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– CENTRE OF BIODIVERSITY AND SUSTAINABLE LAND USE –

Impacts of weeding and fertilisation management on arthropod communities in oil palm plantations

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Abstract

The rapid expansion of oil palm plantations at the expense of lowland rainforests is a major threat to tropical biodiversity. Integration of conservation management into existing oil palm plantations may help to conserve biodiversity. One promising approach is to reduce the application of fertilizers and herbicides, which could positively affect arthropods by enhancing the undergrowth vegetation. However, knowledge on the biodiversity potential of such improved management practices in oil palm plantations is scarce. In this study, I conducted a full-factorial experiment to study the effects of reduced fertilization and weeding management on arthropod communities in a commercial oil palm plantation on Sumatra, Indonesia. I present evidence indicating that the total aboveground arthropod abundance does not benefit from a less intensive management in oil palm plantations. However, I found that the responses of different taxonomic and functional groups were highly variable, ranging from positive to neutral and negative. Reduced fertilizer application enhanced vegetation cover, which benefited lepidopterans and parasitoid wasps. Lepidopterans also positively responded to a high number of flowers in the undergrowth vegetation which were more numerous in study plots with mechanical weeding instead of conventional herbicide application. In contrast, ants, flies and cicadellids were negatively affected by increasing plant cover and presence of a high number of flowers. My study demonstrates the potential of improved fertilizer and weeding management for arthropod conservation even in large-scale commercial oil palm plantations. The diverse responses across arthropod groups indicate that a simple increase in vegetation cover and species richness do not effectively enhance all arthropods. Further improvements of oil palm management may include promoting higher habitat heterogeneity to meet requirements of many different species. Further research, for example on the functional link between plant and arthropod communities, will allow developing even more precisely targeted management practices.

1. Introduction

In the last decades there has been an unprecedented loss of tropical lowland rainforest (Laurance et al. 2014). One reason is the expansion of agricultural areas, especially those of oil palm plantations (Sheil et al. 2009). In 2009 almost 10 % of the world's permanent crop land was used for palm oil production (Sheil et al. 2009). Since rainforests feature high biodiversity, their destruction is a huge threat to flora and fauna. The conversion of rainforest to oil palm plantations leads to an impoverishment of the landscape and the loss of natural habitats (Foster et al. 2011). Furthermore the application of herbicides and pesticides as well as fertilization can negatively affect the remaining biodiversity. Although there are high numbers of studies dealing with the conversion of rainforest to oil palm, only a small proportion of these refer to biodiversity and in particular to the impact of plantation management on biodiversity (Turner et al. 2008). With my master thesis I make a contribution to close this research gap.

Similar to other animal groups, arthropods are often negatively affected by oil palm plantations (Clough et al. 2016). Few studies find a positive effect on them (Turner and Foster 2009; Liow et al. 2001). However, these effects refer to certain arthropod groups (Liow et al. 2001) or habitats on the oil palm (Turner and Foster 2009). There are three main reasons for the negative effect of oil palm plantations on arthropods. First of all, the conversion of rainforest to agricultural land leads to a biological simplification (Foster et al. 2011). Reduction of plant diversity typically results in reduced arthropod diversity (Knops et al. 1999; Taylor et al. 2006). Vegetation variables, like the percentage ground cover of weeds can be very important for certain arthropod groups (Koh 2008). All of these variables are reduced in oil palm plantations compared to rainforests (Foster et al. 2011). Secondly, altered microclimate in oil palms affect the insects (Foster et al. 2011). Humidity and temperature are more extreme and vary more on a daily basis (Foster et al. 2011). These parameters can affect the activity and growth of insects, as well as their food quality and activity of predators (Jaworski and Hilszczański 2013). Lastly, there are direct human impacts (Foster et al. 2011). Since oil palm farming causes a degraded soil quality and nutrient leaching, it relies on fertilizer inputs (Clough et al. 2016). So, high amounts of fertilizer, as well as herbicides are deployed at the plantations (Clough et al. 2016).

Recent research on means to conserve biodiversity focused on the integration of conservation management into existing oil palm plantations beyond protecting tropical rainforests from agricultural use (Teuscher et al. 2016; Koh 2008; Luskin and Potts 2011). One conservation approach is to restore habitat heterogeneity at the plantations. So far, planting tree islands into plantations has been focused on (Teuscher et al. 2016; Corley and Tinker 2008; Chazdon 2008). But, less intensive management practices by reduction of fertilizer and mechanical removal of weeds could also positively affect undergrowth vegetation and thus counteract biological simplification. Especially arthropods could benefit from such conservation actions. Despite the improvement of habitat availability and complexity, more diverse and denser understory vegetation can enhance the microclimate at the ground (Yates et al. 2000; Messier et al. 1998). For example, closer canopy reduces the diurnal variation in temperature (Luskin and Potts 2011). So, less intensive fertilizer and weeding management can address to all three aspects which are mainly responsible for the reduced diversity of arthropods in oil palm plantations: biological simplification, change in microclimate and direct human impacts.

Despite the potential of less intensive management as conservation mean there are only few studies dealing with the effects of fertilization and herbicide use on arthropods in oil palm plantations. Studies from other agricultural systems stress the importance of weeding and fertilization management in bottom-up control of arthropods by altering the vegetation. Arthropods highly depend on plants since they provide food, habitat for egg-laying and refuge from predators (Richards 2001; Skevington and Dang 2002). Consequently, reduction in plant cover, species richness or number of flowers is negatively correlated with arthropod richness and abundance (Knops et al. 1999; Obermaier et al. 2008; Hudewenz et al. 2012). Several studies revealed that herbicide use decreases plant richness and biomass, which in turn affects arthropods negatively (Moreby and Southway 1999; Richards 2001; Kleijn and Snoeijing 1997). So far, in oil palm plantations the negative effect of herbicides has been shown only for belowground arthropods, as well as one spider species (Ashton-Butt et al. 2018; Spear et al. 2018). The effect of fertilizer on arthropods and plants is more ambivalent. Many plants and arthropods are limited by nutrients, especially by nitrogen, and thus benefit from higher amounts of fertilizer (Cobb and Waring 2017; Sun et al. 2011). However an increased fertilization also increases competition for light and by that decreases plant diversity and cover (Thomas et al. 1999). Therefore, higher amounts of fertilizer can also negatively affect arthropods by bottom-up control. Whereas in other agricultural systems multiple studies deal with the importance of management for arthropods, little is known about it in oil palm plantations. My study takes a closer look at effects of both fertilizer and weeding management on arthropods in one oil palm plantation in Indonesia.

In Indonesia, being the top producer of palm oil in the world, large areas of lowland rainforest were converted to oil palm plantations during the last decades with the highest losses of primary forest on Sumatra (Margono et al. 2014). The collaborative German-Indonesian research project “CRC 990 – EFForTS” (Ecological and Socio-economic Functions of Tropical Lowland Rainforest Transformation Systems project) focusses on the ecological and socio-economic impacts of the rainforest transformation on Sumatra. The presented thesis is integrated into this project. I studied the impacts of conventional and reduced fertilization as well as conventional and mechanical weeding on arthropod communities in a large-scale, commercial oil palm plantation. To this end, I described the understory vegetation in response to oil palm management in a full-factorial experiment, and used multiple sampling methods to assess the arthropod diversity across a wide range of taxonomic and functional groups. Specifically, I addressed two hypotheses with my master thesis:

(1) The undergrowth vegetation benefits from less intensive management characterized by mechanical weeding and reduced amounts of fertilizer.

(2) More diverse and highly covering vegetation increases the abundance and species richness of arthropods.

2. Materials and Methods

Study Site

Data were collected in a large-scale, conventional oil palm plantation (PTPN VI) in Jambi Province on Sumatra, Indonesia from June to July 2018 (S 01.70538, E 103.39853; Figure 1). The palms of the plantation were planted in 2002. I sampled in 16 different plots with a size of 50 x 50 m each (Figure 2). The experiment combines the combinations of two agronomically important management factors: fertilization and weeding. One of four different management treatments referring to a combination of weeding (mechanical/herbicide use) and fertilization (reduced/conventional) is conducted on each plot. Each treatment was replicated four times. Conventional fertilization management refers to the application of 260 N, 50 P and 220 K kg/ha/yr, whereas reduced fertilization refers to an application of 136 N, 17 P and 187 K kg/ha/yr. The rates are divided into two applications per year. The removal of weeds is done either mechanically four times per year or by using the herbicide Glyphosate. Amounts of 1500 cc/ha/yr are applied divided into four applications per year. The management treatments are conducted since 2017.

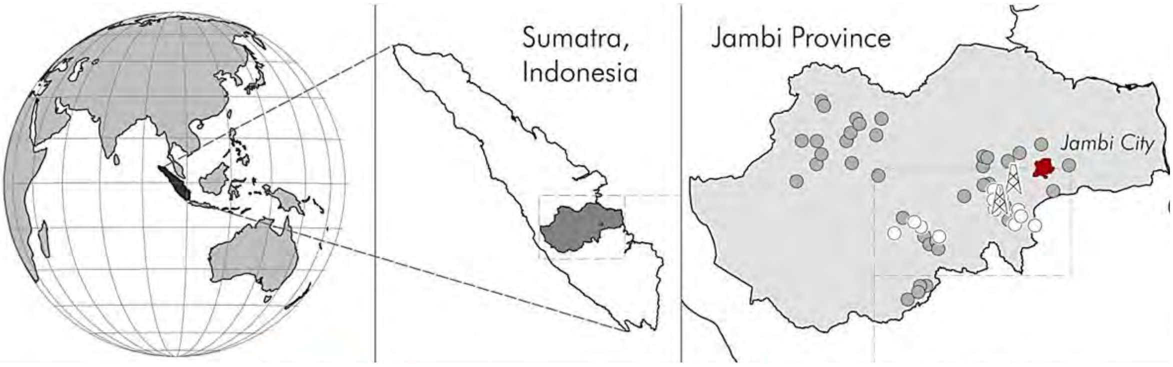

Figure 1: Location of the research area Jambi Province in Indonesia. The red star marks Jambi City, capital of Jambi Province. The oil palm plantation PTPN VI is located southwest of the city.

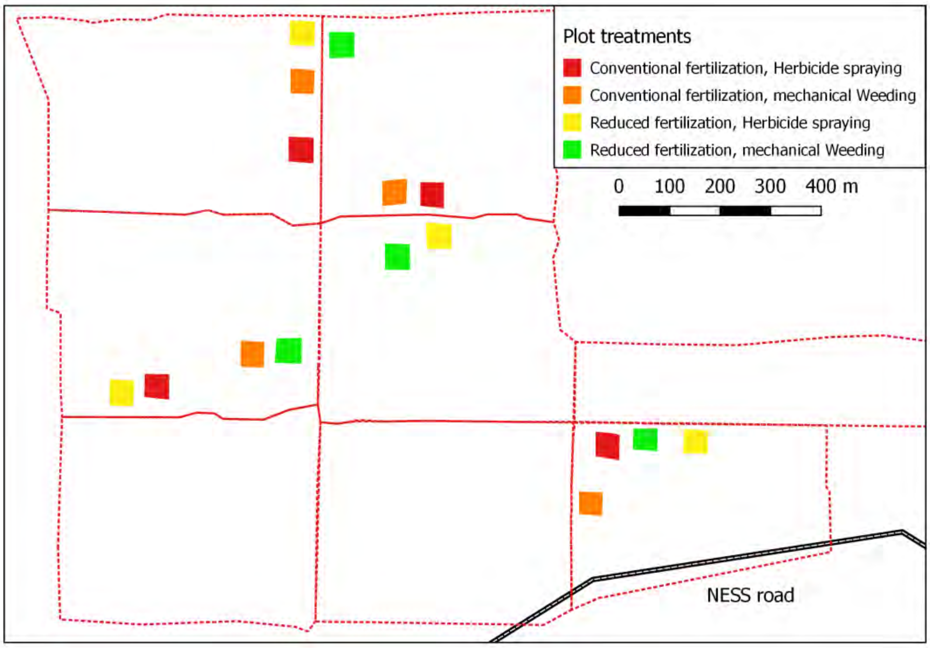

Figure 2: Plot design of the experiment. Each colored square marks one 50 x 50 m plot. Each color symbolizes one management treatment. Red lines mark management units of the plantation.

Sampling

Arthropod samples were collected from 4th of June until 5th of July 2018. I used three different sampling methods: pan traps, sweep netting and malaise traps. Every method was conducted within or close to the core area of the plot to avoid edge effects of bordering plantation management (Figure 3). Pan traps attract flying insects such as bees, wasps (Hymenoptera) and flies (Diptera). I erected 3 pan traps per plot. The traps were hold together by a mesh wire which was attached to a stick. The height of the wire was around the vegetation height. The traps were placed between two palms in a spot with typical undergrowth vegetation (representative in coverage and height). Pan traps were placed in each plot for 48 h. Sweep netting of the undergrowth vegetation was conducted to capture those insects that live within or feed on these plants (e.g. Hemiptera or Coleoptera). I conducted sweep netting on two transects per plot. Transects were placed in areas representing the typical vegetation of each plot. Their length was around 10 m and per transect 10 beats with the sweep net were done. I erected pan traps and conducted sweep netting over the sampling period four times in each plot. The malaise trap was placed between two palms for 24 h. The collected arthropods were stored in 70 % ethanol.

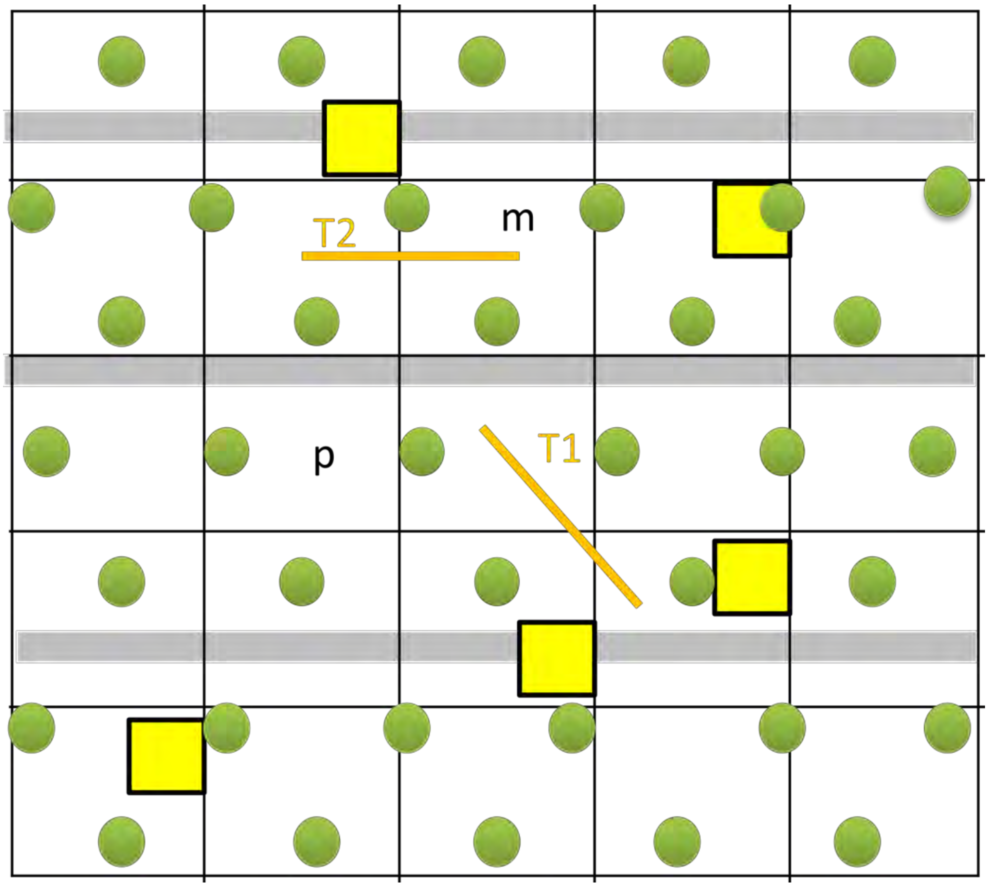

Figure 3: Exemplary position of traps within one plot. Green spot = oil palm, m = malaise trap, p = pan trap, T = transect for sweep netting. Yellow boxes mark position of subplots used for determination of plant species richness.

In addition to the arthropod collection, I also described the undergrowth vegetation in each plot. I noted coverage and number of flowers within 1 m to both sides of the transects I used for sweep netting. Data on plant species richness were provided by expert botanists (Rembold & Kreft, unpublished data), collected in September 2016 and 2017. Plant species of the undergrowth vegetation were determined in each plot in 5 subplots which are 5x5 m in size and randomly distributed over the plot.

All arthropod samples (except the ones of the order Araneae and the group of moths) were identified to the most specific taxonomic level possible (Centre for Land and Biological Resources Research 1993; Schaefer 2010; Triplehorn and Johnson 2005). Specimens which could not be identified to the species level were grouped into morphospecies. One individual of each morphospecies was stored in an extra tube and used as a reference. Arthropods of subsequent samples were compared to the references. When a specimen did not resemble any of the references, it was defined as a new morphospecies. For each sample, the number of individuals per morphospecies was noted.

Statistical Analysis

I used species accumulation curves to test for sampling completeness of arthropod diversity across the different sampling methods. Linear models were conducted to test for the effects of oil palm management treatments on vegetation variables, as well as the effect of vegetation on arthropod diversity and abundance. Before I performed the models, potential correlations between vegetation data were tested by using Pearson's product moment correlation coefficients. Vegetation variables had no or only weak correlations (Pearson’s r of all correlations < 0.56) which allowed me to analyze their effects on arthropods together in one model. For count data (arthropod abundance, species richness and number of flowers) I used generalized linear models with Poisson distribution to analyze the data. For the analysis of plant cover and species richness data I used linear models with Gaussian distributions because mean values were modelled. First, I examined the interactive effect of weeding and fertilizer management on vegetation variables. I tested the effect on plant cover, plant species richness and number of flowers (ln-transformed). When there was no significant interactive effect, I simplified the model and tested for additive effects. Following the vegetation analysis, I examined the additive effect of the three vegetation variables on the abundance and species richness of all arthropods and certain taxonomic groups. For the abundance only subgroups of Diptera, Hemiptera, Araneae and Hymenoptera could be tested because other orders had a number of individuals too small for analysis. I decided to include only families of Cicadellidae, Formicidae and the group of parasitoid wasps of orders Hemiptera and Hymenoptera in the separated analysis because they made up by far their largest groups. Furthermore they represent certain diets or ecosystem services like pollination and biological pest control. One super-dominant ant species (290 individuals) that was recorded almost exclusively on two study plots was excluded from the separated abundance analysis to avoid sampling bias. Similarly to the models for abundance, I analyzed the effects of changes in the vegetation on species richness of dipterans, hymenopterans and hemipterans. Other orders were either not identified to morphospecies level or had too few individuals and were thus not included in the richness analyses.

All data processing and statistical analysis were performed using R (Oksanen et al. 2018; R Core Team 2018) and Microsoft Excel (2010).

3. Results

In total, 8123 arthropods of 16 different orders were collected. The three orders with the highest number of individuals were Diptera (2674 individuals), Hymenoptera (1913) and Hemiptera (1729). The most abundant families were leafhoppers (Cicadellidae, 1373 individuals), ants (Formicidae, 1257) and phorids (Phoridae, 708). The sampling methods differed in their ability to trap arthropods not only in total quantity but also in attraction to certain orders (Appendix, Figure A1). Sweep netting was the most effective sampling method with an average of 65 arthropods per sample. Hymenoptera made up the highest portion of all sweep net samples (27.0 %), followed by Diptera (24.7 %) and Araneae (23.7 %). In pan traps there was an average of 49 animals per sample; slightly more than in malaise traps (47 arthropods per sample). In contrast to sweep net samples, dipterans were the most abundant arthropods in malaise traps (40.3 % of all malaise trap samples) and pan traps (42.0 %). Malaise traps also sampled lepidopterans to a great extent (33.7 % of all malaise trap samples). Hemiptera (29.6 %) and Hymenoptera (21.0 %) were the second and third most abundant orders in pan traps. All sampling methods sampled arthropods to an equivalent extent (Appendix, Figure A2).

The understory vegetation cover across the 16 study plots ranged between 18 % and 85 %. In total, the undergrowth vegetation was composed of 123 different plant species. *Clidemia hirta* (Melastomataceae)*, Centotheca lappacea* (Poaceae) and *Asystasia gangetica* (Acanthaceae) were the species with the highest cover and number of flowers. Number of flowers per transect (20 m^2) ranged from 0 up to 73 flowers.

Management effect on undergrowth vegetation

The analysis of vegetation variables revealed that the understory vegetation was only partly influenced by plantation management. Whereas differences in management practices had no effects on plant species richness, plant cover and number of flowers were significantly affected (Figure 4, Table 1). Cover was higher at reduced fertilization but did not differ between weeding practices, i.e. whether weeds were manually removed or by using herbicides (Figure 4 a). I found an interactive effect of weeding and fertilizer application on number of flowers (Figure 4 c). Most flowers were found at plots with conventional fertilization and mechanical weeding, followed by those with reduced fertilization and herbicide use and reduced fertilization and mechanical weeding. The lowest numbers of flowers were found at conventional fertilization and herbicide use.

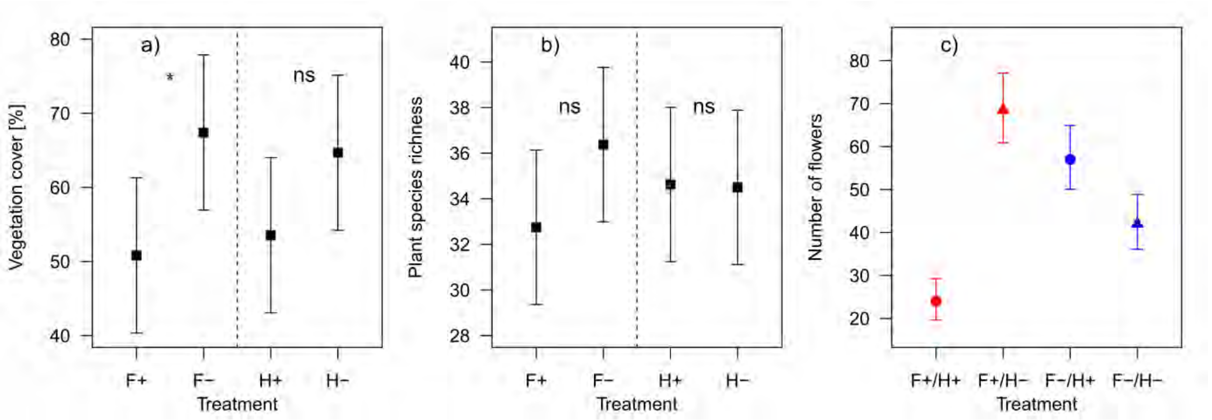

Figure 4: Effect of fertilizer (F) and herbicide (H) treatments on vegetation variables. Figures show predictions of generalized linear models either with additive (dashed middle line) or interactive explanatory variables. In additive models: ns = not significant, * = significant on 0.05 - level. F+ = conventional fertilization, F- = reduced fertilization, H+ = herbicide use, H- = mechanical weeding. Effect on a) vegetation cover, b) plant species richness and c) number of flowers are shown. Red = Conventional fertilization, Blue = reduced fertilization, dot = herbicide use, triangle = mechanical weeding.

Table 1: Plant cover, species richness and number of flowers in response to fertilization and weeding management. Intercept = herbicide use and conventional fertilization. Significant predictors (P < 0.05) are shown in boldface type.

	Estimate	**SE**	**t**	**P**
a) Plant cover				
(Intercept)	45.250	5.937	7.621	<0.001
Mechanical weeding	11.125	6.856	1.623	0.129
Reduced fertilization	**16.594**	**6.856**	**2.420**	**0.031**
b) Plant species richness				
(Intercept)	32.812	1.919	17.099	<0.001
Mechanical weeding	-0.125	2.216	-0.056	0.956
Reduced fertilization	3.625	2.216	1.636	0.126
c) Number of flowers				
(Intercept)	23.999	0.102	31.138	<0.001
Mechanical weeding, conventional fertilization	**2.854**	**0.119**	**8.843**	**<0.001**
Herbicide use, reduced fertilization	**2.375**	**0.122**	**7.110**	**<0.001**
Mechanical weeding, reduced fertilization	**-3.873**	**0.156**	**-8.668**	**<0.001**

Effect of vegetation on arthropod abundance and species richness

Surprisingly, high plant cover, species richness and number of flowers negatively affected the overall abundance of all arthropods (Figure 5 a-c, Table 2). However, separated analyses by taxonomic groups revealed a more diverse suit of responses to plant variables (Figure 5 d-f, Table 2). Whereas the abundances of dipterans and formicids were negatively related to the amount of plant cover, lepidopterans and parasitoid wasps responded positively (Figure 5 d). In the case of parasitoid wasps this effect was only marginally significant. Cicadellids showed no response to plant cover, but they decreased in abundance with increasing plant species richness (Figure 5 e). No other group was influenced by plant species richness. The number of flowers per study plot had contrasting effects on leafhoppers, ants and lepidopterans (Figure 5 f): an increasing number of flowers resulted in reduced abundance of leafhoppers and ants. Contrastingly, lepidopterans were more abundant in plots with higher number of flowers. Spiders were not affected by any of the vegetation variables (Table 2). In contrast to abundance, overall arthropod species richness was not related to variation in vegetation variables (Figure 5 g-l). Plant species richness had no effect on richness of any arthropod group (Figure 5 k). Plant cover only had a negative effect on Diptera richness (Figure 5 j), but did not affect richness of ants, leafhoppers and parasitoid wasps. Likewise, the number of flowers only marginally affected leafhopper richness negatively (Figure 5 l), but impacted no other arthropod group.

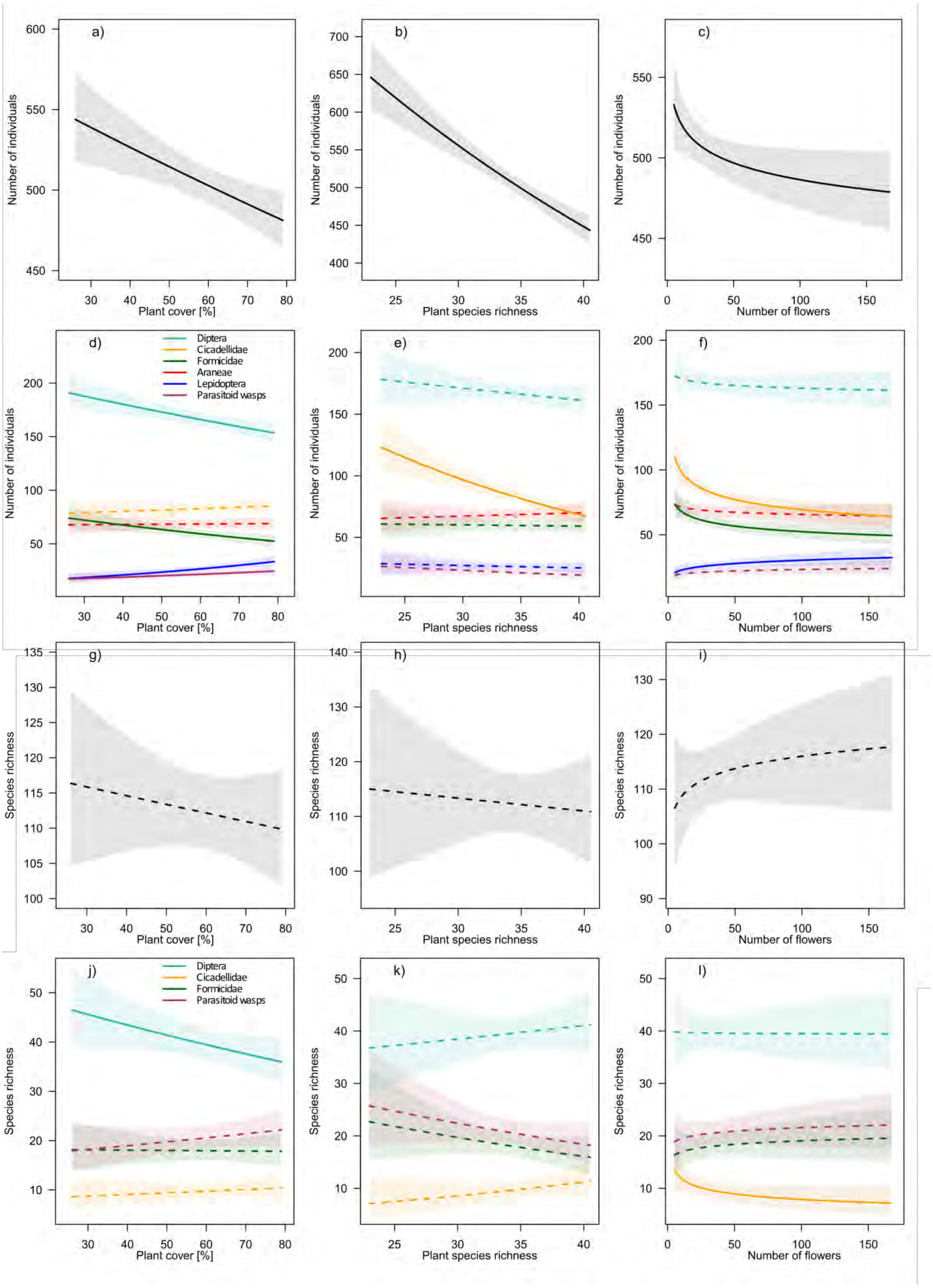

Figure 5: Effects of vegetation variables on arthropod abundance (a-f) and species richness (g-l). Figures show predictions of generalized linear models. Number of flowers was transformed back from logarithmic transformation for a better visualization. Dashed lines = non-significant predictions, continuous lines = significant predictions (P < 0.05). Effects of plant cover on parasitoid wasps (d) and number of flowers on Cicadellidae (l) were only marginally significant (P < 0.10). Effect on total arthropod abundance of plant cover (a), species richness (b) and flowers (c), on certain arthropod groups of plant cover (d), species richness (e) and flowers (f), on total species richness of plant cover (g), species richness (h) and flowers (i) and on richness of certain groups of plant cover (j), species richness (k) and flowers (l) are shown.

Table 2: Arthropod abundance (1) and species richness (2) in response to plant cover, plant species richness and number of flowers. Results of generalized linear models for all arthropods (a) and certain groups (b-g) are noted. Significant predictors (P < 0.05) are shown in boldface type.

	Estimate	SE	z	P		Estimate	SE	z	P
1) Abundance					**2) Species richness**				
a) All Arthropods					**a) All Arthropods**				
(Intercept)	7.207	0.089	81.206	<0.001	(Intercept)	4.759	0.206	23.142	<0.001
Plant cover	**-0.002**	**0.001**	**-3.294**	**<0.001**	Plant cover	-0.001	0.001	-0.733	0.463
Plant species richness	**-0.021**	**0.003**	**-7.273**	**<0.001**	Plant species richness	-0.002	0.006	-0.323	0.747
Number of flowers	**-0.031**	**0.014**	**-2.209**	**0.027**	Number of flowers	0.028	0.029	0.969	0.333
b) Formicidae					**b) Formicidae**				
(Intercept)	4.920	0.259	19.026	<0.001	(Intercept)	3.431	0.494	6.951	<0.001
Plant cover	**-0.006**	**0.002**	**-3.266**	**0.001**	Plant cover	0.000	0.004	-0.090	0.928
Plant species richness	-0.002	0.008	-0.197	0.844	Plant species richness	-0.020	0.016	-1.271	0.204
Number of flowers	**-0.113**	**0.040**	**-2.798**	**0.005**	Number of flowers	0.052	0.073	0.708	0.479
c) Parasitoid wasps					**c) Parasitoid wasps**				
(Intercept)	3.062	0.472	6.488	<0.001	(Intercept)	3.310	0.471	7.020	<0.001
Plant cover	0.007	0.004	1.892	0.059	Plant cover	0.004	0.004	1.118	0.264
Plant species richness	-0.018	0.015	-1.204	0.229	Plant species richness	-0.020	0.015	-1.295	0.195
Number of flowers	0.069	0.067	1.023	0.306	Number of flowers	0.045	0.069	0.654	0.513
d) Cicadellidae					**d) Cicadellidae**				
(Intercept)	6.041	0.202	29.950	<0.001	(Intercept)	1.758	0.719	2.447	0.014
Plant cover	0.002	0.002	0.866	0.386	Plant cover	0.003	0.005	0.681	0.496
Plant species richness	**-0.034**	**0.007**	**-4.801**	**<0.001**	Plant species richness	0.027	0.022	1.200	0.230
Number of flowers	**-0.153**	**0.034**	**-4.481**	**<0.001**	Number of flowers	-0.180	0.100	-1.798	0.072
e) Diptera					**e) Diptera**				
(Intercept)	5.625	0.161	34.845	<0.001	(Intercept)	3.749	0.345	10.881	<0.001
Plant cover	**-0.004**	**0.001**	**-3.427**	**0.001**	**Plant cover**	**-0.005**	**0.002**	**-1.983**	**0.047**
Plant species richness	-0.006	0.005	-1.119	0.263	Plant species richness	0.007	0.011	0.605	0.545
Number of flowers	-0.019	0.024	-0.788	0.431	Number of flowers	-0.003	0.049	-0.053	0.958
f) Araneae									
(Intercept)	4.199	0.263	15.946	<0.001					
Plant cover	0.000	0.002	0.163	0.870					
Plant species richness	0.004	0.008	0.461	0.645					
Number of flowers	-0.036	0.038	-0.944	0.345					
g) Lepidoptera									
(Intercept)	2.387	0.454	5.260	<0.001					
Plant cover	**0.012**	**0.003**	**3.679**	**<0.001**					
Plant species richness	-0.007	0.014	-0.524	0.600					
Number of flowers	**0.125**	**0.061**	**2.063**	**0.039**					

4. Discussion

My study revealed that both undergrowth vegetation as well as above-ground arthropods respond to changes in management practices in oil palm plantations. Thus, in contrast to my assumptions, that there is a clear positive effect of less intensive management, the responses differed strongly between different functional arthropod groups and vegetation variables. Reduced application of fertilizers increased the plant cover which in turn negatively affected ants and dipterans, but enhanced parasitoid wasps and lepidopterans. The amount of flowers was higher when weeding was done mechanically. Thereby lepidopterans were enhanced, whereas cicadellids and ants responded negatively.

Vegetation responses to oil palm management

This work revealed that the effect of treatment practices on the understory vegetation in oil palm plantations is limited. Only cover and flowers, not species richness, actually do benefit from a less intensive management which partly disconfirms my first hypothesis that all vegetation variables would be positively affected. Undergrowth vegetation cover increased with reduction of fertilizer. On the one hand is this in line with other studies which found reduced plant cover with higher amounts of fertilizer because of an increased competition for light (Hautier et al. 2009; Turkington et al. 1998; Thomas et al. 1999). On the other hand, there are also converse studies which show the positive effect of fertilization on plant cover (Gehring et al. 1999; Grellmann 2002). Herbicide use affected only the number of flowers, not vegetation cover and species richness, in contrast to the results of previous work (Kleijn and Snoeijing 1997; Asteraki et al. 2004). The lack of response, especially in plant species richness, could be explained by a time-lag (Metzger et al. 2009; Bertrand et al. 2011). Since the new management treatments of mechanical weeding and reduced fertilization have been applied only for one year, plants had short time to adapt to the changed environmental conditions.

Effect of vegetation on arthropod abundance and species richness

My study showed that total arthropod abundance in oil palm plantations is influenced by changes in the undergrowth vegetation. Total arthropod abundance responded negatively to increasing plant cover, plant species richness and number of flowers. This is in contrast to my second hypothesis, as well as multiple studies which found positive effects of increasing vegetation cover and species richness on arthropods (Knops et al. 1999; Koh 2008; Obermaier et al. 2008; Masters et al. 1998; Taylor et al. 2006). In these studies the benefit of higher plant cover and richness for arthropods is caused mainly by the provision of more feeding sources and egg-laying sites for herbivores with subsequent positive effects on predators and parasitoids (Price et al. 1980).

Nevertheless there are also explanations for the negative response of arthropods to an increase of vegetation cover and richness. For example, the plant community changed in presence or cover ratio of certain plant species. Especially for monophagous herbivores these vegetation characteristics could be causally relevant (Scherber et al. 2006; Hudewenz et al. 2012). Another possible explanation is that nitrogen inputs differ among the fertilizer treatments. Conventional fertilization is characterized by higher inputs of nitrogen. In turn higher nitrogen concentration in plants leads to increased abundance of herbivorous arthropods (Janzen and Schoener 1968; Cobb and Waring 2017; Lu et al. 2007; Masters et al. 1998). Since in my study plant cover was lower at plots with conventional fertilization compared to plots with reduced fertilization, the correlation of lower plant cover and higher arthropod abundance could be explained by a common cause: higher nitrogen inputs. Moreover, it has to be considered that the oil palm plantation already exists for 16 years leading to a reduction in the arthropod diversity prior to my study (Clough et al. 2016). Species which cannot adapt to intensive management have likely already disappeared in the study area. Hence, the examined arthropod community probably consists mostly of species which can exist or even benefit from highly disturbed areas, for example invasive species (Brühl and Eltz 2010).

The presence and direction of effects of vegetation on arthropod abundance differed strongly between taxonomic groups. Plant cover had the most variable effect across the groups: reduced plant cover increased dipteran and ant abundance, while abundance of lepidopterans and parasitoid wasps decreased. Apart from altering food sources, change in vegetation cover can also alter physical factors at the ground, like temperature and light (Yates et al. 2000; Messier et al. 1998). This can be one reason for the decline of formicids at higher plant cover. Some ant species prefer warmer and lighter areas (Vele et al. 2009; Amiri et al. 2009) which are provided more at sites with reduced vegetation cover (Messier et al. 1998; Yates et al. 2000). Furthermore, in oil palm plantations mostly invasive, non-forest ant species are found (Brühl and Eltz 2010), which should benefit from more disturbed, less-shady habitats. For example, I found the two ant species *Anoplolepsis gracilipes* (yellow crazy ant) which is invasive in Indonesia and *Odontoponera denticulata* which occurs often in disturbed habitats in my study area.

The negative response of dipterans to higher plant cover is difficult to explain since this order is extremely diverse and contains a wide variety of lifestyles (Skevington and Dang 2002). Yet, for the most abundant family within the dipterans in this study - Phoridae - one explanation can be offered. Several phorid species parasitize ants (Tonhasca Jr 1996; Guillade and Folgarait 2011; Wuellner and Saunders 2003). Reduction of their host species at higher vegetation cover could be one factor decreasing the abundance of Diptera. The underlying pattern driving the increase of parasitoids at higher plant cover remains unclear. In other studies higher vegetation cover reduced parasitoid foraging by decreasing their detectability of host species (Gols et al. 2005; Kruidhof et al. 2015; Obermaier et al. 2008). Also, higher densities of host species normally lead to increasing parasitism (Knops et al. 1999; Obermaier et al. 2008).

The responses of butterflies and leafhoppers to changes in the undergrowth vegetation indicate changes in the plant community not only with increasing plant species richness but also with increasing plant cover. Butterflies were affected positively by both plant cover and flower abundance. Since nectar is the main feeding source of most adult lepidopterans, they require high number of flowers (Haddad and Baum 1999; Schultz and Dlugosch 1999). Furthermore, both larvae and adults are mainly specialized herbivores, which depend on the presence of certain plant species (Diniz and Morais 2002; Habel et al. 2016). Higher plant covers therefore have potentially increased the percentage coverage of their host plants relative to other plant species. This is supported by a basic comparison of plant species compositions between the plot with the highest and the lowest cover: *Asystasia gangetica* made up 37 % of the total covered area at the highest vegetation cover in comparison to 10 % at the lowest cover. Likewise, *Axonopus compressus* increased from 3 % to 6 %. Both of these plants are important host plants for tropical lepidopteran species (Robinson et al. 2010). Since some lepidopteran larvae are predated by ants (Dyer 1995), their decrease at low plant cover which in turn supports high numbers of ants can also be due to predator avoidance or top-down control (Damman 1987; Sanders and Platner 2007). Similar to lepidopterans, most species of family Cicadellidae are host-specific herbivores. Their negative response to increasing plant species richness and flowers indicates that their host plants decrease in their coverage when these variables increase.

In contrast to arthropod abundance, species richness was influenced by vegetation only in two groups: Diptera and Cicadellidae. Diversity of flies was negatively affected by increasing plant cover. As mentioned before, the high diversity of Diptera makes their results difficult to explain. A wide variety of potential factors could lead to the loss of dipteran species at higher plant cover: absence of host plants for phytophagous species or host arthropods for parasitoid species, temperature (Hendrichs et al. 1991) and light conditions (Aluja and Birke 1993). Lower species richness of cicadellids at higher number of flowers could be a sign for the loss of host plants of certain leafhopper species. While dipterans and leafhoppers responded to changes in the understory vegetation in their species richness, most arthropod groups did not. This indicates that abundance responses were not driven by the loss or gain of species. In fact, only few species provided the majority of the individuals. Hence, the patterns were mostly driven by a few very abundant species. More insights into the ecology of these species could help to better understand the determining factors for their increase or decrease when undergrowth vegetation changes.

Moreover there are a few restrictions due to my experimental set-up which could explain the lack of responses in arthropod species richness. Since the plots are located in the middle of the plantation (total area: 21.54 km^2), immigration of individuals from rainforest patches and shrub land as possible source habitats may be limited. Hence, changes in arthropod communities with management practices could be restricted to the available species pool, and biodiversity gains from colonization of new arthropod species are unlikely. In addition, the management practices with less intensity were established just one year before I collected my data. Before that, the whole oil palm plantation was weeded by using herbicides and fertilized conventionally for 15 years. Thus, there was only short time for arthropods to adapt to the new plant communities and environmental conditions. This time-lag could explain the lack of response in arthropod species richness (Wardle et al. 1999). Moreover species accumulation curves revealed that arthropod sampling may have been incomplete. An underestimation of the arthropod species richness may partly be responsible for the lack of responses. In particular, estimated species richness with Chao 1 indicated effects of changes in the vegetation that were not evident for the observed species richness (see Appendix, Table A1). However, another species richness estimator, ACE, supported the findings for the observed richness of no relationship to plant richness, cover and number of flowers. In addition, the differences between the estimated and observed species richness did not vary systematically among the management treatments (Tukey comparisons of means, $P > 0.10$ in all cases). Hence, although undersampling may explain the lack of richness responses in some cases, no systematic bias with the different experimental treatments was found.

Management recommendations

My study revealed that in oil palm plantations fertilizer and herbicide use affects arthropods by altering the undergrowth vegetation. The reduction of fertilizer increased the plant cover which in turn enhanced lepidopterans and parasitoid wasps, but negatively influenced dipterans and ants. However, mechanical weeding instead of herbicide use supported the highest number of flowers and by that increased lepidopterans but decreased ants and cicadellids. Compared to results from other agricultural systems like grasslands and wheat fields, the effects in my study are more ambivalent (Moreby and Southway 1999; Richards 2001; Hudewenz et al. 2012; Sun et al. 2011). Not only does management not have the same effect on each studied vegetation variable, but also the arthropod responses differ on a functional level.

Thus, in contrast to other agricultural systems a simple enhancement of the vegetation is not beneficial for all arthropods in oil palm plantations. A wide variety of factors can influence the value of vegetation enhancement for a single species. My study showed that diet is not the only determining factor. Rather, other environmental conditions like presence and cover ratio of host plants, appearance and density of predators/parasitoids or host species, as well as changes in abiotic factors (light and temperature) seem to be more important. To meet these habitat requirements of many different arthropod species understory vegetation which is highly diverse in cover and species richness is necessary. This is in line with multiple other studies emphasizing the importance of providing microhabitats in oil palm plantations (Ashraf et al. 2018; Nájera and Simonetti 2010; Spear et al. 2018). In other agricultural systems especially insects which provide ecosystem services like pollination and biological pest control showed positive responses to increased habitat heterogeneity (Tscharntke et al. 2008; Kremen et al. 2007). My study confirms that this also holds true in oil palm plantations.

Whereas previous studies in oil palm plantations concentrated on the effect of herbicide use only (Spear et al. 2018; Ashton-Butt et al. 2018), my work showed the importance of fertilizer management for the enhancement of habitat heterogeneity. Since the reduction of fertilizer increases both plant cover and flowering plants, it could be one approach to conserve biodiversity and ecosystem functions. Disregarding the enhancing effect by bottom-up control on beneficial insects like parasitoid wasps and lepidopterans reduced fertilization would also decrease its harmful environmental impacts (Clough et al. 2016; Hewitt et al. 2009). When considering conservation actions in plantations, potential economic costs due to the reduction in oil palm yields have to be taken into account (Foster et al. 2011). However, first data on oil palm production from the here presented experimental sites display no differences in yields between conventional and reduced management practices (subproject Z01, CRC990; unpublished data). These preliminary findings suggest that a reduction of fertilizer would also be economically justifiable.

Conclusions

Fertilizer and herbicide management in oil palm plantations has complex and cascading effects on vegetation structure and arthropod communities. Arthropods differ highly between taxonomic groups in their responses to changes in the undergrowth vegetation and thus in management with a range from negative, to neutral and positive responses. Thus, a simple increase of the undergrowth vegetation is not enough to conserve aboveground arthropods. Conservation actions within plantations should be focused more on the improvement of habitat diversity to meet demands of as many species as possible. For example, understory vegetation which is more diverse in cover and species composition could offer both dense areas with many host plants for herbivores and lighter areas for ants. One approach to improve the habitat heterogeneity could be to vary the time of weeding and fertilization between neighboring areas within the plantation instead of doing it at the same time for all areas. Hence, recently managed plots with less vegetation would be next to formerly managed plots with more vegetation. Though, further studies are needed, for example on the functional link between plant composition and arthropod communities in oil palm plantations, to be able to develop even more precisely targeted management practices.

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Appendix

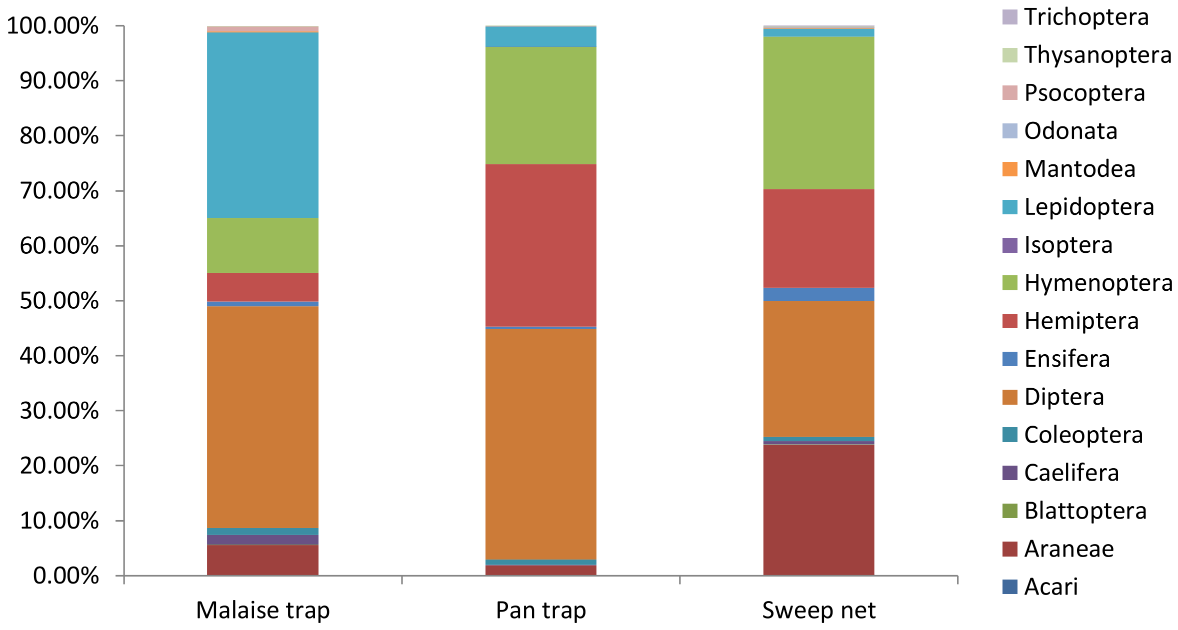

Figure A1: Percentage of all arthropod orders in three different sampling methods. Total number of individuals was the lowest in malaise traps (762), followed by pan traps (3169) and sweep netting (4192).

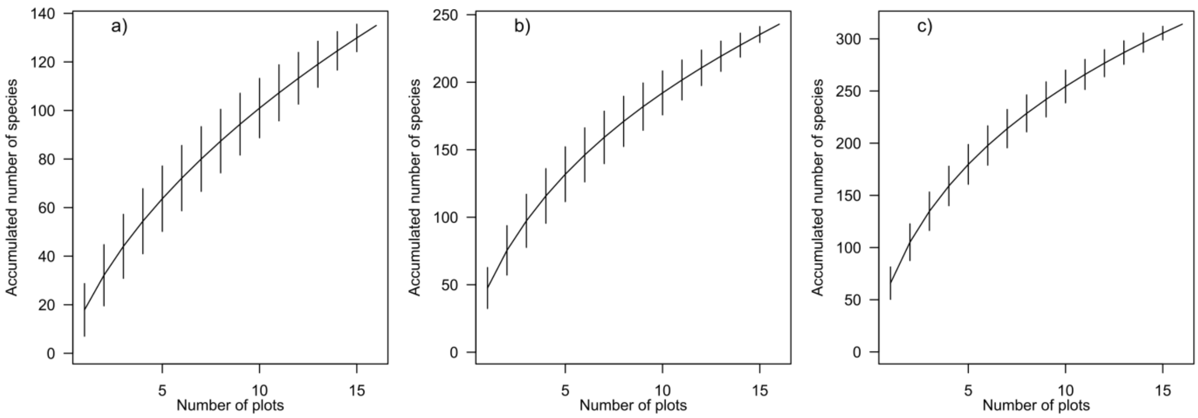

Figure A2: Species accumulation curves of malaise trap (a), pan trap (b) and sweep net (c) samples. Plots show mean numbers of arthropod species for a certain number of sampled sites and their standard deviation.

Table A1: Estimated total arthropod species richness in response to plant cover, plant species richness and number of flowers. Results of generalized linear models are shown. Total species richness was estimated by extrapolation of the observed species richness using two different methods: a) Chao 1 and b) ACE (Abundance Coverage-based Estimator). Significant predictors (P < 0.05) are shown in boldface type.

	Estimate	**SE**	**z**	**P**
a) Chao 1				
(Intercept)	5.126	0.152	33.646	<0.001
plant cover	-0.002	0.001	-1.613	0.107
plant species richness	**0.015**	**0.005**	**3.063**	**0.002**
number of flowers	**-0.050**	**0.021**	**-2.329**	**0.020**
b) ACE				
(Intercept)	5.285	0.144	36.600	<0.001
plant cover	<0.001	0.001	-0.002	0.999
plant species richness	0.006	0.005	1.269	0.204
number of flowers	-0.008	0.020	-0.374	0.709