sugar and pine resin, respectively.

Data collection

Sampling was carried out weekly during October to December 2023, with 16 pitfall traps installed in each stand (four plots per stand, each plot containing four traps, with a distance of 50 m between plots and 10 m between traps) in sugar palm and pine stands at the Unhas Educational Forest, Maros, South Sulawesi. Ground-dwelling insects were captured using pitfall traps (Hohbein and Conway 2018). Traps were spaced approximately 10 meters apart and operated for 24 hours per session. Each trap was made from an 8 cm diameter plastic bottle (15 cm deep) filled to 25% with a detergent-water (90% water and 10% detergent) solution to retain insects.

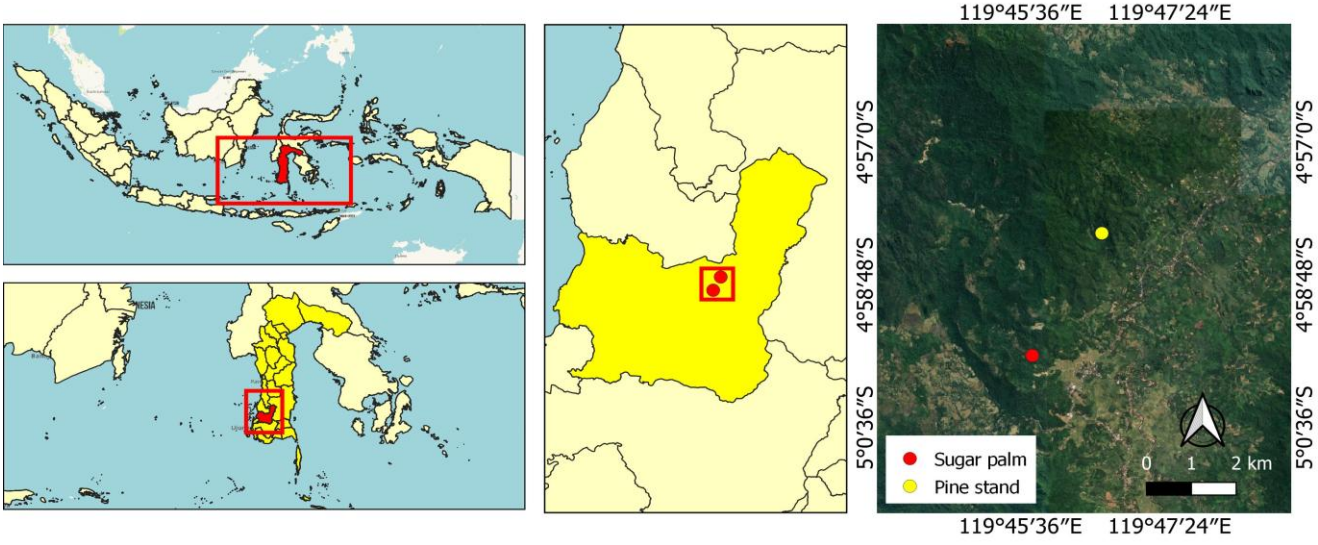

Figure 1. Map of research locations in the sugar palm and pine areas in Unhas Educational Forest, Maros, South Sulawesi, Indonesia

Environmental variables, including air temperature, relative humidity, light intensity, and soil pH, were measured concurrently with insect sampling. Air temperature and relative humidity were recorded using a digital thermo-hygrometer, light intensity was measured with a lux meter (Smart Sensor AS803), and soil pH was determined using a portable soil pH meter (Ituin 4-in-1 Digital Soil Analyzer Teste). These measurements were taken three times daily, morning (07:00-09:00), noon (11:00-13:00), and afternoon (15:00-17:00), to capture temporal variation. Environmental data for both stand types are presented in Table 1.

Identification

Insects collected in the field were initially grouped by order. Specimens that could be identified to the species level were classified on-site, while those requiring further identification were brought to the laboratory. Identification was conducted using a stereo microscope (STEM 2000 with an ERC 5S phototube camera) and cross-referenced with field guides, identification keys, relevant literature (Roy and Das 2015; Nasirian 2016; Noureldin and Farrag 2016; Hristov and Chobanov 2016; Zawadneak et al. 2017; Alaku et al. 2018; Beliën et al. 2018; Musyafa et al. 2019; Noriega et al. 2021; Putri et al. 2021; Schmidt and Overal 2021; Tangkawanit et al. 2021; Ozgen and Mamay 2022; Leksono et al. 2022; Wanna et al. 2022; Khongthawie et al. 2023; Sulastri and Sjam 2023) and the iNaturalist website.

Data analysis

The analysis began with calculating the relative abundance of ground-dwelling insects based on the method by Umami et al. (2024). Further analysis included the use of the diversity index (Alwi et al. 2021), species richness index (Wardhana et al. 2022), evenness index (Salami and Akinyele 2018), and dominance index (Anggraini et al. 2024). Data on diversity index, species richness, evenness, and dominance were analyzed using an independent t-test to compare the differences in mean values between two types of land cover, namely pine stands and sugar palm stands. Prior to the t-test, data normality was assessed and met the assumption of normal distribution ($p>0.05$). This test is used to determine whether the differences between the two groups are statistically significant at a certain level of confidence ($p<0.05$). Additionally, Principal Component Analysis (PCA) was performed using XLSTAT to explore the relationship between insect diversity and environmental variables, such as temperature, humidity, and soil pH, within the sugar palm and pine stands (Habite and Sendekie 2023).

RESULTS AND DISCUSSION

Distribution and relative abundance of ground-dwelling insects

The accumulation of species with increased sampling effort served as a key indicator of biodiversity, particularly in evaluating inventory completeness and comparing habitat quality. The observed trend (Figure 2) showed a consistent increase in species with each additional trap, confirming the richness and variety of insect communities in both the sugar palm and pine stands. However, the sugar palm habitat consistently yielded a higher species count at each sampling point, indicating greater insect diversity.

Based on the relative abundance (Table 2) data of ground-dwelling insects across two types of land cover, sugar palm stand and pine stands, differences were found in species composition and distribution between the locations. A total of 38 species from 21 families and 7 orders were identified. The sugar palm stand recorded a higher number of species (32 species) compared to the pine stand (26 species), indicating greater species richness. However, the pine habitat had a higher total number of individuals (989) than the sugar palm habitat (889), suggesting differences in species abundance and density (Figure 3). The most dominant species overall was *Aphaenogaster laevior* (Hymenoptera: Formicidae), with a relative abundance of 57.43% in the pine habitat and 17.10% in the sugar palm habitat, yielding a combined total of 38.26%. Hymenoptera contributed the largest share of total insect abundance, with several species showing strong habitat preferences.

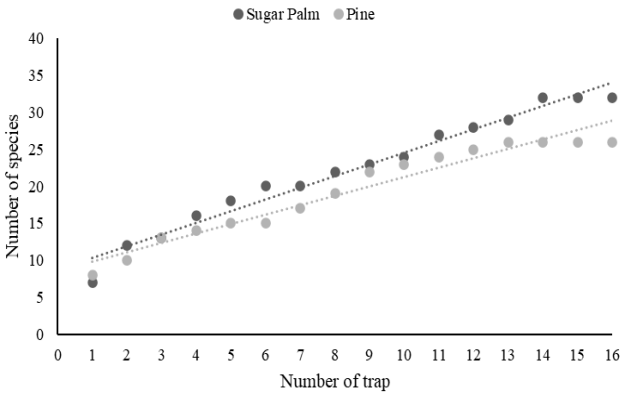

Figure 2. Cumulative curve of the number of ground-dwelling insect species in relation to the number of pitfall traps (16 traps) in sugar palm and pine stands

Table 1. Average environmental conditions in sugar palm and pine stands

Location	Temperature (°C)	Humidity (%)	Light intensity (lux)	Soil pH
Sugar palm stand	31.50±0.30	57.00±1.00	4367.57±38.46	5.39±0.08
Pine stand	25.33±0.32	68.00±1.00	6690.00±57.17	5.74±0.04

Table 2. Relative abundance of ground-dwelling insects in sugar palm and pine stands

Order	Family	Species	Sugar Palm (%)	Pine (%)	Total (%)
Blattodea	Actobiidae	*Blattella germanica* Linnaeus, 1767	0.00	0.20	0.10
	Blattidae	*Periplaneta americana* Linnaeus, 1758	0.00	0.20	0.10
	Ectobiidae	*Loboptera decipiens* Germar, 1817	0.22	0.10	0.16
		Supella longipalpa Fabricius, 1798	0.22	0.00	0.11
Coleoptera	Cerambycidae	*Smodicum* sp.	0.00	0.20	0.10
	Curculionidae	*Anthonomus* sp.	0.11	0.40	0.26
	Nitidulidae	*Epuraea ocularis* Fairmaire, 1849	0.34	0.00	0.17
	Scarabeidae	*Ateuchus* sp.	0.34	0.20	0.27
	Staphylinidae	*Aleochara* sp.	0.34	0.00	0.17
		Dolichoctis tetracolon Chaudoir, 1870	0.22	0.00	0.11
Dermaptera	Diplatydae	*Diplatys flavicollis* Shiraki, 1907	0.22	0.00	0.11
	Forficulidae	*Forficula greeni* Burr, 1907	0.00	0.00	0.00
	Hirundinidae	*Labidura riparia* Pallas, 1773	0.22	0.00	0.11
Hemiptera	Alydidae	*Alydus* sp.	0.34	0.20	0.27
	Cicadellidae	*Agallia* sp.	0.00	0.00	0.00
	Miridae	*Deraeocoris* sp.	0.22	0.51	0.37
	Pyrrhocoridae	*Dysdercus cingulatus* Fabricius, 1775	0.22	0.40	0.31
	Reduviidae	*Diaditus* sp.	0.56	0.20	0.38
	Rhyparochromidae	*Rhyparochromus* sp.	0.45	0.20	0.33
Hymenoptera	Formicidae	*Anoplolepis gracilipes* Smith, F., 1857	4.95	3.64	4.29
		Aphaenogaster laevior Emery, 1887	17.10	57.43	37.26
		Aphaenogaster sp.	1.35	0.81	1.08
		Camponotus sp.	0.45	0.00	0.22
		Cardiocondyla sp.	10.35	10.41	10.38
		Dinoponera sp.	8.32	4.25	6.29
		Iridomyrmex anceps Roger, 1863	5.40	3.03	4.22
		Lepisiota rothneyi Forel, 1894	0.90	0.30	0.60
		Leptogenys diminuta Smith, F., 1857	2.59	1.62	2.10
		Leptogenys sp.	3.26	2.43	2.84
		Nylanderia sp.	9.00	4.75	6.88
		Odontomachus infandus Smith, F., 1858	0.00	0.81	0.40
		Odontomachus simillimus Smith, F., 1858	5.62	3.44	4.53
		Oecophylla smaragdina Fabricius, 1775	6.07	3.44	4.76
		Temnothorax sp.	16.87	0.00	8.44
Isoptera	Rhinotermitidae	*Macrotermes gilvus* Hagen, 1858	0.79	0.00	0.39
Orthoptera	Acrididae	*Trilophidia annulata* Thunberg, 1815	0.22	0.00	0.11
		Apalacris gracilis Willemse, 1936	2.14	0.20	1.17
	Mogoplistidae	*Terraplistes* sp.	0.56	0.61	0.58

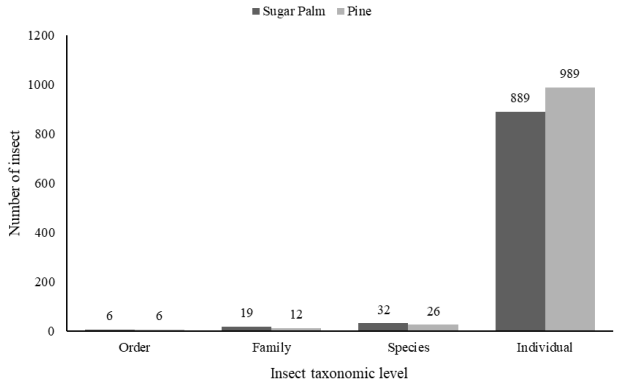

Figure 3. Number of insect orders, families, species, and individuals recorded in sugar palm and pine stands

The composition of ground insects in both habitats showed different species dominance, reflecting the differences in microclimatic conditions between sugar palm plantations and pine forests. *Aphaenogaster laevior* dominated the community in pine forests (57.43%), which can be ecologically associated with lower temperatures (25.33°C), higher humidity (68%), and stronger light intensity (6690 lux), conditions that tend to favor species that are tolerant to high light and humidity (Rainio and Niemelä 2003; Hristov and Chobanov 2016). In the same species, *A. laevior,* was more dominant in sugar palm gardens, indicating a preference for warm environments and more heterogeneous vegetation (Dai 2022). These results indicate that habitat factors such as temperature, humidity, light intensity, and soil pH play a major role in regulating the presence of certain taxa. In addition to being resource users (foragers), several dominant taxa, such as ants (Formicidae) and predatory ladybugs (Reduviidae), also function as biological control agents, which strengthens the ecological indicator value of this community (Noriega et al. 2021; Budiaman et al. 2025). The distribution of taxa is not only influenced by the physical ecological conditions of the habitat, but also

reflects the functions they perform in different ecosystem systems.

Species accumulation curves, as applied in this study, played an essential role in biodiversity assessments. They indicated whether the sampling effort was adequate to represent community diversity and enabled meaningful comparisons of species richness across habitats with differing structural characteristics (Matthews and Whittaker 2019). The pattern observed reinforced the ecological of sugar palm stands in supporting insect biodiversity and underscored their potential as conservation priorities. By capturing the response of insect communities to habitat type, the findings highlighted the value of maintaining diverse and structurally complex ecosystems for sustaining soil-dwelling invertebrate populations. Ants, especially from this family, are known to serve as important bioindicators of environmental health (Bharti et al. 2016). This is according to the research of Budiaman et al. (2025), which states that ants have a role as an indicator of environmental health. The Isoptera order plays a role as a decomposer of organic matter, while the Orthoptera order plays a role as herbivores (Mutmainnah 2024). Decomposing insects increase soil fertility and nutrient cycling (Verma et al. 2023). Dominant predators such as ants (Formicidae) control the population of other arthropods, thereby maintaining community stability. Predatory ants have a role as bioindicators of ecosystem health or biocontrol agents (Lutinski et al. 2024). Herbivores, such as several types of Orthoptera, show direct interactions with plants and can be indicators of vegetation changes (Geppert et al. 2021). The diversity of these functions illustrates the high complexity of the ecosystem and the active role of ground-dwelling insects as bioindicators and supporters of sustainable ecological processes.

Role of ground-dwelling insects in *A. pinnata* and *P. merkusii* stands

The abundance of ground-dwelling insects trapped in the sugar palm and pine stands shows several taxonomic groups with ecological roles supporting ecosystem functions (Table 3). For example, the Blattodea order shows a dominant role as an indicator of environmental cleanliness and the dominant role of insects as disease vectors in both the sugar palm and pine stands. The Coleoptera order shows the dominant role of insects as pollinators that function as pollinating agents for ecosystem sustainability and as detritivores in processing organic matter and soil nutrients. The Dermaptera order is a predator that functions as an ecosystem biocontrol agent, and the Hemiptera order shows various ecological roles as pests and predators.

The high dominance of *A. laevior* in the pine habitat can be attributed to environmental characteristics that support its biological needs. Pine habitats typically have a thick, moist litter layer, providing a suitable microhabitat for decomposers and litter-feeding insects (Raoa et al. 2015). Additionally, the high abundance of *Diaditus* sp., a predator from the order Hemiptera, in both habitats indicates its important role in regulating other insect populations, reflecting a balanced community structure. Predatory species like *Diaditus* sp. occupy a key trophic position in maintaining soil ecosystem stability (Lami et al. 2023). Differences in relative abundance between habitats also reflect variations in vegetation structure, humidity, and food resource availability, which are critical factors influencing the distribution of soil insects (Tsafack et al. 2019).

Table 3. Roles of ground-dwelling insects in sugar palm and pine stands

Species	Roles
B. germanica	Sanitation indicator (Noureldin and Farrag 2016)
P. americana	Transmitting diseases (Alaku et al. 2018)
L. decipiens	Pathogen spreaders (Hristov and Chobanov 2016)
S. longipalpa	Allergens and vectors (Nasirian 2016)
Smodicum sp.	Predators (Kahuthia et al. 2019)
Anthonomus sp.	Pollinators (Beliën et al. 2018)
E. ocularis	Foragers
Ateuchus sp.	Decomposers (Noriega et al. 2021)
Aleochara sp.	Biological control agents (Ozgen and Mamay 2022)
D. tetracolon	Foragers
D. flavicollis	Foragers
F. greeni	Foragers
L. riparia	Predators and biological control agents (Tangkawanit et al. 2021)
Alydus sp.	Foragers
Agallia sp.	Predators (Zawadneak et al. 2017)
Deraeocoris sp.	Predators (Sulastri and Sjam 2023)
D. cingulatus	Pests (Roy and Das 2015)
Diaditus sp.	Foragers
Rhyparochromus sp.	Foragers
A. gracilipes	Bioindicators (Khongthawie et al. 2023)
A. laevior	Seed dispersers (Dai 2022)
Aphaenogaster sp.	Predators and seed dispersers (Budiaman et al. 2025)
Camponotus sp.	Foragers (Budiaman et al. 2025)
Cardiocondyla sp.	Carnivorous and biocontrol agents (Budiaman et al. 2025)
Dinoponera sp.	Predators (Schmidt and Overal 2021)
I. anceps	Bioindicators (Putri et al. 2021)
L. rothneyi	Foragers
L. diminuta	Bioindicators (Khongthawie et al. 2023)
Leptogenys sp.	Bioindicators (Putri et al. 2021)
Nylanderia sp.	Bioindicators (Putri et al. 2021)
O. infandus	Foragers
O. simillimus	Soil structures (Wanna et al. 2022)
O. smaragdina	Biocontrol agents and pollinators (Musyafa et al. 2019)
Temnothorax sp.	Foragers
M. gilvus	Decomposers and bioindicators (Subekti and Mar'ah 2019)
T. annulata	Biocontrol agents (Leksono et al. 2022)
A. gracilis	Foragers and herbivores
Terraplistes sp.	Foragers and herbivores

The dominance of Hymenoptera in the ground-dwelling insect community suggests that this group is well-adapted to both observed habitat types. Formicidae play ecological roles as flexible predators and bioindicators, thriving under various environmental conditions (Wheeler and Krimmel 2015). The more humid and vegetation-diverse *aren* (sugar palm) habitat likely supports species such as *Camponotus* sp. and *Temnothorax* sp., which are recognized as indicators of soil ecosystem quality. The presence of ants as bioindicators reflects a relatively stable habitat that supports nutrient cycling. Meanwhile, the low abundance of certain species found only in one habitat, such as *Camponotus* sp., indicates habitat specialization or high sensitivity to specific environmental factors, consistent with Dejean et al. (2015), who found that ant communities are highly responsive to microhabitat changes and ecosystem degradation.

Diversity, richness, evenness, and dominance of ground-dwelling insects

The diversity, richness, and evenness indices of ground-dwelling insects were significantly ($p<0.05$) higher in the sugar palm plantation location compared to the pine forest (Table 4). In contrast, the dominance index did not show significant ($p>0.05$) differences between the two locations, although its value was slightly higher in the sugar palm stand.

The analysis of ground-dwelling insects' diversity, richness, evenness, and dominance indices showed different values in both locations (Figure 4). The diversity of ground-dwelling insects was higher in the sugar palm stand (2.56) compared to the pine stand (1.76). Similarly, species richness was greater in the sugar palm stand (4.29) than in the pine stand (3.77), indicating a broader variety of insect species. Evenness was also higher in the sugar palm stand (0.75), suggesting a more balanced distribution of individuals among species compared to the pine stand (0.53).

Insect diversity served as a strong indicator of ecosystem health and supported the presence of a wider range of species. A high diversity index at a location describes a more stable ecosystem than other locations (Uhl et al. 2020). The diverse vegetation in sugar palm and pine stands had created varied living spaces and food sources, promoting ecological balance. High diversity reflected environmental stability and well-regulated microclimates (Konig et al. 2024). Ecosystems with rich insect communities were more resilient to disturbance, which was particularly important in South Sulawesi's forests under increasing anthropogenic pressure (Sánchez-Pinillos et al. 2019). The distinct vegetation types in both study areas had generated microhabitats that supported different ground-dwelling insect assemblages.

Higher insect richness and evenness can explain habitats that are abundant food sources (Ramzan et al. 2021). High species richness indicated abundant resources and was shaped by habitat heterogeneity and ecological interactions (Stein 2015). This structural complexity likely attracted a wider range of species, reinforcing biodiversity and strengthening interspecific relationships (Dar et al. 2017). The findings highlight the importance of maintaining diverse vegetation structures and microclimatic conditions to support insect biodiversity, which is essential for ecological balance. This insight can guide sustainable land-use planning and agroforestry practices by promoting habitat heterogeneity to enhance ecosystem functions such as pollination, decomposition, and natural pest control (Noriega et al. 2021). These findings supported the potential of South Sulawesi forests as conservation sites for ground-dwelling insects, as species richness reflected successful habitat management (Noreika et al. 2020).

Both sites also exhibited high evenness, a characteristic of healthy ecological communities with minimal dominance by opportunistic species (Amrulloh et al. 2022). Stable habitats typically supported evenly distributed populations and experienced lower environmental stress (Hardiwinoto and Syahbudin 2020). The pine stand, often dominated by drought-tolerant insects, still maintained balanced communities due to favorable microclimate conditions (Hentschel et al. 2018). Sensitive insect species had likely persisted, suggesting intact microhabitat quality and the role of vegetation structure in supporting community stability. Evenness remained a key parameter in long-term ecosystem monitoring.

Table 4. Values of diversity, richness, evenness, and dominance indices of ground-dwelling insects

Parameters	Pine	Sugar palm
Diversity index*	1.76±0.05	2.56±0.12
Richness index*	3.77±0.10	4.29±0.19
Evenness index*	0.53±0.02	0.75±0.03
Dominance index	0.03±0.01	0.04±0.0

Note: Values are presented as mean ± standard deviation. The symbol (*) indicates a significant difference ($p<0.05$)

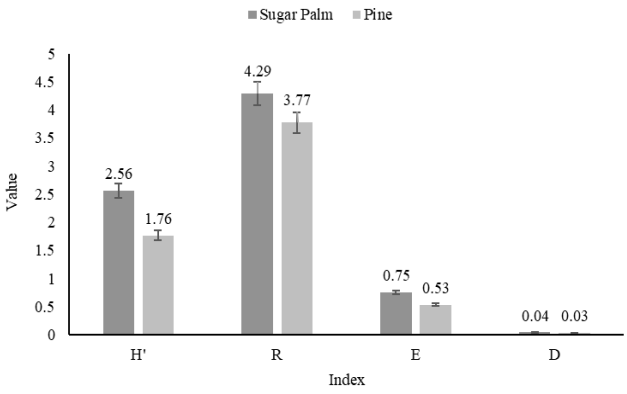

Figure 4. Diversity (H'), richness (R), evenness (E), and dominance (D) index values of ground-dwelling insects in sugar palm and pine stands

The low dominance index at both locations suggested declining environmental pressure and more balanced population structures. While high dominance often indicated stress, reduced dominance was linked to increased sustainability (Schowalter 2022). High diversity typically occurred when no single species became overly dominant (Hallmann et al. 2021). These results implied that sugar palm and pine habitats were transitioning toward greater ecological equilibrium, likely aided by reduced human disturbance, understory vegetation enrichment, and adaptive vegetation management strategies. Ants inhabit temperatures that tend to be high to search for food and build nests (Nascimento et al. 2022). The negative relationship between light intensity and insect diversity in the sugar palm habitat suggests that lower light levels, associated with denser canopy and thicker litter, support a more diverse and evenly distributed insect community. Conversely, the pine habitat, which receives more light, shows a positive correlation with light intensity but supports lower diversity. Other conditions, such as humidity, light intensity, and soil pH, also affect the distribution of ground-dwelling insects. Microclimate conditions can encourage the growth or inhibit particular species in an ecosystem (Cours et al. 2023).

Environmental conditions and the distribution of ground-dwelling insects

The environmental conditions in sugar palm and pine habitats influence the diversity and composition of ground-dwelling insect communities. As shown in Table 5, light intensity emerges as the dominant factor, contributing 87.489% of the variation. This highlights the strong impact of light on insect distribution and activity, especially considering that many ground-dwelling insects, such as ants, are sensitive to variations in light levels.

The results from the PCA showed a strong relationship between the two locations, with PC1 accounting for 100.00% of the variation and PC2 contributing 0.00%. Data variation was primarily explained by the close association between the diversity, richness, evenness, and dominance indices of ground-dwelling insects and soil pH (Figure 5). At the same time, temperature, humidity, and light intensity showed weaker correlations. This pattern highlighted soil pH as a dominant factor influencing the composition and distribution of ground-dwelling insect species. The biplot (Figure 6) further revealed a more complex relationship between insect diversity indices and soil pH, followed by temperature and humidity. In contrast, light intensity appeared to have a minimal role in determining insect abundance across sugar palm and pine habitats. The PCA interpretation underscored the main variables contributing to the observed data patterns and illustrated how local climatic conditions influenced the variability of ground-dwelling insect diversity.

Table 5. Contribution of parameters to the PCA of ground-dwelling insects

Parameters	PC1 (%)	PC2 (%)
Diversity Index	1.854	4.512
Richness Index	1.844	3.431
Evenness Index	1.862	7.716
Dominance Index	1.866	9.161
Temperature (°C)	1.709	**44.569**
Humidity (%)	1.542	**26.714**
Light Intensity (Lux)	**87.489**	0.008
Soil pH	1.836	3.888

Note: The number highlighted in bold indicates a contribution

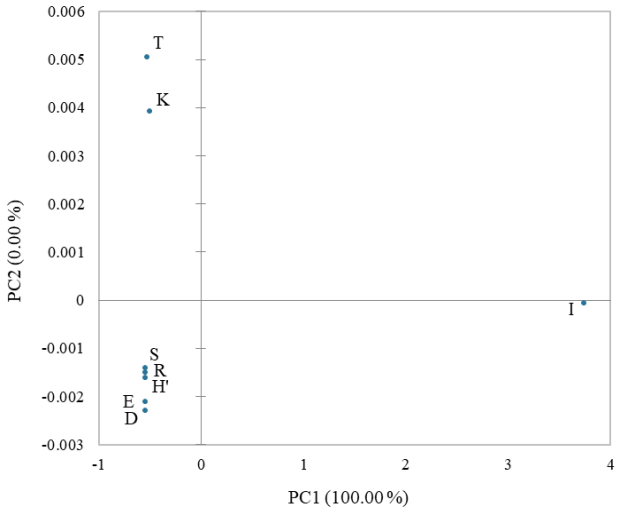

Figure 5. PCA results of the relationship between diversity (H'), richness (R), evenness (E), and dominance (D) of ground-dwelling insects with temperature (T), humidity (K), light intensity (I), and soil pH (S)

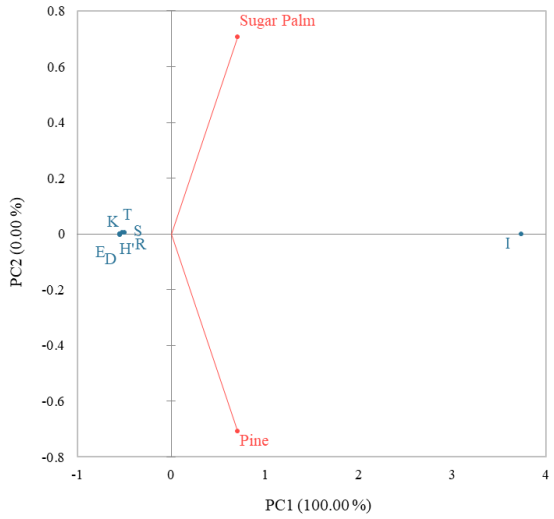

Figure 6. PCA biplot of the relationship between environmental conditions and ground-dwelling insect diversity in the sugar palm and pine stands

PC2 was predominantly influenced by temperature (44.569%) and humidity (26.714%), reinforcing the crucial role that microclimate had played in shaping insect communities. Higher temperatures in the sugar palm stand (31.5°C) appeared to favor thermophilic species such as ants, which are known to increase their foraging and nesting activity in warmer conditions (Nascimento et al. 2022). Conversely, the pine stand, with its lower temperature (25.33°C) and higher humidity (68%), may have limited the presence of certain species while supporting those adapted to cooler, more humid environments. As noted by Pincebourde and Woods (2020), insects are highly responsive to fine-scale thermal and moisture gradients, which can constrain or promote species occurrence and behavioral patterns. In addition, soil pH contributed moderately to both PC1 (1.836%) and PC2 (3.888%), indicating that while it played a secondary role, it still supported soil health and the stability of microhabitats. Optimal pH conditions are known to enhance microbial activity and the decomposition of organic matter (Naz et al. 2022), thereby benefiting detritivorous and ground-dwelling insects indirectly. Although diversity, richness, evenness, and dominance indices each contributed less than 10% to both principal components, the overall strong correlation (0.985) between environmental variables and insect diversity highlighted that shifts in temperature, humidity, and particularly light intensity were key drivers of community structure. These findings aligned with those of Cours et al. (2023) and Prastiyo et al. (2024), who emphasized that localized variation in microclimate played a decisive role in shaping insect assemblages, especially in tropical forest ecosystems. Insect abundance was shaped by habitat characteristics and microclimate conditions (Scherer and Fartmann 2022). Each location exhibited distinct ecological adaptations affecting insect distribution (Zhao et al. 2023). Ground-dwelling insects contributed to essential ecosystem functions such as decomposition, nutrient cycling, and soil aeration (Bagyaraj et al. 2016), and their presence remained dependent on the availability of nesting sites and food resources (Fialho et al. 2018).

In conclusion, ground-dwelling insects, particularly under sugar palm stands and pine stands, are contributors to ecosystem functioning. Their roles as decomposers, predators, biological control agents, and bioindicators are crucial. This study identifies ant species (Formicidae) and predatory bugs (Reduviidae) that emerged as key functional groups that were consistently present and abundant across both habitats. Their strong potential as indicator taxa for monitoring environmental change is a promising finding. The high diversity and evenness observed, especially in sugar palm stands, reflect the ecological stability promoted by heterogeneous vegetation and favorable microclimatic conditions such as higher temperature and lower humidity. These findings underscore the importance of land-use systems with structurally diverse and moisture-retaining vegetation, like sugar palm agroforests, which are better suited to support soil biodiversity. Therefore, incorporating ground-dwelling insect monitoring, particularly Formicidae and Reduviidae, into sustainable land management and restoration programs is a hopeful step towards enhancing biodiversity conservation while supporting ecological processes in South Sulawesi's forested landscapes.

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