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REVIEW

Effects of agroforestry on pest, disease and weed control: A meta-analysis

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Abstract

Agroforestry practices may influence pest incidence and abundance both through increased top-down regulation by natural enemies and via bottom-up factors such as moderation of microclimate, soil nutrients and water content. We conducted a meta-analysis of the effects of agroforestry on the abundance of invertebrate pests, weeds, natural enemies and plant damage due to pests and diseases. We also tested whether effects of agroforestry were dependent on crop type (annual or perennial), type of pest association (above or belowground) and weed type (parasitic *Striga* weeds or non-parasitic weeds).

Agroforestry practices resulted in lower abundances of both parasitic and non-parasitic weeds, and in higher abundances of natural enemies. The effects of agroforestry on invertebrate pests and diseases were dependent on crop type. In perennial crops (e.g. coffee, cocoa and plantain), agroforestry was associated with lower pest abundances and less plant damage. However, the effects were not significant in annual crops (e.g. maize, rice and beans). Despite the limited number of crop-pest systems available for the analyses, overall our results suggest that agroforestry is beneficial in terms of pest, disease and weed management.

Zusammenfassung

Negative Auswirkungen von Entwaldung auf Biodiversität und Ökosystemdienstleistungen können durch Aufforstung im Rahmen der Agroforstwirtschaft gemildert werden. Agroforstwirtschaftliche Maßnahmen sind imstande, Vorkommen und Häufigkeit von Schädlingen zu beeinflussen, sowohl durch verstärkte Top-Down-Regulierung mittels natürlicher Feinde, als auch durch Bottom-Up-Faktoren wie Mikroklimaverbesserungen und Veränderungen von Wasser- und Nährstoffgehalt des Bodens.

Mit Hilfe einer Meta-Analyse wurden die Auswirkungen von Agroforstwirtschaft-Maßnahmen auf das Vorkommen von wirbellosen Schädlingen, Ackerunkräutern, natürlichen Feinden sowie schädlings- und krankheitsbedingten Pflanzenschäden untersucht. Getestet wurde ferner, inwieweit sich der Nutzpflanzentyp (ein- oder mehrjährig), die Art des Schädlingskontakts (ober- oder unterirdisch) und der Unkrauttyp (parasitisch (Striga) oder nicht-parasitisch) beim Einsatz von Agroforstwirtschaft auf die Indikatoren der Schädlingsbekämpfung auswirkt.

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Agroforstwirtschaftliche Maßnahmen reduzierten das Vorkommen von parasitischen wie nicht-parasitischen Unkräutern und erhöhten die Zahl natürlicher Schädlingsfeinde. Die Auswirkungen der Maßnahmen auf wirbellose Schädlinge und Krankheiten waren abhängig vom Nutzpflanzentyp. Bei mehrjährigen Nutzpflanzen (vorwiegend Kaffee, Kakao und Kochbananen) führte der Einsatz von Agroforstwirtschaft zu einem Rückgang von Schädlingsbefall und Pflanzenschäden. Der Effekt bei einjährigen Pflanzen (vorwiegend Mais, Reis und Bohnen) war weniger eindeutig. Insgesamt deutet unsere Meta-Analyse darauf hin, dass Agroforstwirtschaft die Bekämpfung von Pflanzenschädlingen, -krankheiten und Unkräutern begünstigt.

Keywords: Natural enemies; Parasitic weeds; Parasitoids; Plant damage; Predators; *Striga* sp.

Introduction

Deforestation and agricultural intensification are the most important drivers of the loss of biodiversity and associated ecosystem services (Foley et al. 2005). The restoration of tree-cover through agroforestry can mitigate the negative effects of deforestation, and complement the protection of pristine forest ecosystems (Tscharntke et al. 2011). Previous studies have reported many beneficial effects of agroforestry including biodiversity conservation and improved soil fertility (Matata, Gama, Mbwaga, Mpanda, & Byamungu 2011; Sileshi et al. 2014). In developing countries agroforestry can improve food security for smallholder farmers by improving soil health and providing firewood, building material, fodder and fruits (Sileshi et al. 2014). Evidence is also mounting that agroforestry influences other ecosystem services delivered by biodiversity, such as pest control (Sileshi, Schroth, Rao, & Girma 2008; Karp et al. 2013). However, quantitative reviews of the effects of agroforestry on pest control are still lacking.

The incorporation of trees into agro-ecosystems through adoption of agroforestry increases habitat complexity, which generally correlates positively with abundance and diversity of natural enemies both at the field (Letourneau et al. 2011; Iverson et al. 2014) and landscape levels (Chaplin-Kramer, O'Rourke, Blitzer, & Kremen 2011; Tscharntke et al. 2011). However, even if increased habitat complexity may result in reduced pest abundances due to top-down regulation, such effects are context-dependent (Chaplin-Kramer et al. 2011). In some instances trees may benefit pests directly by providing resources or improving microclimate, or indirectly by enhancing host plant nutritional conditions or water availability (Sileshi, Schroth, Rao, & Girma 2008). Therefore, it remains unclear to what extent the different agroforestry practices can improve regulation of pests, diseases and weeds in agro-ecosystems.

Earlier reviews and meta-analyses have tested how the diversity or abundance of either pests or natural enemies is affected by factors such as local plant diversity and landscape structure. Letourneau et al. (2011) found a reduction of herbivores and crop damage as well as an increase in natural enemies with increasing crop diversity. According to Iverson et al. (2014), win–win relationships between per-plant yield of the primary crop and biocontrol are likely in polyculture systems that minimize intraspecific competition via substitutive planting. Chaplin-Kramer et al. (2011) found that complex landscapes including natural habitat benefitted natural enemies, but that effects on pests were more variable. Some reviews about pests and diseases in the humid tropics have shown that the impacts of agroforestry are variable and context-dependent (Schroth, Krauss, Gasparotto, Duarte Aguilar, & Vohland 2000; Sileshi, Schroth, Rao, & Girma 2008).

To date, no meta-analysis has been published on the net effects of agroforestry practices on the regulation of pests, diseases and weeds. Therefore, the objective of this meta-analysis was to investigate the effects of agroforestry practices on the abundance of invertebrate pests, weeds, diseases, natural enemies, and crop damage. We also tested whether (1) agroforestry practices affects pests differently in annual vs. perennial crops, (2) whether above and belowground organisms were differently affected by agroforestry, and (3) if agroforestry practices reduce both parasitic and non-parasitic weeds.

Material and methods

Literature search and data extraction

To retrieve papers that could potentially be suitable for our meta-analyses, we conducted a literature search using ISI Web of Science, focusing on literature published up to October 2013. We searched for studies that reported the effects of agroforestry on invertebrate pests (insects, mites and nematodes), plant diseases (fungi, bacteria and virus) and/or weeds. We considered both sequential and simultaneous agroforestry systems. Sequential systems include improved fallows, relay cropping with trees and rotational woodlot systems where a piece of land is deliberately planted with fast-growing nitrogen-fixing trees. Simultaneous systems include scattered trees in crop land, often known as "parkland agroforestry", alley cropping, cereal-tree intercropping and multi-strata agroforestry (see Appendix A for further descriptions).

The literature search was conducted using 20 terms describing agroforestry interventions and 10 terms describing

Table 1. Complete list of the literature used, including number of data points, response variable(s), taxa and crop studied and the country where the study was carried out. Response variables: (a) pest abundance, (b) proportion of plant damage, (c) abundance of natural enemies, (d) diversity of natural enemies, (e) proportions of pests predated or parasitized, and (f) weed abundance.

	Paper	Number of data points	Response variable	Taxa	Crop	Country
1	Armbrecht and Gallego (2007)	1	e	Coffee berry borer (CBB)	Coffee	Colombia
2	Backlund (2012)	3	a	Aphids, lacebugs, leafminers	Coffee	Kenya
3	Banful, Dzietror, Ofori, and Hemeng (2000)	5	a	Nematodes	Plantain	Ghana
4	De la Mora, Murnen, and Philpott (2013)	8	c, d	Ants	Coffee	Mexico
5	Egbe, Ladipo, Nwoboshi, and Swift (1998)	2	f	Weeds	Maize	Cameroon, Nigeria
6	Ekeleme, Chikoye, and Akobundu (2004)	2	f	Weeds	Maize, cassava	Nigeria
7	Ekeleme, Chikoye, and Akobundu (2005)	1	f	Weeds	Maize	Nigeria
8	Gacheru and Rao (2005)	2	f	Striga weeds	Maize	Kenya
9	Girma et al. (2000)	2	b	Stemborers, beanflies	Maize, beans	Kenya
10	Hoehn, Steffan-Dewenter, Buchori, and Tscharntke (2009)	1	c	Predatory Hymenoptera	Cocoa	Indonesia
11	Ichinose, Hoa, Bang, Tuan, and Dien (2012)	1	b	Citrus greening disease	*Citrus nobilis*	Vietnam
12	Jama and Getahun (1991)	1	f	Weeds	Maize, green gram	Kenya
13	Jonsson, Raphael, Ekbom, Kyamanywa, and Karungi (2015)	3	b, c	CBB, stemborers, entomopathogenic fungus	Coffee	Uganda
14	Karungi et al. (2015)	4	a, c	Scale insects, aphids, ants, spiders	Coffee	Uganda
15	Kandji, Ogol, and Albrecht (2002)	1	a	Nematodes	Maize, beans	Kenya
16	Kiwia, Imo, Jama, and Okalebo (2009)	1	f	Striga weeds	Maize	Kenya
17	Koech and Whitbred (2006)	1	b	Bean rust	Beans	Kenya
18	MacLean et al. (2003)	4	a, f	Rice maggots, white grubs, stemborers, weeds	Rice	Philippines
19	Matata et al. (2011)	1	f	Striga weeds	Maize	Tanzania
20	Midega, Ogol, and Overholt (2004)	1	e	Stemborers	Maize	Kenya
21	Naeem, Compton, Incoll, Wright, and Corry (1997)	1	a	Aphids	Barley, wheat	UK
22	Nestel and Altieri (1992)	1	f	Weeds	Coffee	Mexico
23	Ogol, Spence, and Keddie (1998)	4	e	Stemborers	Maize	Kenya
24	Ogol et al. (1999)	4	a, b	Stemborers	Maize	Kenya
25	Opuni-Frimpong, Karnosky, Storer, and Cobbinah (2008)	2	b	Shootborers	Mahogany	Ghana
26	Reda, Verkleij, and Ernst (2005)	2	f	Striga weeds	Sorghum	Ethiopia
27	Ricci, Filho, and Costa (2008)	1	f	Weeds	Coffee	Costa Rica
28	Riedel, Dorn, Plath, and Mody (2013)	4	a, b	Lepidoptera, Coleoptera	Timber	Panama

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Table 1 (*Continued*)

	Paper	Number of data points	Response variable	Taxa	Crop	Country
29	Rosecrance, Rogers, and Tofinga (1992)	1	f	Weeds	Taro	Western Samoa
30	Sileshi and Mafongoya (2003)	3	a, b	Snout beetles, termites, weeds	Maize	Zambia
31	Sileshi et al. (2005)	5	b	Termites	Maize	Zambia
32	Sileshi and Mafongoya (2006a)	9	c, d	Centipedes, beetles	Maize	Zambia
33	Sileshi and Mafongoya (2006b)	8	c, d	Beetles, ants, centipedes	Maize	Zambia
34	Sileshi et al. (2006)	3	f	Weeds	Maize	Zambia
35	Sileshi and Mafongoya (2007)	9	a, c	Termites, ants, beetles	Maize	Zambia
36	Sileshi, Mafongoya, Chintu, and Akinnifesi (2008)	4	a, c, d	Termites, beetles, centipedes	Maize	Zambia
37	Sjögren, Shepherd, and Karlsson (2010)	1	f	Striga weeds	Maize	Kenya
38	Stamps, Nelson, and Linit (2009)	1	e	Alfalfa weevil	Alfalfa	USA
39	Teodoro, Klein, and Tscharntke (2008)	3	a	Spider mites, coffee berry borers, leaf miners	Coffee	Ecuador
40	Teodoro, Klein, and Tscharntke (2009)	3	a, c	Spider mites, predatory mites	Coffee	Ecuador
41	Varon, Eigenbrode, Bosque-Pérez, and Hilje (2007)	1	b	Leaf cutting ants	Coffee	Costa Rica
42	Velasco, Gallego Ropero, and Armbrecht (2010)	1	d	Natural enemies	Coffee	Colombia

response variables (Appendix B). Moreover, we examined the reference lists of selected papers including previous syntheses on related topics. Papers that presented data on any of the following variables were considered: (1) pest abundance, (2) proportion of plant damage due to pests and diseases, (3) abundance of natural enemies, (4) diversity of natural enemies, (5) proportion of pests predated or parasitized and (6) weed abundance (for a complete list of the literature retrieved, see Table 1). These six categories were treated as different response variables in the analyses. We also recorded whether studies had investigated impact of pest control on crop yield. For two of the response variables (diversity of natural enemies and proportion of pests predated or parasitized) we considered the number of data points to be too small (<15) for a meaningful quantitative meta-analysis. In these cases we used vote-counting (i.e. assessing the proportion of studies reporting a statistically significant effect of agroforestry on the response variable in question) to obtain a semi-quantitative assessment on the effects of agroforestry practices.

Observations were classified according to (1) whether effects on annual or perennial crops were studied, and (2) if the response variable was studied above- or belowground. Moreover, in the case of weed abundance, we classified the weeds either as parasitic or non-parasitic. Weeds were considered as non-parasitic unless explicitly stated otherwise. All studies on parasitic weeds involved *Striga* species (hereafter referred to as striga), the most important yield-reducing weeds in smallholder cereal farming systems in sub-Saharan Africa.

To be included in our analysis, a study had to fulfil the following criteria: (1) the study was conducted at the plot, field or farm scale, (2) a measure of pest control was reported for both a control treatment (i.e. the crop grown without the agroforestry intervention or under low levels of shade) and for one or more treatments subjected to either agroforestry interventions, or higher shade levels, and (3) the same crop was grown in both treatment and control. To reduce potential problems with non-independence of data points, the following steps were taken: (1) if a study presented data for multiple time periods (which could be either multiple years or time series within a year), only the measurement from the final point of measurement was used, (2) in studies where multiple treatments were compared against the same control, we randomly picked one treatment to be compared with the control (except in cases where a study included a shading gradient without agroforestry intervention, then the response of the least shaded treatment was compared to that of the most shaded treatment), (3) in the only study where multiple life stages of an invertebrate were presented, the most damaging stage was selected, and (4) when a paper presented results from single control and treatment plots, the study was not included in the analysis. If the study presented responses from different experiments, they were considered as separate data points and were all included in the analysis. We also treated different pest or predator species within the same study as different data points. See Appendix C for details on specific studies.

The mean values of pest abundance, plant damage, natural enemy abundance, and weed abundance for the treatment and control groups were recorded from all studies. When data were reported in tables or in the text they were taken directly from those sources. When data were reported only in a graphical format, they were digitalized and extracted using the program Image-J (http://imagej.nih.gov/ij/index.html). Forty-two studies fit our criteria for being included in the meta-analyses and the vote counting (Table 1). The studies covered sites located in 19 countries around the world, almost exclusively in tropical regions (40 studies). A total of 125 observations were recorded concerning the effects of agroforestry on pest management: 28 on pest abundance, 20 on proportion of plant damage due to pests and diseases, 29 on abundance of natural enemies, 11 on diversity of natural enemies, 7 on proportion of pests predated or parasitized and 21 on weed abundance. The most common crop studied was maize (58% of all observations), followed by coffee (23%) and the remaining observations were spread across 14 other crop species. There were 13 studies from sequential agroforestry practices and 29 from simultaneous systems (Appendix C). Almost all studies defined as sequential agroforestry were improved fallows (12 studies, all from annual cropping systems), whereas the most common simultaneous agroforestry practices were multi-strata systems (13 studies) and alley cropping (11 studies).

Data analyses

We used the response ratio (RR) as our measure of effect size in all analyses. RR is defined as the ratio of the treatment mean to the corresponding control mean for each study. To satisfy the assumptions of normality and homogeneity of error variance, we analyzed log(RR) as recommended by Hedges, Gurevitch, and Curtis (1999).

An inherent problem with meta-analysis is the potential for publication bias. Here publication bias specifically refers to bias against publication of non-significant results. If severe publication selection exists, it can substantially bias estimates of observed effect sizes (Gurevitch & Hedges 1999). We assessed publication bias and normality in the data using normal quantile–quantile (Q–Q) plots (Wang & Bushman 1998) The Q–Q plots indicated potential publication bias for plant damage (Appendix D), and for natural enemy abundance, pest abundance and weed abundance the Q–Q plots suggested that the effect sizes came from populations with different means (Appendix D). Consequently, we analyzed the effect of moderator variables (i.e. annual vs. perennial crops, above vs. belowground organisms, parasitic vs. non-parasitic weeds) using a mixed modelling approach, allowing for random variation in effect sizes within groups (i.e. between studies within groups) and fixed differences between groups.

In our data set on the abundance of natural enemies, all studies focusing on belowground organisms were conducted in systems with annual crops while all studies involving above ground enemies were from systems with perennial crops. Since the effects of these two moderators could not be separated, these comparisons were not conducted for natural enemies. Furthermore, for weeds only two observations were available from perennial crops and therefore the effects of crop type on effect size was not assessed for weeds. Since many of the studies did not report a measure of variance around the means of control and treatment groups, we did not include the inverse-variance weighting of individual effect sizes typical of many meta-analyses. The mixed modelling procedure was appropriate as the data gathered across studies were unbalanced with respect to predictor variables and sample sizes. All analyses were done using the MIXED procedure of the SAS system 9.3 (SAS Institute Inc., Cary, NC, USA), and parameter estimates were obtained with restricted maximum likelihood estimation (REML). Where moderator variables were not available, robust estimators (trimmed and Winsorized means) were used since these methods effectively reduce the effects of extreme values (outliers) and give unbiased estimates of the population mean (Wu & Zou 2009).

In all cases, we report the means and 95% confidence intervals (CI) of the back-transformed RRs. We follow the standard practice of basing statistical inference on the means and their CI, rather than on significance tests (p-values). This is because the CI functions as a conservative test of hypothesis and it also attaches a measure of accuracy to the sample statistic (Sim & Reid 1999). Means were considered to be significantly different from one another if their 95% CI were non-overlapping.

Results

This meta-analysis indicates that agroforestry generally benefits most aspects of natural pest control. Weeds were significantly less abundant under agroforestry compared to control treatments (Fig. 1A; Appendix E: Table 1). Agroforestry significantly reduced non-parasitic weeds and had a marginally significant negative effect on parasitic weeds (Fig. 1B; Appendix E: Table 2). Natural enemies of pests were significantly more abundant under agroforestry (Fig. 1A; Appendix E: Table 1). Overall, plant damage due to pests and plant diseases was significantly reduced by agroforestry, but pest abundance was not significantly affected (although nearly so) (Fig. 1A; Appendix E: Table 1). However, the effect differed between studies conducted in annual and perennial

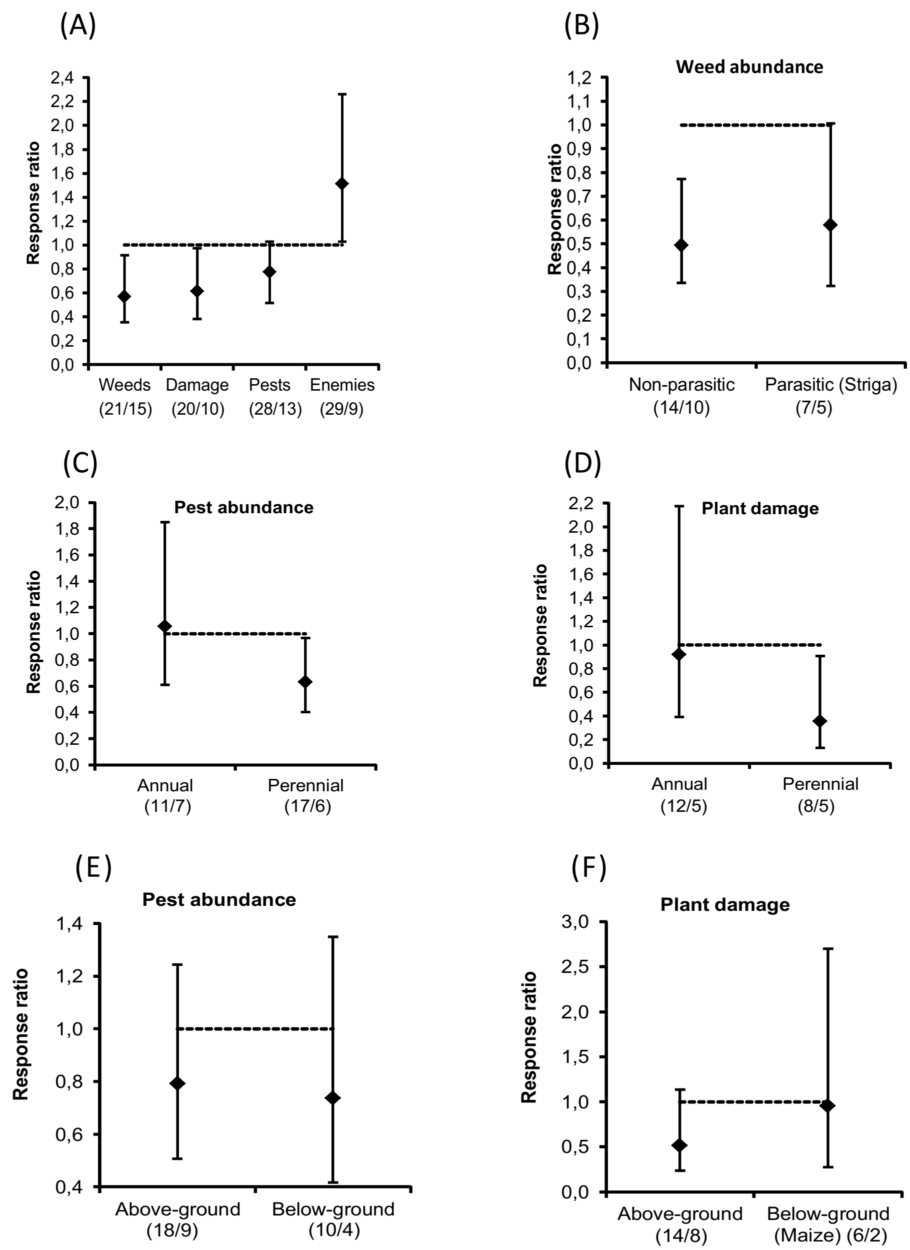

Fig. 1. Effects of agroforestry interventions on (A) overall weed cover, pest abundance, proportion of plant damage, and natural enemy abundance, (B) non-parasitic vs. parasitic (striga) weed abundance, (C) pest abundance in perennial vs. annual cropping systems, (D) proportion plant damage in perennial vs. annual cropping systems, (E) pest abundance above vs. belowground, and (F) proportion plant damage above vs. belowground. Lines and dots represent back-transformed values of 95% confidence interval around mean effect sizes for the respective response variables. Numbers in parentheses represent the number of data points/studies for each category.

crops, with agroforestry causing a significant reduction of both pest abundance and plant damage in perennial crops, whereas it had no effect in annual crops (Fig. 1C and D; Appendix E: Tables 3 and 4). There was no difference between above and belowground pest abundance and plant damage (Fig. 1E and F; Appendix E: Tables 5 and 6). Only two studies investigated if the effects of agroforestry on pest control translated to increased crop yield, and they both found a positive effect (Ogol, Spence, & Keddie 1999; Sileshi, Mafongoya, Kwesiga, & Nkunika 2005). The majority of studies (7 out of 11) showed no effect of agroforestry on enemy diversity and the response of predation and parasitism was mixed, with 3 of the 7 studies showing no effect and the remainder split evenly between positive and negative effects.

Discussion

Our study suggests that agroforestry is beneficial for pest control. Weeds were less abundant and natural enemies were more abundant in agroforestry systems. Furthermore, in perennial crops, pest abundance was reduced in agroforestry systems. Agroforestry also seemed to reduce plant damage due to pests and diseases, but for this response variable a likely publication bias was detected, and therefore this result must be treated with care. Together, these results support the general prediction that higher habitat complexity in agroforestry systems will result in better pest control, as suggested in previous meta-analyses on related topics (Letourneau et al. 2011; Iverson et al. 2014). However, our results also show that the outcomes are highly context-dependent. Factors such as pest and tree species identity and crop type may play a major role (Sileshi, Mafongoya, Chintu, & Akinnifesi 2008).

Weeds

Our results show that agroforestry practices can reduce weed abundance. In sequential agroforestry systems, this may be related to the fact that organic material from the trees had been integrated into the soil, resulting in an improvement of soil quality. In simultaneous systems, shading by trees could be a factor in suppressing weeds (Nestel & Altieri 1992). Improvement in soil nutrient availability has been known to contribute to weed control (Barrios, Kwesiga, Buresh, Sprent, & Coe 1998; Sileshi, Mafongoya, et al. 2008). This is partly because of the better growth that allows crops to out-compete weeds. The beneficial effects of agroforestry may also be due to the moderation of microclimate by trees (Nestel & Altieri 1992; Sileshi, Mafongoya, et al. 2008; Barrios, Sileshi, Shepherd, & Sinclair 2012), with studies reporting that striga emergence and occurrence decreases with soil temperature due to reduced germination (Carson 1989). Additionally, Midega, Pittchar, Salifu, Pickett, and Khan (2013) demonstrated that covering the soil with litter from plants significantly reduced emergence of striga.

Pests and diseases

The effect of agroforestry practices on pest abundance and plant damage depended on the crop type considered. Pest abundance and plant damage were lower in agroforestry treatments for perennial, but not for annual crops. In perennial crops, it is possible that the constant presence of shading by trees diminishes the pest numbers. Bisseleua, Fotio, Yede, Missoup, and Vidal (2013) found that both the numbers of herbivore species and the rate of herbivory on cocoa pods decreased with increased shading by trees. Similarly, Jonsson, Raphael, Ekbom, Kyamanywa and Karungi (2015) found higher abundance of coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) on coffee berries in low-shade compared to high-shade systems. Several mechanisms behind the negative effects of shade trees on CBB have been suggested. First, natural enemies of CBB, such as birds and parasitoid wasps, may be more effective under shade (Perfecto, Rice, Greenberg, & Van der Voort 1996; Karp et al. 2013). Second, shade may reduce CBB development rates (Jaramillo et al. 2009), and third, shade may modify biochemical composition and emission of chemical compounds from coffee berries, making them more difficult to locate for oviposition by CBB females (Jaramillo et al. 2013).

Even though the effects of agroforestry on pest abundance and plant damage in annual cropping systems were not significant in our meta-analysis, some studies provide examples of reduction in maize pests with the use of agroforestry. For example, maize with hedgerows experienced significantly lower stalk borer (*Busseola fusca* (Füller) and *Chilo* spp.) and aphid (*Rhophalosiphum maidis* (Fitch.)) infestations than monocrop maize (Girma, Rao, & Sithanantham 2000). Furthermore, the abundance of stem borers, stem damage and plant mortality due to maize stem borers (*Chilo partellus* (Swinhoe), *Chilo orichalcociliellus* (Strand) and *Sesamia calamistis* Hampson) was significantly lower in *Leucaena leucocephala* (Lam.) alley cropping than in a maize monocrop (Ogol et al. 1999).

However, there are instances where agroforestry has led to an increase in pest abundance. Jonsson, Raphael, Ekbom, Kyamanywa, and Karungi (2015) found that white stem borers, *Monochamus leuconotus* (Pascoe), on coffee were more common in shaded than in sun-exposed coffee plantations, and suggested that this could be due to changes in microclimatic conditions. MacLean, Litsinger, Moody, Watson, and Libetario (2003) suggested that better soil quality and crop nutrition coming from hedgerow biomass may increase the herbivore numbers in some cases. Shade has also been shown to increase coffee rust incidence (Avelino et al. 2006). Thus, the effect of agroforestry on pests and diseases does not only depend on crop type, but also on factors such as pest identity, microclimate, and the microclimatic preferences of the pest (Schroth et al. 2000).

Natural enemies

Agroforestry generally increased the abundance of natural enemies. Our results are consistent with findings from earlier reviews (e.g. Sileshi, Schroth, Rao, & Girma 2008) that suggest that trees in multi-strata agroforestry can influence the abundance of natural enemies. For example, shade trees in coffee favoured the parasitic wasp *Cephalonomia stephanoideri* Betrem and the entomopathogenic fungus *Beauveria bassiana* (Bals.-Criv.) Vuill., which control the coffee berry borer (Beer, Muschler, Kass, & Somarriba 1998). Coconut planted in cocoa provided nest sites for the predatory ants *Dolicoderus* and *Oecophylla*, which reduced *Helopeltis* damage to cocoa (Way & Khoo 1990). Klein, Steffan-Dewenter, and Tscharntke (2002) found an increased predator–prey ratio in more diverse traditional agroforestry systems compared to intensified systems. Several studies have found that improved fallows in annual cropping systems increase abundance of soil fauna (Barrios et al. 2005; Sileshi, Kuntashula, & Mafongoya 2006; Barrios et al. 2012). This is probably due to an improved living environment for ground and soil-based natural enemies, when organic material from the

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improved fallows is incorporated into the soil. In maize-based agroforestry, more belowground natural enemies (specifically ants, carabid beetle larvae and centipedes) have also been recorded in agroforestry compared to the corresponding monoculture (Sileshi & Mafongoya 2006a, 2006b).

The diversity of natural enemies was in most studies not affected by agroforestry. A reason for this might be that the agroforestry treatments usually had low richness of trees, and that the agroforestry trees sometimes were exotic to the study region (Appendix C).

Knowledge gaps

Most of the studies testing how agroforestry practices affect pest control were done in either coffee or maize (>80% of studies). Thus, it is possible that our results are partly dependent on the crop types studied. This caveat is particularly evident for observations of plant damage belowground, where all data points were from studies on maize. Some of the most commonly studied pest taxa included coffee berry borer, stem borers on maize, and parasitic striga weeds. Also, we found a considerable number of studies done on the abundance of predatory ants. However, only two studies explored the impact of agroforestry on plant diseases, and the impact on a large number of important invertebrate pests and natural enemies remain unknown. The trials had been done mainly in Western and Eastern Africa and in Central and South America (36 studies). This is not surprising though, since these are the regions where agroforestry is most practised. The number of studies done in other parts of the world such as Europe, North America or Asia is limited (only 6 studies). Of these only two studies were from temperate regions.

Many of the studies found in the literature search could not be included in our analyses since they either did not include a proper control or they did not present the results in a comprehensible way. The absence of information on standard deviations and number of replicates in many studies also prevented us from using weighted mixed model meta-analysis and our overall effect size estimates are therefore not as accurate as they could have been. Therefore, we echo the request stated by Koricheva and Gurevitch (2013) that future studies should present these parameters in order to make them useful for forthcoming meta-analyses.

Conclusion

The use of agroforestry has been extensively promoted in many developing countries in Africa and in South and Central America and it is commonly used by traditional farmers. However, agroforestry practices have often been applied without a clear understanding of their effects on crop pests, pest enemies, plant diseases or weeds. Our meta-analysis shows that the use of agroforestry practices generally reduces weeds, increases natural enemy abundance and reduces pest abundance in perennial crops. Future studies should assess the effects of agroforestry in a broader range of crops, regions and types of agroforestry systems, and disentangle the mechanisms underlying the effects of agroforestry on pest control.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.baae.2015.08.005.

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