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The effectiveness of a biopesticide in the reduction of coffee berry borers in coffee plants

Sophie Manson [a], Marco Campera [a,b], Katherine Hedger [b], Nabil Ahmad [b], Esther Adinda [b], Vincent Nijman [a], Budiadi Budiadi [c], Muhammad Ali Imron [c], Ganis Lukmandaru [c], K.A.I. Nekaris [a,b,*]

[a] Nocturnal Primate Research Group, School of Social Sciences, Oxford Brookes University, Oxford, OX3 0BP, UK
[b] Little Fireface Project, Cipaganti, West Java, 40131, Indonesia
[c] Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia

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ABSTRACT

Context: Crop pest outbreaks are expected to become more frequent and unpredictable due to climate change, posing risks to ecosystem health and farmers' livelihoods. At the same time, there is growing evidence that chemical pesticides can persist in the landscape and contribute to land degradation. The use of natural pesticides in place of chemical pesticides is hoped to manage pest outbreaks while also restoring pollinator populations and improving the quality of arable land. During the 1970s, many countries committed to promoting and legislating Integrated Pest Management (IPM) strategies (encouraging natural and holistic approaches to pest management), often including using natural pesticides, known as biopesticides.
Objective: We assessed the effectiveness of a biopesticide on coffee berry borer (CBB; *Hypothenemus hampei*) presence in 57 small-holder coffee home gardens in West Java, Indonesia across three years.
Methods: Prior to the application of the biopesticide, we randomly chose ten coffee plants from each field and recorded the proportion of healthy berries per plant (berries without pest infestation) as a control. In April 2020, we distributed the biopesticide in each of the 57 coffee home gardens and repeated the above experiment. The biopesticide was redistributed in October 2020 and April 2021. We repeated the experiment for the last time in April 2021.
Results and conclusions: We found that CBB presence significantly decreased, with an inverse relationship between distance to natural forest and CBB presence and a positive relationship between shade cover and CBB presence. We also interviewed farmers in April 2021 to investigate their perception of the effectiveness of the biopesticide and 87% of farmers thought it was more effective than conventional pesticides.
Significance: We contribute to the growing literature on the effectiveness of natural pesticides through assessing farmers' perceptions of these methods and providing empirical evidence for their effectiveness in remedying CBB infestation. We hope that this study will empower farmers to make conscious land-use choices and provide government authorities with evidence to support increased accessibility to biopesticides.

1. Introduction

There is growing evidence that a global conversion from broad-spectrum chemical pesticides to organic alternatives is necessary if farming is to become more sustainable, and human and environmental health are to be protected (Bhagwat et al., 2008; Jha et al., 2014; Shipley et al., 2020). Bradshaw et al. (2016) estimated that invasive insects that pose a danger to crop species, hereafter referred to as pests, cost the global agricultural industry US$25.0 billion per year, consuming 10–16% of crops before and after harvest. However, this figure increases significantly in tropical areas of Asia and Africa (Sharma et al., 2017). As pest outbreaks occur more often and unexpectedly due to climate

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* Corresponding author. Nocturnal Primate Research Group, School of Social Sciences, Oxford Brookes University, Oxford, OX3 0BP, UK.
E-mail addresses: sophie.manson_2019@brookes.ac.uk (S. Manson), mcampera@brookes.ac.uk (M. Campera), research@littlefireface.org (K. Hedger), ahmadnabilff@gmail.com (N. Ahmad), estheradinda810@gmail.com (E. Adinda), vnijman@brookes.ac.uk (V. Nijman), budiadi@ugm.ac.id (B. Budiadi), maimron@ugm.ac.id (M.A. Imron), glukmandaru@ugm.ac.id (G. Lukmandaru), anekaris@brookes.ac.uk (K.A.I. Nekaris).

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change, it is essential that a commercially viable, organic alternative to synthetic chemical pesticides, hereafter referred to as chemical pesticides, is found in order to protect the environment from irreversible damage, including the loss of up to 70% of insect species (Asegid, 2020; Dudley et al., 2017; Hallmann et al., 2017; Volney and Fleming, 2000; Ware, 1980).

Global agricultural intensification forced smallholder farmers to switch from traditional, inherently organic, farming practices to methods requiring the use of chemicals and machinery to increase productivity, including chemical pesticides (Oka, 2003). Yet decades of prophylactic chemical pesticides, in conjunction with synthetic chemical fertilizers and monocultures (large areas of farmland dedicated to one crop), have severely impacted ecosystem and human health, with pollinator decline and land degradation posing significant threats to farmers around the world (Abdi et al., 2013; Dregne, 1998; Dudley and Alexander, 2017; IPBES et al., 2016; Mahmood et al., 2016; Niering, 1968; Syafrudin et al., 2021; Zhou and Li, 2021).

Biopesticides are one of the most exciting alternatives to chemical pesticides (Liu et al., 2021). The three types of biopesticide include: microbial (bacteria, viruses and fungi), botanical (plant species found to affect pest populations) and biochemical (pheromones) (Srinivasan, 2012). Biopesticides have many advantages, including being more cost effective than producing new chemical pesticides, causing less damage to the environment, targeting specific species and showing no evidence of resistance (Awasthi, 2021; Copping and Menn, 2000; Gupta and Dikshit, 2010; Liu et al., 2021). In Bangladesh, a sex pheromone-based biopesticide led to a 70% reduction in the use of chemical pesticides, with the added benefits of reduced production costs, increased production area and reduced labour requirements. Similarly, a study looking at the use of biopesticides in agroecosystems in Ukraine found that biopesticide use led to a 40% reduced chance of crop loss (Alam et al., 2006; Srinivasan, 2008, 2012). Biopesticides are not without their disadvantages, including their inability to target novel pest outbreaks, lack of accessibility and perceived ineffectiveness (Dhangar and Choudhury, 2021).

Over the last two decades, coffee production in Indonesia has increased dramatically, reflecting the consistent increase in global demand of 4–5% a year (Ibrahim and Zailani, 2010). Indonesia is the fourth largest producer of coffee in the world, producing 792 kg of coffee beans per hectare per year (Ibrahim and Zailani, 2010). One of the primary pests of coffee (*Coffea arabica*) is the coffee berry borer, (CBB; *Hypothanemus hampei*; Coleoptera: Curculionidae). CBB pose the greatest threat to coffee production globally (Baker, 1984; Soto-Pinto et al., 2002) and regularly infest coffee plants in Indonesia. CBB damage coffee through female individuals boring into coffee berries. Here, females lay ~40 eggs, and once developed, these individuals will mate and reproduce within the berry. Male individuals remain in the berry for three months (their entire life-cycle) and female individuals, of which the sex ratio is heavily skewed (13:1), leave to lay eggs in another berry (Bui et al., 2021; Vega et al., 2015). They also disperse pathogens (*Colletotrichum* spp.) that cause coffee berry disease (CBD) (Serrato-Diaz et al., 2020). CBB cause a global economic loss of half a billion US-dollar per year (Escobar-Ramírez et al., 2019).

Of the 1.2 million ha of coffee plantations present in Indonesia, 96% belong to smallholder farmers (Ibrahim and Zailani, 2010; Wahyudi and Jati, 2012). Farmers in Indonesia, particularly in West Java and Bali, commonly use traditional farming practices (Jahroh, 2010; Oka, 2003; Okubo et al., 2010). Smallholder farms within our study site (West Java) most commonly grow arabica coffee and exist within a polyculture, agroforest environment. Furthermore, many traditional farming methods remain cheap and easily accessible. These methods include using manual tools instead of herbicides, organic fertilisers, intercropping and agroforestry, planting trees within and around smallholder farms, practices which have been shown to increase the presence of wildlife (Campera et al., 2021a,b). Although these wildlife-friendly practices are relatively widespread, chemical pesticides remain commonplace in many farming communities due to ease of accessibility, low price and farmers' reluctance to attempt natural pesticides due to scepticism surrounding their effectiveness in the face of frequent pest infestations (Oka, 2003).

Currently, the primary biopesticide methods used to control CBB are the application of the fungus *Beauveria bassiana,* a naturally-occurring entomopathogen of CBB, and the use of coffee attractant traps, attractants being compounds identified in coffee berry effluvia (Aristizábal et al., 2015; Castro et al., 2017; Damon, 2000; Dufour and Frérot, 2008; Hollingsworth et al., 2020; Roblero and Malo, 2013). An example of a widely used coffee attractant trap is the 1:1 ethanol-methanol trap. It is the synergistic effect of both alcohols, emitted by ripe coffee berries, that has been found to be most effective when capturing CBB (Dufour and Frérot, 2008). The use of coffee attractants is plausible as a wildlife-friendly pest control method due to their specificity to coffee pest species and their accessibility and price point within Indonesia.

In this study, we test the effectiveness of a biopesticide (Glumon™) against CBB in coffee plants in an agroforest ecosystem in West Java, Indonesia over the course of two years. Glumon™ is naturally-derived, widely accessible and cheap to buy, therefore, its effectiveness would contribute greatly to IPM strategies within Indonesia. We aim to investigate the applicability of biopesticides and how their success varies depending on whether farmers previously used chemicals, their distance to natural forest, the presence of other crops and shade cover. We expect that biopesticides will cause CBB and, in turn, *Colletotrichum* spp. incidence to decline, with more significant declines in farms that did not previously use chemicals, farms closer to natural forest and farms with higher crop richness and shade cover. We also aim to identify the volatile compounds present in the biopesticide to understand which compounds can attract CBB. Depending on the efficacy of the biopesticide, considering the above factors, we will be able to assess the value of wildlife-friendly methods, such as agroforestry, and provide valuable evidence for the wide-scale use of biopesticides.

2. Materials and methods

2.1. Study site

We carried out experiments in 57 Arabica coffee home gardens in the municipalities of Cipaganti and Pangauban, Garut Regency, West Java, Indonesia (7.2786°S, 107.7577°E). On average, coffee home gardens covered 1229 ± SD 807 m^2 each and 68790 m^2 in total (Campera et al., 2021a,b). These home gardens, referred to hereafter as farms, are situated in an agroforest matrix in which farmers annually rotate the cultivation of perennial crops and ensure the existence of trees within and around their farms (Campera et al., 2021a,b; Nekaris et al., 2017). Farmers usually plant coffee in tandem with understory crops (e.g., cabbage (*Brassica oleracea*), chilli (*Capsicum frutescens*), cassava (*Manihot esculenta*) or underneath frames used to grow chayote (*Sechium edule*) (Campera et al., 2021a,b). The most commonly planted variety of arabica coffee grown here is Selection-795, making up 60–70% of the coffee grown in Cipaganti and Pangauban. Farms are situated at 1105–2105 m above sea level and are, at the least, 15 m and, at the most, 1805 m away from each other (Campera et al., 2021a,b). West Java, Indonesia does not have strict seasons but experiences heavier rainfall between December and April (Campera et al., 2021a,b). Coffee berries are harvested twice a year in May/June and December following flowering periods in April and November (Campera et al., 2021a,b).

2.2. Experimental method

First, we tested the efficacy of Glumon™ (PT Agrosid Manunggal Sentosa, Jakarta, Indonesia), a biopesticide. Glumon™, a sticky, translucent solution, was applied to a yellow, plastic surface (i.e., the trap) measuring 10 cm × 30 cm. Each field had one trap. The trap (Fig. 1.) was placed on the coffee plant deemed closest to the middle of the farm and

Fig. 1. Biopesticide trap placed in 57 coffee home gardens in Cipaganti, West Java. The biopesticide, Glumon™, was applied to a yellow, laminate surface and this was attached to the plant deemed closest to the centre of the coffee home garden ~150 cm above the ground. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

~150 cm above the ground (Dufour and Frérot, 2008; Sinaga et al., 2020). After preliminary testing in ten fields, Glumon™ was then distributed across the 57 farms and other fields not included in the experiment but in the same municipalities. We gave one or more yellow slides depending on the size of the fields (around one slide every 25 m^2). We chose to use yellow slides as other studies within Indonesia, and our area specifically, have used yellow when trialling Glumon™ (Mutakin et al., 2022; Purnama et al., 2013). Glumon™ slides were first distributed in April 2020 and new slides were distributed again in October 2020 and April 2021.

Following the initial experiment, we interviewed 102 farmers (62 females and 40 males) from the two communities between January and April 2021. We asked the following questions: 1) Did you receive the pest control traps given? If so, how many?; and 2) Do you think the biopesticide (note that during the interview we used the term Glumon™ that is known by farmers) has been more effective than the conventional pest control methods? The interviews were approved by the Oxford Brookes University Research Ethics Committee for human participants in research (number 181256).

2.3. Evaluating presence of pests and pathogens in coffee plants

First, as a control, we recorded the presence of CBB and *Colletotrichum* spp. in all 57 farms in April 2019. We did the same evaluations in April 2020, following the first distribution of the Glumon™ slides, then again in October 2020 and then April 2021, following the third distribution of Glumon™ slides. We chose April and October as farmers harvest coffee berries from May–July and November–December. We recorded the proportion of CBB infested berries in coffee plants in each farm. CBB infested berries have a hole at the bottom where the female CBB enters and are often empty (referred to as brocade grains) (Rezende and Taniwaki, 2020). Berries with *Colletotrichum* spp., spread by CBB, are often brown/black and dry (Serrato-Diaz et al., 2020). Healthy berries appear to be red, full and glossy (Fig. 2.). We randomly chose ten plants from each of the 57 farms and assessed the proportion of branches with healthy red berries of each plant. To assess the proportion of branches with healthy red berries, we assigned each plant a score between 0 and 10 (0 = no red berries, 10 = all healthy red berries).

In addition to measuring the proportion of pests in coffee plants, we measured additional environmental variables to consider their influence on CBB presence. These comprised richness of other crops, richness of

Fig. 2. Healthy coffee (*Coffea arabica*) berries (left) and berries displaying coffee berry borer (*Hypothenemus hampei*) infestation and coffee berry disease caused by pathogens (*Colletotrichum* spp.) (right).

shade trees, shade tree cover (%), distance to forest (m) and whether the farmers had previously used chemical farming practices (organic, mixed and intensive use of chemicals). Detailed descriptions of how these data were obtained and calculated are reported in Campera et al. (2021a,b).

2.4. Glumon™ compound analysis

We performed the process by dissolving 1 ml of Glumon™ of the sample in n-hexane (5 ml). We collected the gas chromatography-mass spectrometry (GC-MS) data using GCMS-QP 2010 (Shimadzu, Japan). We injected the 1 μl of *n*-hexane solution into the GC-MS machine. The GC conditions included Rtx-5MS capillary column (30 m × 0.25 mm I.D. and 0.25 μm; GL Sciences, Tokyo, Japan). Column temperature ranged from 70 °C (1 min) to 290 °C at 5 °C/min at an injection temperature of 270 °C. Detection temperature was 290 °C and we used an acquisition mass range of 50–800 amu using helium as the carrier gas. We compared the sample mass spectrum to the NIST library and used the peak relative method to calculate detected compounds (Masendra and Lukmandaru, 2021).

2.5. Data analysis

We tested whether the proportion of healthy red berries (calculated as mean proportion for each coffee garden) was influenced by our intervention and other environmental variables related to the coffee farms. We used the "glmmTMB" function in the "glmmTMB" package. We chose to use Generalised Linear Mixed Models (GLMM) as they allow for response variables of non-normal distributions and the inclusion of random effects. Specifically, the "glmmTMB" function allows different fit families and it is suitable to deal with zero inflated data. We used year, chemical use, shade tree richness, shade cover, crop richness, and distance to forest as fixed effects, and coffee farms as random effect. We tested different fit functions for proportional data (beta, betabinomial, gaussian, Gamma) and included or excluded a zero-inflation term based on the QQ plot residuals and residual vs predicted plot from the package "DHARMa". We thus selected the model with beta family and no zero-inflation based on the diagnostic plots. We ran pairwise contrasts using a Bonferroni-Holm post hoc correction via the function "emmeans" in the package "emmeans". We considered $p = 0.05$ as level of significance. We ran all the analyses with R v 4.0.4 (R Core Team, 2021).

3. Results

We first ran an experiment on the use of biopesticide using ten traps set in ten different coffee farms. This experiment revealed that most of the effectiveness of this pesticide was within the first week after the installation (mean: 227.2; 95% CI: 154.2–300.2 CBB per coffee garden). This number had a non-significant increase after three weeks (mean: 242.6; CI: 168.8–316.4) and five weeks (mean: 251.9; CI: 178.5–325.3). Based on these data, we decided to share traps with the community (intervention) right before the beginning of the fruiting period. From the experiment, we also found that the traps were selective on CBB (mean: 21.4%; 95% CI: 14.9–28.0% of other insects trapped, thus CBB representing ~80% of the total insects trapped), and that most of the trapped insects were mosquitoes, flies, or aphids. Of the other insects trapped, only 6.9% were not mosquitoes, flies, or aphids, corresponding to around 1.5% of the total insects trapped.

The volatile compounds found in Glumon™ were: 77.36% methyl eugenol; 8.98% eugenol; 2.15% trans-Z-α-bisabolene epoxide; 1.93% valeric acid, 4-tridecyl ester; 1.73% 3-heptene, 2,2,4,6,6-pentamethyl; 1.41% formic acid, 2,4,4-trimethylpentyl ester; 1.12% trans,cis-2,6-Nonadien-1-ol; 1.00% cyclohexanone, 3-butyl; 0.92% cyclohexaneethanol, 3-hydroxy-β,4-dimethyl; 0.69% 6-tridecene, 2,2,4,10,12,12-hexamethyl-7-(3,5,5-trimethylhexyl); 0.66% 4-Butoxy-2,4-dimethyl-2-pentene; 0.58% sullforous acid, 2-ethylhexyl octadecyl ester; 0.54% 2,4,4,6,6,8,8-heptamethyl-1-nonene; 0.49% 4-decene, 2,2-dimethyl-, (E)-; 0.43% tetracontane, 3,5,24-trimethyl.

From the farmer feedback forms (n = 102), we found that only 33.3% of the farmers between the two communities declared to not have received the biopesticide. Most of the farmers who received the biopesticide declared to have received either less than five (36.7%) or between 5 and 10 (29.4%) traps. Farmers with larger fields received between 15 and 30 traps (27.9%) or around 50 traps (6.0%). Of the people that received the biopesticide in their farms, 86.6% declared that it was very effective in catching CBB. They often reported the fact that the trap caught many CBB that were clearly visible to assess that it was effective. Some of the farmers noticed that the glue did not stick for long after raining, and that should be considered during the implementation.

From our observation of coffee plants, we found a higher proportion of red berries after the intervention (estimated model means (95% CI); Year 2019: 0.67 (0.64–0.70); Year 2020: 0.86 (0.84–088); Year 2021: 0.82 (0.79–0.85)) with an increase of ~25% compared to the baseline data collected in 2019 (Table 1; Fig. 3). The proportion of red berries increased with the increase in shade cover and decreased when they were further from the forest (i.e., closer to the village) (Table 1; Figs. 4 and 5).

4. Discussion

We found that the proportion of healthy red berries in coffee plants increased throughout the three-year biopesticide treatment. The steepest increase was documented between 2019 and 2020, demonstrating that, in this case, the organic alternative to chemical pesticides was immediately effective at reducing pest presence, in addition to its continued effectiveness following multiple applications. Other studies have documented the success of biopesticides in reducing pests, but often state that chemical pesticides were either more effective or that biopesticides should be used in addition to or in alternation with chemical pesticides (Malinga and Laing, 2021). Our findings add to the growing literature on the effectiveness of biopesticides and show that they can be effective regardless of the use of chemicals.

Our findings suggest that CBB and *Colletotrichum* spp. incidence reduced with increasing shade cover (Fig. 3). The strongest relationship between shade cover and pest incidence was seen in 2019 (control year) prior to the application of the biopesticide. Vegetation variables have previously been found not to significantly affect coffee borer incidence (Piato et al., 2021; Sinu et al., 2021; Soto-Pinto et al., 2002). Differences in classification of vegetation variables and data collection could impact these results. Soto-Pinto et al. (2002) found that shade cover did not impact pest, disease or weed presence, but they took into account shade cover at five separate strata. In our study site, shade cover was only considered at canopy-level. The increase in complexity considered in Soto-Pinto et al.'s study may have contributed to the lack of correlation between shade cover and pest presence. Nesper et al. (2017) studied the effect of shade tree presence on coffee production from two perspectives:

Table 1
Results from the Generalised Linear Mixed Model to understand the determinant of healthy coffee red berries (i.e., not infested by the coffee berry borer *Hypothenemus hampei*) in 57 coffee home gardens in Cipaganti, West Java.

Predictor	Estimate	Std. Error	Z value	p-value
Intercept	1.019	0.261	3.898	<0.001**
Year 2020	1.104	0.119	9.298	<0.001**
Year 2021	0.806	0.114	7.095	<0.001**
Chemical use (mixed)	−0.030	0.109	−0.275	0.783
Chemical use (chemicals)	0.037	0.131	0.282	0.778
Shade tree richness	−0.038	0.032	−1.185	0.236
Shade cover	0.010	0.003	3.460	<0.001**
Crop richness	0.023	0.054	0.426	0.670
Distance to forest	$-2.559*E^{-4}$	$1.341*E^{-4}$	−1.909	0.056*

* trend towards significance; ** highly significant.

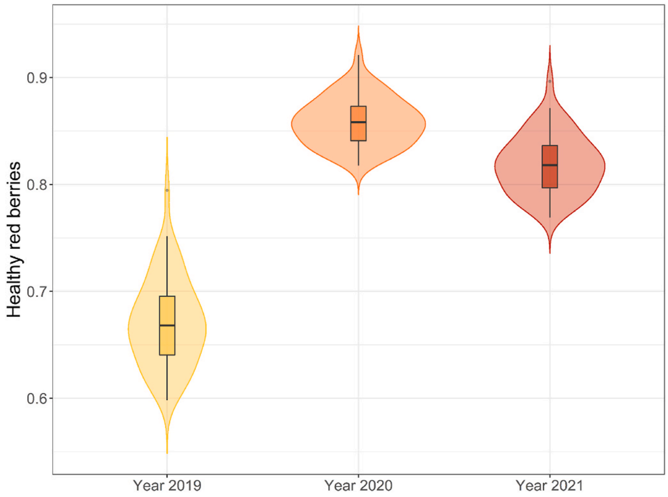

Fig. 3. Proportion of healthy red berries in coffee plants in 2019 (control year), 2020 and 2021 (following the distribution of biopesticide) in 57 coffee home gardens in West Java, Indonesia. Data and model predicted values from Generalised Linear Mixed Models. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

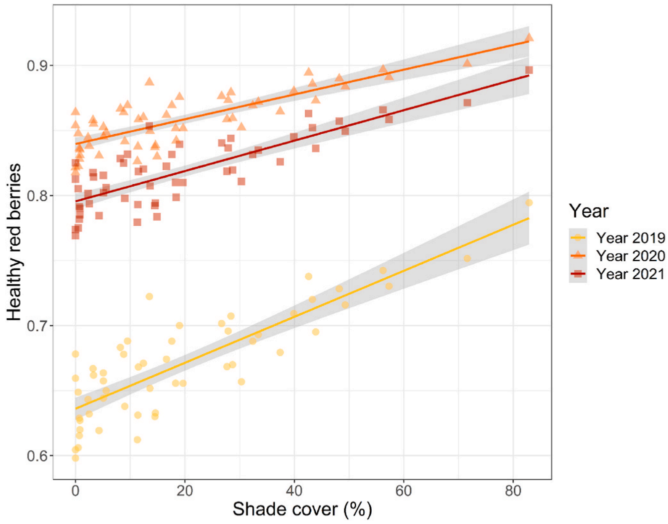

Fig. 4. Proportion of healthy red berries in coffee plants in relation to percentage shade cover of 57 coffee home gardens in West Java, Indonesia. Data are model predicted values and fit lines are from Generalised Linear Mixed Models and grey areas are 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

shade tree diversity and percentage shade cover. They found that CBB incidence increased when percentage shade cover was low (Nesper et al., 2017). Agroforest ecosystems with higher shade cover are resident to increased populations of ants, birds and nematodes, all of which have been shown to be effective predators of CBB (Armbrecht and Gallego, 2007; Clough et al., 2009; Escobar-Ramírez et al., 2019; Sauvadet et al., 2019). Therefore, it is possible that the relationship between shade cover and pest incidence in 2019 (control year) was such due to the natural presence of CBB predators.

Similarly, the proportion of healthy red berries increased the closer farms were to natural forest. This is in line with the findings of Karp et al. (2013) who showed that the presence of forest positively influenced pest removal, with bats reducing the presence of pests by up to 50%. Studies looking to evaluate the effectiveness of wildlife-friendly practices on ecosystem services have often found that agroforestry, shade trees and

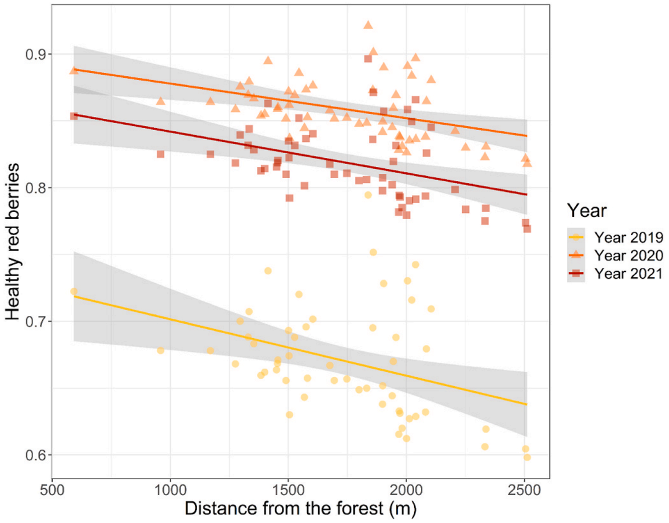

Fig. 5. Proportion of healthy red berries in coffee plants in relation to their distance natural forest in 57 coffee home gardens in West Java, Indonesia. Data are model predicted values and fit lines are from Generalised Linear Mixed Models and grey areas are 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the application of non-chemical fertilisers have neither significantly increased nor decreased the provision of pest control services (Leijster et al., 2019, 2021; Sinu et al., 2021). Evidence suggests that ecosystem complexity is a significant factor in encouraging plant-pollinator networks and insect diversity (Campera et al., 2021a,b; Huang et al., 2021; Piato et al., 2021). Therefore, although more focused research is necessary to confirm this result, our results suggest that there may be increased natural pest control provision in farms closer to natural forest, demonstrating the importance of the presence of wildlife for ecosystem service provision.

Our study contributes to the growing body of literature reporting the effectiveness of wildlife-friendly pest control methods in reducing CBB populations. Following analysis, Glumon™ was found to be primarily methyl eugenol-based. Methyl eugenol is a naturally-occurring chemical that is a type of phenylpropanoid (Haque, 2018). It is found in the leaves, roots, stems, and fruits of *Eugenia caryophyllata* Thunb (clove) and is a powerful insect attractant, primarily used to attract male individuals of various fruit fly species (*Drosophila* spp.) (Haque, 2018; Susanto et al., 2020). Often mixed with fruit juice, it is a cheap and widely available biopesticide method in Indonesia and has been documented as an environmentally-friendly pesticide method (Susanto et al., 2020; Suwinda et al., 2020). However, it remains unclear why the vast majority of insects caught were CBB. Although widely used to control fruit fly populations, de Souza et al. (2020) found that eugenol was successful in attracting CBB and Siregar and Dewiyana (2020) attributed high insect abundance and diversity to the use of methyl eugenol traps in controlling CBB populations in North Sumatra. The attractiveness of methyl eugenol to CBB may be due to the presence of isoeugenol observed in coffee beans exposed to monsoon winds in areas of India (Variyar et al., 2003). Furthermore, trans-Z-α-bisabolene epoxide, one of the volatile compounds found in Glumon™, has been identified as one of the compounds within male stink bug (Heteroptera: Pentatomidae; *Acrosternum hilare*) sex pheromones (Müller and Buchbauer, 2011; Tillman et al., 2010). Although it is not possible to confirm using known published studies, this could suggest that this compound is present in kairomones released by coffee berries, which can attract CBB females. Whilst the use of kairomones as natural pest control is attractive, there needs to be more research regarding the sensory detection of sex pheromones within farms before they are used as a primary pest control method (Ivaskovic et al., 2021).

Beauveria bassiana application and 1:1 ethanol-methanol have been found to be effective biopesticides; however, *B. bassiana* requires extensive field monitoring to ensure that it is being applied at the time in the CBB life cycle that *B. bassiana* infect CBB adults and methanol-ethanol traps are required in large numbers, rendering both methods labour intensive (Wiryadiputra et al., 2009; Mascarin and Jaronski, 2016; Woodill et al., 2021). Damon (2000) outlines numerous CBB cultural management methods that rely on harvesting methods to reduce the impact of CBB on coffee plants, such as pruning, frequent and clean harvesting and monitoring “freak” flowering episodes. When examined alone, these methods were found to be potentially useful, but none were found to be effective outright (Aristizábal et al., 2015; Damon, 2000). Although, farms that implement cultural control methods, without the use of chemicals, were found to have less damage to berries and reduced CBB flight activity (Aristizábal et al., 2015). This suggests that an IPM program, combining all of the above, is necessary to curtail CBB infestations: prevention through managing shade conditions, identifying CBB infestations through effective harvesting and treatment through the use of effective biopesticides (Aristizábal et al., 2017).

Moving forward, more effort should be made to incentivise the application of natural pesticides, such as Glumon™. Many farmers and stakeholders perceive that a switch to organic alternatives will inevitably lead to a reduction in productivity and increased production costs (Chèze et al., 2020). Although there is evidence to suggest that the cost of producing biopesticides will be lower than that of conventional pesticides, until the use and trade of biopesticides is solidified in legislation, chemical pesticides will remain the cheaper option (Arjjumend and Koutouki, 2021). By obtaining certfications and labelling products as eco- and wildlife-friendly, farmers can receive premium prices for their crops (Altmann and Filho, 2020). This process could incentivise farmers to begin investing in wildlife-friendly farming practices, alongside further research examining the effect of biopesticide use on overall yield.

With evidence to prove the effectiveness and economic benefits of biopesticides, particularly in Indonesia, it will be easier for local conservation groups and government departments to encourage their use. We will utilise the existence of farming cooperatives within our study site to disseminate the results of our study and we will promote the implementation of an IPM program to prevent, identify and treat CBB infestations (Aristizábal et al., 2017). In future, we will test the use of red traps as the colour red has been found to be more effective in attracting CBB (Dufour and Frérot, 2008). By making farmers aware of the effectiveness of biopesticides in their locality and the subsequent advantages of biopesticides, such as their cost in relation to chemicals and their impact on soil quality, it is hoped farmers will feel empowered to invest in biopesticides.

5. Conclusions

On a global scale, farmers must move away from the use of chemical pesticides if ecosystem health is to be preserved. Despite studies showing the detrimental effects of chemical pesticides in the 20th century, there has been a lasting reluctance to switch to, and in many cases switch back to, organic farming practices. We found that a sex pheromone-based biopesticide was successful in reducing the infestation of CBB in coffee plants in farms in West Java, Indonesia. In addition, we found that CBB infestation of coffee plants was lower when farms were closer to natural forest. This indicates that the presence of wildlife, through agroforestry and the use of natural pesticides, can enhance the ecosystem services received by local farmers. Our study can act as evidence for the effectiveness of biopesticides and eco-friendly practices in agroforest environments, particularly when farms exist close to natural forest. Longitudinal studies such as these will be required to gauge how effective biopesticides will continue to be in the long term as climate change increases the likelihood of pest outbreaks. The dissemination of our results through existing farming cooperatives will contribute to smallholder farmers’ knowledge surrounding wildlife-friendly farming practices and empower them to make informed choices regarding what pesticide method they choose to use. In addition, by publishing our data, it is hoped that decision makers will be able to use them to make informed decisions regarding the promotion of wildlife-friendly farming practices, such as biopesticides, and what development and training farmers will have access to.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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