Smallholdings with high oil palm yield also support high bird species richness and diverse feeding guilds

Syafiq A Razak¹, Norzanalia Saadun², Badrul Azhar¹,³ and David B Lindenmayer⁴

¹ Department of Forest Science and Biodiversity, Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
² Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
³ Biodiversity Unit, Institute of Bioscience, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
⁴ Sustainable Farms, The Fenner School of Environment and Society, ANU College of Medicine, Biology and Environment, The Australian National University, Canberra, ACT 2601, Australia

E-mail: b_azhar@upm.edu.my

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Abstract

Biodiversity has been devastated globally in the past hundred years, largely because of land conversion and agricultural intensification. Conversion of tropical forest to oil palm plantations is one of the greatest per unit area contributors to biodiversity loss in Southeast Asia. Concerned consumers, mainly from developed countries, have begun demanding sustainable palm oil in response to these issues. More ‘biodiversity-friendly’ oil palm production is also in demand, similar to that of other commodity crops (e.g. coffee, cacao). However, farming practices that improve biodiversity are thought to reduce yield, leading to increased pressure to clear more forest, resulting in further biodiversity loss. Here, we explore relationships between oil palm yield and avian biodiversity. To gather data on yields and agricultural inputs, we interviewed smallholders in Selangor, Peninsular Malaysia. We also quantified bird species richness, feeding guild diversity, abundance, and vegetation structure in smallholdings. We found that smallholdings with high yields were characterised by high species richness and feeding guild diversity, but low bird abundance. Our empirical results show the benefits to both yield and avian biodiversity of a wildlife-friendly strategy in smallholdings. We encourage the integration of farming practices with management that improves biodiversity to reconcile oil palm production and nature conservation.

1. Introduction

The loss of old-growth rainforest, including selectively logged forest, has been driven, in part, by expanding industrial oil palm plantations and smallholdings in Southeast Asia (Gaveau et al 2018). Smallholder oil palm growers produce 40% of global palm oil (RSPO 2018). Smallholdings are small-scale (<50 ha) monocultures or polycultures, often comprised of trees of multiple stand ages. Smallholdings typically support more biodiversity than industrial plantations (Azhar et al 2011, 2013, 2014, 2015a, 2015b, Lee et al 2014a). However, the conservation value of smallholdings is often overlooked by policymakers (Azhar et al 2017). There has been increasing global interest in the environmental sustainability of oil palm production (Mukherjee and Sovacool 2014, Oosterveer 2015, Tayleur et al 2017). This is, in part, due to market pressure and global recognition of the environmental impacts of commercial oil palm production (Azhar et al 2017, Carlson et al 2018).

Certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO) emphasize the need for commercial oil palm growers, including plantation companies and smallholders, to conserve forest and farmland biodiversity (Azhar et al 2017, Saadun et al 2018). Biodiversity in oil palm landscapes is important for maintaining key ecological processes. The number of species that inhabit oil palm plantations and their contribution to healthy ecosystem functioning can be enhanced by increasing
habitat complexity (Foster et al 2011). Sustainability certification supports incentives for land sharing between crop production and biodiversity conservation (Mitiku et al 2018). However, progress has been slow in improving the management of oil palm production landscapes through certification schemes, particularly promoting the conservation of biodiversity within industrial plantations (Ruysschaert and Salles 2014, Azhar et al 2017, Morgans et al 2018).

In contrast to large-scale plantations, smallholdings are characterized by greater levels of landscape heterogeneity (Azhar et al 2015a). Multi-species cropping and the creation of non-uniform stand ages are pivotal management strategies for increasing habitat complexity and landscape heterogeneity in smallholdings (Azhar et al 2015a, 2015b, Atiqah et al 2019). However, smallholdings are thought to generate lower yields than industrial plantations possibly due to less efficient agricultural practices and poorer yielding oil palm varieties (Lee et al 2014a, 2014b, Soliman et al 2016, Yan 2017). In addition, smallholdings subject to greater management inputs (e.g. fertilizers, herbicides) might have higher yields of oil palm but lower biodiversity (Teuscher et al 2015). To increase yields in existing smallholdings in an environmentally sustainable way, all production factors including those affecting biodiversity and ecosystem services need to be understood (Woititz et al 2017). Biodiversity is the foundation of ecosystem services that are essential to sustain agricultural productivity (Koh 2008, Tschamnke et al 2012, Martínez-Salinas et al 2016, Milligan et al 2016, Rusch et al 2016, Smith et al 2018). Studies of coffee and cacao production have shown that alternative practices such as shade-grown planting and agroforestry systems can enhance ecosystem services and provide habitat for many wildlife species (Jha et al 2014, Peery and Pauli 2014, Caudill et al 2015, Gras et al 2016, Guzmán et al 2016, Rodrigues et al 2018).

In this study, we investigated relationships between oil palm yields and avian biodiversity in Selangor, Peninsular Malaysia. We focused on smallholdings because they are an often neglected, yet substantial (i.e. 40 %), part of the global oil palm production system (RSPO 2018). We used data gathered from 92 smallholdings to quantify relationships between oil palm yield and: (1) bird species richness, functional richness, and abundance, (2) management inputs such as fertilizer and herbicide use, and (3) vegetation structure and plant species composition. We sought to determine if key management practices such as fertilizer use and herbicide application eroded, or were broadly compatible with, biodiversity conservation. Specifically, at the outset of this investigation, we posed four hypotheses about potential relationships between oil palm yield, management and biodiversity (figure 1).

Hypothesis #1: Smallholdings with high oil palm yields would be characterized by high avian biodiversity (as reflected by species richness, abundance, and feeding guild diversity), possibly because of increased ecosystem service provision (e.g. pest control) in areas with higher biodiversity (Nurdiansyah et al 2016, Denmead et al 2017).

Hypothesis #2: The use of fertilizers will be important in explaining variation in smallholder oil palm yields because oil palm requires essential nutrients for growth (Lee et al 2014b).

Hypothesis #3: Smallholdings that use large amounts of herbicide will have lower yields due to reductions in ecosystem function. Herbicide use in oil palm plantations is often substantial, despite limited evidence that it boosts yields (Jambari et al 2012, Euler et al 2016).

Hypothesis #4: Heavy herbicide use may negatively affect bird species richness due to reduced vegetation cover and hence impaired habitat suitability, but also greater homogenization of habitat, resulting in less diverse bird assemblage (Boatman et al 2004, Chiron et al 2014).

In the first study of its kind, we quantify relationships between avian biodiversity, plantation management and oil palm yield. Our findings provide evidence that promoting farmland bird conservation in smallholder production landscapes does not undermine high oil palm yields. The findings are important for developing guidelines for biodiversity-friendly oil palm agriculture and sustainable supply chains.

2. Methods

2.1. Study area

We conducted this study in 92 independent oil palm smallholdings at Tanjung Karang, a coastal district in the state of Selangor, Peninsular Malaysia (3°23′51.82″ N, 101°13′14.52″ E) (figure 2). Our oil palm smallholdings covered 7500 ha (Sulai et al 2015). Smallholdings typically supported single- or multi-aged stands interspersed with other commercial plants (e.g. banana Musa, coconut Cocos nucifera, Cassava Manihot esculenta, coffee, Pineapple Ananas comosus or indigenous fruit trees) planted alongside oil palms. Adjacent smallholdings were at least 300 m apart (mean of distance ± SD = 413.2 ± 183.2 m), to ensure spatial independence between smallholdings for most species (Haselmayer and Quinn 2000). Independent smallholders privately manage their farmland, including the management of harvesting, fertilizer application, weeding, and replanting. Their crop is usually sold to local oil palm fruit dealers who then sell it to nearby mills.

2.2. Smallholder interviews

We interviewed only those smallholders who lived in our study area and actively managed oil palm plots.
Figure 1. Oil palm yield is predicted to increase with both the amount of fertilizer used by smallholders, the number of bird species, and bird feeding guild diversity, but decrease with the continuous use or overuse of herbicides and bird abundance (represented by fewer species). Fertilizers are predicted to be of paramount importance for generating high yields compared to other factors (Gockowski and Sonwa 2011). Bird species assemblages with a diverse community composition may have complementary functions such as providing a pest control service (Clough et al 2011, Maas et al 2013). In contrast, a humped-shaped relationship between herbicide use and oil palm yield is predicted to initially increase yield after which there would be a decline in yield due to an increased loss of soil moisture. The soil moisture ensures good growth and yield of oil palm (Bakoumé et al 2013). Prolonged use or overuse of herbicides can lead to bare ground condition, which causes the loss of soil moisture. Bird abundance also may show a hump-shaped pattern following homogenization of understory habitat caused by consistent use of herbicides. Habitat simplification (i.e. through extermination of multispecies of undergrowth plant) has occurred because of prolonged herbicide use, which can in turn, promote overabundance of some (generally common generalist bird taxa, particularly pest bird populations (Clergeau 1995, Geiger et al 2010)).

Each smallholder that we interviewed represented a household farm and their involvement was voluntary. None of the smallholders we contacted declined to be interviewed. We visited oil palm smallholdings (mean area ± SD = 1.4 ± 0.7 ha) during dry season months between May and September 2016 to complete a face-to-face interview with 92 independent smallholders on whose land we subsequently conducted field surveys for birds and vegetation. We geo-referenced the location of each farm using GPS coordinates (figure 2).

We completed interviews using a standardized (closed-ended and open-ended) questionnaire which comprised two sections: (1) the socio-demographic background of smallholders (eight questions), and (2) information on oil palm plantation cultivation (13 questions) (supplementary material: Questionnaire (available online at stacks.iop.org/ERL/15/094031/mmedia)). The questionnaire contained information on smallholder demography (gender, race, age, marital status, job, formal education, length of stay, etc) and oil palm plantation cultivation (farm size, agrochemical inputs, average yield of fresh fruit bunch, farm income, etc.).

2.3. Applications of fertilizers, herbicides and insecticides
To determine the amount of fertilizer and herbicide used by each smallholder, we converted the costs for agrochemicals based on standard prices in Malaysia (fertilizers: MYR 1.30 kg⁻¹; herbicides: MYR 15 l⁻¹). All the smallholders we interviewed reported using herbicides only to control weeds. Out of 92 smallholders, only eight reported the use of insecticides. To our collective knowledge, there are no historical records of major pest insect outbreaks (e.g. bagworm Pteroma pendula) in the study area.

2.4. Bird surveys
We employed point counts to survey birds in 92 oil palm smallholdings. We established a sampling point that was placed in the center of each smallholding. An experienced observer spent 10 min at each point recording the number of different bird species seen and heard within a 50 m radius (Azhar et al 2014). To minimize observer bias associated with bird identification, a single observer conducted all bird surveys. We used a laser range finder to determine the sighting distance to each bird. We identified bird species using the field guide of Robson (2011) and the bird sound
Figure 2. Map of study area in Peninsular Malaysia. The satellite image shows the location of each oil palm smallholding and other land cover types (e.g. forest represented by irregular and uninterrupted green area).

Table 1. Summary statistics for explanatory variables.

| Explanatory variable                  | Mean ± SD  | Median | Min–max |
|--------------------------------------|------------|--------|---------|
| Bird species richness                | 10.53 ± 1.68 | 10.5   | 7–14    |
| Bird abundance                       | 22.59 ± 3.93 | 23     | 13–33   |
| Bird feeding guild diversity         | 5.39 ± 0.71  | 6      | 3–6     |
| Annual amount of fertilizers (kg)    | 2103 ± 2037  | 1498   | 0–12 480|
| Annual amount of herbicides (l)      | 7400 ± 6311  | 6000   | 0–36 000|
| Mean ground vegetation coverage (%)  | 43.41 ± 16.29 | 42.50  | 5–87.25 |
| Mean ground vegetation height (cm)   | 8.45 ± 3.08  | 8.75   | 2.5–17.5|
| Height of oil palm stands (m)        | 5.78 ± 1.37  | 6.25   | 1.3–8   |
| Number of oil palms per 500 m²       | 5.04 ± 1.10  | 5      | 2–10    |
and nectarivores. Frugivores, granivores, carnivores, omnivores, and nectarivores form distinct feeding guilds present at each sampling point (Jeyarajasingam et al. 2015). We conducted bird sampling between 0700 and 1100 h daily on clear and calm days. We surveyed each sampling point twice (with a 30-day interval between sampling dates). The first survey was conducted in the same week that we interviewed smallholders. We computed the average bird abundance from the two sample times. To quantify feeding guild diversity, we grouped the birds into six feeding guilds based on the information from local/regional bird guides and summed the number of birds within these guilds present at each sampling point (Jeyarajasingam et al. 2012, Robson 2019). These feeding guilds were insectivores, carnivores, omnivores, frugivores, granivores, and nectarivores.

### 2.5. Habitat quality measurement

To assess the local- and landscape-level effects of vegetation structure on oil palm yield, we estimated or measured the following vegetation characteristics at each point sampled for birds: (i) mean percentage of ground vegetation cover within three quadrats, each of 1 m × 1 m; (ii) mean height of ground vegetation cover within three quadrats of 1 m × 1 m; (iii) number of oil palms within a plot of 50 m × 10 m; (iv) height of five oil palms within a plot of 50 m × 10 m; (v) the presence or absence of additional crops planted alongside oil palm; and (vi) distance to the nearest forest. We used circular measurements in Google Earth Pro to estimate distance between a sampling point and the nearest forest edge. The vegetation quadrats were established on harvesting paths within oil palm smallholdings. The quadrats were 10 m apart. We did not determine oil palm stand age as some smallholders cultivated at least two cohorts of oil palm on a given farm (Supplementary material: Figure).

### 2.6. Statistical analysis

To quantify the contribution of dominant bird species to the avian community, we performed one-way analysis of similarity percentage (SIMPER). We square-root transformed bird abundance data. We used a Bray-Curtis measure to define similarities within groups and dissimilarities between groups. We completed this analysis in PRIMER version 7 (Clarke and Gorley 2015). We used Spearman’s rank correlation to determine the association between bird feeding guild diversity and species richness as well as abundance. In addition, we checked the level of correlation between bird species richness and annual herbicide use.

We used Generalized Linear Models (GLMs) to quantify relationships between oil palm yields and explanatory variables. We used annual yield of oil palm as a response variable for our analysis. We examined nine explanatory variables (Table 1). We excluded labor costs from the analysis as we did not segregate the types of labor work (e.g. harvesting, spraying herbicides, applying fertilizers). Each kind of work has different costs. The labor rate in the study area also depends on whether the workers are foreign migrants or local people.

We assigned each model a normal distribution and log-link function. We performed correlation tests to assess multi-collinearity among predictor variables within each model. We removed strongly correlated variables (|r| > 0.7) to avoid distortion in model estimation (Dormann et al. 2013). However, none were removed (supplementary material: table).

We selected the most parsimonious models based on Mallows Cp values. The Mallows Cp statistic has been used in multiple regression analysis to select parsimonious models (Lance et al. 2014). The Mallows Cp is likely to select the same models as the Akaike information criterion (AIC) (Quinn and Keough 2002). The criterion can be computed as Dev/f + 2 x p − n, where Dev is the deviance of the current model, f is the dispersion parameter, p is the number of fitted parameters of the current model, and n is the number of units. We reported the adjusted coefficient of regression, r² for the models. We completed our analyses in GenStat 12th Edition (VSN International, Hemel Hempstead, UK).

### 3. Results

#### 3.1. Oil palm yields and herbicide application

Annual oil palm yield (mean ± SD) from the 92 smallholdings was 21.0 ± 11.9 tons of fresh fruit bunches (FFB) ha⁻¹. The adjusted median value for oil palm yield was 19.8 tons FFB ha⁻¹. Of 92 smallholdings, we found that 62 had less than 50% of ground vegetation coverage, whereas 30 smallholdings had more than 50% (table 2; supplementary material: figure). This suggests overuse of herbicides by the majority of smallholders in the study area according to the best management practices for oil palm cultivation (Othman et al. 2012).

#### 3.2. Bird species richness, abundance, composition and feeding guild diversity

We recorded 2078 individual birds from 34 species and 21 families (table 3). The mean ± SD of overall

| % coverage | Number of smallholdings |
|------------|-------------------------|
| <10        | 1                       |
| 10–<20     | 5                       |
| 20–<30     | 9                       |
| 30–<40     | 20                      |
| 40–<50     | 27                      |
| 50–<60     | 17                      |
| 60–<70     | 5                       |
| 70–<80     | 5                       |
| >80        | 3                       |

Table 2. Ground vegetation coverage characterizing oil palm smallholdings.

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Figure 3. Scatterplots with regression (red) line and 95% confidence intervals (blue line) showing the relationships between annual oil palm yield and avian biodiversity, agricultural input, and habitat quality.
species richness was 10.5 ± 1.7 species per smallholding and abundance was 22.6 ± 3.9 birds per smallholding, respectively (table 1). Bird species richness was negatively related to annual amount of herbicide applied (t approximation = −5.97; r = −0.507; p < 0.001). Similarly, bird abundance was negatively related to annual amount of herbicide applied (t approximation = −3.92; r = −0.376; p < 0.001). Ten species constituted >90% of the bird assemblage in smallholdings (table 4). Mean bird feeding guild diversity (mean ± SD = 5.4 ± 0.7) was positively related to bird species richness (t approximation = 4.9; r = 0.519; p < 0.001), but weakly correlated with bird abundance (t approximation = 2; r = 0.284; p = 0.047).

### Table 3. Overview of bird species with taxonomical family and feeding guild.

| Species | Family | Feeding guild |
|---------|--------|---------------|
| Brahminy Kite, Haliastur indus | Accipitridae | Carnivore |
| Crested Serpent Eagle, Spilornis cheela | Accipitridae | Carnivore |
| White-throated Kingfisher, Halcyon smyrnensis | Alcedinidae | Carnivore |
| Stork-billed Kingfisher, Pelargopsis capensis | Alcedinidae | Carnivore |
| Blue-eared Kingfisher, Alcedo meninting | Alcedinidae | Carnivore |
| Edible-nest Swiftlet, Aerodramus fuciphagus | Apodidae | Insectivore |
| Purple Heron, Ardea purpurea | Ardeidae | Carnivore |
| Little Egret, Egretta garzetta | Ardeidae | Carnivore |
| Red-wattled Lapwing, Vanellus indicus | Charadriidae | Omnivore |
| Common Tailorbird, Orthotomus sutorius | Cisticolidae | Insectivore |
| Ashy Tailorbird, Orthotomus ruficeps | Cisticolidae | Insectivore |
| Peaceful Dove, Geopelia striata | Columbidae | Gravire |
| Spotted Dove, Spilopelia chinensis | Columbidae | Gravire |
| Emerald Dove, Chalcophaps indica | Columbidae | Frugivore |
| House Crow, Corvus splendens | Corvidae | Omnivore |
| Asian Koel, Eudynamys scolopaceus | Cuculidae | Omnivore |
| Greater Coucal, Centropus sinensis | Cuculidae | Omnivore |
| Brown Shrike, Lanius cristatus | Laniidae | Insectivore |
| Tiger Shrike, Lanius tigrinus | Laniidae | Insectivore |
| Blue-throated Bee-eater, Merops viridis | Meropidae | Insectivore |
| Oriental Magpie Robin, Copsychus saularis | Musicapidae | Insectivore |
| Brown-throated Sunbird, Anthrepetes malacensis | Nectariniidae | Nectarivore |
| Purple-naped Sunbird, Hypogramma hypogrammicum | Nectariniidae | Nectarivore |
| Olive-backed Sunbird, Cinnyris jugularis | Nectariniidae | Nectarivore |
| Black-naped Oriole, Oriolus chinensis | Oriolidae | Frugivore |
| Eurasian Tree Sparrow, Passer montanus | Passeridae | Gravire |
| Red Junglefowl, Gallus gallus | Phasianidae | Omnivore |
| Common Flameback, Dinopium javanense | Picidae | Carnivore |
| Long-tailed Parakeet, Psittacula longicauda | Psittacidae | Frugivore |
| Yellow-vented Bulbul, Pyconotus sinuosus | Pyconotidae | Frugivore |
| White-breasted Waterhen, Amaurornis phoenicurus | Rallidae | Omnivore |
| Javan Myna, Acridoideas javanicus | Sturnidae | Omnivore |
| Common Myna, Acridoideas tristis | Sturnidae | Omnivore |
| Asian Glossy Starling, Aplonis panayensis | Sturnidae | Frugivore |

3.3. Factors associated with oil palm yield
We found that oil palm smallholdings with high yield also supported high levels of bird species richness and feeding guild diversity (table 5). The most parsimonious model explaining annual palm oil yield included five explanatory variables (Mallows Cp = 3.85). Annual oil palm yield increased with bird species richness (slope = 0.1949), annual amount of fertilizer used (slope = 7.31 x 10⁻⁵), and bird feeding guild diversity (slope = 0.143) (figure 3). Annual yields decreased with bird abundance (slope = −0.1279), and height of oil palm stands (slope = −0.1844) (figure 3). Our statistical model explained 43.7% of the variation in annual oil palm yield. In terms of avian biodiversity, 8.0%, 16.9%, and 1.7% of the variation in annual oil palm yield was attributed to bird abundance, species richness, and feeding guild diversity, respectively. The height of oil palm stands and fertilizers explained 15.4% and 1.8% of the variation in annual oil palm yield, respectively. Oil palm yield was not associated with annual amount of herbicide used, oil palm tree density, ground vegetation coverage, and height, distance to nearest forest, the type of adjacent crops or the amount of ground vegetation cover.

4. Discussion
We have demonstrated that biodiversity-friendly oil palm production is not at odds with high yields of oil palm. We found a strong relationship between oil
Table 4. Cumulative contribution of bird species to the bird community in oil palm smallholdings. The SIMPER analysis computed the contribution of each species (%) based on the Bray–Curtiss dissimilarity matrix.

| Species                  | Average abundance | Contribution % | Cumulative contribution % |
|--------------------------|-------------------|----------------|---------------------------|
| Oriental Magpie Robin    | 1.89              | 19.38          | 19.38                     |
| Eurasian Tree Sparrow    | 1.9               | 18.81          | 38.19                     |
| Javan Myna               | 1.84              | 17.86          | 56.05                     |
| Peaceful Dove            | 0.98              | 6.51           | 70.24                     |
| Brown-throated Sunbird   | 0.81              | 6.4            | 76.64                     |
| Common Myna              | 0.98              | 3.52           | 80.17                     |
| Spotted Dove             | 0.66              | 3.45           | 83.61                     |
| Yellow-vented Bulbul     | 0.59              | 3.32           | 86.94                     |
| White-throated Kingfisher| 0.59              | 3.14           | 90.07                     |
| Brahminy Kite            | 0.53              | 2.99           | 93.06                     |
| House Crow               | 0.55              | 1.68           | 94.74                     |
| Common Tailorbird        | 0.4               | 1.07           | 95.81                     |
| Asian Glossy Starling    | 0.34              | 0.86           | 96.67                     |
| Asian Koel               | 0.28              | 0.79           | 97.46                     |
| Greater Coucal           | 0.27              | 0.77           | 98.23                     |
| Purple-naped Sunbird     | 0.16              | 0.29           | 98.52                     |
| Black-naped Oriole       | 0.16              | 0.25           | 98.77                     |
| Olive-backed Sunbird     | 0.16              | 0.23           | 99.9                      |
| Blue-throated Bee-eater  | 0.16              | 0.15           | 99.38                     |
| Brown Shrike             | 0.16              | 0.15           | 99.53                     |
| Tiger Shrike             | 0.12              | 0.11           | 99.64                     |
| Emerald Dove             | 0.12              | 0.08           | 99.72                     |
| Common Flameback         | 0.09              | 0.06           | 99.77                     |
| Crested Serpent Eagle    | 0.08              | 0.05           | 99.83                     |
| White-breasted Waterhen  | 0.08              | 0.04           | 99.91                     |
| Red Junglefowl           | 0.07              | 0.03           | 99.99                     |
| Red-wattled Lapwing      | 0.07              | 0.02           | 100                       |
| Ashy Tailorbird          | 0.07              | 0.01           | 100                       |
| Edible-nest Swiftlet     | 0.07              | 0.00           | 100                       |
| Stork-billed Kingfisher  | 0.05              | 0.00           | 100                       |
| Blue-eared Kingfisher    | 0.04              | 0.00           | 100                       |
| Purple Heron             | 0.03              | 0.00           | 100.00                    |
| Little Egret             | 0.01              | 0              | 100                       |
| Long-tailed Parakeet     | 0.02              | 0              | 100                       |

Palm yield and bird species richness in smallholdings. Our data also revealed that bird feeding guild diversity was associated with high oil palm yield. Carnivores, insectivores, and omnivores constituted nearly 68% of the bird species in oil palm smallholdings. Mathews et al (2007) reported that the oriental magpie robin (Copsychus saularis), white-collared kingfisher (Halcyon smyrnensis), yellow-vented bulbul (Pycnonotus goiavier), and greater coucal (Centropus sinensis) consumed a wide range of pest insects, including caterpillars (e.g. Darna trima), beetles (e.g. Oryctes rhinoceros), and grasshoppers (e.g. Valanga nigricornis) in oil palm plantations. Given this, it is possible that pest animal populations (e.g. insects or rodents) might be regulated by avian predators. Our findings are consistent with the results of the study by Maas et al (2013), which demonstrated the functional importance of birds and bats in the suppression of arthropod densities and an associated increase of cacao crop yield in tropical agroforestry landscapes. In contrast, Denmead et al (2017) found that oil palm yield was not associated with the occurrence of ants, birds and bats in oil palm smallholdings in Sumatra, Indonesia. Smallholdings had similar average yields (21 tons FFB ha⁻¹) to intensively farmed, large-scale oil palm plantations in Malaysia (20 tons FFB ha⁻¹) (Ismail et al 2003, Sime Darby Plantation 2018), but slightly higher than the average yields (19 tons FFB ha⁻¹) produced by large-scale plantations operating in Indonesia, Liberia, Papua New Guinea and the Solomon Islands (Sime Darby Plantation 2018). The yields produced by Malaysian smallholdings are higher than plantations in Indonesia (16 tons FFB ha⁻¹) and Liberia (4 tons FFB ha⁻¹), but lower than plantations in Papua New Guinea and the Solomon Islands combined (24 tons FFB ha⁻¹) (Sime Darby Plantation 2018).

Although smallholders often under-perform in terms of yield compared to industrial plantations in many settings (Lee et al 2014b, Euler et al 2016), our data indicated there is potential for yield gains by smallholders. It could be that the sample of smallholders included in this study more closely resembles the exception than the norm. In Malaysia, some independent smallholders reap an annual average FFB harvest of above 30 tons ha⁻¹ (MPOC 2020).
Although we did not survey industrial plantations within oil palm plantations does not reduce yields. Therefore, our findings suggest that conserving biodiversity and ecosystem functioning in oil palm stands (Choo et al 2018, Tohiran et al 2017). However, an increased amount of understory vegetation improves soil biodiversity and ecosystem functioning in oil palm stands (Ashton-Butt et al 2018) and this can be associated with high bird species richness (Tohiran et al 2017). Our findings suggest that farmers could reduce

### Table 5. Best subsets from candidate models. The most parsimonious model (labelled with “∗”) has six explanatory variables with a lowest Mallow Cp and a high $R^2$.

| Model | Explanatory variable                                                                 | DF | Mallows Cp | Adjusted $R^2$ |
|-------|--------------------------------------------------------------------------------------|----|------------|----------------|
| 5∗    | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity | 6  | 3.85       | 43.72          |
| 6     | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity + annual amount of herbicides | 7  | 4.02       | 44.3           |
| 7     | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity + annual amount of herbicides + additional crop | 8  | 5.15       | 44.24          |
| 4     | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers | 5  | 5.19       | 42.15          |
| 8     | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity + annual amount of herbicides + additional crop + distance from nearest forest | 9  | 6.92       | 43.72          |
| 3     | Bird abundance + bird species richness + height of oil palm stands | 4  | 6.99       | 40.32          |
| 9     | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity + annual amount of herbicides + additional crop + height of ground vegetation + ground cover | 10 | 8.59       | 43.27          |
| 10    | Bird abundance + bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity + annual amount of herbicides + additional crop + height of ground vegetation + ground cover + distance from nearest forest | 11 | 10.09      | 42.92          |
| 11    | Bird abundance + Bird species richness + height of oil palm stands + annual amount of fertilizers + bird feeding guild diversity + annual amount of herbicides + additional crop + height of ground vegetation + ground cover + distance from nearest forest + number of oil palms | 12 | 12         | 42.27          |
| 2     | Bird abundance + bird species richness | 3  | 29.83      | 24.88          |
| 1     | Bird abundance | 2  | 55.51      | 7.96           |

This is far above the national average of oil palm yield (20.2 tons FFB ha$^{-1}$) and surpasses the average yield produced by smallholders (18 tons FFB ha$^{-1}$) (Azman et al 2018, MPOC 2020). Furthermore, Malaysian oil palm smallholders are more motivated than their counterparts in other producing countries as they receive the government subsidies for replanting, certification, livestock integration, and pest control (Vermeulen and Goad 2006, Majid Cooke 2012, Nagiah and Azmi 2013).

We found that smallholdings with high bird species richness had higher than average yields. Therefore, our findings suggest that conserving biodiversity within oil palm plantations does not reduce yields. Although we did not survey industrial plantations in our study area, work in the region by Azhar et al (2011) indicated that oil palm smallholdings supported higher species richness (mean = 19.9 species per km) than industrial plantations (mean = 15.3 species per km). However, our data confirmed that avian biodiversity in oil palm smallholdings is highly impoverished relative to natural forests (Azhar et al 2011, Hawa et al 2016). Therefore, biodiversity losses from the conversion of natural forests to oil palm cultivation will not be offset by the smallholding management system.

We did not find a relationship between oil palm yields in smallholdings and annual amount of herbicide applied. Herbicides are often used to control the understory vegetation in oil palm plantations (Choo et al 2011, Tohiran et al 2017). However, an increased amount of understory vegetation improves soil biodiversity and ecosystem functioning in oil palm stands (Ashton-Butt et al 2018) and this can be associated with high bird species richness (Tohiran et al 2017). Our findings suggest that farmers could reduce
operating costs without compromising yield by omitting the use of herbicides (MYR150/ha). Our findings are consistent with the conclusions of Darras et al (2019) who suggested that palm oil production could be profitable without herbicides. Darras et al (2019) found no detrimental effects of non-chemical weeding on soil nutrients and functions. There is also evidence highlighting the value for biodiversity and production of increasing understory vegetation; cattle grazing to control weeds as opposed to herbicide spraying; and polyculture farming (Tohiran et al 2017, Yahya et al 2017, Ashton-Butt et al 2018).

We found that oil palm yields increased in plantations with greater biodiversity. We suggest that this is likely due to increased ecosystem services provision (Pywell et al 2015, Landis 2017, Grab et al 2018). Oil palm smallholdings are known to support higher biodiversity than large-scale plantations (Azhar et al 2011, Yahya et al 2016, 2017). However, smallholdings have been thought to generate lower yields because of inefficient production practices (Yan 2017). Therefore, some authors argue that smallholder agriculture may not be compatible with forest conservation due to the need for more land area to be under cultivation to produce the same yield (Teuscher et al 2015, Soliman et al 2016). In contrast, our study indicates that smallholders have the capacity to produce high yields and support high levels of avian biodiversity.

Our results indicated that bird abundance was negatively related to oil palm yield in smallholdings, which is consistent with its weak correlation with bird feeding guild diversity. Only three bird species were dominant in the smallholdings; oriental magpie robin, Eurasian tree sparrow, and Javan myna. In oil palm landscapes, faunal communities are generally represented by a small number of hyper-abundant, disturbance-tolerant, and often non-native species (Fayle et al 2010). These species may have only a limited ecosystem service role, with little benefit to oil palm production. Denan et al (2019) found that there was little predation by generalist bird species on artificial caterpillars in oil palm plantations. In addition, Gaston et al (2018) suggested that some bird species and combinations of species, particularly when at high numbers, can have a negative effect on ecosystem services (e.g. crop destruction).

Oil palm yield decreased with the height of oil palm stands, most likely because of a strong correlation of the age of oil palm trees with height (Tan et al 2014). Once oil palms mature, height increases linearly with age, but there is limited increase in stem diameter (Tan et al 2014). This coincides with the young mature phase, 4–7 years after planting, when leaf area and yield increase linearly (Woittiez et al 2017). Yields then plateau during the mature phase, 8–14 years after planting, when yield and leaf area are stable (Woittiez et al 2017). Oil palm yield declines typically 15–25 years after planting (Woittiez et al 2017).

Our results suggest a need for a rethink about how oil palm plantations are managed. Better management of existing oil palm production landscapes would sufficiently increase yields on existing plantations such that further expansion into forested areas may be unnecessary, providing that zero-deforestation policies are enforced by governments and certification bodies. In addition, industrial plantations could rely less on chemical insecticides to control pest insects if bird species richness and feeding guild diversity are promoted in plantations. In addition, the management of existing large-scale oil palm plantations could be altered so that such areas develop attributes similar to those of smallholdings. Modified practices may include intercropping, small-scale oil palm replanting, and livestock grazing (Azhar et al 2017, Tohiran et al 2017, 2019, Ashraf et al 2018). These smallholding attributes have been shown to support biodiversity in production areas of cacao and rubber in South-east Asia. In Thailand, Warren-Thomas et al (2020) reported that rubber agroforestry generates ecosystem services and provides moderate biodiversity benefits relative to monocultures, without compromising yields. Similarly, Clough et al (2011) suggested that farming practices in Indonesian cacao agroforests can be combined with a complex habitat structure to support high biodiversity as well as high yields. However, there are limitations to upscaling these alternative production systems, including harvesting, access, and replanting thousands of hectares (Rhebergen et al 2018, Schoneveld et al 2019).

We have demonstrated that high yields in smallholder plantations can be achieved through appropriate practices such as increasing fertilizer use. Furthermore, these practices can increase within-plantation biodiversity. This is an important finding for oil palm sustainability because 40% of oil palm globally comes from smallholdings. Although the smallholdings we sampled produced similar yields to their large-scale plantation counterparts, we argue that yields in smallholdings can be further improved with the use of additional approaches to sustainable production.

One of the most common yield-determining factors is planting density (Woittiez et al 2017). The conventional planting density of oil palm in large-scale plantations ranges from 136–148 oil palm plants per ha (Latif et al 2003). However, the planting density in our study area was 100 oil palms per ha. This may have contributed to increased oil palm yield because there was less competition between plants for sunlight, water, and nutrients (Bonneau et al 2014). Planting at lower oil palm density would be a better option than planting at higher density. This is because planting more oil palms per hectare has additional costs as there are more oil palms to maintain, fertilize, and harvest per unit area (Bonneau et al 2018). Hence,
planting at lower oil palm density could contribute to better oil palm yield in smallholdings. Nevertheless, we acknowledge this is likely to vary both within Southeast Asia and across other production regions.

Smallholders often have limited access to agronomic knowledge (such as efficient fertiliser and herbicide application). In Malaysia, independent smallholders grow oil palms without direct technical help from the government or any private agency. They are less efficient than other commercial growers due to their small plot size and poor agricultural practices (Rahman et al. 2008, Azman et al. 2018). Hence, they usually do not follow weed management guidelines. They are also not able to access higher yielding varieties of oil palm which are used by corporations that run large-scale oil palm plantations (Yan et al. 2017). Better uptake of agronomic information and the use of higher yield oil palm varieties combined with other practices such as herbicide reduction, rotational cattle grazing to control undergrowth and polyculture (Azhar et al. 2017, Tohiran et al. 2017, Ashraf et al. 2018) may help further boost within-plantation and landscape-level biodiversity, facilitate greater provision of ecosystem services, and result in higher yields of oil palm.

Our study has methodological limitations with respect to the bird sampling (i.e. one point count per smallholding and two ten-minute surveys at each smallholding). However, the average smallholding area was just 1.4 ha. This is too small to establish several sampling points within each smallholding. In Sumatra, Teuscher et al. (2015) used one point count per plot at each oil palm smallholding, independent of the plot size. Each plot was visited only twice, similar to our study. We also acknowledge the findings from our present investigation might change in response to landscape variables (e.g. remaining forest area, composition, connectivity) and thus may not necessarily be applicable to other settings.

5. Conclusion

Our study adds vital evidence to the growing body of research suggesting that biodiversity-friendly agriculture is not at odds with producing high yields (Tscharntke et al. 2012, Garibaldi et al. 2017, 2018). We suggest that the conservation of bird communities and ecological functions is essential for ensuring ecosystem services and crop productivity in oil palm production landscapes. We argue that reconciliation of oil palm production and nature conservation in smallholdings is a realistic goal and broadly consistent with sustainable palm oil certification schemes (e.g. RSPO and MSPO) in terms of their criterion for environmental protection. Sustainability goals can be met by better integrating farming practices with biodiversity management.

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Data availability

The data that support the findings of this study are available upon request from the authors.

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