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Spatial Patterns and Environmental Influences on Soil Surface Collembola in Forest and Non-Forest Ecosystems

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ABSTRACT

Forests are one of the ecosystems with different habitat characteristics for certain species. The transition from forest to non-forest will affect the ecosystem and its resident species. The study aims to determine the presence of soil surface Collembola within various ecosystems, identify the types of soil surface Collembola present and their locations, analyze the impact of environmental conditions on their distribution, and identify the association between soil surface Collembola and Acari. The field procedures comprise the setup of litter traps, litter harvesting and extraction, measurement of environmental factors, and identification of soil surfaces in Collembola and Acari. Collembula is found in oil palm plantations. A total of 1,618 individuals were found in all ecosystem types, including 13 genera and 6 families: Cyphoderidae, Entomobryidae, Isotomidae, Oncopoduridae, Paronellidae, and Dicyrtomidae, along with 2 orders, Entomobyromorpha and Symphypleona, which showed grouped patterns in each ecosystem types. Several environmental factors, both biotic and abiotic, strongly influence the soil surface of Collembola. From all ecosystem types, only secondary forest ecosystems lack an association between soil surface Collembola and Acari.

Introduction

An ecosystem is a system that consists of living organisms and their environments, where there is an interaction between the two that maintains their survival. Forests, as one type of ecosystem, have different habitat characteristics that support various species. Indonesia, as a tropical country with vast forest areas, experiences forest degradation every year due to the high rate of deforestation compared to other tropical countries [1]. The change in forest function, from forest to non-forest, also plays a role in altering the ecosystem and species within the forest. Moreover, the change in land use from forest to monoculture plantation systems has negative impact on the diversity of species constituting the ecosystem, one of which is the soil-dwelling Collembola.

Collembolla belong to the subphylum Hexapoda, have bodies equipped with setae, but lack wings. Because of their tail that resembles a spring, people also refer to Collembola as springtails. Collembola are soil organisms classified as mesofauna. Collembola have a wide distribution, inhabiting various habitats, including polar regions, deserts, and subtropical and tropical areas [2]. The presence of Collembola in a habitat can be influenced by physical factors such as temperature, pH, humidity, soil or habitat water content, toxic substances, spatial season, or climate [3]. Planning for the protection of Collembola can benefit from studying their distribution on the soil surface within an ecosystem. By examining the distribution of this species, we can identify the factors that influence their survival, especially in certain types of land use. The study of the distribution patterns of surface Collembola in an ecosystem can provide valuable information for conservation planning, as analyzing the distribution of surface Collembola will reveal the factors affecting the

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presence of these species, especially in different land uses. Furthermore, their presence can serve as an indicator of the health of an ecosystem and provide an overview of the presence of other organisms.

Bungku Village is one of the villages in Jambi Province, which generally has a varied topography, with hills and lowlands, most of which are agricultural and plantation areas. This village comprises four distinct ecosystems with varying land-use types. The four ecosystems were secondary forest areas, natural rubber forests (also known as jungle rubber), rubber plantation forests (also referred to as rubber plantations), and oil palm plantations. This study aimed to determine the prevalence of each species of soil surface Collembola, identify the species found, map the distribution of soil surface Collembola, analyze the impact of environmental factors on their presence, and explore the relationship between soil surface Collembola and Acari. This research is expected to explain the distribution patterns of surface soil Collembola in the four ecosystems.

Materials and Methods

Study Area

This study was conducted in Bungku Village, Bajubang District, Batang Hari Regency, Jambi Province (Figure 1). For the first stage, namely sampling of soil surfaces, Collembola and Acari were sampled in four forest ecosystems. In the second stage, we identified soil surface Collembola and Acari at the Entomology Laboratory, Department of Silviculture, Faculty of Forestry, IPB. Books identified by Borror et al. [4] and Suhardjono et al. [5] were used to identify Collembola and Acari. The materials were stored at the Forest Entomology Laboratory, Department of Silviculture, Faculty of Forestry, IPB. Additionally, 70% alcohol was used to preserve the specimens during the identification process.

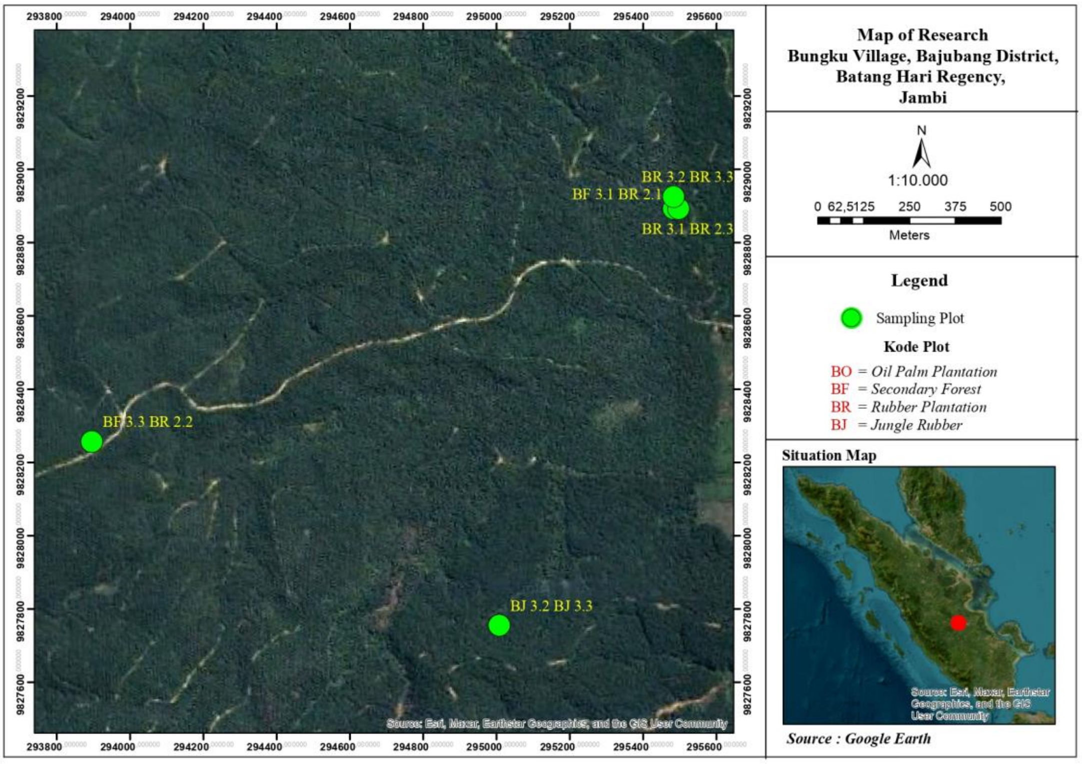

Figure 1. A map of study area.

Methods

Litter-Trap Preparation

Litter traps were created by placing trash bags in each ecosystem at three points or plots, with 150 m separating the plots and a plot size of 1 × 1 m. The litter was then placed into a litter bag, which was then buried at a depth of 5 cm in the ground. The procedure was repeated three times with a distance of 5 m between each replication [6].

Litter Harvesting and Extraction

Litter harvesting from litterbags was performed at 0, 2, 4, 6, 8, 10, and 12 weeks after litter trap placement in the same plot. The collected litter was extracted using a Berlese-Tullgren funnel for 24 hours. After extraction, the soil surface Collembola and Acari were collected and placed in a collection bottle containing 70% alcohol using the hand-sorting technique [6]. They were then identified using the books by Borror et al. [4] and Suhardjono et al. [5].

Measurement of Environmental Factors

The environmental factors measured, which were considered to have a significant impact on the presence of surface-dwelling Collembola, included soil and air temperature as well as air humidity. These factors were observed three times per day: in the morning (09:00), afternoon (12:00), and late afternoon (15:00), with each observation lasting 10 to 15 minutes. A pH meter was used for pH measurements, and litter thickness measurements were performed at three observation points. Additionally, measurements of canopy density were taken using a densitometer, and one observation plot was measured in four cardinal directions. The average of these measurements was the value of the canopy cover level [7]. The vegetation strata were then measured based on the composition of the ecosystem, which consisted of trees, bushes, shrubs, undergrowth, epiphytes, and lianas [6].

Analysis

Distribution pattern data analysis was conducted by calculating species abundance and applying the standardized Morisita Index. Species association analysis was performed using the presence-absence method in combination with the Ochiai Index. Species abundance refers to the number of individuals present in a given ecosystem, providing insight into population density and ecological balance. The Morisita Index, a widely used tool for analyzing spatial distribution, was employed to determine the distribution pattern of soil surface Collembola. Specifically, the standardized Morisita Index [8] was used to assess whether the distribution of these organisms was uniform, random, or aggregated (Equation 1).

$$Id = n\frac{(\sum x_i^2 - \sum x_i)}{(\sum x_i)^2 - \sum x_i} \quad (1)$$

Description:
Id = Morisita Index
n = Number of total plots
x_i = Number of individuals of a certain species in the *i*-th plot.

The distribution pattern is shown through the *Mu* and *Mc* formulas, as follows in Equations (2) and (3).

$$Mu = \frac{\chi^2_{0.975} - n + \sum x_i}{(\sum x_i) - 1} \quad (2)$$

$$Mc = \frac{\chi^2_{0.025} - n + \sum x_i}{(\sum x_i) - 1} \quad (3)$$

Description:
Mu = *Id* for uniform distribution pattern
$\chi^2_{0.975}$ = Value of χ^2 table with degrees of freedom n-1 and a confidence interval of 97.5%
Mc = *Id* for clustered distribution pattern
$\chi^2_{0.025}$ = Value of χ^2 table with degrees of freedom n-1 and a confidence interval of 2.5%
n = Number of total plots
x_i = Number of individual species in *i*-th plot

The formula calculates Morisita's standard degree, expressed from Equations 4 to 7. Based on the *Ip* value, it can be concluded that the distribution pattern was Uniform (Ip < 0), Random (Ip = 0), Clustered (Ip > 0).

$$Ip = 0.5 + 0.5\left(\frac{Id - Mc}{n - Mc}\right);\ if\ Id \geq Mc > 1 \quad (4)$$

$$Ip = 0.5\left(\frac{Id - 1}{Mc - 1}\right);\ \text{if } Mc > Id \geq 1 \quad (5)$$

$$Ip = 0.5\left(\frac{Id - 1}{Mu - 1}\right);\ \text{if } 1 > Id > Mu \quad (6)$$

$$Ip = 0.5 + 0.5\left(\frac{Id - Mu}{Mu}\right);\ \text{if } 1 > Mu > Id \quad (7)$$

Association between Soil Surface Collembola and Acari Abundance

In general, the dominant arthropod populations on the soil surface are Collembola and Acari [4]. Therefore, analyzing the association between these two groups in essential. This analysis was conducted using the presence-absence method and the Ochiai index, following steps: a) Summarizing the presence of each species (Table 1); b) Formulating a null hypothesis assuming that the presence of each species is independent (no correlation); c) Performing statistical tests with the Yates' correction (Equation 8). The critical value of the χ^2 for 1 degree of freedom at the 5% significance level is 3.84, the null hypothesis is accepted; d) Analyzing the type of association based on correlation (Equation 9). If a > E(a), the association is considered positive; if a ≤ E(a), the association correlation is negative, where E(a) is the expected frequency of event a; and e) Calculating the association index using the Ochiai Index (OI) (Equation 10). The Ochiai Index ranges from 0 to 1, with a value closer to 1 indicating a stronger association [9].

Table 1. Contingency matrix to recapitulate the presence of both species.

		B Species presence	Absence	
A Species	Presence	*a*	*b*	*m = a + b*
	Absence	*c*	*d*	*n = c + d*
		r = a + c	*s = b + d*	*n = a + b + c + d*

Description: a = Frequency of finding both species in the plot. b = Frequency of finding only A species in the plot. c = Frequency of finding only B species in the plot. d = Frequency of both A and B species not found in the plot.

$$\chi^2 = \frac{N[|(ab) - (bc)| - (\frac{N}{2})]^2}{mnrs} \quad (8)$$

$$E(a) = \frac{(a + b)(a + c)}{N} \quad (9)$$

$$OI = \frac{a}{\sqrt{a + b}\sqrt{a + c}} \quad (10)$$

Results and Discussion

Results

Abundance of Soil Surface Collembola

The data indicated that the oil palm plantation ecosystem had the highest average species abundance, with a recorded value of 72.0 individuals. A high number of individuals correlates with the decomposition rate, as the soil surface of Collembola serves as a decomposer. The ability of soil surface Collembola to decompose organic matter has been proven by Sékou et al. [10], which states that reduced predators can increase Collembola populations and, at the same time, increase the rate of litter decomposition on the forest floor. Species abundance was determined based on the number of individuals in each ecosystem (Table 2).

Table 2. The abundance of soil surface Collembola species in each ecosystem.

Ecosystem	Sample plot									Mean
	1A	1B	1C	2A	2B	2C	3A	3B	3C	
BF	66	112	67	33	33	160	51	79	47	28.1
BJ	82	36	62	14	10	8	7	11	23	32.7
BR	61	35	39	49	63	54	35	54	33	47.0
BO	63	62	20	21	23	29	32	28	16	72.0

Description: BF = Secondary Forest; BJ = Jungle rubber; BR = Rubber plantation; BO = Oil palm plantation; 1, 2, 3 = plot numbers; A, B, C = replications.

Types of Soil Surface Collembola Found

The identification of soil surface Collembola, conducted in reference to Suhardjono et al. [5], revealed 13 genera from six families: Cyphoderidae, Entomobryidae, Isotomidae, Oncopoduridae, Paronellidae, and Dicyrtomidae, belonging to two orders: Entomobryomorpha and Symphypleona, with a total of 1,618 individuals. These findings indicate that the identified genera represent approximately 10.48% of the 124 known genera in Indonesia. For example, *Heteromurus* sp. and *Homidia cingulata* were found in Sumatera and Java (Figure 2). Some members of the soil surface Collembola showed high adaptability to new environments during the distribution process, resulting in their cosmopolitan distribution. One of the cosmopolitan Collembola species found on soil surfaces in this study belonged to the genera Folsomides and Lepidocyrtus (Figure 3).

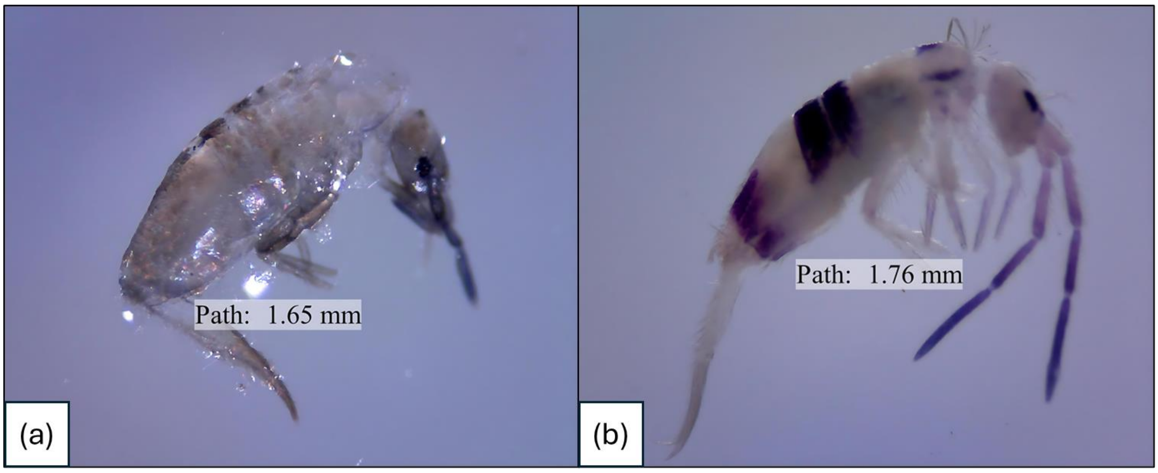

Figure 2. Types of soil surface Collembola recently found in Sumatra and Java: (a) *Heteromurus* sp., (b) *Homidia cingula* (Path = body length).

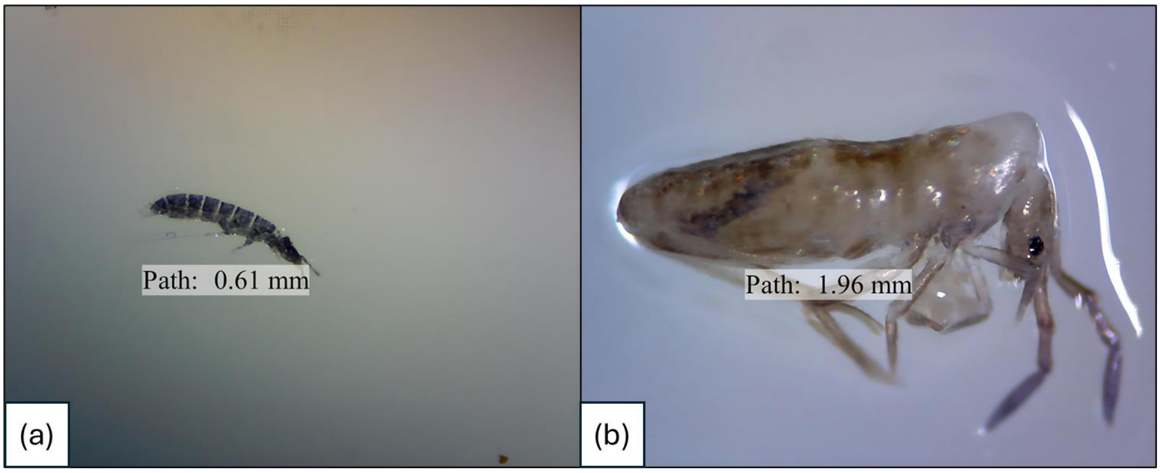

Figure 3. Cosmopolitan soil surface Collembola species: (a) *Folsomides* sp. and (b) *Lepidocyrtus* sp. (Path = body length).

Soil Surface Collembola Distribution Patterns

In an ecosystem community, three basic distribution patterns of a species have been recognized: random, clustered, and uniform [11]. Various distribution indices, such as the ratio of variance to mean, clumping index, green coefficient, and standardized Morisita index, can identify the spatial distribution pattern of a species. The Morisita index is frequently used because simulation research results demonstrate its superiority in measuring an individual's spatial distribution pattern, independent of population density and sample size [12]. The standardization of the Morisita index is an improvement over the original Morisita Index, as it places an absolute scale between –1 and 1. Table 3 shows the patterns of soil surface Collembola distribution in each ecosystem.

The standardized Morisita Index calculations for the soil surface Collembola population across different ecosystem types indicated a clustered distribution pattern in each ecosystem, as the index value (Ip) was greater than 0 (Ip > 0). The clustered distribution pattern indicates that each life in a habitat that suits their needs or benefits [12]. It can be ascertained that the four types of ecosystems are still based on the needs of soil surface Collembola, or that several environmental factors support the presence of soil surface Collembola. Furthermore, the rapid reproduction factor of the soil surface Collembola supports its distribution pattern.

Table 3. Soil surface Collembola distribution patterns in each ecosystem.

Ecosystem	$\sum x_i$	$\sum x_i^2$	Id	Mu	Mc	Ip	Distribution patterns
BF	648	60,218	1.28	0.99	1.02	0.52	Clustered
BJ	253	12,923	1.79	0.98	1.04	0.55	Clustered
BR	423	20,983	1.04	0.99	1.02	0.50	Clustered
BO	294	12,088	1.23	0.98	1.03	0.52	Clustered

Description: BO: Oil palm plantation; BF: Secondary forest; BR: Rubber plantation; BJ: Jungle rubber. $\sum x_i$: Total number of individual species in plot-i. $\sum x_i^2$: The total square of the number of individual species in the i-th plot. *Id*: Morisita Index. Mu: Morisita Index for uniform distribution pattern. Mc: Morisita index for clustered distribution pattern. *Ip*: Standardized Morisita Index.

Effect of Environmental Factors

The environment, including biotic and abiotic factors, significantly affects the soil surface Collembola. Based on the data obtained, tree species (4) were the most abundant in BF, and the soil temperature (27.8) and air temperature (30.0) were the highest in BO. Litter thickness (5.85), canopy density (85), soil acidity (5), and air humidity (91.00) were highest in BJ. Table 4 lists the measured environmental factors. Canopy density measurements revealed that the jungle rubber ecosystem had the highest canopy density of 85% (Figure 4a), while the secondary forest had a medium canopy density (Figure 4b), and the oil palm plantation ecosystem had the lowest canopy density of 64% (Figure 4c).

Table 4. Environmental factors that affect the presence of the soil surface Collembola.

Environment factors	BO	BF	BR	BJ
Vegetation strata	I	III	II	III
Tree species	1	4	1	1
Litter thickness (cm)	0.31	5.20	4.15	5.85
Soil temperature (°C)	27.8	26.8	27.6	26.1
Air temperature (°C)	30.0	29.0	29.1	28.0
Canopy density (%)	64	84	78	85
Soil acidity	4	4	4	5
Air humidity (%)	75.00	86.20	85.40	91.00

Description: BO = Oil palm plantation; BF = Secondary Forest; BR= Rubber plantation; BJ = Jungle rubber; I: very low; II: low; III: moderate; IV: high; V: very high [13].

Figure 4. Condition of vegetation strata (a) jungle rubber, (b) secondary forest, (c) oil palm plantation ecosystem.

Association Analysis Between Soil Surface Collembola and Acari

One commonly observed soil fauna is Acari, a member of the class Arachnida and the phylum Arthropoda. Acari are characterized by their round or oval-shaped, non-segmented bodies and four pairs of limbs adapted for locomotion. After identification using [4], the total number of Acari found in all ecosystem types was 2,393 individuals, consisting of four suborders: Acaridida, Orabatida, Gamasina, and Uropida (Figure 5). Table 5 illustrates the interactions between Collembola and Acari soil surfaces in each ecosystem.

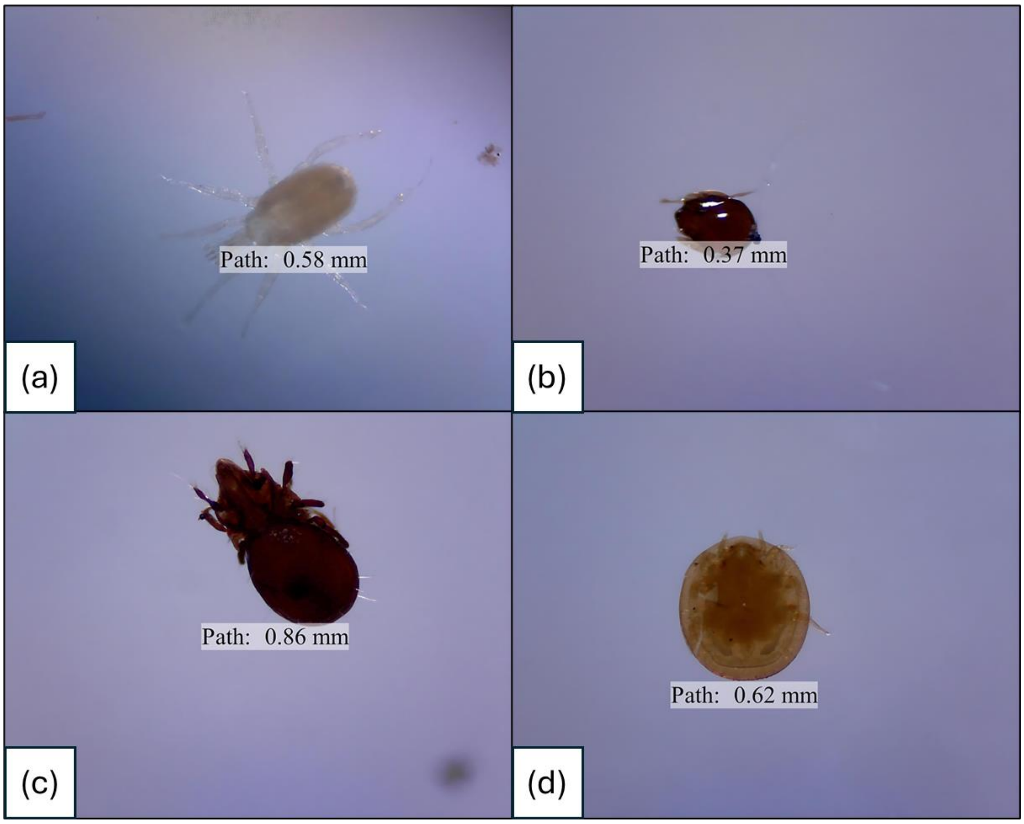

Figure 5. Types of suborders Acari found (a) Acaridida, (b) Oribatida, (c) Gamasida, and (d) Uropida (Path = body length).

Based on the results of calculations using the presence-absence method across all ecosystem types (Table 5), only secondary forest ecosystems showed no association between soil surface Collembola and Acari. Additionally, no Acari were found in the litterbags during the fourth week of litter harvesting. This changed the frequency of Acari presence in the contingency matrix, which is why the χ^2 test value was less than the χ^2 table value at a 5% significance level and 1 degree of freedom. Santi et al. [14] reported that the number of Collembola found was higher than that of Acari on pepper plantations, with a density of 84.5% for Collembola and 15.5% for Acari.

Table 5. Interaction between the soil surface Collembola and Acari in each ecosystem.

Ecosystem	a	b	c	d	x^2	$E(a)$	OI	Association
BO	23	19	8	23	4.99	17.84	0.64	**
BF	12	20	14	12	2.28	–	–	*
BR	27	21	4	27	13.08	18.84	0.70	**
BJ	18	27	2	19	4.94	13.64	0.60	**

Description: BO: Oil palm plantation; BF: Secondary forest; BR: Rubber plantation; BJ: Jungle rubber. a: Frequency of finding both species in the plot. b: Frequency of finding only A species in the plot. c: Frequency of finding only B species in the plot. d: Frequency of both A and B species not found in the plot. x^2: Chi-square test. $E(a)$: The expected value of the a event occurs. OI: Ochiai Index. * : Independent. ** : Maximum positive association.

Discussion

Abundance of Soil Surface Collembola

According to Arista et al. [15], palm oil leaves have a very high lignin content (27.6%), so the decomposition process in palm oil plantations requires more decomposers. Collembola can be categorized as mesofauna because they are larger than the other two groups and have a relatively small body size (approximately 0.25–8 mm) [16]. The abundance of Collembola species in oil palm land had a positive impact. According to research conducted by Akhila and Entoori [17], mesofauna utilize their metabolism by excreting feces containing various nutrients that plants and other soil organisms can utilize.

Types of Soil Surface Collembola Found

Soil surface Collembola is a wingless and weak-limbed animal that is generally not actively walking, so their distribution range is not too large. Collembola use their furcula when moving to relatively distant locations. These limitations result in some members of the soil surface Collembola being endemic to specific areas, such as the genus Heteromorus, whose distribution in Indonesia has been found only in Sumatra [5]. One species of the genus Homidia, *Homidia cingula*, is distributed in Indonesia and has been recorded in Wai Lima and Bogor [5] (Figure 1). According to Oktavianti et al. [18], *Folsomides sp*. are easily found in moist humus soil or decomposing organic matter. The genus Lepidocyrtus is also the most common genus among Collembola genera [19]. Based on their habitat, Collembola are grouped into three categories: edaphic (living permanently in the soil), hemi-edaphic (living in soil and litter), and edaphic or atmobiotic (living above the soil surface and vegetation) [5]. The identification of 13 soil surfaces belonging to the genus Collembola revealed that all of them live in litter or soil (hemi-edaphic).

Soil Surface Collembola Distribution Patterns

According to Suhardjono et al. [5], Collembola lays 400 to 800 eggs on the soil surface during its life. Collembola lay eggs individually or in small clumps on the surface of litter or soil, and they can deposit eggs in areas where other females of the same species have already laid their eggs. Eggs typically hatch within 10 to 15 days at normal temperatures. With high egg production and short hatching period, eggs are generally laid in groups among individuals of the same species. This behavior contributes to the clustered distribution pattern of soil surface Collembola from the moment they hatch. Two factors primarily drive the social behavior of soil surface Collembola, known as aggregation behavior: attractive environmental conditions and the presence of aggregation pheromones [20]. Soil surface Collembola aggregation occurs due to stimulation from one of these factors, which creates a strong attraction for them, allowing them to simultaneously inhabit the same habitat.

Effect of Environmental Factors

The level of vegetation strata in each ecosystem varied depending on its constituent composition. The very low vegetation strata category (I) is found in oil palm plantation ecosystems, and the medium-level vegetation strata category (III) is found in secondary and jungle forest ecosystems, dominated by rubber trees, bushes, shrubs, and undergrowth, which are quite dense (Figure 3). The difference that causes these conditions is a factor in the constituent tree species. In secondary forest ecosystems, the constituent tree species are rubber trees, bamboo, *ulin*, and *rambutan*. In addition to vegetation strata, canopy density is influenced by the composition of its constituent species.

Variations in canopy density, whether low or high, influence air humidity, air temperature, and soil temperature in each ecosystem by altering the amount of sunlight that penetrates. In addition to canopy density, biotic environmental factors, such as vegetation strata, constituent trees, and litter thickness, exhibit correlations. According to Suhardjono et al. [5], the composition of plants or trees affects the surrounding environment, including vegetation strata, quality, and litter thickness. It indirectly affects the life of the soil surface of Collembola. The abundance of the Entomobryomorpha order was significantly correlated with humidity, litter thickness, and canopy space [21].

The results of litter thickness measurements reveal that the oil palm plantation ecosystem has the lowest litter thickness, measuring only 0.31 cm, with only oil palm constituent plant species. However, this ecosystem had the highest soil surface Collembola abundance, averaging 72.0 individuals. This finding is consistent with Moningka et al. [22], which indicates that oil palm plantation areas have the highest population density. This is attributed to the fallen oil palm leaves that cover the ground, creating favorable environmental conditions for Collembola and other soil insects to thrive. According to Arista et al. [15], palm oil leaves contain a high lignin content of 27.6%, which slows the decomposition process and increases the demand for decomposers in palm oil plantations.

Another important factor affecting soil surface Collembola is air humidity, as humidity is the primary reason for low soil surface Collembola population levels in dry months [23]. Observational data revealed that canopy density influences humidity in each ecosystem, with higher canopy density leading to higher humidity levels. For the soil surface of Collembola to survive, the minimum humidity required for both air and soil was 50%, while the maximum humidity was 100% [24]. Humidity measurements in four types of ecosystems fall between the minimum and maximum humidity ranges of 75 to 91%, as stated by Moningka et al. [24], ensuring that the humidity meets the needs of Collembola's soil surface.

In addition, other abiotic factors influenced by canopy density are air and soil temperatures; the higher the canopy density, the lower the air and soil temperatures. The air temperature in the ecosystem also affected the variation in the presence of soil surface Collembola. From the data obtained, the air temperature ranges from 28 to 30 °C. According to Coleman et al. [25], the temperature range of 25 to 32 °C is the optimal and tolerant temperature for soil fauna activity in the tropics. In addition, soil temperature also determines the presence and density of soil surface Collembola. Soil temperature determines the rate of soil decomposition of organic matter.

Soil temperature is a physical factor that greatly determines the diversity of soil fauna types. The results of soil temperature measurements in four types of ecosystems are in the range of 26.1 to 27.8 °C. According to Safitri et al. [26], the minimum soil temperature that supports Collembola life is –50 °C, while the maximum temperature is 34 °C. Thus, the soil temperature in each ecosystem supports the existence of soil surface Collembola. Several species of Collembola migrate twice a year, depending on environmental conditions such as temperature, water, and food supply.

Soil acidity was measured as the final abiotic environmental factor. According to a previous study [27], a relationship exists between several types of Collembola and soil pH values, suggesting that high or low soil pH values influence the populations of specific Collembola species, with varying correlation values. The results of measurements on four types of ecosystems showed that the degree of soil acidity in each ecosystem was weak, with a pH range of 4 to 5. Although the soil was weakly acidic, many Collembola were found on the soil surface. The food channel (intestine), typical of the soil surface Collembola, is responsible for this phenomenon. The soil surface Collembola has an intestine split into three main parts. The foregut has a pH range of 5.4 to 6.9, the middle intestine has a pH of 8.2, and the hind intestine has a pH range of ± 5. This means that the soil surface Collembola can live in environments with either acidic or alkaline soils [28]. Therefore, we can conclude that the soil acidity levels in the four ecosystems align with the requirements of the soil surface in Collembola. The soil's total N and organic C content influence the abundance of Collembola and soil acidity [29].

Association Analysis Between Soil Surface Collembola and Acari

Interactions between community species can be associational or independent [30]. Determining the association between two species can be accomplished in three steps: testing the presence or absence of an association using the presence-absence method, assessing the type of association (positive or negative), and measuring the degree of association using the association index [11]. The Ochiai, Dice, and Jaccard indices are the most commonly used association indices. The Ochiai Index is the association index with the best degree of association, as the unit sampling size and frequency of occurrence have a minimal effect on the calculation results [31].

Collembola was higher because Collembola can survive in various types of soil conditions, and Collembola also has many different species. This is confirmed by Menta and Remelli [32], who state that plantation land is a suitable habitat for Collembola development, resulting in abundant individuals and species diversity, categorized as moderate. There is an association relationship for the other three types of ecosystems because the χ^2 test value is greater than the χ^2 table value. The association type of the three ecosystem types is positive because the value of a > E(*a*). In contrast, the degree of association in the three ecosystem types is maximum because the OI values are close to 1, which are 0.64, 0.70, and 0.60.

There are times when the presence of one species can be indicated by the presence of another species [9]. For example, if Collembola are found on the soil surface in all three ecosystem types due to the right environmental conditions, Acari will likely also be found nearby. Microhabitat differences affected Acari abundance [33]. The association relationship type for the three ecosystem types was positive, indicating that the soil surfaces of Collembola and Acari require similar conditions [34]. According to Heiniger et al. [35], the relationship between soil surface Collembola and Acari is an interspecific competition. Interspecific competition is a form of competition between different species that share similar needs. However, another opinion states that a predation relationship exists between soil surface Collembola and Acari.

According to Suhardjono et al. [5], Acari are the primary predatory group of soil surface Collembola and a key factor in determining the population size of soil surface Collembola, as Acari can prey on 2 to 14 soil surface Collembola. There are two forms of association between the two species owing to the different roles of each Acari sub-order. Acari also act as biological controls (predators) against the eggs and larvae of flies and nematodes [36]. According to Borror et al. [4], the Mesostigmata group (Gamasida and Uropida) of Acari primarily inhabits litter and soil as predators of other soil fauna, including soil surface Collembola. In contrast, the majority of Astigmata (Acaridida) members serve as parasites and decomposers of rotting material. The Oribatida suborder, often found in litter, under bark, on rocks, and in soil, functions as a decomposer, preferring microorganisms such as fungi, bacteria, and plant residues [37].

Conclusions

The number of soil surface Collembola individuals found in all ecosystem types was 1,618 individuals, consisting of 13 genera and 6 families, which are Cyphoderidae, Entomobryidae, Isotomidae, Oncopoduridae, Paronellidae, Dicyrtomidae, and 2 orders, namely Entomobyromorpha and Symphypleona. Four ecosystem types, namely secondary forest, jungle rubber, rubber plantations, and palm oil plantations, exhibited a clustered distribution pattern due to the presence of *Ip* > 0. Several environmental factors, including vegetation strata, tree species ecosystems, litter thickness, canopy density, air humidity, air temperature, soil temperature, and soil pH, significantly influence the presence of soil surface Collembola in each of these ecosystems. The interaction between the soil surface Collembola and Acari indicated a maximum positive association between the two species and a form of interspecific competition and predation.

Author Contributions

NFH: Conceptualization, Methodology, Writing-Review & Editing; **PR**: Software, Writing-Review & Editing; and **MH**: Investigation, Writing-Review & Editing.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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