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ORIGINAL ARTICLE

Key environmental factors underlying terrestrial arthropod abundance and diversity in alley-cropping and monoculture oil palm plantations

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ABSTRACT Oil palms are extensively planted in tropical countries and causing a severe decline in biodiversity. Alley-cropping is an agroforestry practice that has been proven to sustain greater diversity of terrestrial arthropods than monoculture plantations. However, the environmental factors responsible for these differences remain unclear. This study aimed to identify the environmental factors influencing terrestrial arthropod abundance and richness in alley-cropping and monoculture oil palm plantations. We sampled terrestrial arthropod using 840 pitfall traps under seven treatments: oil palm alley-cropping systems with Bactris, bamboo, black pepper, cacao, and pineapple; and two oil palm monoculture systems. We assessed the microenvironment (presence/absence of alley cropping, vegetation coverage, soil surface temperature, soil moisture, light intensity, and relative air humidity) at each sampling site. Overall, 14,358 arthropods belonging to 19 orders were collected. The presence of alley-cropping was the only factor that positively affected the arthropod abundance and order richness. Arthropod abundance was negatively affected by soil moisture, suggesting that the dominant species, even in alley-cropping, were generalist species acclimated to dry soil conditions. Our study suggests that alley-cropping in oil palm plantations could increase the terrestrial arthropods diversity by increasing the diversity of vegetation (even with only one additional crop), rather than improving habitat microclimate. However, as microclimate remained intense, alley-cropping with only one secondary crop in our study site would not be sufficient to conserve forest specialist species. We suggest that producers of oil palm pay close attention to the potential of alley-cropping incorporating multiple secondary crops to increase biodiversity in plantations.

Key words: biodiversity conservation, agroforestry, *Elaeis guineensis*, insects, pitfall trap.

INTRODUCTION

The oil palms (*Elaeis guineensis*) are the most prolific and commonly used oil of plant origin in the world. Palm oil is used in various cooking products, cosmetics, detergents, medicines, and biofuels (Azhar et al. 2017; Gray et al. 2015; Loh 2017; Mba et al. 2015). In 2018, Indonesia (57 %) and Malaysia (27 %) accounted for approximately 85 % of the palm oil produced globally (FAO 2021). Increasing world-wide demand, particularly from large countries, such as India and China, has exerted great pressure for increasing crop yield (Wilcove and Koh 2010). For instance, Malaysian palm oil exports to India increased by 31.3 % between 2020 and 2021, from 2.75 million to 3.60 million ton (MPOB 2021). By 2050, the global palm-oil yield is expected to reach 240 million tons per year, approximately twice the yield in 2009 (Corley 2009). Oil palm crop development and expansion have been increasing over the years to meet rising demand. For example, in Malaysia, land used for oil palm cropping expanded substantially from 4.48 million hectares in 2008 to 5.87 million in 2020 (MPOB 2021).

The expansion of oil palm plantations has had a major impact on biodiversity and climate change. Floral and faunal diversity, particularly that of indigenous and specialist species, is under a severe threat, potentially leading to extinction (Fitzherbert et al. 2008; Foster et al. 2011; Laurance et al. 2010). As any other monoculture, oil palm plantations feature a much simpler composition that natural vegetation communities, and, consequently, higher diurnal temperatures, and lower ambient humidity prevail in them than they do in forests (Luskin and Potts 2011; Turner and Foster 2009). Furthermore, compared to forests, the rates of soil erosion and the frequency of flash flood events are higher in monoculture plantations (Obidzinski et al. 2012). Hence, promoting oil palm plantation management to safeguard existing biodiversity and ecosystem services is essential for agricultural sustainability and biodiversity conservation (Foster et al. 2011). Moreover, commercial growers have an economic incentive to develop and apply sustainable methods, as there is a market demand for palm oil that achieves certification as "sustainable" by the Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO).

Nonetheless, oil palm plantations are expected to grow predominantly in tropical settings; therefore, developing measures to mitigate the negative impacts of the palm oil industry on biodiversity and ecosystem functioning is of paramount importance (Foster et al. 2011). As a promising alternative, incorporating an agroforestry system is one strategy that may contribute to raise the level of biodiversity present in oil palm plantations. Agroforestry is a component of agroecology in which novel, improved, or adaptive approaches that support organic, alternative, or ecologically friendly farming are introduced (Wezel et al. 2009). Specifically, alley-cropping is a part of agroforestry comprising a set of practices that purposefully combines trees and palms with other crop plants, pastures, and/or animals to improve the environment and economy (Gold and Garret 2009). Alley-cropping implies planting in the alley between rows of hedges/trees along a contour line (Paudel et al. 2022). Agroforestry practices offer a wide range of ecosystem services and environmental advantages, including the improvement of soil fertility and water quality, prevention of erosion, enhancement of carbon storage, and recovery of biodiversity, including mammals, birds, and insects (Azhar et al. 2015; Atiqah et al. 2019; Garret et al. 2009; Garrity 2004; Nair et al. 2009; Jose 2009; Razak et al. 2020; Williams-Guillén et al. 2008; Yahya et al. 2022), although the services can differ depending on the crop and region (Zamora and Udawatta 2016).

Soil biodiversity is important for ecological services that support soil sustainability within agricultural landscapes (Lavelle et al. 2006; Nielsen et al. 2011; Bardgett and van der Putten 2014). Terrestrial arthropods are one of the major components of soil biodiversity. Further, they are major contributors to biodiversity in terrestrial environments and drive critical ecological functions including organic matter decomposition, plant pollination, herbivory, and pest control (Nurdiansyah et al. 2016; Potapov et al. 2020; Yang and Gratton 2014). However, ongoing land-use changes and agricultural intensification pose a lethal threat to soil biodiversity, which in turn might have a great negative impact on ecosystem functioning (Franco et al. 2016; Tsiafouli et al. 2015). Thus, for instance, a decrease in decomposer functional diversity reduced decomposition rates, as well as carbon and nutrient cycling, which are crucial for soil formation and fertility (Handa et al. 2014; Nielsen et al. 2011).

Although monoculture plantations are widespread, there is growing evidence that diverse cropping systems are required to balance agricultural output and environmental sustainability (Liebman and Schulte 2015). To date, most research has focused on the impact of oil palm monoculture development on soil organisms, such as aboveground and belowground arthropods and soil microorganisms. Additionally, although increasing evidence indicates that multiple crop planting also affects aboveground species, few studies have investigated whether and how agricultural diversification affects the diversity and community structure of aboveground organisms. Thus, for example, Ashraf et al. (2018) discovered that terrestrial arthropods were more abundant and diverse in alley-cropped oil palm plantations than those in monoculture plantations. Additionally, they found more undergrowth, and lower temperature and sunlight exposure in some alley-cropping plantations, suggesting that alley-cropping systems might mitigate the harsh microenvironment conditions prevalent in monoculture oil palm plantations (Ashraf et al. 2019).

However, what specific environmental factors are responsible for promoting arthropod diversity in alley-cropping oil palm plantations remains unclear. Presumably, there are two possible factors, vegetation and microclimate. As vegetation-related factors, the presence of alley cropping or secondary crops can increase available niches for arthropods by increasing the diversity of resources (e.g., leaves, twigs, flowers, fruits, and litter, among others) and the structural complexity of the vegetation community (Moreira et al. 2012). Similarly, the amount of undergrowth can promote arthropod diversity (Ashton-Butt et al. 2018). On the other hand, improved microclimate by alley-cropping might be more suitable for many arthropods adapted to tropical rainforests. Although these factors are not mutually exclusive, their relative importance bears strong implications for the question as to whether we should increase vegetation diversity or improve the microclimate within plantations. Therefore, this study focused on terrestrial arthropod assemblages and microenvironments in alley-cropping and monoculture oil palm plantations, and examined the relative importance of each environmental factor for maintaining arthropod assemblages.

MATERIALS AND METHODS

Study area

We conducted the study in an oil palm plantation in Keratong, Pahang, Peninsular Malaysia (2°47′1″ N, 102°55′ 22″ E) from July until November 2016. The plantation had a 607-hectare experimental plot with no discernible difference in elevation between 0 and 10 m above sea level. The plantation is managed by the Malaysian Palm Oil Board (MPOB). The experimental plots were divided into two management systems: (1) monoculture systems, in which only oil palms were cultivated (Figure 1a), and (2) alley-cropping systems, in which oil palms were cultivated alongside other crop plants (Figure 1b). Seven treatments were established: five for alley cropping and two for monoculture plots. The five treatments in the alley-cropping plots included oil palms aged 7 to 10 years and were intercropped with (1) Bactris (*Bactris gasipaes*), (2) bamboo (*Gigantochloa albociliata*), (3) black pepper (*Piper nigrum*), (4) cacao (*Theobroma cacao*), and (5) pineapple (*Ananas comosus*). The two treatments in the monoculture plots included oil palms aged (6) seven- and (7) fifteen-years, respectively. Treatment plots were separated by at

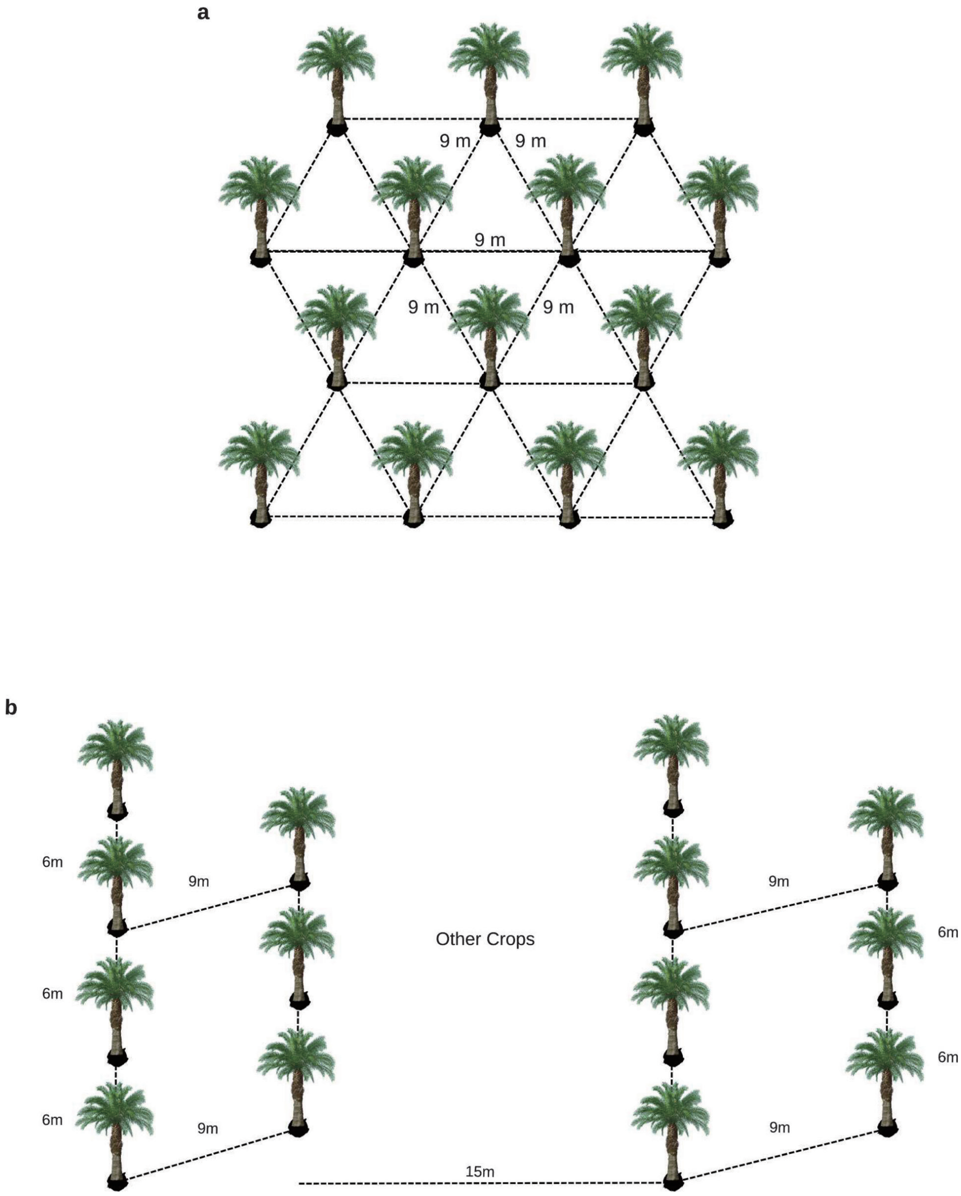

Fig. 1. Layout of palms and the secondary crop in the conventional monoculture plots (a) and in alley-cropping plots (b)

least 300 m.

Sampling of terrestrial arthropods

Thirty pitfall traps were placed along the harvest path in each treatment. We adopted a systematic sampling strategy from a random beginning point, where such point was placed at any location, and subsequent points were regularly spaced from the first point (Krebs 1999). We repeated the sampling four times from July to November 2016, resulting in 840 pitfall traps over the sampling period (30 traps × 7 treatments × 4 rotations). The pitfall location was moved during each sampling rotation. The pitfall traps were at least 5 m apart from each other and from the edge of the harvesting path. Pitfall traps were built using an open plastic container with a diameter of 8 cm and a depth of 12 cm. The pitfall was buried in the ground, and the container lid was set at ground level. The suspended plates were covered with pitfall traps to prevent animal invasion and water flooding. Traps were filled with detergent and salt solution to kill and preserve the arthropod samples. After seven days, the traps were emptied. Arthropods were identified to the order level which allows a fast evaluation of biodiversity and feasible for non-specialist (Biaggini et al. 2007). Many previous studies have used order level identification in agricultural landscapes (e.g. Ebeling et al. 2014; Pashkevich et al. 2021; Vasconcellos et al. 2013; Velasquez and Lavelle 2019). Several guidelines have been used to aid in the identification procedure (Bland and Jaques 2010; Coleman et al. 2017; Romoser and Stoffolano 1998).

Measurement of microenvironments

We visually measured the percentage of undergrowth coverage in a 1 m × 1 m quadrat around each sampling point, in three separate directions, facing north, east, and west, one meter from the sampling location. Additionally, we measured (i) relative humidity (%), (ii) light intensity (LUX), (iii) soil moisture and (iv) soil surface temperature (℃). Light intensity was measured 10 times and averaged, whereas relative humidity was measured three times and averaged. We used a digital anemometer-thermometer-hygrometer (Skywatch Atmos series, JDC Electronics SA, Switzerland) to measure relative air humidity, and a digital photometer (ISO-TECH ILM 1332a, Isothermal Technology Limited, England) to assess light intensity. We used a resistive soil moisture meter (Bond three-way soil meter, Bond Manufacturing, United States) to measure the soil moisture level. The soil meter used a scale from level 1 (low moisture) to 10 (high moisture). All microclimate variables were measured between 1300 and 1430 h, corresponding to the solar noon interval.

Data analysis

We applied generalized linear mixed models (GLMM) in the R package "lme4" (Bates et al. 2014) to investigate the association between two arthropod assemblage metrics, i.e., total number of arthropod individuals (abundance) and the number of arthropod orders (order richness), and environmental variables. To account for overdispersion, we fit the GLMM to a negative binomial distribution. The fixed variables were undergrowth coverage (average percentage per sampling point), soil surface temperature (average temperature per sampling point), relative humidity (average humidity percentage per sampling point), light intensity (average light reading per sampling point), soil moisture (level 1–10), and the presence/absence of alley cropping (presence = 1, absence = 0). The sampling rotation (1st through 4th) was designated as a random variable. We first tested for multicollinearity among all the explanatory variables in the global models, but found no significant correlations, where r = 0.186 ("alley-cropping" and "undergrowth coverage") was the highest. Because ants were often dominant in terms of abundance in the sample, which might mask the pattern of arthropods other than ants, we also examined the models on total abundance, excluding ants. All statistical analyses were conducted using R version 1.3.1093 (R Core Team 2022).

RESULTS

Arthropod richness and abundance

We collected 14,358 arthropods belonging to 17 orders from all treatment plots (Table S1). Hymenoptera was the most abundant (5,918 individuals), followed by Coleoptera (3,124 individuals) and Orthoptera (2,781 individuals). These orders accounted for 82.4 % of the total abundance. Bactris had the highest abundance (2358 individuals) among all treatments, followed by bamboo (2298 individuals) and cacao (2260 individuals), while OP7 had the lowest (1436 individuals). The mean abundance ± SD per trap for all the treatments was 17.1 ± 8.8. Bactris had the highest number of individuals per trap (19.7 ± 9.8), while OP7 had the lowest

(12.0 ± 6.0) (Fig. S1a). When excluding ants, Bactris had still the highest abundance per trap (12.4 ± 7.6), while OP7 had the lowest abundance per trap (7.1 ± 4.3). The mean order richness per trap for all the treatment was 4.0 ± 1.3. Cacao had the highest order richness per trap (4.4 ± 1.2), while OP7 had the lowest (3.3 ± 1.0) (Fig. S1b).

Relationship between environmental variables and arthropods assemblages

The presence of alley-cropping showed the most significant and positive effect on arthropod abundance (Table 1). On the other hand, soil moisture had a significantly negative effect on arthropod abundance. Similarly, arthropod abundance excluding ants positively correlated with the presence of alley-cropping but negatively with soil moisture (Table 2). Alley cropping had a significant and positive effect on arthropod order richness (Table 3). On the other hand, none of the other variables, i.e. undergrowth coverage, soil surface temperature, relative humidity, and light intensity, did not significantly affect the abundance or order richness of terrestrial arthropods.

Table 1. Model output of GLMM upon examination of the relationship between arthropod abundance and environmental variables

	Number of Individuals			
	Coefficient	Standard Error	Z value	P value
Alley cropping	0.374	0.037	10.142	<0.001
Undergrowth coverage	0.019	0.016	1.153	0.249
Soil surface temperature	0.026	0.016	1.602	0.109
Relative humidity	0.007	0.016	0.403	0.687
Light intensity	−0.020	0.016	−1.203	0.229
Soil moisture	−0.057	0.017	−3.241	<0.001

Table 2. Model output of GLMM upon examination of the relationship between arthropod abundance (excluding ants) and environmental variables

	Number of individuals (non-ants data)			
	Coefficient	Standard Error	Z value	P value
Alley cropping	0.367	0.422	8.686	<0.001
Undergrowth coverage	0.029	0.019	1.582	0.114
Soil surface temperature	0.032	0.019	1.699	0.089
Relative humidity	0.032	0.019	1.688	0.092
Light intensity	−0.034	0.019	−1.837	0.066
Soil moisture	−0.049	0.019	−2.453	<0.01

Table 3. Model output of GLMM upon examination of the relationship between arthropod order richness and environmental variables

	Number of order			
	Coefficient	Standard Error	Z value	P value
Alley cropping	0.202	0.040	5.025	<0.001
Undergrowth coverage	0.007	0.018	0.369	0.712
Soil surface temperature	0.022	0.018	1.219	0.223
Relative humidity	0.012	0.018	0.697	0.486
Light intensity	−0.004	0.018	−0.215	0.830
Soil moisture	−0.002	0.018	−0.130	0.897

DISCUSSION

The presence of alley cropping was the most important factor supporting the higher abundance and order richness of terrestrial arthropods in oil palm plantations. This is likely because arthropods have access to more resources in polyculture systems than in monoculture systems (Akbulut et al. 2003; Meyer 2019). Although the alley-cropping system we surveyed had only one additional crop between the oil palm crops, alley-cropping systems showed higher arthropods individuals and order richness compared to those in monoculture plantations, especially the younger ones (Fig. S1a, b). Although the difference in the arthropod order richness is not very large between alley-cropping and monoculture treatments, the difference is likely to be greater if we identify them into family or genus level. Similarly, Ghazali et al. (2016) found greater arthropod diversity in oil palm plantations where polyculture farming was practiced. Smallholder plantations, which are often mixed with several crops or fruit trees, are likely to promote arthropod abundance and diversity by increasing habitat heterogeneity. Although the abundance and order richness were not significantly different among the alley-cropping crops used in this study (Fig. S1a, b), different crop combinations might have different effects on arthropod diversity. Future research should aim to determine the best combination of crops to increase arthropod diversity.

Undergrowth coverage did not significantly affect the abundance and richness of terrestrial arthropods, although numerous previous studies have reported significant effects (Ashton-butt et al. 2018; Denan et al. 2020; Dislich et al. 2017; Gray et al. 2015; Mitchell et al. 2014; Munro et al. 2009). The non-significant effect of undergrowth coverage in this study might be due to the relatively high undergrowth coverage of our study site; specifically, 84.4 % of our sampling points had more than 50 % undergrowth coverage (Fig. S2a), which makes it difficult to clarify the effects of undergrowth coverage. However, the importance of alley cropping also implies the importance of the vegetation other than oil palms.

Microclimatic conditions had a lesser or non-significant influence on arthropod abundance and order richness when compared to the presence of alley-cropping. Among these, and quite unexpectedly given that terrestrial arthropods in tropical rainforests favor humid environments, soil moisture had a significantly negative correlation with arthropod abundance (Turner and Foster 2009; Foster et al. 2011). Based on our data, the soil moisture in both alley-cropping and monoculture systems falls under the range of dry conditions; 94.2 % of the sampling points were level 1–3 (considered as "dry" according to the soil moisture meter) while 5.8 % were level 4–6 ("moist") and only 0.2 % were level 7–10 ("wet") (Fig. S2b). Despite having a greater arthropod population, the alley-cropping plots with bamboo had lower soil moisture than the monoculture plots. (Fig. S1a). This implies that the majority of the arthropods sampled, even in alley-cropping treatments, were generalist species that have adapted to open and dry conditions, such as those in oil palm plantations (Lucey and Hill 2012). Despite the fact that this research did not identify arthropods at the species level, such insights are critical for the efficacy of oil palm plantations, whether monoculture or alley-cropping, in preserving biodiversity in tropical rainforests. Our results imply that implementing alley-cropping systems with just one additional crop planted alongside oil palms may not be sufficient to conserve specialist species, because microclimates in alley-cropping are still too intense for these species to live in (Fig. S2a–e). Alternatively, syntrophic farming, which involves the cultivation of a wide range of plants and crops, provides milder microclimates. Multiple layers of plants and crops create a more complex vegetation stratification that works as a heat sink, keeping the soil moist and lowering the ambient temperature (Andrade et al. 2020).

Alley cropping might be a viable alternative to monoculture oil palm cultivation, not only for restoring biodiversity but also for farmer livelihoods, particularly for smallholder farmers who have limited farming areas and are affected by crop price fluctuations. Indeed, some smallholders choose intercropping methods to diversify the family income sources and maintain a consistent revenue over time. A mixture of different crops, on the other hand, may have an effect on the overall productivity of the farmland. Slingerland et al. (2019) in Indonesia reported that several smallholders include rubber, fruit trees like durian and mango, and sometimes even timber species including Sengon (*Paraserianthes falcataria*) and meranti (*Shorea leprosula*) in their oil palm plantations. However, there is intense competition for light, water, and nutrients between oil palms and other crops, resulting in lower outputs. Crop integration requires optimal spacing and density to ensure that crops receive sufficient nutrients and sunlight for growth. Therefore, better combinations and layouts of secondary crops in oil palm plantations need to be identified in future studies.

CONCLUSION

Our findings showed that alley cropping is a better option than monoculture to increase the abundance and richness of terrestrial arthropods. Compared with monoculture plantations, agroforestry alley cropping offers more abundant and diverse resources for arthropods. These arthropods may contribute to critical ecological services such as soil nutrient cycling and pest control in oil palm plantations. However, the effectiveness of alley cropping with just one additional crop planted alongside the oil palms as an alternative habitat for specialist species is questionable, because the microclimate remains too severe. Adopting a syntrophic farming technique can help reduce the impact of microclimate on alley-cropping oil palm plantation landscapes. To encourage farmers to embrace alley cropping, further research is required to determine the ideal crop combination and layout such as to increase biodiversity and palm oil production.

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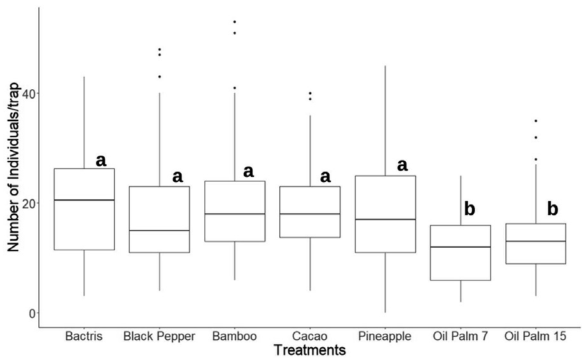
SUPPLEMENTARY INFORMATION

a



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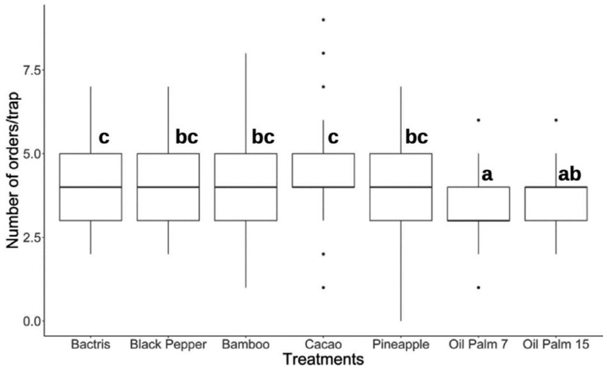

Fig. S1. Box plots showing comparison for the abundance (a: the number of individuals) and order richness (b: the number of order) of terrestrial arthropods in the alley-cropping (oil palm plantations with Bactris, Black Pepper, Bamboo, Cacao and Pineapple) and monoculture (Oil Palm 7 (oil palms age: 7 years) and Oil Palm 15 (oil palms age: 15 years)). Different lowercase letters indicate significant differences for the means among treatments ($p < 0.05$, multiple comparisons for GLMM)

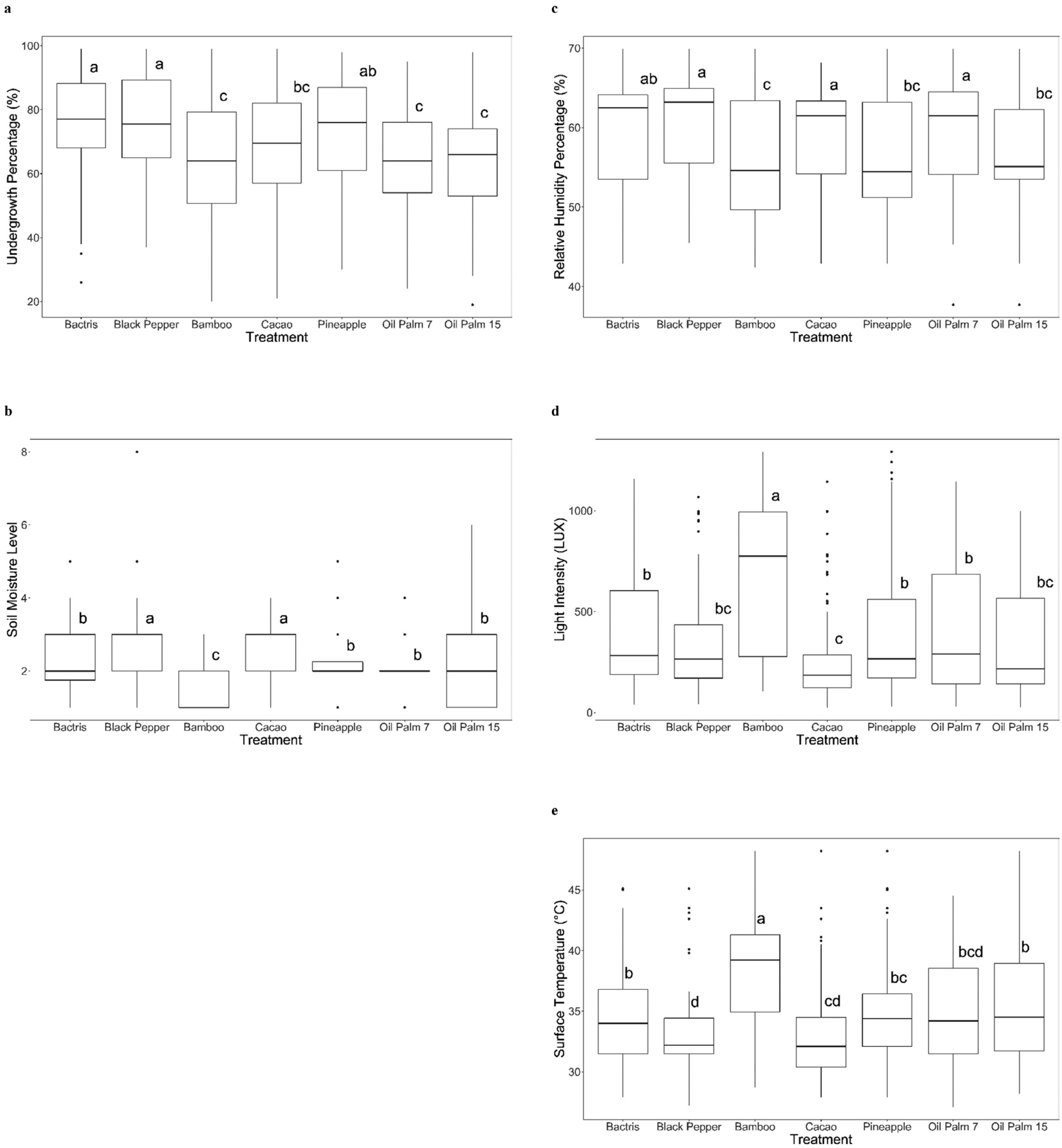

Fig. S2. Box plot showing (a) Undergrowth vegetable percentage; (b) Soil moisture level from 1 (low moisture) to 10 (high moisture); (c) Relative humidity percentage; (d) Light intensity (LUX); (e) Surface temperature (℃) in the alley- cropping (oil palm plantations with Bactris, Black Pepper, Bamboo, Cacao and Pineapple) and monoculture (Oil Palm 7 (oil palm ages 7 years) and Oil Palm 15 (oil palm ages 15 years). Different lowercase letters indicate significant differences in means among treatments ($p < 0.05$, Analysis of Variance (ANOVA) with post-hoc Tukey test)

Table S1. Table showing the abundance of total arthropods found in all the alley-cropping and monoculture plots in their respective Order

	Bactris	Bamboo	Black pepper	Cacao	Pineapple	Oil palm 7-years	Oil palm 15-years	Total
Araneae	134	117	102	96	118	75	68	710
Blattodea	59	49	42	45	52	28	40	315
Coleoptera	569	390	455	528	533	317	332	3124
Dermaptera	8	9	12	9	2	1	4	45
Diptera	137	112	91	107	112	83	76	718
Geophilomorpha	2	1	0	1	1	1	0	6
Hemiptera	11	20	17	18	11	0	0	77
Hymenoptera (all Formicidae)	870	1128	909	889	855	585	682	5918
Isoptera	57	71	60	66	23	28	24	329
Mantodea	0	0	3	6	2	0	0	11
Microcoryphia	9	18	9	30	8	2	3	79
Neuroptera	1	0	1	0	3	0	0	5
Orthoptera	457	344	392	430	479	289	390	2781
Scorpiones	0	0	0	1	1	1	0	3
Spirobolida	33	23	22	24	28	24	16	170
Thysanura	8	5	4	6	2	2	7	34
Trombidiformes	3	11	12	4	0	0	3	33