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# Shade trees and agrochemical use affect butterfly assemblages in coffee home gardens

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## Abstract

Agroforestry systems have been recognised as a possible refuge for biodiversity especially when bordering intact landscapes. The intensification of crop management to increase yields is usually associated with a reduction of shade trees and heavy use of chemicals, typically correlated with a decrease in biodiversity. The relationship between intensity of crop management and biodiversity, however, is not clear-cut and is dependent on environmental and geographical differences. We assessed the influence of different shade cover, shade tree richness, richness of other crops, distance from the forest, and use of chemicals on the diversity, richness and abundance of butterflies, a bioindicator in coffee home gardens. We collected data in 42 coffee home gardens in West Java, Indonesia, via Pollard transects, totalling 15.1 km (July-August 2019 and July-August 2020). We found 54 species of butterflies in the gardens. Via Generalised Additive Mixed Models, we found that the use of chemicals negatively influenced the abundance (p=0.001) and richness (p=0.039) of butterflies, while shade tree richness positively influenced the abundance (p<0.001), diversity (p=0.046) and richness (p<0.001) of butterflies. The other predictors did not have a significant effect. The high diversity of butterflies in the study area suggests that the agroforestry environment is now resilient, but the relationship between butterfly abundance, diversity, and richness with shade tree richness indicates an urgency to maintain and improve current ecosystem complexity. The negative relationship between butterfly abundance and richness and the use of chemicals further indicates that organic farming should be promoted to preserve ecosystem services provided by pollinators. Coffee production in Indonesia has dramatically increased in the last 10 years and producers are keener to use more intensive farming techniques with a consequent reduction of ecosystem complexity. This process can break the resilience of agroforestry habitats if actions are not taken immediately.

**Keywords:** agroforest; Indonesia; pollination; Lepidoptera; biodiversity; organic

## 1. Introduction

Given the wide transition from forest to human modified habitats, agroforestry systems have been recognised as an alternative refuge for biodiversity (Bhagwat et al., 2008; Jha et al., 2014). Rustic systems, in which crops grow under a natural canopy, have been shown to host similar levels of biodiversity to those of forest habitats (Perfecto et al., 2003; Santos-Heredia et al., 2018). There is usually a reduction in biodiversity as a consequence of an intensification in crop management that is associated with a reduction in shade tree diversity and increased use of chemicals (Gordon et al., 2007; Philpott et al., 2008; Browne et al., 2013). The term "agricultural intensification" refers to both changes in vegetation diversity (e.g. crop and shade tree diversity) and in crop management practices (e.g. use of chemical fertilisers and pesticides) (Philpott, 2013). The intensification of crop management to increase yields has occurred in most commercial crops (Keys & McConnell, 2005; Laurance et al., 2014). Several taxa have been recognised as bioindicators to assess the state in agroforestry environments (e.g. ants, Andersen et al., 2002; bats, Jones et al., 2019; several taxa of pollinator insects, Kevan, 1999). Butterflies have often been used as bioindicators of healthy ecosystems as their abundance and richness is associated with environmental variables and vegetation diversity (Maleque et al., 2009). In coffee fields, butterflies have an important role as pollinators and can be considered as bioindicators (Munyuli, 2013; Bravo-Monroy et al., 2015).

Coffee (*Coffea* spp.) is one of the most important commodity crops in the world (DaMatta et al. 2019), with around 25 million people estimated to depend on its production for their livelihoods (Bunn et al. 2015). Coffee fields are particularly suitable to host high levels of biodiversity as they are traditionally cultivated under dense and diverse shade canopy (Moguel & Toledo, 1999). In the last 30 years, however, the intensification in the management of coffee fields resulted in a shift towards sun-exposed fields to gain more revenue (Perfecto et al., 2005; Borkhataria et al., 2012b). Sun-exposed coffee fields, in fact, are claimed to have higher fruit yields than coffee under shade trees, although this expectation is often unsupported (Soto-Pinto et al., 2000; Perfecto et al., 2005; Meylan et al., 2017). Sun-exposed coffee plants are also expected to have fewer coffee fruit borers (*Hypothenemus hampei*, a beetle, originally native to Africa, that severely damages coffee seeds and reduces coffee productivity and quality; Morris et al. 2018) than shade-grown coffee due to the more intense use of pesticides with the increase in management and lower temperatures suppressing coffee borer incidence (Armbrecht & Gallego, 2007; Borkhataria et al., 2012a; López-Bravo et al., 2012; Jha et al., 2014; De Leijster et al., 2021), although there are instances when coffee borers are fewer in shade coffee (e.g. Mariño et al., 2016). Conversely, shade-grown coffee fields show smaller temperature fluctuations (López-Bravo et al., 2012; Mariño et al., 2016), better soil quality (Barrios et al., 2018) and can provide key resources for wildlife (Perfecto et al., 1996).

The patterns of animal biodiversity in relation to different degrees of sun exposure is not straightforward and evidence comes mainly from the Neotropics. Many researchers reported higher animal abundance, diversity and richness in shade-grown coffee fields than in sun-exposed coffee fields (e.g. ants, Armbrecht et al., 2003, Perfecto et al., 2003; birds, Greenberg et al., 1997, Perfecto et al., 2003, Gordon et al., 2007, Borkhataria et al., 2012a, Philpott & Bichier, 2012; butterflies, Perfecto et al., 2003, Borkhataria et al., 2012a; mammals, Gordon et al., 2007, Caudill et al., 2014). In some cases, however, sun-exposed fields were reported to host higher abundance and diversity (e.g. birds, Perfecto et al., 2003, Smith et al., 2015; lizards, Borkhataria et al., 2012a) or no difference in abundance of some taxa (e.g. bees, Classen et al., 2014) between sun- and shade- grown coffee. The response to shade tree removal seems taxon-specific and possibly influenced by other factors such as biogeographical differences and differences in food availability (Smith et al., 2015). As pointed out by Smith et al. (2015), it is difficult to draw conclusions on broad-scale patterns such as the value of sun and shade coffee habitats unless studies comparing these two agriculture systems are extended to regions other than the Neotropics.

Pollinators can be influenced by the intensive use of chemicals in crops in direct and indirect ways (Russo et al., 2020). The use of chemical pesticides (also called synthetic pesticides, i.e. chemical substances used to kill, repel, or control pests) directly affecting pollinators and other non-targeted organisms (Goulson et al., 2015; Iwasaki & Hogendoorn, 2020). The use of chemical pesticides also has indirect negative effects on pollinators by disturbing community structure and influencing vectoring opportunities (Evans et al., 2018). The use of chemical fertilisers (also called synthetic fertilisers, i.e. chemical substances containing readily available elements that improve the growth and productivity of crops; Russo et al. 2020) in soil has an indirect role in shaping pollinator communities as it affects the plant communities (Schippers &

Joenje, 2002). Chemical fertilisers, in fact, decrease soil pH with a consequent modification of the bacterial and plant communities (Zhang et al., 2017). High levels of chemical fertiliser application can reduce soil invertebrate biodiversity by altering microclimate at the soil level (Hole et al., 2005), and this can cascade through food chains and impact pollinators (Russo & Shea, 2017). The use of organic fertilisers and pesticides has been shown to increase the abundance and diversity of several taxa (reviewed in Bengtsson et al., 2005, Hole et al., 2005, Tuck et al., 2014), although these reviews highlighted the need of further studies in the tropics.

In Indonesia, few studies have quantified animal biodiversity in coffee fields (e.g. Philpott et al., 2008; Rasiska & Khairullah, 2017) and none of these have investigated the difference between sun- and shade- grown coffee or the impact of using chemical fertilisers (but see Supriadi & Pranowo, 2016). This is a big gap in the literature, especially considering that Indonesia is not only the fourth largest coffee producer in the world (Szenthe, 2020) but also a global biodiversity hotspot (von Rintelen et al., 2017). Coffee production in Indonesia has increased since 2010, both in terms of local and exported coffee markets (Nopriyandi & Haryadi, 2017; Prajanti et al., 2020). With the increase in these markets, it is plausible to expect an intensification in the management of coffee fields, the consequent reduction of shade-grown coffee and the increased use of chemicals. For example, Schroth et al. (2015) predicted that there would be a production decline in *Arabica* coffee due to climate change and that this will result in an expansion of coffee cultivated areas of around 30% by 2050. It is thus key to understand the implications of shifting to an intensive management in this biodiversity hotspot. Here, we aim to investigate the relationship between shade cover and the abundance, diversity, and richness of butterflies in coffee home gardens in West Java, Indonesia. As significant pollinators, butterflies are key bioindicators of the state of coffee fields (Bravo-Monroy et al., 2015). Based on previous studies (Perfecto et al., 2003; Borkhataria et al., 2012a; Nesper et al., 2017), we expect a lower abundance, diversity, and richness of butterflies in sun-exposed fields and in fields with a lower shade tree diversity. Based on previous reviews (Bengtsson et al., 2005; Hole et al., 2005; Tuck et al., 2014), we also expect a decrease in abundance, diversity, and richness of butterflies with an increase in the use of chemicals. In addition, we predict that the presence of other crops and the closeness to the forest edge can positively influence the presence of butterflies (Boreux et al., 2013; Ho et al., 2017).

## 2. Methods

### *2.1. Animal surveys*

During two flowering seasons of coffee plants (July-August 2019 and July-August 2020), we sampled the abundance of butterflies in 42 coffee home gardens in the municipality of Cipaganti, Garut Regency, West Java, Indonesia (7.2786° S, 107.7577° E). Coffee home gardens covered a mean area of 1229 ± SD 807 $m^2$, for a total of 68790 $m^2$. The habitat around Cipaganti is a mosaic of traditional home gardens, where local farmers practice an annual perennial rotating crop system (Nekaris et al., 2017). Coffee is often planted together with understory crops (e.g. cassava, chili) and shade trees. Out of the ~400 coffee home gardens present in the area, we sampled a subset of gardens randomly chosen to represent the different management types in the agroforestry environment. We knew that some of the gardens were using organic farming (they obtained the certification ORGANIK Indonesia from ICERT) and we tried to include a similar number of inorganic gardens. The sampled coffee home gardens were at a distance of 1673 ± SD 328 m (range = 1105-2105 m) from the edge of the continuous forest from which they are connected by a series of home gardens and bamboo forest patches. Coffee home gardens were at a minimum distance of 15 m and at a maximum distance of 1805 m between each other. We considered distance from the nearest forest edge and calculated it in ArcGIS v 10.7.1. Before the data collection period, we identified and catalogued the species of butterflies present in the area based on inventories regularly done by the Little Fireface Project between 2012 and 2019. We created a list of species with images to allow quick identification. For new species missing from the list, we described a morphospecies and took a picture for further identification. We collected data via Pollard transects inside coffee home gardens, walking at around 0.2-0.4 km/h to record the individuals of butterflies within 5 m from the observer (Pollard & Yates, 1993). We set up six trails that included seven coffee home gardens each and recorded the encountered individuals of butterflies only inside gardens. We walked one trail per day, collecting data between 9:00 and 13:00 hrs. The period between May and September is relatively dry in the study area (Nekaris et al., 2017), and we did not collect data when raining. We set transects to cover the longest side of the coffee gardens via a straight line (mean side length was 37.9 ± SD 16.2). We walked a total distance of 15.1 km.

To determine shade cover in coffee home gardens, we used the Canopeo App that calculates the proportion of area shaded from pictures (Patrignani & Ochsner, 2015). We took four random and independent (minimum distance between points of 10 m, minimum distance from garden edge of 5 m) pictures and calculated the mean value for each coffee home garden. We ensured that the photos did not include understorey canopy such as banana leaves that would have biased the calculation of the tree shade cover. We also took note of the richness (i.e. number of species) of shade trees and of other crops in each home garden.

### *2.2. Farmers’ use of chemicals*

To estimate the use of chemical fertilisers and pesticides by coffee farmers, we interviewed the owners of coffee home gardens between March and April 2021. We asked them for the amount of chemical fertiliser used per year, the frequency of chemical fertilisation, the amount of chemical pesticide used per year, and the frequency of using chemical pesticides. The interviews were approved by the Oxford Brookes University Ethics Committee (number 181256). We used ordinal categories for the use of chemicals in home gardens as most of the farmers used organic (i.e., chemical-free farming). We categorised the use of chemicals as 1: no chemicals used; 2: chemical fertilisers and pesticides mixed with organic products; 3: intensive use of chemical fertilisers and pesticides, no organic materials used.

### *2.3. Data analysis*

In each coffee home garden, we calculated the number of individuals encountered (abundance), the Shannon Index (diversity), and the number of species (richness) of butterflies. We tested the effect of shade cover, shade tree richness, crop richness, distance from the forest, and use of chemicals on the number of individuals, the number of species and the Shannon Index per garden via Generalised Additive Mixed Models via “gamm” command in R 3.5.1 package “mgcv” (Wood, 2018). We used GAMM as they provide a flexible approach because they do not assume a linear or other parametric form of relationship *a priori* and can be used to reveal and estimate non-linear effects of the covariate on the dependent variable (Wood, 2017). For shade cover and distance from the forest we tested model with or without smooth terms and selected the model with the best fit based on the lowest Akaike Information Criterion. The other predictors were set as fixed factors in the models. We tested for multicollinearity and detected none as all the correlations coefficients were below 0.5. In case of number of individuals and number of species, we fit the dependent variables with Poisson distributions for count data and we used the $\log_{10}$ of the distance walked in each garden as offset in the analysis to account for the different size of gardens and the different sampling effort. This is a suggested procedure when handling count data derived from transects (e.g. Hedley et al., 2004; Campera et al., 2020). In case of Shannon index, we fit the dependent variable with a Gaussian distribution. Since the coffee home gardens were likely to be spatially correlated (Figure 1), we included a Gaussian spatial correlation structure in the models using the latitudes and longitudes of each garden (i.e. the coordinate of the centre of coffee gardens) (Dormann et al., 2007). GAMM was also chosen as it allows to control for spatial correlation. We used full restricted maximum likelihood method for model selection, tensor product smooth and penalised regression spline (Wood, 2017).

## 3. Results

The mean shade cover per coffee home garden was 20.3 ± SD 20.0 % (range=0.5-82.9 %); the mean shade tree richness was 2.5 ± SD 1.9 species (range=0.0-8.0 species); the mean richness of other crops was 1.2 ± SD 1.0 species (range=0.0-3.0 species). A total of 22 home gardens were organic, 11 used chemical fertilisers and pesticides mixed with organic products, and 8 had an intensive use of chemical fertilisers and pesticides. We recorded 54 species of butterflies (Nymphalidae = 23, Pieridae = 11, Papilionidae = 10, Lycaenidae = 3, and unidentified morphospecies = 7) in coffee home gardens. The butterflies of the family Papilionidae were encountered more frequently in coffee home gardens (0.033 ± SD 0.026 individuals/m; range = 0.002-0.106 individuals/m), followed by the Nymphalidae (0.020 ± SD 0.016 individuals/m; range = 0.000-0.083 individuals/m) and Pieridae (0.009 ± SD 0.008 individuals/m; range = 0.000-0.036 individuals/m). We recorded individuals belonging to species of the Lycaenidae only 16 times in all coffee home gardens. The abundance of butterflies was negatively influenced by the use of chemicals ($p=0.001$) and positively influenced by shade tree richness ($p<0.001$). The other predictors did not have a significant effect: crop richness ($p=0.130$), distance from the forest ($p=0.218$), shade tree cover ($p=0.780$). The diversity of butterflies was only influenced by shade tree richness ($p=0.046$). The other predictors did not have a significant effect: crop richness ($p=0.971$), distance from the forest ($p=0.955$), shade tree cover ($p=0.266$), use of chemicals ($p=0.596$). The richness of butterflies was negatively influenced by the use of chemicals ($p=0.039$) and positively influenced by shade tree richness ($p<0.001$). The other predictors did not have a significant effect: crop richness (p=0.181), distance from the forest (p=0.928), shade tree cover (p=0.380) (Table 1, Figure 2).

## 4. Discussion

We found a high diversity of butterflies in coffee home gardens, with a positive relationship between the richness of shade trees and the abundance, diversity and richness of butterflies. Home gardens with a complex structure have been shown to attract several taxa of pollinators, while sun-exposed fields attract only a few taxa (Classen et al., 2014). In our case, shade cover was not significant when the richness of shade trees was also taken into account, as also found by Nesper et al. (2017). This mean that the complexity of the home gardens is more important than the cover offered by shade trees. This might be a consequence of the fact that in the area, often shade cover is provided by *Eucalyptus* spp. that are known to reduce the productivity of coffee (Latini et al., 2020). The shade cover still has an important effect as it affects the microclimate (López-Bravo et al., 2012; Mariño et al., 2016), but the variety of shade trees is more important. This is further backed up by De Leijster et al. (2021) who found a positive, asymptotic relationship between butterfly richness and time after agroforestry implementation; this relationship varied significantly depending on the type of agroforestry, i.e., whether shade trees were planted sporadically throughout coffee farms (most successful), whether they bordered the farms or whether they were planted in “alleys”. Conversely, the presence of other crops in coffee home gardens did not have an impact on the presence of butterflies. The presence of other crops might still be beneficial since they can indirectly increase the productivity of coffee (Ho et al., 2017). The other factor that was not significant in the models was the distance from the forest, contrary to other studies that found a higher presence of pollinators in proximity of the forest (e.g. Boreux et al., 2013; González-Chaves et al. 2020). The lack of significance might be due to the fact that the forest was too far from the coffee home gardens (>1000 m), considering that butterflies usually cover distances of about 200-300 m (Brakefield, 1982). Finally, the use of chemicals had a negative influence on the abundance and richness of butterflies, confirming the general view that organic farming can favour the presence of pollinators (Bengtsson et al., 2005, Hole et al., 2005, Tuck et al., 2014). The diversity of butterflies was not influenced by the use of chemicals, meaning that the species evenness is similar in the area and that the intensively managed coffee home gardens benefit from the closeness of organic gardens.

The study area has a high diversity of butterflies and other animal pollinators; this can benefit crop production as most of the crops benefit from cross-pollination through the increased production of fruit and/or increased fruit quality (Klein et al., 2007). Pollination also helps in the maintenance of crop genetic variability by reducing inbreeding depression and improving resistance to environmental change (Garibaldi et al., 2011). It thus appears that the study area is capable of resilience, which is promising for conservation as this agroforestry environment hosts key animal species, such as the Javan slow loris *Nycticebus javanicus*, Javan palm civet *Paradoxurus javanicus*, Javan ferret badger *Melogale orientalis*, greater short-nosed fruit bat *Cynopterus sphinx*, and Javan kingfisher *Halcyon cyanoventris*, and several species of threatened songbirds (Nekaris et al., 2020).

Our findings highlight the importance of having a diverse shade cover and avoiding intensive use of chemical fertilisers and pesticides in coffee home gardens. This is because the abundance and richness of butterflies is clearly influenced by these two variables and a shift towards more intensive crop management might reduce the resilience of this environment in the near future. We are promoting several measures to ensure the maintenance of the complexity of this environment whilst at the same time promoting less intensive crop management (Campera et al., 2021). We are working with local coffee farmers to ensure they use more organic practices by specific training and incentives (e.g. equipment). For example, through the use of organic fertilisers, it is possible to reverse soil acidification and restore soil fertility (Adil et al., 2006). We promoted wildlife-friendly initiatives, such as a hunting ban and increased use of organic fertilisers and pesticides, and the coffee farmers obtained official certification from the Wildlife Friendly Enterprise Network in October 2020 (Campera et al., 2021). We are continuously ensuring that the values of the certification and the importance of wildlife-friendly practices are shared with local farmers as this has been shown to promote farmer participation (Chapman et al., 2019).

With the increase in the coffee market in Indonesia (Prajanti et al., 2020), it is important to study the effects that a possible intensification in crop management can produce. Indonesia has been particularly affected by a reduction of remnant forest and the subsequent shift to agriculture, therefore, promoting sustainable agriculture is crucial also considering the steep increase of the human population (Jha et al., 2014). Furthermore, *Arabica* coffee production may be particularly affected in the near future in Indonesia due to climate change and the consequent increase in temperature and reduction in rainfall (Schroth et al., 2015), as well as increased levels of insect pests and reduced numbers of their natural enemies (Chain-Guadarrama et al., 2019). Many parts of Indonesia are usually subject to an extended six-month drier period every year and protecting coffee plants from direct sun is essential to reduce plant dryness considering that many areas do not have adequate irrigation systems (Hussain et al., 2006). Promoting wildlife-friendly practices in coffee fields might be the key to ensure the maintenance of resilient agroforestry environments. Several studies in the Neotropics also showed that the yield does not necessarily increase with the reduction of shade cover, rather there might be a peak in productivity at intermediate shade cover (Soto-Pinto et al., 2000; Perfecto et al., 2005; Meylan et al., 2017). We showed that the shade tree diversity is a strong predictor to explain the presence of butterflies in coffee home gardens. This trend is also supported by Nesper et al. (2017) who showed that maintaining a diverse tree shade cover helps to maintain high coffee production and quality through a variety of mechanisms such as increased ecosystem services offered by pollination and natural pest control. Shade trees, in fact, provide key services such as increasing soil quality by nitrogen fixation and increasing litter biomass, protecting from direct sun, and attracting pollinators (Perfecto et al., 1996). We need to find ways to have a dialogue with coffee farmers to share our knowledge on wildlife-friendly practices, promote the benefits of wildlife-friendly practices, and provide advanced training and incentives (Campera et al., 2021). Complex agroforestry environments might represent the future of conservation for some threatened species that prefer human-modified habitats and ensuring the resilience of these environments is pivotal.

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**Table 1.** Results from the Generalised Additive Mixed Models to understand different predictors on the abundance (number of individuals), diversity (Shannon index), and richness (number of species) of butterflies in 42 coffee home gardens at Cipaganti, West Java, Indonesia.

| **Response variable** | **Gaussian spatial correlation** | **Predictor** | **Estimate** | **Std. Error** | **t-value** | **Smooth term** | |
|---|---|---|---|---|---|---|---|
| | | | | | | **edf** | **F** |
| Abundance | 3.02e-05 | Intercept | 0.61 | 0.24 | 2.53* | | |
| | | Crop richness | -0.07 | 0.04 | -1.55 | | |
| | | Distance from forest | 1.59e-04 | 1.27e-04 | -1.25 | | |
| | | Shade cover | | | | 1.00 | 0.08 |
| | | Shade tree richness | 0.18 | 0.02 | 8.41** | | |
| | | Use of chemicals | -0.21 | 0.06 | -3.59** | | |
| Diversity | 3.17e-04 | Intercept | -0.82 | 0.32 | -2.57* | | |
| | | Crop richness | 0.19e-02 | 5.30e-02 | 0.04 | | |
| | | Distance from forest | 0.10e-04 | 1.69e-04 | 0.06 | | |
| | | Shade cover | | | | 1.00 | 1.28 |
| | | Shade tree richness | 0.06 | 0.03 | 2.09* | | |
| | | Use of chemicals | -0.03 | 0.06 | -0.54 | | |
| Richness | 4.30e-04 | Intercept | -0.38 | 0.42 | -0.90 | | |
| | | Crop richness | -0.08 | 0.06 | -1.37 | | |
| | | Distance from forest | 0.20e-04 | 2.21e-04 | 0.09 | | |
| | | Shade cover | | | | 1.00 | 0.79 |
| | | Shade tree richness | 0.11 | 0.03 | 3.62** | | |
| | | Use of chemicals | -0.16 | 0.07 | -2.15* | | |

* p-value<0.05, **p-value<0.01

**Figure 1.** Location of the 42 coffee home gardens surveyed in relation to: A) the use of chemicals (1: organic; 2: mixed organic and chemicals; 3: intensive use of chemicals); B) tree shade richness (number of shade tree species) at Cipaganti, West Java, Indonesia. The size of the circles is proportional to the sampling effort on each garden calculated as $\log_{10}$ of the distance walked during transects. The line indicates the edge of the protected forest.

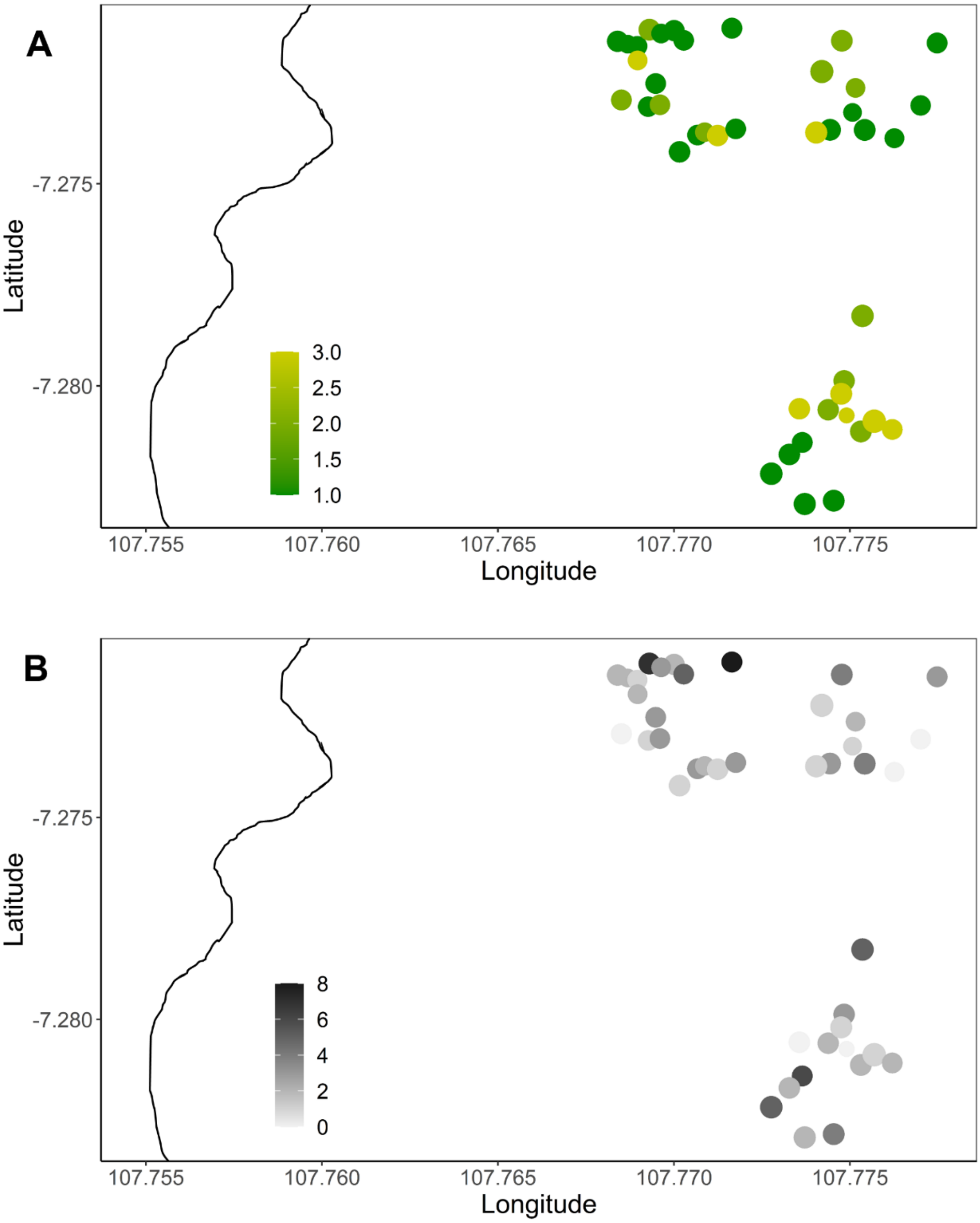

**Figure 2.** Abundance (A), diversity (B), and richness (C) of butterflies in relation to the use of chemicals (1: organic; 2: mixed organic and chemicals; 3: intensive use of chemicals) and tree shade richness (number of shade tree species) in 42 coffee home gardens in West Java, Indonesia. Data are model predicted values and fit lines from Generalised Additive Mixed Models, and grey areas are 95% confidence intervals. We only show the two predictors that were significant in the models.