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Local management and landscape drivers of pollination and biological control services in a Kenyan agro-ecosystem

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ABSTRACT

Arthropods that have a direct impact on crop production (i.e. pests, natural enemies and pollinators) can be influenced by both local farm management and the context within which the fields occur in the wider landscape. However, the contributions and spatial scales at which these drivers operate and interact are not fully understood, particularly in the developing world. The impact of both local management and landscape context on insect pollinators and natural enemy communities and on their capacity to deliver related ecosystem services to an economically important tropical crop, pigeonpea was investigated. The study was conducted in nine paired farms across a gradient of increasing distance to semi-native vegetation in Kibwezi, Kenya. Results show that proximity of fields to semi-native habitats negatively affected pollinator and chewing insect abundance. Within fields, pesticide use was a key negative predictor of pollinator, pest and foliar active predator abundance. On the contrary, fertilizer application significantly enhanced pollinator and both chewing and sucking insect pest abundance. At a 1 km spatial scale of fields, there were significant negative effects of the number of semi-native habitat patches within fields dominated by mass flowering pigeonpea on pollinators abundance. For service provision, a significant decline in fruit set when insects were excluded from flowers was recorded. This study reveals the interconnections of pollinators, predators and pests with pigeonpea crop. For sustainable yields and to conserve high densities of both pollinators and predators of pests within pigeonpea landscapes, it is crucial to target the adoption of less disruptive farm management practices such as reducing pesticide and fertilizer inputs.

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1. Introduction

Historically, there has been a trade-off between achieving sustainability in food production and conserving biological diversity, a problem that is particularly pertinent to the developing world where growing populations place ever greater pressure on finite biological resources (Abalu and Hassan, 1998; Steffan-Dewenter et al., 2005). In the context of developing countries, the importance of the relationship between agricultural biodiversity, local management and landscape context is poorly studied, while potentially being of great importance for human livelihoods (Abalu and Hassan, 1998). For many crops, agricultural production benefits from both pollination and natural pest control services that are provided by invertebrates (Landis et al., 2000; Ricketts et al., 2008). Insect pollinators are important in supporting 15–30% of global food production, and are worth an estimated €153 billion *p.a.* to the world economy (Gallai et al., 2009). Similarly, arthropod natural enemies contribute significantly to pest control, by controlling herbivorous invertebrate populations in crops, thereby reducing yield losses. The estimated value of this contribution to natural pest control in agricultural crops is $4.5 billion per year in the USA alone (Losey and Vaughan, 2006). Insect pollinators and arthropod natural enemies are major groups of invertebrates that significantly contribute to the crop production by delivering pollination and natural pest regulation.

Insect communities associated with agriculture, whether pollinators, natural enemies or pest species, have been shown to be affected by both local management practices and the context of the farm in the wider landscape (Bianchi et al., 2006; Ricketts et al., 2008). Here, the term ‘landscape context’ is used to refer to the land cover and land use surrounding a site (Bianchi et al., 2006). The impact of local management practices, such as pesticide application, fertilizer application and tillage, on invertebrates has been well

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documented for many agricultural systems (Brittain et al., 2010; El Hassani et al., 2005; Kevan, 1999; Thompson, 2001). However, the landscape context within which these management practices operate is likely to be of fundamental importance in the maintenance of both pollination and bio-control ecosystem services (Bianchi et al., 2006; Ricketts et al., 2008). To date, attempts to determine the relative effects of landscape context and local management have largely focused on individual crops species such as Cacao (Cassano et al., 2009) and coffee (Klein et al., 2003); insect communities such as bees (Carre et al., 2009; Féon et al., 2010), beetles (Purtauf et al., 2005; Woodcock et al., 2010), spiders (Öberg et al., 2007; Pluess et al., 2010), and single ecosystem services such as pollination (Brittain et al., 2010; Kleijn and van Langevelde, 2006) and bio-control (Bianchi et al., 2006; Eilers and Klein, 2009). Furthermore the effects of how both landscape context and farm management impact on insect communities is also typically documented only in developed countries, particularly in Europe and North America. There is therefore a pressing need to elucidate the relationship between landscape context, local farm management practices, and the components of insect biodiversity that underpin the provision of ecosystem services, such as pollination and bio-control in developing nations, such as those within the developing world.

In this study, the focus was on the impact of local management and landscape context on Kenyan arthropod natural enemies and pollinators associated with pigeonpea (*Cajanus cajan* (L.) Millsp: Leguminosae), one of the most economically important crops in Kenya (Kimani et al., 1994). The hypotheses were that: (1) landscape factors are more important drivers of pollinator and natural enemy abundance and species richness and delivery of their related services than local factors (i.e. management). This is because some insects have wide foraging distances e.g. ballooning spiders (Thomas et al., 2003), pollinators (Greenleaf et al., 2007) and Carpenter bees (Pasquet et al., 2008). Therefore they are likely to escape some local effects by dispersing to suitable habitats within their flight ranges; (2) the provision of pollination and pest regulation ecosystem services will correlate with the abundance of pollinators and natural enemies.

2. Methods

2.1. Study area and study crop

The study was conducted in Kibwezi District, Eastern Kenya (2°15′S and 37°45′E) between February and June 2007. The area is located 150 km South East of Nairobi (Fig. 1). Vegetation comprises a complex of plant communities including trees (mainly *Acacia-Commiphora* vegetation), and a number of shrubs and herbs (Bogdan, 1958). We chose pigeonpea among the other crops grown in this area because it is dominant and widely grown in the dry Lower Eastern regions of Kenya, and is cultivated in more than 150,000 ha in total (Johansen et al., 1993). It is mainly grown for human dietary protein provision and fodder for animals (Price, 1998). Pigeonpea is commonly intercropped with cereals such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), millet (*Panicum miliaceum* L.), and legumes, such as beans (*Phaseolus vulgaris* L.) and cowpea (*Vigna unguiculata* L. (Walp.)) (Omanga et al., 1996). A large number of insect pest species attack pigeonpea, with key among them in causing significant yield reduction being, *Helicoverpa armigera* (Hübner) (Noctuidae: Lepidoptera) and *Maruca vitrata* (Fabricius) (Pyralidae: Lepidoptera) (Shanower and Romeis, 1999). It is estimated that pests cause an annual yield loss of about 17–27% (Silim-Nahdy et al., 1999). Although its flowers are mainly self-pollinating, out-crossing does occur (Shiying et al., 2002). Insects, especially bees, contribute between 5% and 40% of the total cross pollination (McGregor, 2002).

The study was conducted in Kibwezi District, Eastern Kenya between February and June 2007. Three broad regional blocks of agricultural intensification were identified (Fig. 1) based on the proportion of semi-native patches. In all cases semi-native habitats were considered to be patches of vegetation that although altered by land management were composed predominantly of native plants and animals. The blocks were: (1) Kibwezi Block (2°31′S, 38°01′E), the region characterized by a high proportion of arable land (fields with more than 50% of arable land), and low proportion of semi-native habitat patches (fields with less than 50% of semi-native habitats); (2) Makindu Block (2°18′S, 37°57′E), the region characterized by almost equal proportions of arable land and semi-native habitats; and (3) Athi Block (2°13′S, 38°03′E), the region characterized by a low proportion of arable land and a high proportion of semi-native habitat patches. It was expected that variations in the composition of vegetation in these semi-native patches will structure the community of pollinators, pests and natural enemies. This is because insect community composition is closely linked to the spatial–temporal availability and distribution of resources (Potts et al., 2003).

2.2. Landscape context

Within each of the above three regional blocks, three pairs of sites were selected to reflect local landscape conditions necessary to fulfil the pairing of a simple and complex landscape. Each pair of farms was separated by at least 2 km and they were at approximately the same altitude. The proportional area of semi-native vegetation in complex landscapes was 279 ± 34.89 SE m^2 compared to 174 ± 55.18 SE m^2 for simple landscapes. Within each pair, the site situated in a simple landscape context was characterized as being far away from semi-native habitats and surrounded within a 1 km radius by mainly arable land combined with a low proportion of non-crop habitats (mean of 0.23 ± 0.16 SE). The other site of the pair was located within a complex landscape context, which was characterized as close to semi-native habitats and surrounded by a heterogeneous mixture of crop and non-crop areas within a 1 km radius (0.36 ± 0.17 SE). This radius was chosen to reflect the typical flight and foraging distances of many insects including pollinators (Greenleaf et al., 2007). In Kibwezi block, the average distance to semi-native vegetation patches was much further (Mean = 956 m ± 465 m SE) than that in Athi block (Mean = 175 m ± 81 m SE). Likewise, the proportion of semi-native habitat patches within 1 km radii in the complex landscape farm pairs was much higher in Athi (Mean = 0.42 ± 0.05 SE) than Kibwezi (Mean = 0.15 ± 0.06 SE). Farms where pigeonpeas were intercropped with maize were selected to typify the most common cropping practice of the area. Site details are given in Supplementary material S1.

In all cases, site selection was based on elevation and land use maps overlaid within ArcGIS 9.2. For elevation the Shuttle Radar Topographic Mission (SRTM) data (Farr et al., 2007) was used, while land use maps were produced from Landsat 7 Enhanced Thematic Mapper image (2003) combined with additional ground-truthing of site conditions in January 2007. Landscape context and structure were evaluated on rasterized land cover maps (1:500,000). Landscape metrics were then calculated using the Patch Analyst tools in ArcGIS 9.2 (Elkie et al., 1999). The landscape parameters chosen were assessed by generating a correlation matrix, excluding collinear metrics and selecting major factors that have been previously shown to be important in structuring insect communities (Table 1) (Barbaro et al., 2005; Steffan-Dewenter et al., 2005). The landscape metrics retained for further analysis were: the number of semi-native habitat patches (the measure of spatial heterogeneity within a landscape) of semi-native and the proportion of the landscape which was arable land (see Elkie et al., 1999 for full descriptions of these metrics).

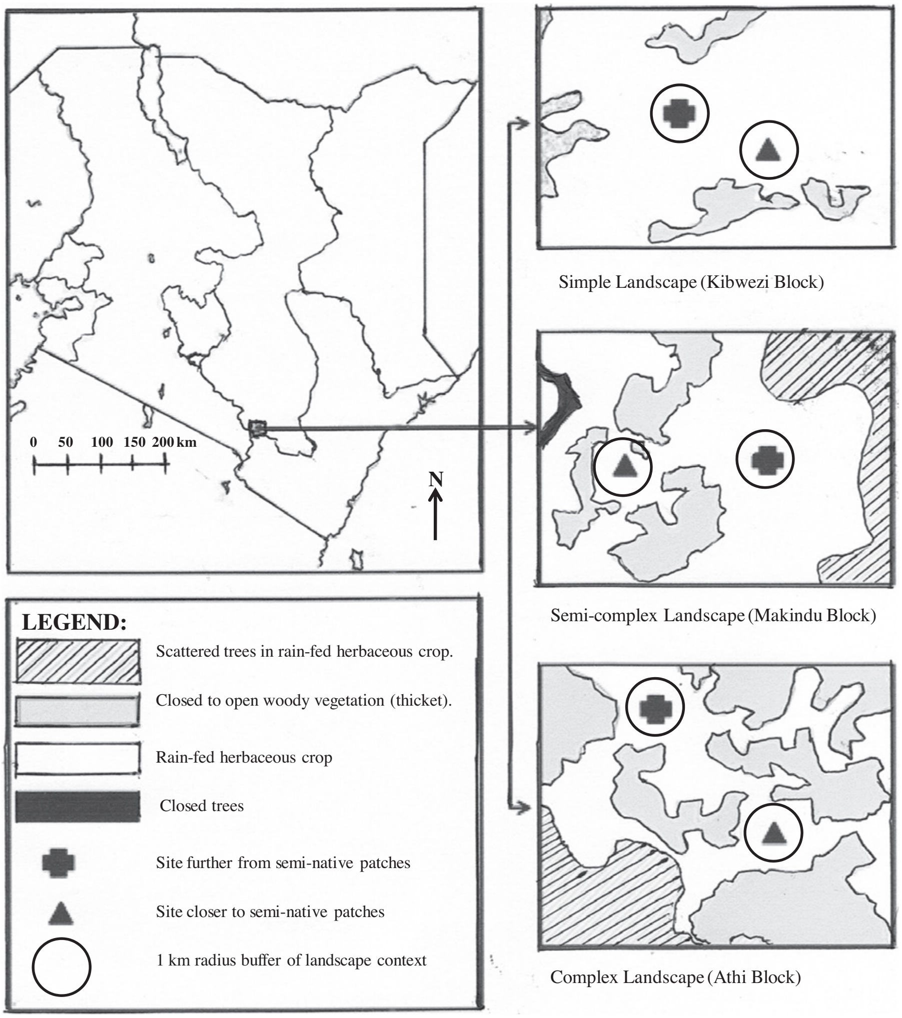

Fig. 1. A map of Kenya showing example gradient of landscape structural complexity. Study site is at the center of the 1 km sampling radius shown by the circles.

Table 1
Correlation matrix of the landscape metrics abbreviated as follows: No. patch is the number of semi-native habitat patches; MPS is mean patch size; MPI is mean proximity index; ED is edge density; Prop. arable is proportion of arable land; IJI is interspersion and Juxtaposition Index and Prop. SN is proportion of semi-native patches.

	No. patch	MPS	MPI	ED	Prop. arable	IJI	Prop. SN
No. patch	1						
MPS	−0.86	1					
MPI	0.16	−0.5	1				
ED	−0.28	−0.07	0.59	1			
Prop. arable	−0.72	0.76	−0.43	0.02	1		
IJI	0.71	−0.37	−0.16	−0.39	−0.45	1	
Prop. SN	0.72	−0.76	0.43	−0.02	−1	0.45	1

2.3. Local management

Structured questionnaire surveys (Supplementary material S2) were conducted on each farm to assess local management practices. These provided presence/absence information on whether the farms used pesticides and fertilizers or not. Seven fields were found to have had pesticides applied to the pigeonpea crop, but the remaining 11 did not. Farmers were found to use pesticides preventively regardless of whether or not pest populations were high. Fertilizer application was scored as: (1) low to medium input characterized by the application of organic based manures e.g. green, compost and farmyard and (2) high input characterized by application of large amounts of inorganic fertilizers. Thirteen fields were scored as low to medium input and five fields were scored as high input. Both pesticide and fertilizer application were the main farm management practices across the study area. For those farmers who did not use these agro-chemicals on their fields, financial restriction was usually the main reason.

Pesticide and fertilizer data were used as explanatory variables representing local farm management practices. These two variables were selected based on the knowledge that they have profound impacts on biodiversity and ecosystem services (see Kevan, 1999; Mozumder and Berrens, 2007).

2.4. Measurement of pollinator and natural enemy diversity

At each site, invertebrate sampling and service provision measurements were made along three parallel, 50 m line transects.

Each of these transects was located at least 5 m from the edge of the experimental field to avoid edge effects (Laslett, 1982), while individual transects were spaced 10 m apart. All transects taken in the fields had the same orientation i.e. North to South. Sampling was done from February to June 2007 for two sampling bouts per crop phenology covering pre-flowering, peak flowering and post-flowering stages of pigeonpea crop season (see Supplementary material S3 for sampling periods and bouts).

Pantraps were used to assess insect pollinator (especially bee) diversity and abundance. A cluster of three pantraps (UV bright yellow, blue and white – Westphal et al., 2008), were placed at both ends of each 50-m transects and half filled with water and one drop of liquid soap to break the surface tension of water. These pans were left for 24 h before insects caught were collected and preserved in 70% ethanol before identification.

For natural enemies, two main groups were identified i.e. (i) ground (surface) active predators, and (ii) foliar active predators. Pitfall traps were used to mainly sample surface active predators (e.g. predatory beetles, spiders, scorpions). One pitfall trap was sunk at both ends of each transect. The pitfalls were filled with water only, thus avoiding the use of any chemical preservative that could have attracted invertebrates associated with such products (Southwood and Henderson, 2000). These pitfalls were put out at the same time as pantraps but were left open for 3 days before specimens were collected. Foliar active natural enemies (e.g. ladybird beetles and leaf spiders) were collected using beat trays. On each transect, five pigeonpea plants were chosen at random and on each plant, a 50 cm long branch was selected. The branch was vigorously shaken to release any insects to a beat tray held beneath (Southwood and Henderson, 2000). Invertebrates were immediately transferred to insect killing jars impregnated with ethyl acetate and later to storage vials containing 70% ethanol. Both pitfall traps and beat trays also captured pest species that were treated and preserved as described for each method above. These pests were categorized as either chewers or suckers based on their feeding specialization. For the pollinators, natural enemies and pests, identification to recognizable taxonomic unit (RTU – Bolger et al., 2000; Oliver and Beattie, 1993) was undertaken with specialist help from experts at the National Museums of Kenya. A reference collection of the materials is deposited at the National Museums of Kenya and also at the CAER laboratory, at the University of Reading.

2.5. Measurement of pollination services

Insect pollinator exclusion experiments were undertaken based on protocols described by Ricketts (2008). These were conducted to quantify the contribution of insects to the pollination of pigeonpea for each of the three transects at 5 m, 25 m and 45 m. At each of these points, one plant of the same approximate height and size (~1.5 m tall) was selected. On each of these plants, one branch with fresh flower buds was selected and covered with a Tulle (fine cloth netting) bag to keep out insect pollen vectors, while allowing self and wind pollination. A second branch was covered with an osmolux bag to keep out both wind and insect pollen vectors. A third branch was not covered and thus was left open to both wind and insect pollination. The bags were left on the plants until fruiting when the number of pods formed was quantified. Pollination due to insects, as measured by fruit set, was calculated following the formula described by Ricketts et al. (2008):

$$\text{Insect pollination} = \text{open pollination [control]} - (\text{self pollination} + \text{wind pollination [tulle bags]})$$

In addition, insect pollinator visitation rates to flowers were quantified by observing a cluster of 10 freshly open flowers on three randomly chosen plants per transect. The flowers were observed continuously for 10 min of every hour from 08:30 to 16:30 on a weekly basis during peak flowering season between April and May 2007.

2.6. Measurement of pest control service

The impact of natural enemies on foliar insect pests was assessed by recording the extent of leaf damage on pigeonpea plants. This measure can be used as a proxy for pest regulation because it indicates herbivore pressure which correlates with natural enemy populations (Augustin et al., 2004). It was not possible to control for variation in herbivore pressure which was assumed to be uniform among pesticide treated and untreated fields respectively. A total of five plants were chosen per transect and for each of these the total number of leaves were counted on one randomly selected branch of 50 cm length. Out of the total number of leaves on each of these branches, the number of leaves damaged as a result of chewing insects was recorded, and from this the percentage of leaves damaged per branch was calculated.

2.7. Data analysis

Data were analysed in R version 2.10.1 (R Project, 2009). Linear mixed effects models (lmer, lme4 package) were run for the following response variables: pollinator (i) abundance and (ii) species richness; floral visitor (iii) abundance and (iv) species richness; surface active predator (v) abundance and (vi) species richness; foliar active predators (vii) abundance and (viii) species richness; chewing insect pest (ix) abundance and (x) species richness; Sucking insect pest (xi) abundance and (xii) species richness; (xiii) fruit set and (xiv) leaf damage.

All response variables were continuous and each was tested using the same mixed effects model structure comprising both fixed and random explanatory variables. The optimal model structure was specified using random intercept and slope models with different combinations of random effects (crop phenology, region, area and site) and comparing the Akaike Information Criterion (AIC) numbers of these models (Bates, 2005; Crawley, 2007). The best fit model was one with the lowest AIC number with random variables comprising of field site nested within region and nested within crop phenology (i.e. pre-flowering, peak flowering and post-flowering seasons). Each model was fitted with Poisson errors (Bates, 2005; Crawley, 2007). There were five fixed effect explanatory factors included in each model. These were: (i) the presence or absence of pesticide usage; (ii) the score of fertilizer application (both considered as management effects); (iii) local proximity to non-crop habitat (considered as a local site effect); (iv) number of semi-native habitat patches within 1 km radii; (v) the proportion of arable land within 1 km radii. The explanatory variables (i) and (ii) were local management effects, (iii) was a categorical variable classifying sites as being either near or far from non-cropped habitat and was considered as a local site effect describing sites as either high quality (closer to non-cropped habitat patches) or low quality (further away from non-cropped habitat patches); (iv) and (v) described landscape structure and were considered as landscape scale effects.

To determine the delivery of each tested ecosystem service (fruit set and leaf damage), pollinator and natural enemy abundance and species richness were included as fixed terms in addition to the above explanatory and categorical variables in the model. For all models, stepwise deletion of least significant effects within the mixed models were used to achieve minimum adequate models for each of the above response variables based on the assessment of their explanatory power. Only those factors whose deletion caused a significant reduction in the explained deviance of the model were retained in the minimum adequate model

(Crawley, 2007). Interactions between each landscape effect term with the local site to and management effect were tested. Similar interactions tests were run between the local site effect and each of the management effect terms. Paired sample *t*-tests were used to assess the difference between fruit set when pollinators were excluded and not.

3. Results

3.1. Pollinator communities and pollination service

3.1.1. Pollinator abundance and species richness

A total of 477 insect pollinators representing 98 species were recorded. The most dominant were honey bees (Apidae: Hymenoptera) which constituted 29.56%, carpenter bees (Apidae: Hymenoptera) (27.46%), sweat bees (Halictidae: Hymenoptera) (16.56%), blow flies (Calliphoridae) (12.79%), leaf cutter bees (Megachilidae: Hymenoptera) (9.44%) and bee flies (Bombyliidae) (3.35%) (refer to Supplementary material S4 for full list).

At local site level, proximity of fields to semi-native patches had a significant impact on pollinator abundance. Significantly more pollinators were found on sites further from semi-native patches than those in close proximity to these patches ($P < 0.001$ – Table 2). The abundance of pollinators was significantly lower pesticide treated fields than untreated fields ($P < 0.001$ – Table 2). On the contrary fertilizer application had a significant positive impact on the abundance of pollinators. Significant negative interactions were found between the proximity of fields to semi-native habitat patches and pesticide use ($P < 0.001$). This effect was far more profound on fields further from semi-native patches than closer ones. Without pesticide application, fields further from semi-native habitats clearly had significantly more pollinators. However, with pesticide application, the effects were more severe on fields further from semi-native than closer ones (Fig. 2).

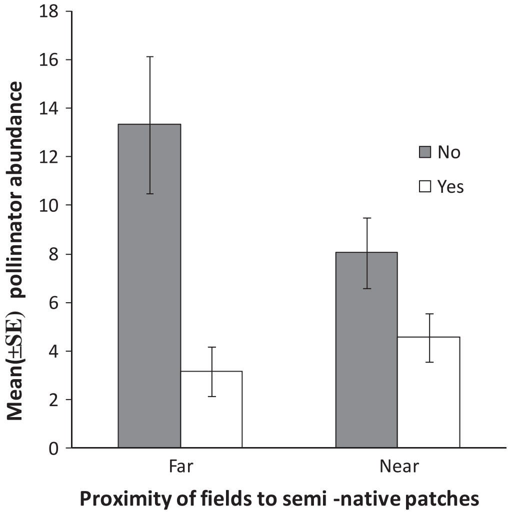

Fig. 2. The effect of pesticide use (yes/no) on pollinator abundance on fields closer and further from semi-native patches of vegetation.

Table 2

Z-values and levels of significance from linear mixed effects models relating to responses of pollinator, natural enemy and pest abundance and species richness and insect floral visitation rates, fruit set and leaf damage in pigeonpea fields to five predictive factors: (i) the number of semi-native patches (No. patch); (ii) the proportion of arable land (Prop. arable); (iii) the local proximity to non-crop habitats (Prox. to SN); (iv) the presence or absence of pesticide usage (Pestic.); and (v) fertilizer application (Fert.).

Response	Mixed effects: minimum adequate model factors	Est.	SE	*Z*
(a) Pollinator abundance				
Pollinator abundance	No. patch	0.35	0.13	2.69^{**}
	Prox. to SN	1.53	0.23	6.72^{***}
	Pestic.	2.71	0.87	3.12^{**}
	Fert.	1.70	0.47	3.66^{***}
	No. patch: Pestic.	−1.35	0.41	-3.31^{***}
	Prox. to SN: Pestic.	−2.20	0.37	-5.91^{***}
	No. patch: Fert.	−0.34	0.17	-2.05^{*}
	Prox. to SN: Fert.	−1.82	0.37	-4.93^{***}
Visitation rates	None	–	–	–
Pollinator spp. richness	None	–	–	–
(b) Natural enemy abundance and species richness				
Surface active abundance	None	–	–	–
Surface active species richness	None	–	–	–
Foliar active abundance	Prop. arable	0.50	0.30	1.67
	Pestic.	−1.24	0.56	-2.22^{*}
	Prop. arable: Pestic.	1.60	0.69	2.33^{*}
Foliar active species richness	None	–	–	–
(c) Pest abundance and species richness				
Chewers abundance	Prox. to SN	0.56	0.09	6.14^{***}
	Pestic.	0.69	0.11	6.57^{***}
	Fert.	0.67	0.10	6.43^{***}
	Prox. to SN: Pestic.	−1.25	0.12	-10.07^{***}
	Prox. to SN: Fert.	−0.59	0.18	-3.22^{**}
Chewers species richness	Prox. to SN	0.24	0.11	2.26^{*}
	Pestic.	0.26	0.11	2.39^{*}
	Fert.	0.36	0.11	3.38^{***}
	Prox. to SN: Pestic.	−0.66	0.15	-4.43^{***}
	Prox. to SN: Fert.	−0.12	0.16	−0.77
Suckers abundance	Prop. arable	1.11	0.24	4.63^{***}
	Pestic.	−0.48	0.53	−0.90
	Prop. arable: Pestic.	−0.43	0.62	−0.69
Suckers species richness	Fert.	0.48	0.13	3.78^{***}
(d) Delivery of services				
Fruit set	Floral visits	1.00	8.00	9.47^{*}

Species richness was not correlated with any of the fixed landscape factors, local site effects or farm management practices. For measures of landscape structure at 1 km spatial scale, pollinator abundance was negatively correlated with the number of semi-native habitat patches ($P < 0.001$ – Table 2). In addition, the number of semi-native habitat patches was found to negatively interact with (1) pesticide use ($P < 0.001$) and (2) fertilizer application ($P < 0.05$).

3.1.2. Insect visitation rates and fruit set

A total of 393 visits were recorded across sites (Mean per branch 1.90 ± 0.10 SE). Insect floral visitation did not significantly respond to any of the fixed terms, and there were no significant interactions. However, insect visitation rates were positively correlated with fruit set ($P < 0.05$). Furthermore, fruit set per branch across fields declined significantly ($t = 2.10$, $P < 0.001$), when pollinators were excluded from the system (Mean fruit set in fields with pollinators = 88.67 ± 4.81 SE and without pollinations = 22.72 ± 3.23 SE).

3.2. Natural enemy abundance, species richness and bio-control service

A total of 1279 arthropods from 149 species recognized as predators of pests based on published information and expert opinion were recorded. Of these, 511 were foliar active predators comprising mainly of sphecid wasps (Sphecidae: Hymenoptera) (59.49%), flies (Diptera) (13.11%), paper wasps (Vespidae: Hymenoptera) (10.37%), ladybird beetles (Coccinellidae: Coleoptera) (7.63%), lace wing larvae (Neuroptera) (4.11%) and Assasin bugs (Reduviidae) (2.15%). Surface active predators were 747 individuals comprising 63.99% spiders, 28.51% ground beetles and 4.82% camel spiders. The others (antlion, rove beetles and springtails) constituted less than 1% of the total number of surface active predators.

At local site level, pesticide use had a significant negative effect on foliar-active predator abundance ($P < 0.05$ – Table 2). Proximity of fields to semi-native patches and fertilizer application had no impact on predator abundance. At landscape level, foliar-active predators did not respond to any factor. However, their abundance was negatively affected by an interaction between the proportion of arable fields and pesticide use ($P < 0.05$). This abundance was higher in pesticide untreated fields that were further from semi-native patches than treated fields in similar context. Species richness was not affected by any of the tested fixed factors. Surface active predator abundance and species richness were both unaffected by either landscape or local scale factors.

3.3. Pest abundance and species richness

A total of 2754 arthropods from 323 species recognized as pests of pigeonpea were recorded. Of this number, 65.1% were found to be chewers and 24.7% to be suckers. The main chewers were; bean weevils (Chrysomelidae: Coleoptera) ($n = 851$), black crickets (Gryllidae: Orthoptera) ($n = 142$), blister beetles (Meloidae: Coleoptera) ($n = 188$), bush crickets (Tettigoniidae: Orthoptera) ($n = 111$), grasshoppers (Acrididae: Orthoptera) (101), leaf beetles ($n = 174$), leaf miners (Agromyzidae: Diptera) ($n = 121$), stemborers (Pyralidae) ($n = 200$). Sucking insects consisted of; aphids (Aphididae: Hemiptera) ($n = 49$), fruitflies (Drosophilidae: Diptera) ($n = 263$), leaf hoppers (Cicadellidae: Homoptera) ($n = 171$), plant bugs (Miridae: Hemiptera) ($n = 44$), stink bugs (Pentatomidae: Hemiptera) ($n = 51$) and treehoppers (Membracidae: Hemiptera) ($n = 44$).

Chewers abundance and species richness were negatively affected by proximity of fields to semi natural patches ($P < 0.001$ and $P < 0.05$ respectively). Pesticide application and fertilizer both had significant negative effects on chewers abundance ($P < 0.001$ and $P < 0.05$ respectively) and species richness ($P < 0.001$ for both factors). Proximity to semi-native habitat patches interacted negatively with pesticide application to affect both chewer abundance and species richness ($P < 0.001$ in both cases). Furthermore, proximity of fields to semi-native patches negatively interacted with fertilizer application to negatively affect chewers abundance ($P < 0.01$ – Table 2). Landscape factors did not have significant effects on chewer abundance or species richness.

For suckers, their abundance was only positively affected by the proportion of arable fields ($P < 0.001$), while species richness positively responded to fertilizer application ($P < 0.001$ – Table 2). No other factor or interactions significantly impacted on chewers. Furthermore, neither chewers nor suckers abundance nor species richness correlated with leaf damage or fruit set.

4. Discussion

Landscape structure in terms of the proportion of semi-native patches, within a given spatial scale has been previously reported to positively affect pollinator and natural enemy abundance and species richness (Landis et al., 2005; Bianchi et al., 2006; Ricketts et al., 2008). However, we found contradictory results for insect abundance that showed a negative response to the number of semi-native patches at a 1 km spatial scale.

Pesticides are widely used in controlling pest species attacking crops, but the compounds in some of these chemicals have also been demonstrated to have severe negative impacts on non-target species such as pollinators and natural enemies (Theiling and Croft, 1988; Brittain et al., 2010). In the context of the developing world, the problem of insecticide use is of particular concern since their application depends on many variables such as household income, level of literacy and availability (Mbuvi, 2009). Added to this, there is very little understanding that the presence of beneficial insects among the pool of insects (generally all regarded as pests) could provide financial benefits for the growers. Of all the measured local site factors in this study, insecticide use emerged as a major factor linked to reduced abundance of pollinating insects and natural enemies.

This study has investigated the role played by both local management and landscape context in determining the availability of invertebrate pollinators and natural enemies within pigeonpea crops, and their capacity to deliver associated ecosystem services. Given the economic importance of this crop in Kenya and other parts of the developing world, a better understanding of our ability to maximize naturally occurring ecosystem services is needed to maintain crop production. There is potential to provide direct benefits to farmers by increasing crop yields, while being compatible with the aims of local biodiversity conservation in the Afrotropics. However, to our knowledge this is the first study to consider how pollinators and natural enemies respond to landscape context and farm management in tandem in the context of the developing world.

4.1. Pollinator communities and pollination services

Contrary to hypothesis 1, both landscape structure and local farm management were important drivers of pollinator abundance. It is widely reported that an increase in the proportion and number of semi-native habitat patches enhances the diversity and abundance of pollinators (Bianchi et al., 2006; Landis et al., 2005; Ricketts et al., 1999). However, the findings of this study are not consistent with this pattern. This is likely to be influenced by local site conditions. For example, semi-arid landscapes dominated by drought hardened plants such as those within our study area are of comparatively low value to pollinators (Bogdan, 1958). Areas of low semi-native habitat patches are characterized by arable fields dominated by crops. This could contribute to pollinators switching to high rewarding crops, like pigeonpea when they are in flowering phase (Shanower and Romeis, 1999). An increase in the area of pigeonpea fields and therefore reduction in sizes of semi-native patches could have caused this effect as more resources (floral and nectar) became available to pollinators. Pigeonpea mass flowers and so may be more competitive in attracting large numbers of nectar and pollen feeding invertebrates than low quality native vegetation within similar landscape contexts. However, we did not record a higher abundance of within-field pollinators closer to semi-native patches which could be due to the fact that these insects were already foraging deeper into the crop. Mass flowering has been demonstrated to be an effective determinant of high densities of pollinators, especially bees, regardless of landscape context (Westphal et al., 2003). This fact is further supported by the finding that fields that were closer to semi-native habitat patches at the local scale had significantly fewer pollinators than those further away (largely dominated by pigeonpea crop). Pesticide usage was a negative predictor of pollinator abundance and is likely that pollinating insect populations are being severely negatively impacted as a consequence (Brittain et al., 2010; El Hassani et al., 2005).

The enhancement of pollinator abundance by fertilizer application is possibly due to an increase in floral attractiveness with greater crop growth responding to additional nutrient availability. However, this also caused a dis-service because it enhanced the proliferation of chewing pest populations. Although fertilizer use may result in massive increases in the yield of the crop, the trade-off is challenging and could be a matter of probability to the farmers whether or not to apply it and risk the dis-service associated with it. An increase in pest population triggers farmers to increase the amount of pesticide inputs, most of which will also result in high levels of mortality for non-target arthropods such as pollinators (see Müller et al., 2005). This is where farmer education and increased awareness could be targeted as an intervention to conserve pollinator species and other beneficial arthropods (Müller et al., 2005).

The negative interactions between the number of semi-native habitat patches at landscape scale and also proximity of fields to semi-native habitat patches at local scale with the number of pesticide applications confirm the significant impacts of pesticide application on pollinators. Fields dominated by the mass flowering pigeonpeas further from semi-native habitat patches and pesticide-free had significantly more pollinators than pesticide-treated fields in similar contexts. A similar effect was found in fertilizer-treated fields. For pigeonpea fields, it may be important to reduce pesticide and minimize fertilizer inputs in order to conserve pollinator populations, given the significant contribution of pollinating insects to fruit set. However, it is worth noting that in the context of developing countries, particularly in the developing world, attaining sustainable pesticide use is extremely difficult given the large inter-annual variability in pest damage and high financial risks associated with non-use of pesticides (Ngowi et al., 2007). As a result, the future of pollinator communities and consequently their functioning in the ecosystem is likely to be under serious threat from uncontrolled pesticide use (Kevan, 1999).

The significant decline in fruit set when pollinators were excluded clearly show that pigeonpea requires insects for pollination. Conservation measures that promote an increase in pollinator populations would link to increased pigeonpea yield production. Comparable results in tropical context have also been reported in other crops such as coffee (Klein, 2002).

4.2. Natural enemies, pests and pest control service

Farm management played a key role in foliar-active predator abundance and both the abundance and species richness of chewing and sucking pests. Although pesticide application had a strong effect in suppressing pest populations, it did not complement the effects of natural enemy abundance or species richness. Instead, an antagonistic effect of pesticide use on natural enemies, particularly on foliar active predators was found. This is not surprising because they have direct contact with leaves and may be more exposed to direct application of pesticides or ingest the compounds via prey items (e.g. predatory beetles – Theiling and Croft, 1988). In the context of these findings, this effect is likely to have been responsible for lack of a correlation between natural enemies and leaf damage. Furthermore, lack of correlation between natural enemy abundance or species richness and leaf damage could mean that there was generally a low proportion of chewing insects following pesticide application at the time this study was conducted.

The interaction between the proportion of arable fields and pesticide application provide evidence that both landscape and farm management factors affected foliar active predator abundance. Pesticide free fields within landscapes contexts comprising a high proportion of arable habitats had significantly more foliar active predators than those in similar contexts but pesticide treated.

The presence of a high concentration of pigeonpea in fields further away from semi-native habitat patches could have resulted in a range of pest communities being attracted. These fields also had high abundance of pollinators and foliar active predators. To enhance the populations of beneficial insects while eradicating pests can be difficult and needs a lot of knowledge and understanding (Kearns et al., 1998). To maintain a high density of both pollinators and foliar pest predators in pigeonpea fields it is relevant to target a reduction of both pesticides and fertilizer inputs.

Proximity of pigeonpea fields to semi-native habitat patches and pesticide usage appear to be important local drivers of pollinator, foliar active predator and pest abundance. Although pesticides save a significant amount of crops and therefore economic returns, their cost on biodiversity, especially beneficial insects, cannot be ignored. It is important to apply a careful approach to pesticide usage within set guidelines and regulations and, most importantly, adopt integrated pest management programs to limit the costs to biodiversity and the environment while increasing the benefits of pesticides in crops. This would enhance sustainable pigeonpea yields and conserve communities of both pollinators and predators of pests within pigeonpea landscapes. In addition local farmer education on the benefits of insect mediated ecosystem services to crop production would greatly boost the conservation of these beneficial insects because they would be more aware of the consequences of high pesticide usage on service providing insects.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2011.06.013.

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