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The spillover effect of bird functional groups on oil palm smallholdings in Indonesia

DIMAS HARYO PRADANA[1], MUFTI PETALA PATRIA[1], YASMAN[1], NURUL LAKSMI WINARNI[2,♥]
[1]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Indonesia. Jl. Prof. Dr. Mahar Mardjono, Depok 16424, West Java, Indonesia
[2]Research Center for Climate Change, Faculty of Mathematics and Natural Sciences, Universitas Indonesia. Jl. Prof. Dr. Mahar Mardjono, Depok 16424, West Java, Indonesia. Tel.: +62-21-7863436. ♥email: nwinarni@gmail.com

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Abstract. *Pradana DH, Patria MP, Yasman, Winarni NL. 2024. The spillover effect of bird functional groups on oil palm smallholdings in Indonesia. Biodiversitas 25: 5055-5062.* In Southeast Asia, oil palm plantations are a major cause of deforestation, a situation that demands urgent attention. On the other hand, oil palm is important for the economy of Southeast Asian countries. Thus, there are attempts to develop sustainable palm oil production. The spillover effect of bird functional groups on oil palm smallholdings was studied in Indonesia from 14 September to 14 October 2022 and from 23 September to 20 October 2023. Whether birds at oil palm smallholdings provide insect pest control was also examined. The point count method was used to count birds at the oil palm smallholding, ecotone, and adjacent forest remnant at four oil palm smallholdings in Riau Province and two in Central Kalimantan. A bird exclosure experiment was used to examine whether birds provide insect pest control. The difference in bird abundance of the three habitat types was analyzed using the Kruskal-Wallis and Wilcoxon test as the post-hoc test. Wilcoxon test was also used to analyze the difference in herbivory rate of bird exclosure and control of oil palm leaflet seedlings. Carnivore birds showed lower abundance at the oil palm smallholdings than at the ecotone, indicating a spillover effect process. However, there was no significant difference between the herbivory rate of control and bird exclosure treatment, suggesting insect pest control service provided by birds dispersed to oil palm smallholdings could be more optimal.

Keywords: Bird, ecosystem services, functional group, insect pest

INTRODUCTION

Deforestation is still threatening biodiversity in the world. A study found that forest loss has caused the population decline of several vertebrate species. It also found that this risk is higher in relatively intact than fragmented landscapes (Betts et al. 2017). Moreover, deforestation is also one of the major threats to plant species. One of the human activities that caused forest loss is the conversion of forests to cropland, either commercial crop monocultures or small-scale cultivation by smallholders (Corlett 2016). Some species are resilient to forest loss and fragmentation if the deforestation does not exceed critical thresholds. However, their abundance will decline if the forest cover in the landscape is reduced to 10-30% (Betts et al. 2017).

Among all regions in the world, Southeast Asia is experiencing a higher rate of cropland expansion. In this region, the development of forests into cropland occurs in lowland forests and highlands (Zeng et al. 2018). Cropland that majorly causes forest loss in this region is oil palm plantation. A study revealed that 45% of the oil palm plantations in Southeast Asia were on land that was forested in 1989 (Vijay et al. 2016).

The argument usually used to expand oil palm plantations is yield gaps, the difference between potential and actual yield (Woittiez et al. 2017). In Indonesia, yield gaps of oil palm smallholding are higher than large plantations (Monzon et al. 2023). The gap in yields obtained by oil palm smallholding is estimated to be 50%, while government or estate oil palm plantation is only 10-15% (Soliman et al. 2016). Pests are one of the factors that cause yield gaps. The rat can cause 5% yield gaps, while insect pests, such as the *Oryctes rhinoceros* and leaf-eating insects, can cause higher gaps, ranging between 15% and 50% (Woittiez et al. 2017). Thus, this problem needs to be addressed, especially in oil palm smallholding, to prevent further expansion.

Oil palm is an important plant for the economy of Indonesia and other Southeast Asian countries. Despite the negative impacts, this crop has positive effects in Indonesia, such as employment of local communities, improved income, and contribution to state revenue (Ayompe et al. 2021). Thus, there are attempts to develop sustainable palm oil production management that minimizes deforestation. One sustainable management option is retaining natural forests within oil palm plantations (RSPO 2018). Although retaining forests will decrease the area of land under cultivation, oil palm plantations may benefit from insect pest control services. This ecosystem service is provided by generalist insect predators that disperse from source (natural) to sink (cropland) habitat, the so-called spillover effect mechanisms (Rand et al. 2006; Mohd-Azlan et al. 2023). One of the generalist insect predators is birds.

Some bird species can disperse and live in cropland such as ricefields (Pradana and Mustaqim 2019), rubber (Zhang et al. 2017), coconut (Winarni et al. 2024), and oil palm plantations (Prabowo et al. 2016; Nursyamin et al. 2023; Tohiran et al. 2024). Moreover, some bird functional groups could become insect pest control. Birds with certain foraging strategies, foraging strata, diet, and body size can provide this ecosystem service to croplands (van Bodegom and Price 2015). Thus, the spillover of certain bird functional groups could benefit croplands.

Some previous studies on the spillover effect have been done in oil palm plantations. One study was conducted by Mohd-Azlan et al. (2023), but they examined the spillover effect of insects on oil palm plantations. Prabowo et al. (2016) researched the response of bird species and functional group abundance to different habitats in Sumatra, including forests and oil palm smallholdings. However, they only examine the abundance difference of diet and foraging strata groups. Thus, a more comprehensive study on the spillover effect of bird functional groups in Indonesian oil palm smallholdings is needed. Hence, the influence of different habitat types (forest and oil palm smallholdings) on the abundance of bird functional groups was examined in oil palm smallholdings in Indonesia to study this mechanism. The spillover effect is indicated by lower abundance in sink habitats (oil palm smallholdings) than in ecotone (Rand et al. 2006; Mohd-Azlan et al. 2023). Whether bird functional groups that dispersed to oil palm smallholdings provide insect pest control was also assessed using a bird exclosure experiment.

MATERIALS AND METHODS

Study area

Bird surveys were conducted and the bird exclosure experiment was set in six oil palm smallholdings in Indonesia that still have adjacent forest remnants. Four study sites were in Rupat, Riau Province, Sumatra (1.78375 N, 101.73651 E) and two in Katingan Hilir, Central Kalimantan Province, Kalimantan (1.82961 S, 113.44884 E), Indonesia. The oil palm smallholdings area was approximately 2 ha and was owned by different independent smallholders. The distance between the smallholdings was ≥1 km, but the two smallholdings in Sumatra sampling sites were only 0.2 km apart. The adjacent forest remnants in Rupat were mangrove forests, while peatland forests were in Katingan Hilir. The area of the forest remnants ranged from approximately 0.34 to 35.41 ha (Table 1). The study in Sumatra was conducted from 14 September to 14 October 2022, while in Kalimantan was from 23 September to 20 October 2023.

Bird surveys

Bird surveys were conducted from 06.00-08.00 and 15.00-17.00 using the point count method (Thunhikorn et al. 2016). The duration and the radius of each point were 15 minutes and 50 m, respectively. On each smallholding, one point count was carried out on forest remnants and smallholding at 200 m from the edge, and also one point at the ecotone (Figure 1). The bird observation was aided by 10×50 mm binoculars and conducted twice for each site on different days and point orders. Species, individual numbers, foraging strategies, and foraging strata of each bird seen or heard were recorded.

The recorded bird species were classified into functional groups based on traits related to insect pest control service, i.e., foraging strategies, foraging strata, diet, and body size traits (van Bodegom and Price 2015; Smith et al. 2018). Birds were classified into three foraging strategy groups: gleaning (birds that pick prey from nearby substrate), hawking (those that attack prey in continuous flight), and sallying (birds that fly from a perch to attack prey and then return to a perch). Foraging strategy classification was based on Remsen and Robinson's terminology (1990). Birds were classified into three foraging strata: understory (birds that forage on the ground or in the understory), canopy (those that forage in the mid or upper canopy), all strata foragers (birds that forage across all strata or in aerial environments). Moreover, bird diets were classified into three groups that are related to insect pest control: insectivores (birds that feed exclusively on insects), omnivores (those that feed on animals and plants), and carnivores (birds that feed on animals). Finally, birds' body sizes were classified into four distinct body size groups: tiny (body mass <15 g), small (body mass 15 g to <30 g), medium (body mass 30 g to <60 g), large (body mass 60 g to <120 g), and extra-large (body mass ≥120 g). The classification of diet and body size was based on data from Birds of the World (2022).

Bird exclosure treatment

Bird exclosure treatment and one control group were set at the center of the oil palm smallholding bird sampling point. The treatment was an oil palm seedling enclosed within a closed mesh cage (100×100×120 cm, 2.5×2.5 cm mesh). Meanwhile, the control group was an oil palm seedling left untreated and placed 10 m from the treatment. All seedlings had a similar height (approximately 1 m) and age (approximately 1 year old) and were obtained from the same nursery in each province. Twenty undamaged leaflets were randomly chosen from each seedling, and their laminae base was marked using a waterproof permanent marker. The marked leaflets were collected and photographed after 21 to 22 days. Bird exclosure treatment procedure was following Koh (2008). The missing laminae area per leaflet per day for the seedlings remaining at the sampling site was used to measure herbivory rates. The missing laminae areas were measured using ImageJ (Rasband 2018).

Table 1. Area of the oil palm smallholding and adjacent remnant forests on the sampling sites[a]

Sampling sites	Oil palm smallholding area (ha)	Forest remnant area (ha)
Rupat 1	2.65	5.10
Rupat 2	0.14	0.34
Rupat 3	2.47	5.10
Rupat 4	0.15	6.50
Katingan Hilir 1	3.48	30.44
Katingan Hilir 2	4.46	35.41

Note: [a]Estimated from satellite imagery using Google Earth Engine

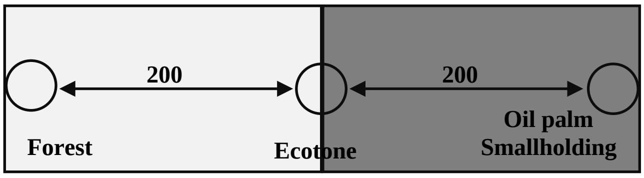

Figure 1. Illustration of bird observation point position within each sampling site

Data analysis

Bird abundance at oil palm smallholding or forest will be lower than at the edge if there is a spillover effect (Rand et al. 2006; Mohd-Azlan et al. 2023). The significant difference in bird abundance at different habitat types was evaluated using the Kruskal-Wallis test and the Wilcoxon test as the post hoc test. Only bird species recorded as living in both forest and cropland habitats were included in the statistical analysis. Poisson Generalized Linear Mixed Model (GLMM) was used to assess the relationship between forest remnants and oil palm smallholding areas and the abundance of bird functional groups in smallholding habitats. That is the effect of those variables on the number of birds that dispersed to oil palm smallholding. The response variable was the individual number of each bird functional group. The fixed effect was forest remnants and smallholding areas, while the random effect was a sample of sites.

The Wilcoxon test was also used to evaluate the significant difference in herbivory rate of bird exclosure treatment and control. Binomial GLMM was used to assess whether bird access to seedlings led to a reduction in herbivory rates. Thus, the response variable for the binomial GLMM was the herbivory rates of the control treatment. Meanwhile, the fixed effect was the individual number of each bird functional group, and the random effect was sampling sites. All statistical analyses were done using R 4.2.2 (R Core Team 2022) using the glmm package (Knudson 2022) to run the binomial and poisson GLMM. The graphs of the results were made using the ggpubr package (Kassambara 2023). The bird functional composition and abundance of the three habitat types were visualized using nonmetric multidimensional scaling (NMDS) based on Bray-Curtis distances derived from an abundance community matrix. The NMDS was carried out using the vegan package (Oksanen et al. 2015).

RESULTS AND DISCUSSION

The spillover effect of bird functional groups on oil palm smallholding

Based on bird surveys, 197 birds from 21 species were found at the oil palm smallholding, ecotone, and adjacent remnant forests sampling sites. Insectivores, hawking, all strata, and tiny birds have the highest individual numbers in all habitats. Oil palm smallholding has the lowest number of individuals and species (34 individuals from 11 species). Meanwhile, ecotone, as would be expected from the transition between two habitats, has the highest number of individuals and species (Table 2). Generally, bird functional groups in oil palm smallholding also have the lowest abundance, except for carnivores and small birds (Table 3).

Table 2. Species, functional groups, and individual numbers of birds found at the sampling sites

Species	Diet	Feeding strategy	Feeding strata	Body size	Individual number[a]		
					F	E	O
Eudynamys scolopaceus Linnaeus	Omnivore	Gleaning	Canopy	Extra large	1	0	0
Phaenicophaeus sumatranus Raffles	Insectivore	Gleaning	Understory	Large	1	1	0
Centropus sinensis Stephens	Omnivore	Gleaning	Understory	Extra large	1	1	1
Collocalia esculenta Linnaeus	Insectivore	Hawking	All strata	Tiny	47	31	12
Hemiprocne longipennis Rafinesque	Insectivore	Hawking	All strata	Medium	0	8	3
Halcyon smyrnensis Linnaeus	Carnivore	Sallying	Understory	Large	0	4	1
Todiramphus chloris Boddaert	Carnivore	Sallying	Understory	Large	1	2	0
Merops philippinus Linnaeus	Insectivore	Sallying	All strata	Medium	2	2	0
Merops viridis Linnaeus	Insectivore	Sallying	All strata	Medium	2	5	1
Eurystomus orientalis Linnaeus	Insectivore	Hawking	All strata	Extra large	2	0	0
Eurylaimus javanicus Horsfield	Insectivore	Sallying	Canopy	Large	2	2	0
Hirundo tahitica Gmellin	Insectivore	Hawking	All strata	Small	0	0	2
Pycnonotus aurigaster Vieillot	Omnivore	Gleaning	All strata	Medium	0	1	0
Pycnonotus goiavier Scopoli	Omnivore	Gleaning	Canopy	Medium	11	17	6
Oriolus chinensis Linnaeus	Omnivore	Gleaning	Canopy	Large	1	0	0
Mixornis gularis Horsfield	Omnivore	Gleaning	Understory	Small	3	3	3
Macronus ptilosus Jardine & Selby	Insectivore	Gleaning	Understory	Medium	1	1	1
Orthotomus ruficeps Lesson	Insectivore	Gleaning	All strata	Tiny	3	3	1
Orthotomus sericeus Temminck	Insectivore	Gleaning	Understory	Tiny	2	0	0
Muscicapa griseisticta Swinhoe	Insectivore	Sallying	Canopy	Small	0	1	0
Rhipidura javanica Sparrman	Insectivore	Gleaning	Canopy	Small	0	1	3
Total individual number					80	83	34
Total species number					15	16	11

Notes: [a]F: Forest, E: Ecotone, O: Oil palm smallholding

Table 3. Species and individual numbers of bird functional groups were found at the sampling sites

Functional group	Individual number			
	Total (%)	Forest (mean ± SD)	Ecotone (mean ± SD)	Smallholding (mean ± SD)
Gleaning	67 (34.01)	4.00 ± 2.53[a]	4.67 ± 3.83 [a]	2.50 ± 2.81 [a]
Hawking	105 (53.30)	8.17 ± 7.47 [a]	6.50 ± 6.35 [a]	2.83 ± 3.37 [a]
Sallying	25 (12.69)	1.17 ± 1.33 [a]	2.67 ± 2.42 [a]	0.33 ± 0.52 [a]
Understory	27 (13.71)	1.50 ± 1.64 [a]	2.00 ± 2.10 [a]	1.00 ± 1.55 [a]
Canopy	45 (22.84)	2.50 ± 1.97 [a]	3.50 ± 3.39 [a]	1.50 ± 1.64 [a]
All strata	125 (63.45)	9.33 ± 8.69 [a]	8.33 ± 7.20 [a]	3.17 ± 3.60 [a]
Insectivore	140 (71.07)	10.33 ± 9.16 [a]	9.17 ± 8.61 [a]	3.83 ± 4.26 [a]
Omnivore	49 (24.87)	2.83 ± 1.94 [a]	3.67 ± 3.93 [a]	1.67 ± 2.25 [a]
Carnivore	8 (4.06)	0.17 ± 0.41 [a]	1.00 ± 0.63 [b]	0.17 ± 0.41 [a]
Tiny	99 (50.25)	8.67 ± 8.59 [a]	5.67 ± 3.56 [a]	2.17 ± 1.60 [a]
Small	16 (8.12)	0.50 ± 0.84 [a]	0.83 ± 1.17 [a]	1.33 ± 1.86 [a]
Medium	61 (30.97)	2.67 ± 2.16 [a]	5.67 ± 6.77 [a]	1.83 ± 3.13 [a]
Large	15 (7.61)	0.83 ± 0.98 [a]	1.50 ± 1.05 [a]	0.17 ± 0.41 [a]
Extra large	6 (3.05)	0.67 ± 0.82 [a]	0.17 ± 0.41 [a]	0.17 ± 0.41 [a]

Note: Different superscripts represent significant differences

Table 4. Herbivory rate of bird exclosure treatment and control conducted on each oil palm smallholding sampling site

Sampling sites	Herbivory rate (mm^2)	
	Bird exclosure	Control
Rupat 1	0.05	0.30
Rupat 2	0.34	0.83
Rupat 3	0.13	0.01
Rupat 4	0.02	0.01
Katingan Hilir 1	0.01	0.06
Katingan Hilir 2	0.03	0.04
Mean ± SD	0.10 ± 0.13	0.21 ± 0.32

Table 5. Relationship between individual number of bird functional groups and herbivory rate

Response	Fixed effect: herbivory rate		Random effect: Site	
	z	p-value	z	p-value
Gleaning	-0.93	0.35	1.64	0.05
Hawking	-1.04	0.30	0.32	0.38
Sallying	-0.88	0.38	0.37	0.36
Understory	-0.90	0.37	0.35	0.36
Canopy	-0.89	0.38	0.28	0.39
All strata	-1.09	0.27	0.42	0.34
Insectivore	-1.13	0.26	0.46	0.32
Omnivore	-0.84	0.40	1.06	0.14
Carnivore	-0.47	0.64	0.41	0.34
Tiny	-1.27	0.20	1.13	0.13
Small	-0.95	0.35	0.48	0.32
Medium	-0.73	0.47	0.42	0.34
Large	-0.47	0.64	0.37	0.36
Extra large	-0.65	0.51	0.85	0.20

Although almost all bird functional groups exhibit the lowest abundance of oil palm smallholdings, no significant abundance difference was found. The visualization of bird functional group composition and abundance of each habitat type also showed clear overlaps (Figure 2). Thus, the composition and abundance of forests, ecotones, and oil palm smallholdings were relatively similar. However, carnivorous birds showed abundance differences between habitat types. Carnivore bird individual number at oil palm smallholdings and also in the forest was significantly lower than at the ecotone (χ^2=7.44, p-value=0.02; W=30.5, p-value=0.03) (Table 3; Figure 3), indicating spillover effect process.

Insect pest control service provided by dispersed bird functional group

The herbivory rate in the oil palm smallholding sampling sites ranged from 0.01 to 0.83 (Table 4). On average, the control had a higher herbivory rate than the bird exclosure treatment. However, the difference in herbivory rate between the two treatments showed no significant difference (W=17, p-value=0.94) (Figure 4). A strong negative relationship between the individual number of bird functional groups in oil palm smallholding and herbivory rate was also not found (Table 5).

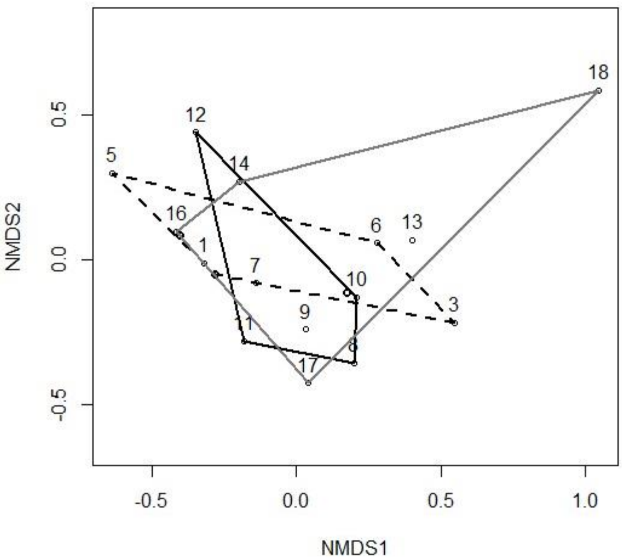

Figure 2. Bird functional group composition NMDS in forest (1-6), ecotone (7-12), and oil palm smallholding (13-18) sampling sites

Table 6. Relationship between forest remnant and smallholding area and individual number of bird functional groups

Response	Fixed effect: Forest area		Random effect: Site	
	z	p-value	z	p-value
Gleaning	**2.25**	**0.03**	0.77	0.22
Hawking	**6.50**	**0.00**	1.67	0.05
Sallying	-1.01	0.32	**1.70**	**0.04**
Understory	1.24	0.22	0.31	0.38
Canopy	0.58	0.56	0.47	0.32
All strata	**6.31**	**0.00**	0.74	0.23
Insectivore	**4.68**	**0.00**	0.92	0.18
Omnivore	1.85	0.06	0.49	0.31
Carnivore	-1.22	0.22	1.66	0.05
Tiny	**3.61**	**0.00**	0.91	0.18
Small	**2.20**	**0.03**	**1.72**	**0.04**
Medium	0.18	0.86	0.95	0.17
Large	-1.20	0.23	0.33	0.37
Extra large	-1.02	0.31	0.94	0.17
Response	**Fixed effect: Oil palm smallholding area**		**Random effect: Site**	
	z	p-value	z	p-value
Gleaning	1.85	0.06	0.87	0.19
Hawking	**2.98**	**0.00**	0.86	0.20
Sallying	-1.09	0.28	1.01	0.16
Understory	0.45	0.66	0.50	0.31
Canopy	0.60	0.55	0.65	0.26
All strata	**3.45**	**0.00**	0.93	0.18
Insectivore	**3.72**	**0.00**	0.90	0.19
Omnivore	0.87	0.39	0.64	0.26
Carnivore	-1.43	0.15	0.37	0.36
Tiny	**3.69**	**0.00**	1.66	0.05
Small	0.85	0.40	0.42	0.34
Medium	-0.02	0.98	1.05	0.15
Large	-1.39	0.17	0.22	0.41
Extra large	-1.42	0.16	1.71	0.04

Note: Significant z value (p-value<0.05) appears in boldface

Table 7. Relationship between forest remnant and oil palm smallholding area and herbivory rate

Response	Fixed effect: control herbivory rate		Random effect: Site	
	z	p-value	z	p-value
Forest area	-0.89	0.37	1.35	0.09
Oil palm smallholding area	-1.26	0.21	0.71	0.24
Response	**Fixed effect: bird exclosure herbivory rate**		**Random effect: Site**	
	z	p-value	z	p-value
Forest area	-1.09	0.28	1.33	0.09
Oil palm smallholding area	-1.20	0.23	1.24	0.11

A positive relationship between smallholding areas and individual numbers of hawking, all strata, insectivores, and tiny birds was found (Table 6). Similarly, forest areas could increase the individual number of gleaning, hawking, all strata, insectivores, and tiny and small birds. However, a significant negative relationship between forest remnants and oil palm smallholding areas with herbivory rate was not found (Table 7). Thus, the increasing number of certain bird functional groups did not affect the number of insect pests.

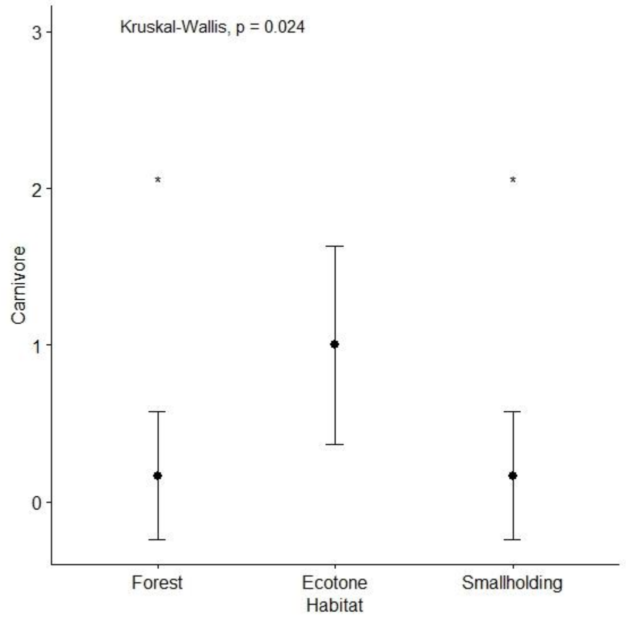

Figure 3. The carnivore abundance on forest, ecotone, and smallholding at sampling sites

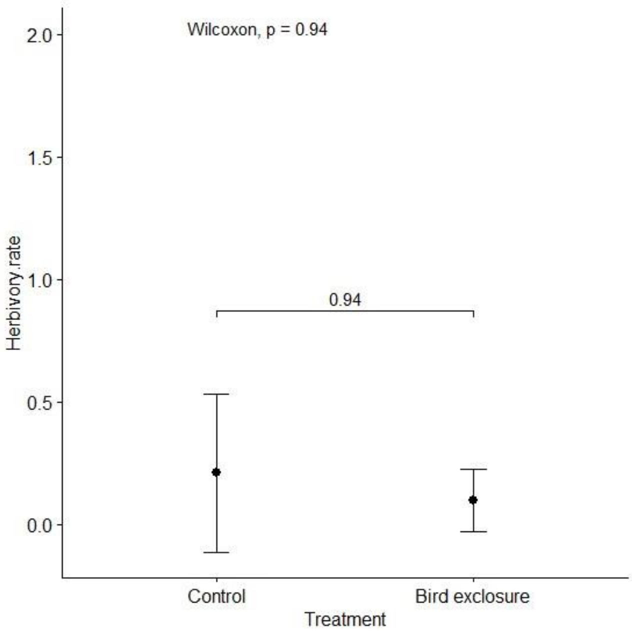

Figure 4. The difference in herbivory rate between bird exclosure treatments and control at sampling sites

Discussion

This study examined the response of the bird functional group related to insect pest control services (foraging strategy, body size, diet, and foraging strata) to forest, ecotone, and oil palm smallholding habitats. A previous study by Prabowo et al. (2016) also examined the response of diet and foraging strata groups to forest and oil palm smallholdings. The diet and foraging strata groups also examined by them were insectivores, omnivores, understory, and canopy birds. In this research, forest sampling sites have more insectivorous and omnivorous birds than oil palm smallholdings. Prabowo et al. (2016) also found more insectivorous birds in their forest sampling sites than in the oil palm smallholding. However, they found fewer omnivorous birds in the forest than in the oil palm smallholdings. Meanwhile, forest understory and canopy birds in this study were higher than in oil palm smallholdings. Prabowo et al. (2016) also reported that canopy birds were more abundant in the forest. However, understory birds were more abundant in the oil palm smallholding than in the forest. These findings have practical implications for pest control strategies, as they provide a deeper understanding of bird responses to different habitats, which can inform more effective pest control measures.

Overall, this study found no significant difference in bird functional group abundance between all habitat types. Prabowo et al. (2016) also found no individual number difference in diet and foraging strata groups between forests and oil palm smallholdings in Sumatra. That said, carnivorous birds showed significant abundance differences between all habitats, indicating a spillover effect process. Carnivore birds at the sampling sites showed reciprocal positive edge response. That is, bird abundance peaks at the ecotone due to complementary resource utilization. This response would be expected when bird benefits from varied resources of crops and natural habitats. Reciprocal positive edge response also indicates that both habitats have similar productivity or carrying capacity (Rand et al. 2006). This result also suggested that the habitat quality of forest remnants at the sampling sites could have been better for birds. Hence, the forest remnants in the sampling sites were not the source habitat of birds in oil palm smallholdings. However, the smallholders must be educated on the benefits of retaining forest remnants, such as bolstering insect pest control by birds, climate regulation, and ecotourism opportunities (Ayompe et al. 2021). Hence, they will be encouraged to preserve the forest remnants.

Carnivorous birds observed at our sampling sites were all sallying, understory, and large. The species that have these four functional traits were the *Halcyon smyrnensis* and *Todiramphus chloris* (Table 2). These two birds feed on a wide variety of prey, including lepidopteran insects (Birds of the World 2022), an insect whose larval stage is an insect pest on oil palm plantations (Koh 2008; Denmead et al. 2017). Moreover, *H. smyrnensis* Linnaeus also eats caterpillars (Woodall and Kirwan 2020). Oil palm smallholdings may get insect pest control service from this bird functional group, especially from *T. chloris* Boddaert, which we observed in the forest habitat, by retaining the forest. *H. smyrnensis* Linnaeus was not observed during the bird survey. However, this bird species usually also uses forests as their habitat (Woodall and Kirwan 2020).

The result of the bird exclosure experiment is similar to that of a study conducted by Denmead et al. (2017) on smallholder oil palm plantations. This result indicates that insect pest control service at the sampling sites was not optimal. That is, ecosystem service provided by adjacent remnant forests was found to be equivalent to an ecosystem dis-service, acting as a source of insect pests (Luke et al. 2019). A study by Mohd-Azlan et al. (2023) observed the spillover effect of lepidopteran insects on oil palm plantations from adjacent forests. Moreover, herbivore insect movement to the plantation from adjacent natural habitats is a common pattern (Frost et al. 2015), especially in tropical regions (Rand et al. 2006). The dominant bird functional group at our sampling sites probably affected our result (Table 2). Although insectivore birds were dominant, most were tiny, all strata, and hawking birds that may not be effective predators for caterpillars on oil palm leaflets. Bird species that consume a variety of insects in oil palm, such as *Pycnonotus* species, may also have influenced the bird exclosure experiment result. This species may also eat the natural enemies of oil palm insect pests (Prabowo et al. 2016). Moreover, *Parus major* and *Centropus bengalensis* that consume insect pests of oil palm (Desmier de Chenon and Susanto 2006) were absent from all oil palm smallholding sampling sites. The absence of these species is probably caused by the height of the oil palm, ranging from 2 to 3 m, and the low understory cover of the smallholding at the sampling sites. *P. major* Linnaeus usually forages on the canopy of trees (Kirwan et al. 2024), while *C. bengalensis* Gmelin forage on understory (Payne 2020). These findings highlight the need for a holistic approach to pest management that considers the complex interactions in agricultural ecosystems.

The fauna-area effect of MacArthur and Wilson's Island Biogeography theory (Whittaker et al. 2017) may also be another plausible explanation for this result. The area of oil palm smallholdings on our sampling sites might need to be higher to support a high number of birds. The sampling site with the highest herbivory rate was Rupat 2, which had the smallest forest remnant and smallholding area. Furthermore, the oil palm smallholding area on Denmead et al. (2017) study sites was also low, ranging from 2 to 10 ha. On the contrary, a bird exclosure experiment conducted by Koh (2008) in an approximately 19,000-ha oil palm plantation complex showed a significant difference in herbivory rate. Moreover, a significant relationship between smallholding and forest areas and bird functional groups' abundance was found. That said, area only affects individual numbers of several bird functional groups that are ineffective for reducing caterpillars (Table 6). According to this classic theory, distance to source habitat affects the number of species. Thus, the distance between the bird exclosure and the forest remnants may also affect insect pest control service. However, the distance effect was not tested in this research. Overall, our findings suggest that retaining forest within the plantation must be combined with other methods to address insect pest problem in oil palm smallholdings. This method can be combined with insecticides and nest box construction. The latter is one of the most effective methods to increase the insectivorous or carnivorous birds (Garcia et al. 2020).

This study found that only carnivorous birds indicated a spillover effect process. Thus, retaining forests will probably provide insect pest control on oil palm smallholdings by this bird functional group. However, the response of this bird group indicated the poor quality of the forest remnant in the sampling sites. This indication also explains the abundance response to all habitat types of bird functional groups other than carnivores. The result of the bird exclosure experiment indicated that the insect pest control service provided by birds could have been more optimal. Besides the forest remnants in the sampling sites not being source habitats for birds, the dominant bird functional group and certain bird species may affect insect pest control services in our study area. Further study about the distance effect on herbivory rates is needed to explain more insect pest control provided by birds in oil palm smallholdings. The bird exclosure experiment further demonstrated that pest control by birds was limited, likely influenced by the composition of bird functional groups and specific species, as well as the quality of nearby forest habitats. Dominant bird species that are small or less effective in pest control likely contributed to the observed limitations. Consequently, our study suggests that optimizing forest remnants near oil palm plantations could improve pest control services, offering an optimistic outlook for the future of pest management in oil palm smallholdings. This requires an understanding of habitat quality, structure, and the proximity of these remnants to agricultural areas. Future research should explore the effects of remnant quality and proximity on herbivory rates, as well as the specific roles of various bird functional groups, to provide more insights into enhancing ecological pest management in oil palm smallholdings.

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