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1 Local and landscape effects on bee functional guilds in pigeon pea crops in Kenya

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17 **Abstract**

18 Pollinators face many challenges within agricultural systems due to landscape changes and intensification
19 which can affect resource availability that can impact pollination services. This paper examines pigeon pea
20 pollination and considers how landscape context and agricultural intensification in terms of pesticide use
21 affects the abundance of bees characterized by species guilds on crops. The study was conducted on six
22 paired farms across a gradient of habitat complexity based on the distance of each farm from adjacent semi-
23 natural vegetation in Kibwezi Sub-county, Kenya.

24 The study found that farms which do not use insecticides in farm management, but are in close proximity to
25 natural habitat have greater bee guild abundance, but at further distances, overall abundance is reduced with
26 or without insecticide use. At 1 km landscape radius, the complexity of habitats but not patch size had a
27 positive impact on the abundance of cavity nesting bees and mason bees, which can be attributed to the
28 interspersed of the small-holder farms with semi-natural habitats across the landscapes producing mosaics
29 of heterogeneous habitats. The study revealed the strongest relationships between fruit set and bee
30 abundance to be with the carpenter bee, social bee and solitary bee guilds, which are among the most
31 abundant bees visiting pigeon pea flowers in this system. Our findings provide the foundation for
32 conservation efforts by identifying which bee guilds pollinated pigeon peas. From this study, we suggest
33 managing the floral and nesting resources that would best support the most abundant crop pollinators, and
34 also reducing insecticide application to the crop.

35

36 **Keywords**

37 Functional group, Landscape effects, Pesticide, Semi-native, Species guild, Tropical
38 Agroecosystems

39

40 **1. Introduction**

41 Bees provide the critical ecosystem service of pollination (Garibaldi et al. 2013), and as free-foraging
42 organisms, they face many challenges within agricultural systems due to intensification (Kremen, Williams
43 and Thorp 2002; Tscharntke et al. 2005). Broadly, agricultural intensification includes increased inputs of
44 agro-chemicals, decreased crop diversity, and reduction of adjacent natural and semi-natural habitats
45 (Tscharntke et al. 2005; Garibaldi et al. 2013; Deguines et al. 2014). These changes cause alterations in the
46 spatial-temporal distribution of resources for insect pollinators, and reduce resource availability which can
47 contribute to overall pollinator decline (Kremen, Williams and Thorp 2002; Tscharntke et al. 2005;
48 Winfree et al. 2007; Ricketts et al. 2008; Rundlof et al. 2008; Potts et al. 2010; Cameron et al. 2011).

49 Challenges for pollinators arise at both the local farm management level as well as the larger landscape
50 level, both of which can affect pollination services. At the local farm-level increased inputs, such as
51 insecticide usage, can negatively impact pollinator populations through direct and indirect exposure
52 (Brittain et al. 2010 a&b), which can also reduce pollination efficiency (Sabatier et al. 2013; Feltham, Park
53 and Goulson 2014).

54 At the larger landscape-level, challenges due to intensification include increased habitat fragmentation and
55 simplification of landscapes that result in habitat isolation and reduced abundance and diversity of floral
56 and nesting resources (Garibaldi et al. 2011; Ferreira, Boscolo and Viana 2013) that are unable to support
57 diverse pollinator communities (Tscharntke et al. 2005; Andersson et al. 2013). Proximity of crop fields to
58 semi natural vegetation is important in enhancing pollinator diversity and the level of pollination to crops
59 (Karanja et al. 2010; Blitzer et al. 2012; Klein et al. 2012); However, proximity to semi natural vegetation
60 may vary with the landscape context (Steffan-Dewenter et al. 2002; Ricketts et al. 2008; Jha and Kremen
61 2013). The reduction of supportive natural habitat also reduces pollinator abundance in adjacent field crops,
62 which negatively impacts pollination services within agricultural systems (Steffan-Dewenter et al. 2002;
63 Ricketts et al. 2008). Indeed, several studies have established close correlations between increasing
64 agricultural intensification and declining abundance and diversity of insect pollinator species (Kremen,
65 Williams and Thorp 2002; Hendrickx et al. 2007; Hagen and Kraemer 2010) and resulting decline in crop
66 yield (Klein, Steffan-Dewenter and Tscharntke 2003; Isaacs and Kirk 2010; Otieno et al. 2011).

67 Many pollinator-based landscape studies focus on the response of bee communities to species richness,
68 abundance and pollination efficiency (e.g. recently Ricketts and Lonsdorf 2013; Williams and Winfree
69 2013; Andersson et al. 2013; Bailey et al. 2014). The conclusions of these studies provide information that
70 benefits land management efforts for specific agricultural systems. An example is the establishment of agri-
71 environmental schemes (AES) throughout Europe, which aims to reduce biodiversity loss (Kleijn and
72 Sutherland 2003). Additional management strategies include mitigating habitat fragmentation (Harrison
73 and Bruna 1999), preserving natural habitat (Kremen et al. 2004), and providing additional foraging and
74 nesting resources for free-foraging pollinators (Scheper et al. 2013). Yet, as these studies are used to
75 understand pollinator relationships to the environment, most are limited to North America and Europe; few
76 studies consider African and Asian agricultural systems (Archer et al. 2014). These systems face similar
77 agricultural intensification, but differ in pollinator communities and agricultural cycles. Thus conclusions
78 from most pollinator studies cannot be readily transferred into other agricultural systems worldwide.

79 In this study we focused on the pollinators in the economically important pigeon pea (*Cajanus cajan*. (L.)
80 Millsp.: Leguminosae) agricultural system in Kenya. Pigeon pea is a dominantly grown crop in the dry
81 Lower Eastern regions of Kenya covering approximately 150,000 ha and mainly used for human dietary
82 protein provision and fodder for animals (Otieno et al. 2011). We considered the effects of agricultural
83 intensification on species richness, abundance and pollination efficiency, and we further considered bee
84 abundance in relation to species guilds. Here, a guild is defined as a group of species that utilize related
85 resources in similar ways (Simberloff and Dayan 1991). By grouping bees into guilds we can identify
86 common patterns of response to agricultural intensification pressures within a habitat and transfer them into
87 other habitats with completely different species communities that share similar guilds. Conclusions from
88 this study using species guild abundances will benefit this specific crop in Africa and other tropical regions.
89 Moreover, the results can also be used to increase the generality of findings beyond the specific habitat
90 within which they were undertaken (Williams et al. 2010; Blaum et al. 2011).

91 For this study our aim was to examine the pigeon pea cropping system by evaluating how agricultural
92 intensification affects the pollinator community as characterized by species guilds. Specifically, we asked
93 the following questions: (1) how do local and landscape factors impact on the abundance of pollinator

94 guilds? (2) What are the patterns of bee abundance when farms area farther from semi-natural vegetation
95 and either sprayed insecticides or not compared to those closer to semi-natural habitats? (3) is there a
96 difference in fruit set when pollinators are excluded from flowers or not?

97 Agricultural intensification was characterized by: landscape complexity, which captures resource diversity;
98 proximity of a field to natural habitat, which captures resource accessibility; and management practices,
99 such as insecticide application, which may negatively impact pollinators. We characterized bee guilds by
100 key traits such as nesting, sociality, and diet breadth, which are related to habitat requirements. Pollination
101 efficiency was measured by comparing restricted self-pollination with open pollination. This study
102 highlights conclusions relevant to Kenyan agriculture, but also conclusions that are transferable among
103 ecosystems worldwide.

104 **2. Methods**

105 2.1 Site selection

106 We conducted the study in Kibwezi Sub-county, Makueni County, Kenya (2°15'S and 37°45'E) at 723-
107 1015 m above sea level, about 150 km South East of Nairobi from April to June 2009. The climate is
108 broadly characterized by annual temperatures reaching 30°C and annual rainfall of 644 mm (Mbuvi 2009).
109 The landscape is generally comprised of rain-fed agricultural fields that rely completely on natural
110 precipitation, and non-cropped patches of semi-natural vegetation adjacent to crop fields that are comprised
111 predominantly of native plants.

112 We selected six pairs of pigeon pea crop fields along a gradient of landscape heterogeneity totaling to 12
113 sites. Each pair had a simple and a complex site in a similar area determined on land use/land cover
114 (LULC) map at a 1 km radius buffer surrounding each field. Landscape heterogeneity ranged from simple
115 landscapes characterized by a high percentage of arable land (>50% cropped fields) within the 1 km buffer
116 at each site to complex landscapes (<50% cropped fields) within the same spatial landscape radius. We
117 maintained a minimum distance of 2 km between the site pairs as determined using LULC maps in ArcGIS
118 9.3 so that pollinator communities do not overlap. We used the LULC map derived from a Landsat 7
119 Enhanced Thematic Mapper image (2003) ground truthed in April 2009 to check the accuracy and
120 consistency of different land cover types.

121 2.2. Agricultural intensification

122 2.2.1. *Proximity to natural habitat*

123 To assess the effects of this factor on species guilds, we categorized each site of each pair based on its
124 proximity to semi-natural habitat which is important for resource accessibility to pollinators (Rathcke and
125 Jules 2003). Of the 12 study sites assigned into six pairs, we had a total of six far sites and six near sites.
126 “Far” sites were typically located in a simple landscape more than 200 m from the nearest non-cropped
127 patch and were dominated by a mix of cropland and human habitation. “near” sites were located in
128 complex landscape less than 200 m from non-cropped patches (Otieno et al. 2011; Sabatier et al. 2013;
129 Feltham, Park and Goulson 2014). We used “far” and “near” as categorical explanatory variables for
130 further analysis.

131 2.2.2. *Insecticide usage*

132 To assess the field management used on each site, we conducted face-to-face interviews with farmers and
133 concluded that insecticide usage was a key farm management practice. This emerged as the most consistent
134 practice either used or not used by farmers. The active ingredients in the insecticides applied across the
135 study sites were: Thiamethoxam; Dimethoate; Alpha-Cyphpermethrin; Beta-Cyfluthrin; Lambda
136 Cyhalothrin; Azoxystrobin and Methomyl (see Appendix 1 for common names and target pests). We
137 therefore used the number of applications of insecticide per crop season as an indication of local
138 management intensity for the pigeon pea crop.

139 2.2.3. *Landscape complexity*

140 We derived metrics to measure landscape context to quantify agricultural intensity using the Patch Analyst
141 extension in ArcGIS 9.3 (Elkie, Rempel and Carr 1999; Ferreira, Boscolo and Viana 2013) based on the
142 1:500,000 LULC maps described above. We selected non-collinear landscape metrics following a
143 collinearity test (Table 1). The selected metrics have been shown to have a significant ecological influence
144 on pollinators (Barbaro et al. 2005; Tschardt et al. 2005; Steffan-Dewenter, Potts and Packer 2005;
145 Andersson et al. 2013) (Table 1). These were: (1) Mean Shape Index, which is a measure of patch
146 complexity taking into account the perimeter and area of each patch type within the 1 km landscape radius

147 (McGarigal and Marks 1994; Elkie, Rempel and Carr 1999; Steffan-Dewenter et al. 2002; Ricketts et al.
148 2008), used to measure the effects of landscape structure on pollinators (Coulson et al. 2005; Krupke et al.
149 2012); (2) Mean Patch Size, which is the mean number of patches of different sizes at the site; (3) Edge
150 Density of non-cropped patches, which is the amount of habitat patch edge within a landscape area (i.e. 1
151 km radius here). Edge density measures landscape configuration, and is important in making comparisons
152 between landscapes of variable complexities and sizes and how that affects resource availability to animals.
153 Collectively, these metrics provide a quantitative description of landscape complexity.

154 2.3. Pigeon pea pollinators

155 2.3.1. *Bee abundance and species richness*

156 Bee abundance was measured by observing bee visitation to flowers. Bees were observed along five 100 m
157 transects at each pigeon pea crop field; transects were placed north to south, each separated by a minimum
158 of 10 m at each site. Bee visitations within 2 m of the transect were recorded as we walked each transect for
159 10 minutes, twice a day (between 09h00 and 16h00). A total of 49 days were spent to sample all the 12
160 sites between 20th April and 20th June 2009. Bee species richness (number of species) was quantified by
161 collecting bees and identifying them to species or to morphospecies, for those which available keys could
162 not identify them to species, by aid of reference collection and bee experts at the National Museums of
163 Kenya, York University and University of Pretoria.

164 2.3.2. *Bee abundance by guild*

165 Bee guilds were categorized based on a compilation of ecological and life histories from the
166 existing literature (Michener 2000; Blaum et al. 2011; Garibaldi et al. 2013). We then identified and
167 assigned three of the most ecologically relevant and widely used traits (Kremen, Williams and Thorp 2002;
168 Tschardt et al. 2005; Moretti et al. 2009; Woodcock et al. 2009; de Bello et al. 2010; Bommarco et al.
169 2010; Williams et al. 2010) to each bee species/morphospecies for further analysis. We considered the
170 following traits: sociality, diet breadth, and nesting specialization to delineate bee guilds. Sociality traits
171 were categorized as: social bees, semi-social bees, solitary bees. Diet breadth traits were categorized as:
172 oligolectic bees, and polylectic bees. Nesting traits were categorized as: carpenter bees, soil cavity nesting

173 bees, mason bees, above ground cavity nesting bees (e.g. honey bees), and no-nest bees. (See Table 2 for
174 detailed description and species groupings and appendix S1 for species trait information). These guilds
175 were created to include the most relevant natural history traits that are related to bee resource requirements
176 and are also commonly studied in the functional ecology of insects.

177 2.4. Pollination services

178 Crop response was measured by quantifying pollination services. This was done by determining the
179 proportion of fruit set attributable to insect pollinators using paired comparisons of pigeon pea crop either
180 open or closed to insect pollinators (Tschamtker et al. 2005; Ricketts et al. 2008; Garibaldi et al. 2013;
181 Deguines et al. 2014). We selected three plants in each transect within the crop at 5 m, 50 m and 95 m
182 totaling to 180 plants across all sites (3 plants per transects x 5 transects x 12 sites = 180). Each plant we
183 selected had at least two branches (50 cm long each) with unopened flower buds. We covered one of these
184 branches with a fine cloth netting (Tulle bag) to stop insect pollen vectors. We left open the other branch as
185 a control (open pollinated). We counted the number of pods (fruit) set on both the experimental and control
186 branches per plant at the end of the experiment and quantified the amount of pollination due to insects
187 following the formula from Ricketts et al. 2008.

$$188 \text{ Insect Pollination} = \text{Open pollination [control]} - \text{Self-pollination [Tulle bags]}.$$

189 In the analysis, fruit set attributable to bees was quantified as the percentage of the difference between open
190 and closed pollination.

191 2.5. Data analysis

192 We summed bee data and fruit set from each field for the entire sampling period and analyzed
193 these using linear mixed effects models (lmer, lme4 package) in R for Windows version 2.15.2 (eg.
194 Kremen, Williams and Thorp 2002; Steffan-Dewenter 2003; Neumann and Carreck 2010; vanEngelsdorp et
195 al. 2010; Otieno et al. 2011) to relate proximity to natural habitat, insecticide use, landscape complexity
196 and pollination services with bee abundance.

197 Each model was fitted with five fixed effect explanatory factors and site as a random effect. The fixed
198 explanatory factors were: (i) proximity to natural habitat and (ii) the number of insecticide applications (iii)

199 mean shape index, (iv) mean patch size and (v) edge density. A mixed effect model was constructed for
200 each response variable, which were total bee abundance, overall bee species richness, and each bee guild as
201 characterized by sociality, diet breadth and nesting trait (listed previously, Table 2). The data had higher
202 variance than the means, so each model was fitted with Poisson errors, which are typically suited for count
203 data with this distribution (Harrison and Bruna 1999; Bates 2010; Crawley 2012; Kéry and Schaub 2012).
204 We specified the best model structure using a random intercept and slope models and compared the fit of
205 individual models using the Akaike Information Criterion (AIC) (Kleijn and Sutherland 2003; Bates 2010;
206 Crawley 2012). In this process, we compared models with and without one explanatory variable to obtain a
207 minimum adequate model with the lowest AIC number.

208 Pollination service was also measured with a similar linear mixed effects model structure with fruit set as
209 the response variable. Pollinator abundance and species richness were included as fixed terms in addition to
210 the explanatory and categorical variables in the model. The interactions between proximity to natural
211 habitat, the number of insecticide applications and each of the landscape effect terms were non-significant
212 and not included in the model.

213 To determine the patterns of bee abundance when farms were farther from semi-natural vegetation and
214 either sprayed insecticides or not compared to those closer to semi-natural habitats, we averaged data
215 across sites and performed a generalized linear mixed-effects model (glmer, lme4 package) with Poisson
216 error distribution (Bates 2010; Chateil and Porcher 2014). Here, we had two categorical fixed factors: local
217 proximity to natural habitat (either near or far) and insecticide use (either yes or no). Site was included as a
218 random effect. We tested for the effect of interactions between local proximity to natural habitat and
219 insecticide use on the abundance of each of the bee traits (Table 2) used in the previous analysis as
220 response variables.

221 Paired sample t-tests were used to assess the difference between fruit set when pollinators were excluded
222 from flowers or not. Simple regression models were run to test for linear relationships between the
223 abundance of bees of different traits and fruit set.

224

225

226 3. Results

227 3.1 Pollinators in the pigeon pea system

228 We recorded a total of 1,008 bee visitors from 31 genera. The most abundant bees were *Megachile spp.*
229 (Megachilidae: Hymenoptera) (28.57%), *Apis mellifera* (Apidae: Hymenoptera) (19.94%), *Ceratina spp.*
230 (18.35%) and *Xylocopa spp.* (6.85%). *Megachile spp.* are all solitary (8 species) and mostly soil cavity
231 nesting, with one mason species. *A. mellifera* are social and above-ground cavity nesters. *Ceratina spp.* and
232 *Xylocopa spp.* are both semi-social and categorized as carpenter bees. All of the most abundant species are
233 polylectic bees.

234 3.2 The impacts of local and landscape factors on overall bee abundance and species richness.

235 At the farm level, the number of insecticide applications had a significant negative impact only on the total
236 bee abundance ($z=-6.537$, $p<0.001$ - Fig. 1b), but not species richness ($z = -1.658$ and $p>0.05$). Out of all
237 the landscape complexity metrics used to characterize agricultural intensification, only Mean Shape Index
238 (i.e. patch complexity) had a significant positive effect on total bee abundance ($z=4.76$, $P<0.001$ - Fig. 1a),
239 whereas Mean Patch Size and Edge Density did not have a significant effect on species richness or bee
240 abundance.

241 3.3 The impacts of local and landscape factors on of bee guilds

242 Proximity of sites to natural habitat patches at the local scale had a significant effect on the abundance of
243 mason, miner and polylectic bees. We found significantly higher number of mason bees in fields farther
244 away from semi natural habitat patches (Table 3). We found the opposite effect of the proximity of sites to
245 semi-natural habitats on mining bees and polylectic bees (Table 3).

246 The number of insecticide applications on pigeon pea crop had significant negative effects on the
247 abundance of carpenter bees, bees nesting in soil cavities and mining bees (Table 3). Similarly, we detected
248 significant negative effects of the number of insecticide applications on social, solitary, and semi-social
249 bees (Table 3). However, only polylectic bees of the two lecty traits examined were negatively affected by
250 the number of insecticide applications (Table 3).

251 Habitat complexity had various effects on bee diversity when bees were considered by guild. At 1 km
252 spatial scale, Mean Shape Index had significant positive effects on the abundance of cavity nesting bees
253 and mason bees (Table 3). Conversely, for the sociality traits only solitary bee and polylectic bee
254 abundance was significantly positively affected by mean shape index (Table 3). Mean Patch Size had
255 significant positive effects on carpenter bee and mason bee abundance (Table 3). We found a similar effect
256 with edge density on carpenter bees and mason bees respectively (Table 3).

257 With regards to the patterns of bee abundance when farms were farther from semi-natural vegetation and
258 either sprayed insecticides or not compared to those closer to semi-natural habitats, proximity to semi-
259 natural habitats was the key factor affecting all functional guilds except cleptoparasites and oligolectic bees
260 (Table 4). Carpenter bees were significantly more abundant on farms that were near semi-natural habitats.
261 However, there was no difference in the abundance of these bees on sites farther from semi-natural
262 vegetation whether they sprayed insecticides or did not. Similar results were obtained for soil cavity
263 nesters, miners and above ground cavity nesters (Table 4). There was no effect on mason bees although
264 mason bees were more abundant on farms farther from semi-natural vegetation that did not spray
265 insecticides. Bees with no nests could not be modeled using interaction terms of insecticide use and
266 proximity to semi-natural habitat most likely due to the very low abundance hence low statistical power.
267 Polylectic bees were significantly more abundant on farms closer to semi-natural vegetation that did not
268 spray insecticides (Table 4). The abundance of these bees on sites farther from semi-natural habitat
269 (whether they sprayed insecticides or not) did not differ. Similar to bees without nests, oligolectic bees
270 could not be modeled given the reason above.

271 The abundance of semi-social and social bees was affected by a significant interaction between proximity
272 of sites to semi-natural habitat and insecticide use with far sites that did not spray having significantly more
273 of these bee guild than near sites that sprayed (Table 4). For solitary bees, although their abundance was
274 significantly more on sites closer to semi-natural habitats, there was no difference in their abundance on
275 sites farther from semi-natural habitats regardless of insecticide use.

276

277

278 3.4 Pollination services

279 Overall, there was a significant decline in the pigeon pea fruit set when pollinators were excluded from the
280 system ($t=-7.88$, $p<0.001$), with mean fruit set being almost halved in the absence of insect pollinators
281 (mean number of fruits per 50 cm branch with pollinators= 42.08 ± 3.76 ; without= 24.58 ± 2.86). Independent
282 of this overall effect, none of the local management or landscape factors were identified as having a
283 significant effect on the difference in fruit set between open and closed treatments. Total bee abundance
284 significantly correlated with fruit set ($p=0.022$). Using separate regressions for each trait with fruit set, we
285 found a significant positive relationship between the abundance of carpenter bees and fruit set ($R^2=0.63$,
286 $F_{1,10}=17.11$, $p=0.002$ - Fig. 2a). We found a similar effect on fruit set with social bees abundance ($R^2=0.34$,
287 $F_{1,10}=5.06$, $p=0.048$ - Fig. 2b) and solitary bee abundance ($R^2=0.40$, $F_{1,10}=6.76$, $p=0.026$ - Fig. 2c). None of
288 the other traits measured correlated with fruit set ($p>0.05$).

289 **4. Discussion**

290 4.1 The impacts of local and landscape factors on of bee abundance and guilds

291 Our study shows that farms which do not use insecticides but are in close proximity to natural habitat have
292 greater bee abundance, but at further distances, overall abundance is reduced with or without insecticide
293 use. Natural habitats for example forest edges form important refugia for pollinators. Our results, although
294 done on a different cropping system (pigeon pea), are comparable to Bailey et al. (2014) who found the
295 edges of semi-natural vegetation to support a large number of ground nesting bees in oil seed rape fields.
296 These results confirm that natural habitat edges surrounding crop fields play an important function in
297 providing extra food, pollinator nesting sites and even breeding and oviposition sites (Roulston and Goodell
298 2011; Carvalhero et al. 2010; Smith et al. 2013; Bailey et al. 2014; Nayak et al. 2015). Cavity nesting bees,
299 above ground nesting bees, polylectic, semi-social, social and solitary bee foragers were significantly more
300 abundant closer to the semi-natural habitat than they were farther into the field. These bee species,
301 commonly live within natural or semi-natural vegetation. Cavity-nesting bees have been shown to respond
302 negatively to intense agriculture, presumably in response to loss of nesting habitat availability (Sheffield et
303 al. 2013).

304 The inability to model the interactive effects of proximity of crop fields to natural habitat and insecticide
305 use on oligolectic bees and bees with no nests is most likely caused by the low abundance resulting into
306 low statistical power. The study findings for these bee guilds need to be treated with caution when dealing
307 with large abundances as the response to the tested parameters may differ. It is recommended that more
308 precise methods of sampling the less abundant groups be adopted to determine how they respond to
309 proximity to semi natural vegetation and insecticide application.

310 Insecticides had a negative effect on bee abundance. When the impact of insecticides was assessed by
311 guild, there was a significant negative effect on the abundance of most bee guilds, which included:
312 carpenter bees, soil nesting bees, miner bees, polylectic bees, and bees of all sociality types. Pollinators of
313 pigeon pea crops could be affected by insecticide use due to traits captured by guild characteristics. Nesting
314 sites may make some bees more vulnerable to lethal or sublethal affects (Brittain et al. 2010 a&b; Brittain
315 and Potts 2011, Krupke et al. 2012). Furthermore diet breadth and exposure to insecticides and insecticide
316 drift may impact bees (especially oligolectic) bees at a higher rate due to limited and concentrated food
317 sources (Brittain and Potts 2011). However, polylectic bees in this study system do not have many wild
318 nectar sources (M.O. personal observation) other than from other crops planted as intercrops, a common
319 practice in small-holder agriculture. So, both guilds would face the same fate because all crops on the farm
320 receive insecticides either from direct spray or from drift.

321 We predicted that all three landscape complexity metrics would have a positive relationship with bee
322 abundance and species richness, but only Mean Shape Index was positively related while Mean Patch Size
323 and Edge Density did not. Here we used landscape complexity as a proxy for agricultural intensification
324 where simple landscapes are generally more intensively managed compared to complex landscapes that are
325 less intensively managed and have a mix of resources available for free-foraging organisms (Tschardt et
326 al. 2005). Species richness was not affected by any complexity factor. The farming system in our study area
327 is small-holder driven and farms are typically interspersed with semi-natural habitats across the landscapes
328 producing mosaics of heterogeneous habitats.

329 From our findings, we propose the adoption interventions such as organic farming that are by far more
330 effective in sustaining healthy populations of important crop pollinators such as bees than conventional
331 farming (Holzschuh et al. 2008, Allsopp et al. 2014). The practices used in organic farming support more
332 pollinators than conventional farming (Holzschuh et al. 2008). For example, unlike conventional farming
333 where bees are exposed to numerous toxic chemicals through a variety of routes, organic farming is
334 characterised by reduced bee exposure to pesticides and other toxic chemicals. In addition, organic
335 farming practices promote the existence of a variety of habitats within agricultural landscapes that provide
336 habitat corridors and links between patches (Le Coeur et al. 2002). This is important for supporting higher
337 bee diversity and could potentially benefit pollinators in our study system by enabling bees to forage for
338 pollen from diverse sources across the landscape (Holzschuh et al. 2008; Power and Stout 2011, but see
339 Sarospataki et al. 2009 and Brittan et al. 2010a).

340 **4.2 Pollination services**

341 There was a significant decline in pigeon pea seed set when pollinators were excluded from flowers. The
342 strongest relationships between fruit set and bee abundance were carpenter bees, social bees and solitary
343 bees, which are among the most abundant bees visiting the flowers in this system. Although pigeon pea is
344 self-compatible to some degree, recent cultivars released to farmers rely on bees and other insects for
345 sufficient pollination, with bees effecting 70% of out-crossings (Choudhary 2011). Bee species belonging
346 to these guilds should be targeted for conservation for this cropping system, and conservation strategies can
347 be developed around the resources required by these bees, such as nesting suitable for carpenter bees. In
348 addition, abundant floral resources should be available for colonies of social bees when the target crop is
349 not in bloom in order to sustain the population. Insecticide application should be appropriately managed to
350 mitigate effects on solitary bees.

351 No other study, to our knowledge, has examined legume crop pollination at local and landscape levels in-
352 tandem in a tropical setting. Our findings provide the foundation for conservation efforts by identifying
353 which bee guilds pollinated the crop. From our study, we suggest managing the floral and nesting resources
354 that would best support the most abundant crop pollinators, and also reducing insecticide application to the
355 crop. Further work will need to focus on more direct measures of bee visitation by guild to pigeon pea in

356 controlled experiments to determine the independent and combined contribution of fruit set and to establish
357 economic value. By identifying specific guilds to target for conservation, future efforts can examine the
358 best way to manage resources required by particular bees. Targeted measures for conserving resources
359 would not only sustain yields, but also benefit conservation of biodiversity and promote a sustainable
360 agricultural system within this small-holder agricultural landscape.

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532

533 **List of Tables**

534 **Table 1:** Correlation matrix of landscape metrics generated by Patch Analyst within ArcGIS 9.3 at 1 km
535 spatial radius. *MPS* refers to Mean Patch Size, *TE* refers to Total Edge, *MSI* refers to Mean Shape Index,
536 *MPFD* refers to Mean Patch Fractal Dimension, *TCA* refers to Total Core Area and *LPI* refers to Largest
537 Patch Index of each habitat patch.

538 **Table 2:** Bee functional trait description and functional groups under each trait used for analysis. Trait
539 groups were determined based on published literature. Each trait category was calculated from pooled bee
540 abundance per site. Different functional groups of traits per trait group were analysed to determine the
541 response of each to landscape structure and local site conditions/ management.

542 **Table 3:** Z - values of the outputs of linear mixed effects models showing results of the impact of landscape
543 complexity (Mean Shape Index), patch size (Mean Patch Size) and configuration (Edge Density); Local
544 proximity to semi natural habitats and management (number of insecticide application (number of sprays))
545 on the abundance of bees and functional traits. (astriks notations: * p < 0.05; ** p < 0.01; *** p < 0.001).

546 **Table 4:** t-values of linear mixed effects model showing bee guild trait responses to proximity of sites to
547 semi-natural habitats and insecticide application. (astriks notations: * p < 0.05; ** p < 0.01; *** p < 0.001;
548 ∞ denotes failure of model to converge due to low abundance).

549

550 **Table 1**

	<i>MPS</i>	<i>TE</i>	<i>ED</i>	<i>MSI</i>	<i>MPFD</i>	<i>TCA</i>	<i>LPI</i>
Mean Patch Size	1.00						
Total Edge	0.40	1.00					
Edge Density	0.40	1.00	1.00				
Mean Shape Index	0.21	0.83	0.83	1.00			
Mean Patch Fractal Dimension	0.33	0.80	0.80	0.97	1.00		
Total Core Area	0.91	0.52	0.52	0.15	0.27	1.00	
Largest Patch Index	0.92	0.55	0.55	0.21	0.33	0.99	1.00

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552

553 **Table 2**

Trait groups	Categories	Definition
Social status	Solitary	Single adult constructs and provisions nest
	Social	Colonial life form, Single reproductive adult with multiple worker, non-reproductive adults
	Semi-social	Shows primitive social life history. Multiple adults functioning in colony, division of labor among adults.
Feeding specialization	Oligolectic	Forages on limited resources and requires specific components from the habitat.
	Polylectic	General forager utilizing a broad range of floral resources.
Nest specialization	Carpenter	Excavates (drills nests in wood).
	Miners	Excavate nests in the ground.
	Renters	Nests in existing aerial tunnels and cavities (e.g. trees, fallen logs, stems.
	Soil cavity nesters	Nests in existing tunnels and cavities in the soil e.g. old termite mounds.
	Mason	Builds nests with mud
	No nest	Cleptoparasites or parasitic, occupy other bee nests.

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Fixed effects from the minimum adequate model

Response factors	Local factors		Landscape factors		
	Local proximity to semi natural habitats	No. insecticide application	Mean Shape Index	Mean Patch Size	Edge density
(a) Total bee abundance		-6.537***	4.76***		
(b) Total bee species richness		-1.658			
(c) Nesting					
Carpenter (N=262)	-	-.4.954***	-	3.26**	5.02***
Soil cavity (N=300)	-	-.4.262***	8.215***	-	-
Mason (N=29)	2.441*	-	-2.313*	2.218*	2.319*
Miner (N=172)	-.4.557***	-.3.803***	-	-	-
Renter (N=235)	0.236	-1.462	0.024	0.859	0.71
No Nest (N=10)	0.483	0.62	-0.388	0.68	0.642
(d) Sociality					
Semi Social bees (N=266)	-	-.5.082***	-	3.262**	5.214***
Social (N=290)	-	-.3.729***	-	3.222**	5.845***
Solitary (N=452)	-	-.4.247***	8.115***		
(e) Diet breadth					
Oligolectic (N=17)	-0.286	1.449	0.667	-0.343	-0.728
Polylectic (N=991)	-.2.115*	-.6.736***	4.635***	-	-

558 **Table 4**

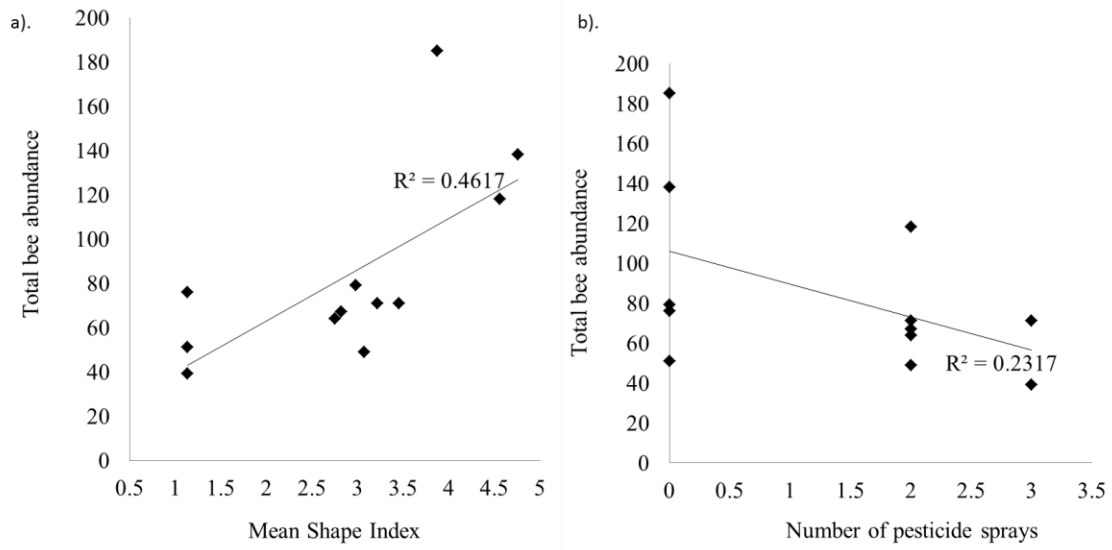
Bee guild	Bee trait	Fixed factor	Estimate	Std. Error	z-value	P	
Nesting	Carpenter	Local - near	3.26	0.29	11.09	<0.001	
		Local - far	-0.27	0.19	-1.40	0.16	
		Inseticide use - no	0.47	0.31	1.51	0.13	
		Inseticide use - yes	-0.33	0.27	-1.23	0.22	
		Local: Inseticide use	-0.47	0.27	-1.75	0.08	
	Cavity soil	Local - near	3.51	0.43	8.25	<0.001	
		Local - far	-0.63	0.30	-2.10	0.04	
		Inseticide use - no	0.27	0.43	0.65	0.52	
		Inseticide use - yes	-0.30	0.39	-0.77	0.44	
		Local: Inseticide use	-0.46	0.40	-1.15	0.25	
	Mason	Local - near	0.69	0.82	0.85	0.40	
		Local - far	0.69	0.65	1.07	0.28	
		Inseticide use - no	-0.29	1.00	-0.29	0.77	
		Inseticide use - yes	-0.69	0.65	-1.07	0.28	
		Local: Inseticide use	0.69	0.91	0.76	0.45	
	Miner	Local - near	3.44	0.35	9.70	<0.001	
		Local - far	-0.66	0.25	-2.65	0.01	
		Inseticide use - no	-0.10	0.38	-0.28	0.78	
		Inseticide use - yes	-0.78	0.33	-2.37	0.02	
		Local: Inseticide use	-0.32	0.36	-0.88	0.38	
	Above-ground	Local - near	3.31	0.30	10.91	<0.001	
		Local - far	-0.42	0.19	-2.19	0.03	
		Inseticide use - no	0.20	0.33	0.62	0.53	
		Inseticide use - yes	-0.28	0.28	-0.97	0.33	
		Local: Inseticide use	-0.53	0.30	-1.77	0.08	
No nest	∞	∞	∞	∞	∞		
Diet breadth	Polylectic	Local - near	4.76	0.21	22.55	<0.001	
		Local - far	-0.50	0.15	-3.32	<0.001	
		Inseticide use - no	0.23	0.22	1.04	0.30	
		Inseticide use - yes	-0.38	0.19	-1.96	0.05	
		Local: Inseticide use	-0.31	0.20	-1.55	0.12	
	Oligolectic	∞	∞	∞	∞		
	Sociality	Semi-social	Local - near	3.12	0.30	0.31	<0.001
			Local - far	-0.23	0.19	-1.22	0.22
			Inseticide use - no	0.67	0.32	2.10	0.04
			Inseticide use - yes	-0.20	0.28	-0.73	0.46
Local: Inseticide use			-0.54	0.27	-2.03	0.04	
Social		Local - near	3.64	0.27	13.44	<0.001	
		Local - far	-0.42	0.18	-2.29	0.02	
		Inseticide use - no	0.29	0.29	0.99	0.32	
		Inseticide use - yes	-0.51	0.25	-2.05	0.04	
		Local: Inseticide use	-0.87	0.28	-3.09	<0.001	
				-0.87	0.28	-3.09	<0.001
Solitary		Local - near	4.13	0.36	11.36	<0.001	
		Local - far	-0.64	0.26	-2.40	0.02	
		Inseticide use - no	-0.15	0.36	-0.42	0.68	
		Inseticide use - yes	-0.45	0.33	-1.37	0.17	
	Local: Inseticide use	0.07	0.34	0.21	0.83		

560 **List of Figures**

561 **Fig 1:** Relationship between (a) landscape complexity (measured by Mean Shape Index metric) and total
562 bee abundance and (b) number of insecticide spray and total bee abundance. Values at “0” on the x-axis
563 (e.g. 1a) indicate fields with no insecticide application.

564 **Fig 2:** Relationships with significant positive correlation between fruit per branch and (a) abundance of
565 carpenter bees, (b) abundance of social bees, (c) abundance of solitary bees.

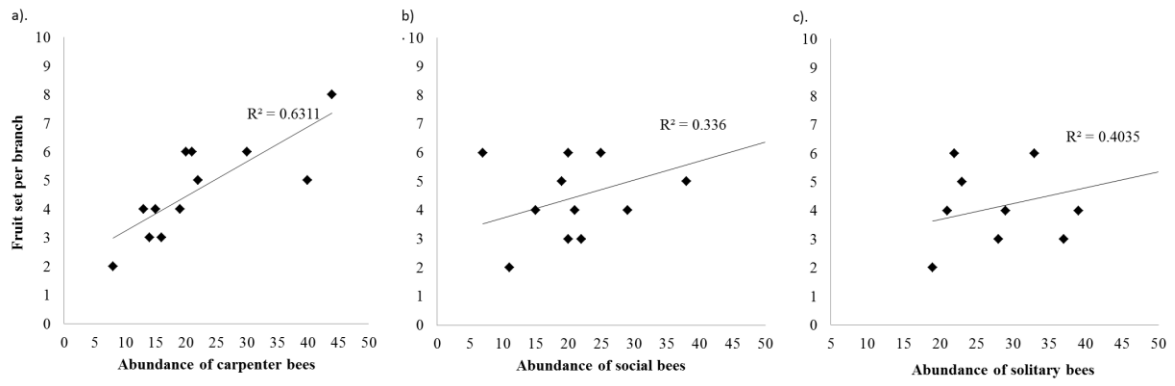
566 **Fig. 1**



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568

569 **Fig. 2**



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571 **Supplementary materials**

572 **Supplementary materials S1: Insecticide brands used for pigeon pea pest control in some of the sampled farms.**

Insecticide name	Active ingredient	Rate	Target pest
Actara	Thiamethoxam	250g/Kg	Systemic broad spectrum, insecticide for control of sucking and some chewing insects in vegetables, ornamentals, flowers and leaf miner in coffee; For use on Tobacco to control aphids, weevils, whiteflies and leaf beetles.
Alphadime	Dimethoate Alphacypermethrin	400g/L + 15g/L	Insecticide for the control of bollworms, stainers, aphids and loopers in cotton; stem borer on maize, aphids on barley; aphids and whiteflies on morby dick flowers; a thrips, aphids and whiteflies on French beans.
Bestox	Alpha- Cyphpermethrin	100g/L	For agricultural use - in cotton, for armyworm control
Bulldock	Beta-Cyfluthrin	25g/Kg	Insecticide for the control of biting and sucking insect pests in cotton and leaf miner on coffee
Dimethoate	Dimethoate	400 g/L	Insecticide for the control of bean fly, thrips, whiteflies, aphids and bollworms on French beans and Capsicum.
Karate	Lambda Cyhalothrin	25g/Kg	An insecticide for the control of aphids, thrips, caterpillars and whiteflies, on vegetables.
Ortiva	Azoxystrobin	250g/L	Fungicide for control of rust and ring spot in carnations, botrytis and powdery mildew in Roses; botrytis in statice; powdery mildew and Ascochyta in peas; rust and bean anthracnose in french beans.
Weiling	Methomyl	90%	Insecticide to control thrips and aphids on Roses.
Arginate	No information	No information	No information

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S/n	Species/Morphospecies	Sociality	Nesting	Lecty
1	<i>Amegilla caelestina</i>	Solitary	Miner	Polylectic
2	<i>Amegilla cymatilis</i>	Solitary	Miner	Polylectic
3	<i>Amegilla sp.1.</i>	Solitary	Miner	Polylectic
4	<i>Amegilla sp.2.</i>	Solitary	Miner	Polylectic
5	<i>Amegilla sp. 2</i>	Solitary	Miner	Polylectic
6	<i>Anthidium sp.</i>	Solitary	Soil cavity	Polylectic
7	<i>Anthophora sp.</i>	Solitary	Miner	Polylectic
8	<i>Apis mellifera</i>	Social	Above-ground cavity	Polylectic
9	<i>Braunsapis sp.</i>	Social	Above-ground cavity	Polylectic
10	<i>Ceratina sp.</i>	Semi social	Carpenter	Polylectic
11	<i>Coelioxys sp.</i>	Solitary	no nest	Polylectic
12	<i>Dactylurina sp.</i>	Social	Above-ground cavity	Polylectic
13	<i>Euaspis abdominalis</i>	Solitary	no nest	Polylectic
14	<i>Halictus</i>	Social	Miner	Polylectic
15	<i>Heriades sp.</i>	Solitary	Mason	Polylectic
16	<i>Hypotrigena gribodoi</i>	Social	Above-ground cavity	Polylectic
17	<i>Lassioglossum sp.</i>	Semi social	Miner	Polylectic
18	<i>Lipotriches sp.</i>	Solitary	Soil cavity	Polylectic
19	<i>Lithurgus sp.</i>	Solitary	Carpenter	Oligolectic
20	<i>Macrogalea candida</i>	Social	Above-ground cavity	Polylectic
21	<i>Megachile (Chalicodoma) sp.</i>	Solitary	Mason	Polylectic
22	<i>Megachile bicolor</i>	Solitary	Soil cavity	Polylectic
23	<i>Megachile flavipennis</i>	Solitary	Soil cavity	Polylectic
24	<i>Megachile sp.1</i>	Solitary	Soil cavity	Polylectic
25	<i>Megachile sp.2</i>	Solitary	Soil cavity	Polylectic
26	<i>Megachile sp.3</i>	Solitary	Soil cavity	Polylectic
27	<i>Megachile sp.4</i>	Solitary	Soil cavity	Polylectic
28	<i>Megachile sp5.</i>	Solitary	Soil cavity	Polylectic
29	<i>Meliponula sp.</i>	Social	Soil cavity	Polylectic
30	<i>Nomia sp.</i>	Solitary	Miner	Polylectic
31	<i>Pachyanthidium cordatum</i>	Solitary	Above-ground cavity	Polylectic
32	<i>Pachymelus conspicuus</i>	Solitary	Soil cavity	Polylectic
33	<i>Plebeina hildebrandti</i>	Social	Soil cavity	Polylectic
34	<i>Pseudapis sp.</i>	Solitary	Miner	Polylectic
35	<i>Pseudoanthidium sp.</i>	Solitary	Soil cavity	Polylectic
36	<i>Pseudophilanthus sp.</i>	Solitary	Miner	Polylectic
37	<i>Systropha aethiopica</i>	Solitary	Soil cavity	Oligolectic
38	<i>Tetralonia sp.</i>	Solitary	Miner	Polylectic

39	<i>Tetraloniella sp.</i>	<i>Solitary</i>	<i>Miner</i>	<i>Polylectic</i>
40	<i>Thyreus pictus</i>	<i>Solitary</i>	<i>no nest</i>	<i>Polylectic</i>
41	<i>Xylocopa caffra</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
42	<i>Xylocopa erythrina</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
43	<i>Xylocopa imitator</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
44	<i>Xylocopa inconstans</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
45	<i>Xylocopa senior</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
46	<i>Xylocopa somalica</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
47	<i>Xylocopa sp.1</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
48	<i>Xylocopa sp.2</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>
49	<i>Xylocopa sp.3</i>	<i>Semi social</i>	<i>Carpenter</i>	<i>Polylectic</i>

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