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Landscape and crop management strategies to conserve pollination services and increase yields in tropical coffee farms

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ABSTRACT

Agricultural intensification has reduced biodiversity and leads to fundamental trade-offs between food production and conservation. Conventional approaches to food production are thus no longer suitable. In the present work, we discuss the influence of local management and landscape context variables on coffee yield and crop pollination services. We used 34 coffee farms (15 with low impact and 19 with high impact management) located in Chapada Diamantina, Bahia, Brazil. We analysed the floral visitor patterns and yield and their relationships with landscape and management context over two years. Using a GLM analysis, we found that farms close to natural areas and with low management intensity have higher potential to reduce yield gaps and maintain biodiversity. Biodiversity in turn (represented here by pollinators) improved yields by 30%, and yields were lower on larger, intensively managed farms. Low impact farms, on the other hand, may depend not only on diversified landscapes but also on proper investment in sustainable production practices. Combining landscape and management strategies should thus generate synergies between multiple ecosystem services, such as pollination, yield, farm profitability, and others not analysed here, such as natural enemies and nutrient cycling, among others.

1. Introduction

Global agricultural production was increased substantially by the introduction of new lands into continuous farming, the intensive use of off-farm inputs (fertilizers, pesticides, machinery), and the use of genetically modified crops, mostly after the "Green Revolution". However, new strategies to increase crop yields are needed to meet the current projections of global population growth. Moreover, the techniques utilized previously, such as intensive use of pesticides, have led to major losses in global biodiversity, leading to fundamental trade-offs between food production and conservation. Recent research demonstrates that conventional high input strategies are no longer suitable because the differences in crop yields between high and low-yielding farms in a given region (i.e., yield gaps) are increasing (Aizen et al., 2009). Yield gaps arise from multiple causes, including deficiencies in the supply of nutrients or pollination. Yet the ever-increasing input of nutrients and organic matter, or increases in cropping intensity and the expansion of irrigated area, are costly and may only bring about ever diminishing returns. Thus, researchers have been advised to focus on identifying the specific causes of yield gaps in order to develop sustainable and profitable alternatives to existing measures.

A new strategy to address the biodiversity-production trade-off is to optimize or improve crop yields at the same time as enhancing biodiversity, or at least minimize negative impacts, a paradigm also known as "ecological intensification". These strategies, however, are not so simple, because they require an understanding of complex relationships between the biological community composition and ecosystem function in contrasting management and landscape-level scenarios.

It has been suggested that trade-offs between food production and conservation areas are more likely to be alleviated through an optimal spatial arrangement (Fischer et al., 2008; Phalan et al., 2011; Gabriel et al., 2013; Hulme et al., 2013; Tuck et al., 2014; Ekroos et al., 2016). This could potentially include the combination of high-yield agriculture with areas of protected natural habitat (Ramankutty and Rhemtulla, 2012; Ekroos et al., 2016) or the integration of biodiversity conservation and crop production in the same area, such as in agroecosystems.

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There is no consensus yet for the best strategy. The best type of farming for biodiversity conservation seems to be dependent on the demand for agricultural products and how pollinator communities change with agricultural yield. The high chemical inputs of pesticides and nitrogen used to assure high yield on conventional farms leads to side effects, such as soil and water pollution (Potts et al., 2010; Foley et al., 2011). Agroecosystems, on the other hand, tend to present lower yields, requiring a larger land area for production.

Biodiversity and yield patterns are influenced not only by management and landscape context, including different spatial scales but also by the type of crop being grown and geographic region, further increasing the complexity of the relationship between crop production and conservation. Empirical studies linking landscape aspects, local management and ecosystem services are still scarce (Kremen, 2015), especially for some groups of species, such as pollinators.

Pollination is an example of an ecosystem service on which agricultural production is highly dependent, determining the yield in 75% of important global crop species. In coffee (*arabica* variety), although not considered a dependent crop since the plants are autogamous, pollinators can increase productivity (31% on average). Even so, despite its importance, pollination has been largely neglected in studies analysing yield gaps. Crops located far from natural areas, for example, may suffer losses in pollinators, stability, and production (Garibaldi et al., 2011b). However, to what extent this can be influenced by other landscape aspects such as patch diversity and crop management still requires further investigation.

In this study, we compared the influence of local management and landscape context variables on coffee yield and crop pollination services. We tested the following hypotheses using the approach described above: (i) floral visitor patterns and yields can be explained and influenced by differences in landscape and management context; and (ii) floral visitor composition also influenced coffee yields. We then examined what type of landscape-level scenario and management is the most suitable for biodiversity conservation and production purposes using coffee farms in Chapada Diamantina, Bahia, Brazil as a practical model.

2. Materials and methods

2.1. Study area and selection of sampling units

The present study was conducted on coffee farms located in the cities of Mucugê and Ibicoara in the Chapada Diamantina region, Bahia, Brazil (limits: 41°42′11” W, 12°43′36” S; 41°15′5” W, 12°43′52” S; 41°42′51” W, 13°44′8” S; 41°15′40” W, 13°44′ 23” S, altitude between 900 and 1400 m; Fig. 1). This region has an average annual precipitation of 1379 mm, an annual average maximum temperature of 25.7 °C, with a minimum temperature of 16 °C (2013 to 2014 local weather station data from the Landowners Association “Agropolo Mucuge/Ibicoara”; see Fig. A1 Appendix A). Chapada Diamantina, is dominated by the typical Brazilian Cerrado savannah, and shows a considerable variation in the physiological characters of the flora. This result in a mosaic of vegetation types, including from open meadows to semi-deciduous forests, with variable degrees of heterogeneity.

Using a geographic information system (GIS) with a SPOT image (year 2009, 5-m spatial resolution) and information about the region from field checks, we selected 34 sampling points. As criteria for this selection, we considered the surrounding proportion of cultivated area and landscape diversity, visually estimated from the image, with a buffer of 1.5 km around each sampling point. The distribution of sampling points within the study area followed an orthogonal gradient between the cultivated acreage and landscape diversity. A linear distance of 2 km was adopted as the minimum distance between sampling units (final minimum nearest neighbour distance = 2 km, mean = 22 km, maximum = 75.5 km; Fig. 1). These distances are consistent with the foraging range and dispersal distance of most Hymenoptera flower visitors and may be sufficient to minimize spatial pseudo replication (Greenleaf et al., 2007; Ricketts et al., 2008).

All sampling points corresponded to coffee farms that met our selection criteria (see below), and grew the same coffee variety (*Coffea arabica* variety Catucai). Farm management and characteristics were assessed through interviews at farms in a previous study. On the basis of these interviews, 19 of 34 farms were considered conventional farms with high impact management strategies, characterized by heavy use of pesticides. The remaining 15 farms were considered farms that used low impact management that supported “low input agriculture”, according to the definition of such by the Sustainable Agriculture Network (2010). This definition includes the low or non-existent use of pesticides and encompasses either certified organic farms lacking or having highly reduced the use of herbicides and fertilizers as well.

2.2. Flower visitor surveys

Following the method described by Vaissière et al. (2011), flower visitors were recorded in plots (50 × 25 m) located in the centre of small farms (up to 4 ha) and halfway between the centre and edge of medium and large farms (those larger than 5 ha) at each coffee farm in 2013 and 2014 (see Fig B1 Appendix B). The flower-visitor density was measured by visual scans, sampling a fixed number of open floral units (three to five open flowers in an inflorescence) inside the plots of each farm until 4000 floral units were reached (since the number of plants inside plots could vary according to the spacing used). The flower visitor species richness was measured by netting all visitors along four 25 m long transects for 5 min each. This resulted in 20 min of active net sampling per farm, with the clock stopped each time a captured insect was being handled.

Sampling was repeated at each coffee farm under sunny or cloudy conditions, but never during rain, and in at least two periods: morning (8:00 to 12:00) and afternoon (13:00 to 17:00) in the main flowering season (October to December). All visitors collected by net samplings were identified to the lowest possible taxonomic level by specialists and were deposited in the entomological collections of the Universidade Federal da Bahia (MZUFBA) and of the Instituto Nacional de Pesquisas da Amazônia (INPA).

Because the flower density may influence the attraction of flower visitors, we estimated the flower production at each farm by counting the number of flowers that were closed (buds), open, and old (no nectar or pollen present) on up to 20 inflorescences from different coffee plants (inside plots). From this, we estimated the total number of open flowers on each farm based on the size and plant spacing.

2.3. Yield gap

One to three days before flowering, 200 buds in pre-anthesis (one to eight buds per plant inside plots, on a total of 5000 flowers per treatment considering the 50 sampling points where we were able to perform this analysis) were assigned to one of the following treatments: (a) spontaneous self-pollination, where the bud was bagged with voile fabric bags (0.05 mm mesh size) to prevent insect flower visitors, and (b) open pollination, where the flower remained open to flower visitors. Bags were removed from the self-pollination treatment after 10–15 days when no more pollen transfer was possible and the risk of abortion caused by differences from light or temperature inside the voile bags could be minimized. Approximately six to seven months after flowering, marked coffee fruits were harvested. Yield gaps were calculated from the difference between the number of formed fruits in bagged versus unbagged flowers and extrapolated to the entire crop area (% formed fruits ha^{-1}). Information for extrapolation counts (number of open flowers, buds, and fruits) were gathered from the monitoring of 20 branches within 20 plants on each farm in both years. Counting was performed in at least two periods (when the bags were placed and at the harvest period). To account for the yield gap, we considered the final

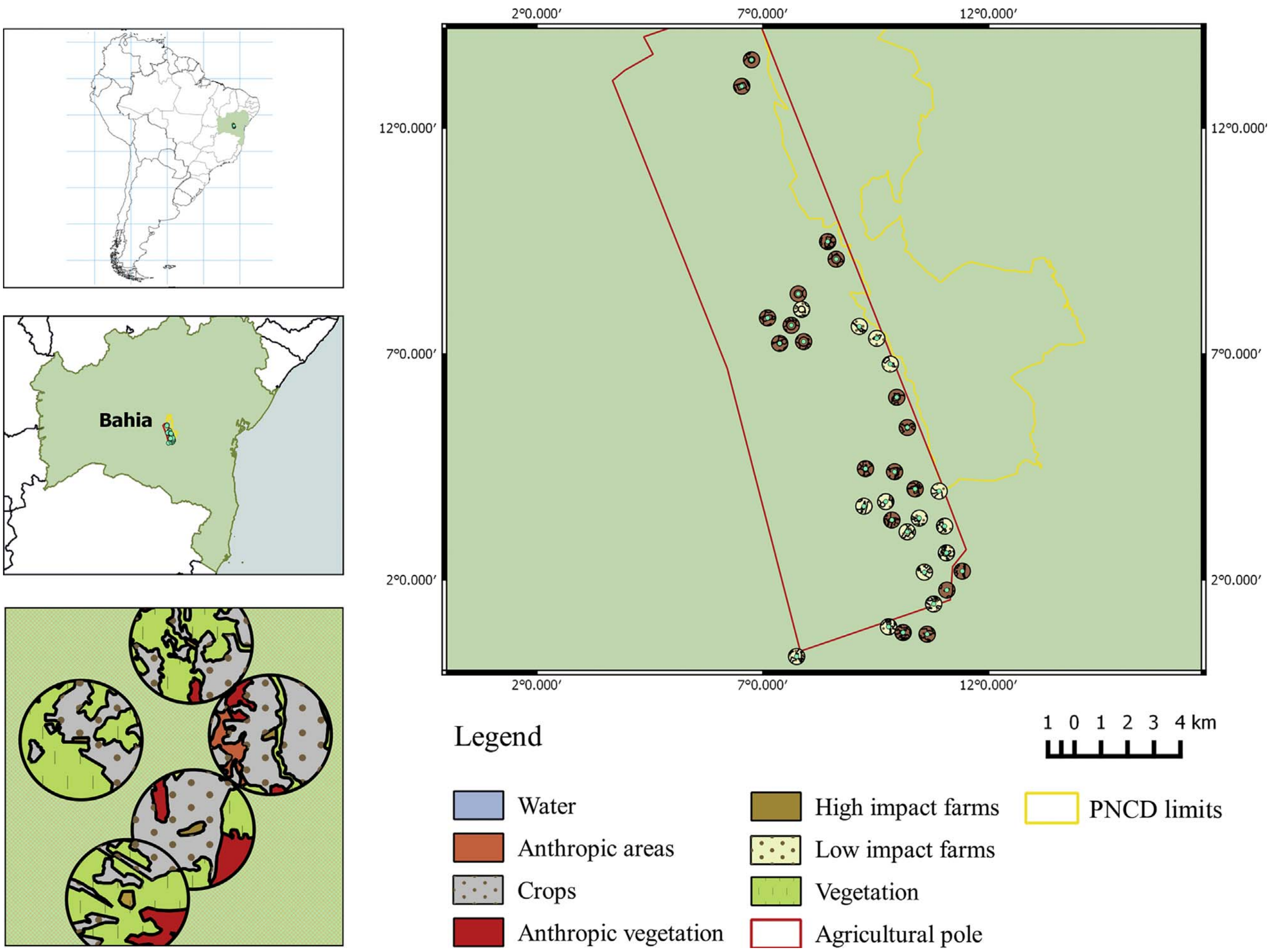

Fig. 1. Map of the study region (limits: 41°42′11″ W, 12°43′36″S; 41°15′5″W, 12°43′52″S; 41°42′51″W, 13°44′8″S; 41°15′40″ W, 13°44′ 23″S), showing high and low impact coffee farms in Chapada Diamantina, Bahia, Brazil. Figures show the Brazil and Bahia region within South America, as well as the sampling units with a 1.5 km buffer. Sampling units were inside the agricultural development areas and close to the National Park of Chapada Diamantina (PNCD).

period (when the harvest was conducted).

2.4. Landscape metrics

Circular landscape maps with a radius of 1.5 km around sampling points were produced from a supervised classification using ArcGIS 9.3 ESRI 2008 from high-resolution images (SPOT/2009, five metre pixels). The size of the maps was selected to include the flying range of most bees. Date differences between images and samplings were corrected through ground truthing. The classification encompassed 17 classes, including low or high impact coffee farms, other non-coffee crops, water, clouds, shade, anthropic areas (roads, buildings and anthropogenic bare soil) and vegetation classes according to IBGE, including grass-woody savannah, anthropic vegetation, woodland savannah, *Campos Gerais*, wooded savannah, rock fields, forested savannah steppe, grass-woody savannah steppe, semi-deciduous forest, and deciduous forest.

After obtaining the land-use map, four metrics describing the landscape structure were calculated. To represent landscape composition, we chose (i) a simple index for the proportion of the landscape under intensive cultivation containing the proportion of annual crops, anthropic areas and natural vegetation area (intensity index), where a high-intensity index represents a lower proportion of natural vegetation within the 1.5 km buffer (for full index description, see Appendix C). We also chose (ii) Shannon's Evenness Index (SHEI), which produces an ecologically scaled index of habitat quality between 0 and 1 that goes beyond simple values of class diversity. To represent landscape configuration, we chose the (iii) mean Euclidean distance to the nearest natural or semi-natural vegetation patch (to represent crop isolation) (ENN_MN), and the (iv) Landscape Shape Index (LSI), which provides a measure of total edge or edge density of the landscape. All metrics (with the exception of the intensity index) were calculated in Fragstatsv4.2.1.

2.5. Statistical analysis

To understand how flower visitor richness ($\log_{10}$ number of species per field in 20 min of net sampling), flower-visitor density ($\log_{10}$ mean of visitors per 4000 flowers), and crop yield (% formed fruits ha^{-1}) are influenced by landscape vs. local effects in farms, we used the landscape indexes (SHEI, intensity index, isolation and LSI), type of management (low or high impact), number of open flowers (open flowers ha^{-1}) and crop size (planted coffee area/ha) as explanatory variables. Because honeybees (*Apis mellifera*) are very common in coffee crops, and their abundance in flower visitor analyses can lead to differences in results in relation to other visitors (Garibaldi et al., 2011a, 2013), we analysed the flower visitor abundance with and without the presence of honey bees by constructing generalized linear models (GLM) with and without this species. Because the sampling effort did not differ significantly between years, no nested structure was necessary. All models were constructed in the R software (version 2.15.1, "glm" function, and Gaussian error distribution). The most parsimonious model was considered to be that with the lowest Akaike Information Criterion with a second-order correction for small sample sizes, AICc.

Crop yield can also be influenced by the flower visitor richness

Table 1
Coffee flower visitor's collected on netting samplings within low and high impact farms in Chapada Diamantina, Bahia, Brazil. Identification was done only to the greatest possible level by specialists.

Order	Family	Genus	Species	Low	High
Hymenoptera: Apocrita	Apidae	*Apis*	*A. mellifera*	24	31
		Bombus	*B. brevivillus*	2	3
		Bombus	*B. morio*	3	
		Centris	*C. aenea*	2	2
		Centris	*C. decolorata*	3	1
		Centris	*C. flavifrons*		1
		Centris	*C. tarsata*	1	
		Ceratina	*C. chloris*		1
		Exomalopsis	*E.* cfr. *iridipennis*	1	
		Geotrigona	*G.subterranea*	3	2
		Nannotrigona	*N. testaceicornes*	2	
		Paratrigona	*P.* sp.	2	1
		Partamona	*Pa.* sp.	2	
		Plebeia	*Pl.* sp.	1	2
		Trigona	*T. spinipes*	7	5
		Xylocopa	*X. grisescens*	3	1
		Xylocopa	sp.	2	1
	Bracronidae			2	1
	Chalcididae			1	
	Crabronidae			2	
	Halictidae	*Lasioglossum*	sp.	3	1
		Augochloropsis	sp.	1	1
	Ichneumonidae			1	
	Scoliidae			1	1
	Sphecidae				2
	Vespidae	*Brachygastra*	*B. lecheguana*	2	1
		Mischicyttatus	*M. rotundicollis*	1	
		Omicron	sp.	2	1
		Polybia	*P. ignobilis*		2
		Polybia	*P. sericea*	1	
		Polybia	spp.		1
		Synoeca	*S. cyanea*	1	1
Hymenoptera: Symphyta	Symphyta				1
Diptera	Asilidae	*Efferia*	sp.		2
		Eichoichemus	sp.	5	1
	Bibionidae			1	
	Bombyliidae	*Hemipenthes*	sp.		2
		Villa	sp.		1
	Calliphoridae				1
	Fanniidae			2	1
	Calliphoridae				2
	Syrphidae	*Ocyptamus*	*O. gastrostactus*	2	
		Ornidia	*Or. obesa*	1	
		Palpada	*P. furcata*	2	1
		Palpada	*P. pygolampus*	1	
		Pseudodorus	*P. clavatus*	1	1
		Toxomerus	*T. floralis*	2	
	Tabanidae	*Stenotabanus*	sp.		1
		Chrysops	*C. varians*	2	2
	Tachinidae			1	
	Tephritidae	*Ceratitis*	*C. capitata*	3	8
Coleoptera	Cantharidae				1
	Cerambycidae			1	
	Chrysomelidae			1	2
	Coccinelidae			2	1
	Curculionidae			2	
	Dermestidae				2
	Lycidae			1	
	Melolonthidae			1	2
	Ripiphoridae			1	
	Tenebrionidae				1
Lepidoptera				3	4
Hemiptera				1	2
Neuroptera					2
Orthoptera					3
Odonata					1

(Ricketts et al., 2004; Garibaldi et al., 2011a, 2014). For that reason, we evaluated whether yield could also be influenced by visitor composition. Therefore, in a second analysis, we then added flower visitor richness as an explanatory variable to the yield model.

Based on the second order Akaike's Information Criterion (AICc), we selected the best model after evaluating the results of all possible combinations of the predictor variables (flower-visitor density, flower-visitor richness, and field size) and their interactions (MuMIn package, dredge function). We also estimated the R^2 based on the square of the Pearson's correlation coefficient between the observed and predicted

Table 2
Dependent variables (visitoŕs richness, visitoŕs abundance, yield 1 and yield 2) and their relationships with best predictor response variables ordered by contributiońs order (importance) on model (values within parentheses). At management variable L- Refers to low impact management relation and H- to high impact management. At yield variable, ^{1}- Refers to first yield model with no visitoŕs richness on analysis; ^{2}- Refers to second yield model, with visitoŕs on analysis. Index = Intensive index, LSI = Landscape Shape Index, SHEI = Shannon's Evenness Index and Isolation = Mean Euclidean distance to the nearest natural vegetation patch.

Models						
	Best	A	B	C	D	E
Visitoŕs richness						
Isolation	**−0.00026**	**−0.00027**	**−0.000362**	**−0.000273**	**−0.00025**	**−0.000256**
Managment	**L**	**L**		**L**	**L**	**L**
Index			**0.00172**			**0.00067**
SHE				**0.1236**		
AICc	6.956	7.221	8.709	9.069	9.099	9.158
delta AIC	0	1.56	1.69	1.96	2.18	2.37
Visitoŕs abundance						
Managment	**H**	**H**	**H**	**H**	**H**	**H**
Crop size				**0.00177**		
Isolation		**−0.00029**				
SHEI			**−0.455**			
Open flowers						**1.1E-06**
AICc	75.26	75.99	76.72	77.15	77.2	77.55
delta AIC	0	0.73	1.46	1.88	1.93	2.29
Non Apis abundance						
Isolation	**−0.0004**	**−0.0004**	**−0.000357**	**−0.000376**	**−0.00038**	**−0.000405**
Open flowers			**2.03E-06**			
LSI		**0.04373**				
Management					**L**	
Crop size				**−0.000558**		
SHEI						**0.09076**
AICc	36.66	38.31	38.4	38.9	38.93	38.95
delta AIC	0	1.65	1.74	2.25	2.27	2.29
Yield^{1}						
Index	**−0.449**	**−0.365**	**−0.356**		**−0.173**	**−0.229**
Isolation		**−0.0124**		**−0.0157**	**−0.0124**	
Crop size	**0.1388**	**0.1708**				
SHEI	**52.33**	**42.35**	**35.09**			
AICc	432.1	432.3	432.3	432.5	432.6	433
delta AIC	0	0.24	0.26	0.43	0.58	0.9
Yield^{2}						
Visitoŕs richness	**2.811**	**2.776**	**3.087**	**2.574**	**2.498**	**3.250**
Index	**−0.4139**	**−0.2148**	**−0.2356**	**−0.3705**	**−0.304**	**−0.4204**
Crop size	**0.172**		**0.098**	**0.186**		
SHEI	**44.31**			**39.55**	**24.28**	**32.6**
Isolation				**−0.0067**		
AICc	426.7	427.9	428.6	428.6	428.8	429
delta AIC	0	1.24	1.9	1.97	2.15	2.3

(considering both fixed- and random-effects) dependent variables in the final models. All predictor variables were tested for correlation between variables using variation inflation factors (VIF) in the "car" package, as well as possible interactions among them (those with values higher than 10 were excluded). All sampling units were tested for a possible spatial autocorrelation considering the visitoŕs richness and farm coordinates with a mantel test in the "vegan" package. Models were also tested for residual autocorrelation with the "dwt" function in the "car" package.

2.6. Ethical issues and survey permits

In accordance with the environmental legislation of Brazil (norm n°. 154/2007), we obtained authorization to collect biological material during the entire period of this study (N° 40044-3, authentication code N° 95691194 Sisbio/IBAMA). The farmers who owned the sites in which the sampling was conducted were asked about their interest in participating in the study and approved it before the study started.

3. Results

3.1. General findings

A total of 530 individuals from 84 insect species (bees and non-bees) were sampled within coffee farms distributed in eight different orders (Hymenoptera, Coleoptera, Diptera, Hemiptera, Lepidoptera, Neuroptera, Odonata, and Orthoptera) (Table 1). Bees (Hymenoptera: Apoidea, 19 species), were the most abundant group (72.6% of 530). Per farm site, the average total visitor richness was 4 ± 2.08 (species) and average total abundance was 70 ± 139.8 (floral visitors) (Appendix D).

3.2. Floral visitor richness

Across all fields, flower visitor richness was best predicted by isolation from natural areas and field management type (high vs low impact) (Table 2) ($R^2 = 26.29$, $p < 0.05$). This relationship demonstrated that the best predictor variables were the proximity to natural areas (Fig. 2a), followed by low impact management (Fig. 2b; Table 2).

3.3. Flower visitor density

Visitor abundance (flower visitor density) showed highly different patterns when honey bees were included in the analysis. Visitor abundance including honey bees was most related to high impact management ($R^2 = 11.35$, $p < 0.05$) (Table 2; Fig. 2c), but visits not including honey bees were related to the proximity of the farm to natural vegetation (Table 2; $R^2 = 14.07$, $p < 0.05$; Fig. 2d).

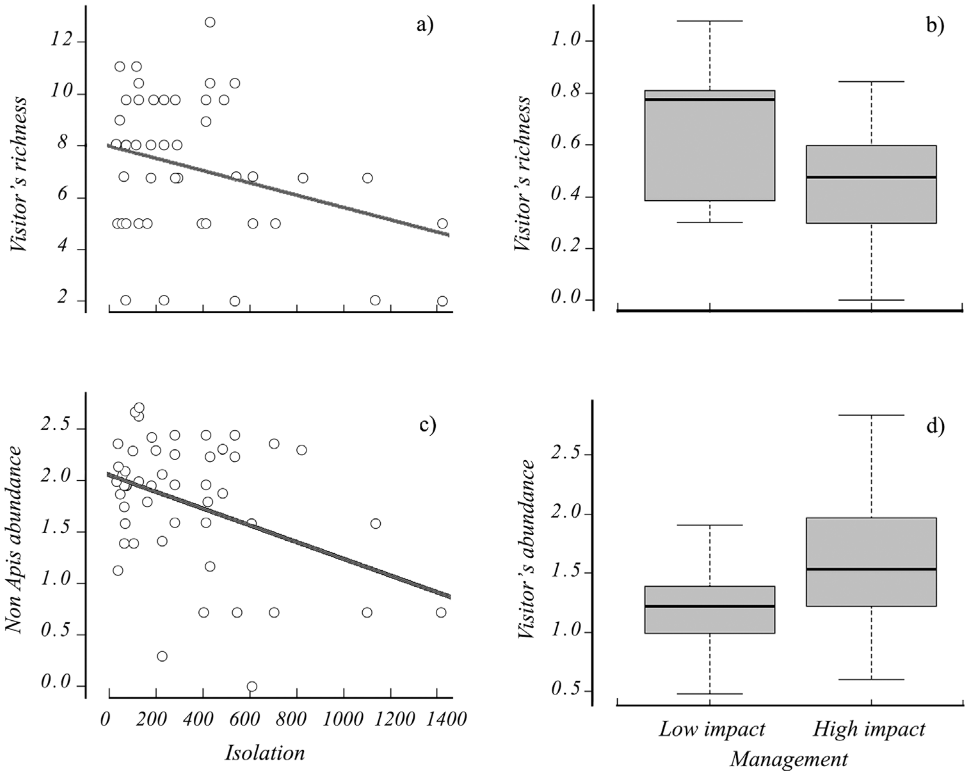

Fig. 2. Relationships between the dependent variables and their best explanatory variables. (a) Relationship between flower-visitor richness (or visitoŕs richness) = $\log_{10}$ number of species per field in 20 min of net sampling and isolation; (b) non Apis abundance (visitoŕs abundance without honey bees) = $\log_{10}$ mean of visitors in 4000 flowers excluding visits from honeybees (*Apis mellifera*) with isolation; (c) visitoŕs richness and low impact management as second best variable and; (d) flower-visitor density (visitoŕs abundance) = $\log_{10}$ mean of visitors in 4000 flowers and high impact management. Each point is a sampling location, and lines are the prediction from the best model in scatter graphs (a and d).

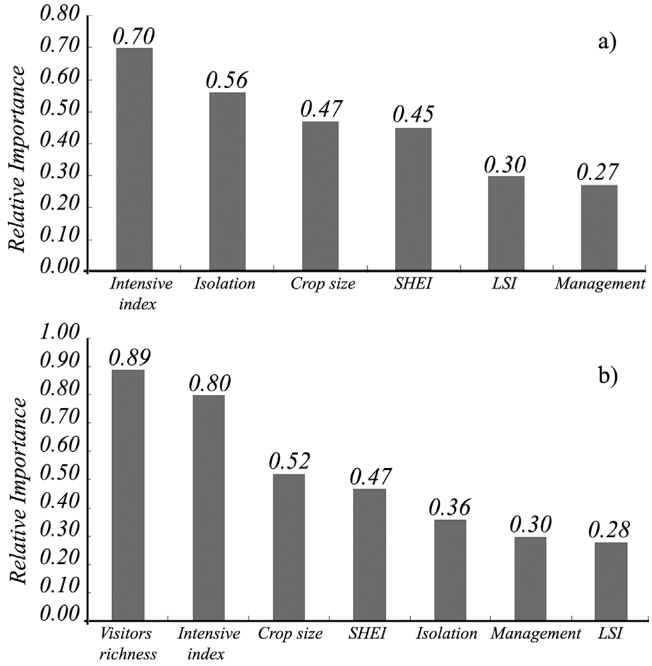

Fig. 3. The relative importance is the sum of the Akaike Information Criterion weights of the models with each predictor on each bar on the graph corresponding to the sum of the importance of each variable (considering all tested models). Intensity index = proportion of the landscape under intensive cultivation, isolation = distance to semi natural or natural areas, farm size = coffee planted area (ha), SHEI = Shannon's evenness index, LSI = landscape shape index, management = type of used management (low or higher impact). Graphs show that the (a) 'intensity index' and 'isolation' are the most important predictors of yield in coffee (pollination deficits) when the visitoŕs richness is absent from analysis; and (b) 'visitoŕs richness' (flower-visitor richness) and 'intensity index' are the most important predictors of yield in coffee (pollination deficits) when visitoŕs richness was added to the model analysis.

3.4. *Yield*

The mean proportion of formed fruits in flowers with visitors (open flowers) was 57 (± 24) and was 29 (± 16) in flowers without flower visitors (closed flowers). Thus, coffee flower visitors on average improved the yield by 30% (± 18.08%) (*t*-test p = 1.82551e-14). Yield (or pollination deficit) was best explained by the negative relationship between two landscape variables: isolation and intensity index ($R^2 = 25.9$, $p < 0.05$; Table 2; Figs. 3 and 4). However, when the yield was analysed with flower visitor richness, the results differed from the first analysis (without this variable), with the contribution of this variable ($p < 0.05$) increasing the overall predictive power ($R^2 = 29.8$, $p < 0.05$). Flower visitor richness explained most of the yield (Figs. 3 and 4), followed by the proportion of the landscape under intensive cultivation (e.g., a low intensity index; Table 2). Larger coffee farms (crop size) with a higher landscape diversity (evidenced by SHEI) also exhibited higher yields (with and without visitors in the analysis) (Table 2).

4. Discussion

As expected, farms located far from natural or semi-natural areas had lower visitor richness and abundance. Similar results were found in previous studies in which crop isolation was an important cause of crop stability losses (Ricketts et al., 2004; Carvalheiro et al., 2010; Garibaldi et al., 2011b). In addition, low impact management, with no or low use of pesticides, was also related to a higher level of biodiversity. Landscapes composed of low impact coffee fields close to natural areas should be favoured by better pollination services, and this is more representative of a land sharing strategy.

We reinforce the statement that pollinator persistence depends on both the maintenance of high quality habitats around farms and wildlife-friendly local management (low impact agriculture). Proximity to natural and semi-natural habitats will also favour wild visitor abundance, but not honeybees. It is not surprising to find no relationship between honey bees and habitat isolation (Garibaldi et al., 2011b;

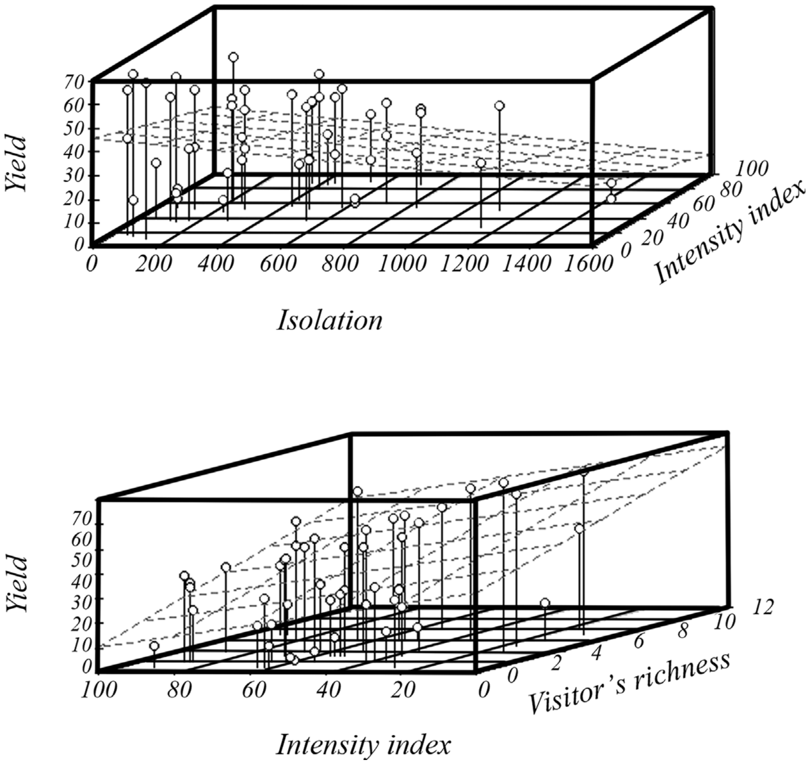

Fig. 4. Relationships between the dependent variable crop yield (% formed fruits ha^{-1}) and its best explanatory variables without visitoŕs richness in the analysis (upper graph) and with visitoŕs richness (below graph). In the first graph, yield responds negatively to intensity index and isolation; on the second graph, yield is still negatively related to the intensity index but positively related to visitoŕs richness. Each point is a sample; squares are the predictions from the best model with the two response variables.

Winfree et al., 2009). Honey bees are typically less sensitive to landscape disturbance than other taxa (Aizen and Feinsinger, 1994; Aguilar et al., 2006; Ricketts et al., 2008), for reasons that include (but are not limited to) a larger foraging range (Steffan-Dewenter and Kuhn, 2003; Greenleaf et al., 2007) and human hive management within crops in order to improve production.

Despite the fact that coffee is an autogamous species, visitor richness improved yields. Similar results have been found for *Coffea arabica* in other regions (Klein et al., 2003; De Marco and Coelho, 2004; Ricketts et al., 2004; Vergara and Badano, 2009; Saturni et al., 2016). Landscape characteristics, such as the proximity to natural areas and a higher proportion of natural vegetation, also played an important role in yields. Farms located far from natural areas were more likely to receive reduced visitation by wild pollinator species and have more pronounced yield gaps than farms in close proximity to natural areas (Garibaldi et al., 2011b).

Yield was higher on larger farms in close proximity to natural and semi-natural areas, which were associated with a lower proportion of intensive cultivation. However, the stronger relationship between yield and flower visitor richness and the yield improvement provided by pollinators suggests that combining low impact agriculture with the proximity to natural areas is still the best way to reconcile the "biodiversity-production trade-off". Furthermore, as evidenced by previous work in the same study region, a proportion of agriculture up to 40% would be ideal to conserve a sufficiently high flower visitor diversity (Moreira et al., 2015). Higher economic investment in large farms to improve yields could reduce non-pollination related factors contributing to the yield gap, such as nutrient and water availability, and proper farm management must also consider these other factors. However, even if such additional factors can be addressed, the resulting yield increases on large farms would not be stable in the long term, and strategies to maintain pollinators and their services would still be required (Garibaldi et al., 2011b; Ponisio et al., 2014).

In some instances, it is possible to produce equivalent or higher yields in low impact crops compared to high impact crops, thereby enhancing both ecosystem services and profitability, as demonstrated in other low impact farms (organic crops) (Kremen and Miles, 2012; Seufert et al., 2012; Ponisio et al., 2014). However, as noted in other regions around the world, most research in this area is conducted in large scale agriculture marked by intensive inputs, a very different management scenario compared to the smallholders that are neglected in most studies. Some farmers in this study did not apply proper management (nutrient management, for example) due to a lack of money or information, which may have affected the final yield. The long-term success of low input agricultural systems thus depends not only on science and practice, but on establishing conditions that can ensure economic sustainability.

As has been recently demonstrated, ecological intensification is a viable approach to reducing yield gaps, but proper management policies should likewise be established in order to increase profitability for smallholders that practice low impact agriculture. This should lead to increased biodiversity and yields, reducing or eliminating possible tradeoffs. Obstacles to farmers adopting low impact agriculture include powerful vested interests and existing policies, a lack of information and knowledge, weak infrastructure and other economic challenges, and misperceptions and cultural biases (Reganold and Wachter, 2016). The same approach should be taken by other Brazilian crops and in other regions. Since most of the cropland area and economic funding (87%) are concentrated with large producers or industries (MAPA, 2014), yields may be higher due to economic and research investment in high impact management, but pollination deficits will persist due to low biodiversity. However, initial increases in yield due to higher inputs could confound arguments as to which is the best strategy in the long term to maintain biodiversity and productivity.

Here, we provide evidence that farms close to natural areas that have low intensity management (low impact agriculture) have a higher potential to reduce yield gaps and maintain biodiversity. Those low impact farms usually lack proper information (e.g., agricultural extension services) and scientific research compared to highly intensive farms (high impact). These low impact farms should thus receive more attention from society because they represent a better way to achieve sustainability. Small-scale sustainable agriculture, especially in tropical landscapes, is more likely to preserve biodiversity in the long term.

In several areas of the world, it has been empirically demonstrated that pollinator diversity improves productivity by reducing yield gaps (Garibaldi et al., 2016). Although we agree that there is no single correct spatial scale for segregating biodiversity protection and production, a strategy with proper investment in sustainable production (especially those focusing on low impact farms) and diverse landscapes, as opposed to larger farms with high impact management, is the preferred way to generate synergies between biodiversity and production.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.09.038.

References

Aguilar, R., Ashworth, L., Galetto, L., Aizen, M.A., 2006. Plant reproductive susceptibility to habitat fragmentation: review and synthesis through a meta-analysis. Ecol. Lett. 9, 968–980. http://dx.doi.org/10.1111/j.1461-0248.2006.00927.x.

Aizen, M.A., Feinsinger, P., 1994. Habitat fragmentation, native insect pollinators, and feral honey bees in argentine chaco serrano. Ecol. Appl. 4, 378. http://dx.doi.org/10.2307/1941941.

Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., Klein, A.M., 2009. How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. Ann. Bot. 103, 1579–1588. http://dx.doi.org/10.1093/aob/mcp076.

Carvalheiro, L.G., Seymour, C.L., Veldtman, R., Nicolson, S.W., 2010. Pollination services decline with distance from natural habitat even in biodiversity-rich areas. J. Appl. Ecol. 47, 810–820. http://dx.doi.org/10.1111/j.1365-2664.2010.01829.x.

De Marco, P., Coelho, F.M., 2004. Services performed by the ecosystem: forest remnants influence agricultural cultures' pollination and production. Biodivers. Conserv. 13, 1245–1255. http://dx.doi.org/10.1023/B:BIOC.0000019402.51193.e78.

Ekroos, J., Ödman, A.M., Andersson, G.K.S., Birkhofer, K., Herbertsson, L., Klatt, B.K., Olsson, O., Olsson, P.A., Persson, A.S., Prentice, H.C., Rundlöf, M., Smith, H.G., 2016. Sparing land for biodiversity at multiple spatial scales. Front. Ecol. Evol. 3. http://dx.doi.org/10.3389/fevo.2015.00145.

Fischer, J., Brosi, B., Daily, G.C., Ehrlich, P.R., Goldman, R., Goldstein, J., Lindenmayer, D.B., Manning, A.D., Mooney, H.A., Pejchar, L., Ranganathan, J., Tallis, H., 2008. Should agricultural policies encourage land sparing or wildlife-friendly farming? Front. Ecol. Environ. 6, 380–385. http://dx.doi.org/10.1890/070019.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. http://dx.doi.org/10.1038/nature10452.

Gabriel, D., Sait, S.M., Kunin, W.E., Benton, T.G., 2013. Food production vs. biodiversity: comparing organic and conventional agriculture. J. Appl. Ecol. 50, 355–364. http://dx.doi.org/10.1111/1365-2664.12035.

Garibaldi, L.A., Aizen, M.A., Klein, A.M., Cunningham, S.A., Harder, L.D., 2011a. Global growth and stability of agricultural yield decrease with pollinator dependence. Proc. Natl. Acad. Sci. 108, 5909–5914. http://dx.doi.org/10.1073/pnas.1012431108.

Garibaldi, L.A., Steffan-Dewenter, I., Kremen, C., Morales, J.M., Bommarco, R., Cunningham, S.A., Carvalheiro, L.G., Chacoff, N.P., Dudenhöffer, J.H., Greenleaf, S.S., Holzschuh, A., Isaacs, R., Krewenka, K., Mandelik, Y., Mayfield, M.M., Morandin, L.A., Potts, S.G., Ricketts, T.H., Szentgyörgyi, H., Viana, B.F., Westphal, C., Winfree, R., Klein, A.M., 2011b. Stability of pollination services decreases with isolation from natural areas despite honey bee visits. Ecol. Lett. 14, 1062–1072. http://dx.doi.org/10.1111/j.1461-0248.2011.01669.x.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., Cariveau, D., Chacoff, N.P., Dudenhöffer, J.H., Freitas, B.M., Ghazoul, J., Greenleaf, S., Hipólito, J., Holzschuh, A., Howlett, B., Isaacs, R., Javorek, S.K., Kennedy, C.M., Krewenka, K., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlöf, M., Seymour, C.L., Schüepp, C., Szentgyörgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B.F., Wanger, T.C., Westphal, C., Williams, N., Klein, A.M., 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science 80. http://dx.doi.org/10.1126/science.1230200. (Published).

Garibaldi, L.A., Carvalheiro, L.G., Leonhardt, S.D., Aizen, M.A., Blaauw, B.R., Isaacs, R., Kuhlmann, M., Kleijn, D., Klein, A.M., Kremen, C., Morandin, L., Scheper, J., Winfree, R., 2014. From research to action: practices to enhance crop yield through wild pollinators. Front. Ecol. Environ. 339 (6127), 1608–1611. http://dx.doi.org/10.1890/130330.

Garibaldi, L.A., Carvalheiro, L.G., Vaissiere, B.E., Gemmill-Herren, B., Hipolito, J., Freitas, B.M., Ngo, H.T., Azzu, N., Saez, A., Astrom, J., An, J., Blochtein, B., Buchori, D., Garcia, F.J.C., Oliveira da Silva, F., Devkota, K., Ribeiro d, M.F., Freitas, L., Gaglianone, M.C., Goss, M., Irshad, M., Kasina, M., Filho, A.J.S.P., Kiill, L.H.P., Kwapong, P., Parra, G.N., Pires, C., Pires, V., Rawal, R.S., Rizali, A., Saraiva, A.M., Veldtman, R., Viana, B.F., Witter, S., Zhang, H., 2016. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. Science 80 (351), 388–391. http://dx.doi.org/10.1126/science.aac7287.

Greenleaf, S.S., Williams, N.M., Winfree, R., Kremen, C., 2007. Bee foraging ranges and their relationship to body size. Oecologia 153, 589–596. http://dx.doi.org/10.1007/s00442-007-0752-9.

Hulme, M.F., Vickery, J.A., Green, R.E., Phalan, B., Chamberlain, D.E., Pomeroy, D.E., Nalwanga, D., Mushabe, D., Katebaka, R., Bolwig, S., Atkinson, P.W., 2013. Conserving the birds of Uganda's banana-coffee arc: land sparing and land sharing compared. PLoS One 8, e54597. http://dx.doi.org/10.1371/journal.pone.0054597.

Klein, A.M., Steffan-Dewenter, I., Tscharntke, T., 2003. Fruit set of highland coffee increases with the diversity of pollinating bees. Proc. Biol. Sci. 270, 955–961. http://dx.doi.org/10.1098/rspb.2002.2306.

Kremen, C., 2015. Reframing the land-sparing/land-sharing debate for biodiversity conservation. Ann. N.Y. Acad. Sci. 1355 (1). http://dx.doi.org/10.1111/nyas.12845.

Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecol. Soc 17http://dx.doi.org/10.5751/ES-05035-170440. (art40).

MAPA – Ministério da Agricultura, P.e.A., 2014. Plano Agrícola e Pecuário 2013/2014.

Moreira, E.F., Boscolo, D., Viana, B.F., 2015. Spatial Heterogeneity Regulates Plant-Pollinator Networks across Multiple Landscape Scales. PLoS ONE 10 (4). http://dx.doi.org/10.1371/journal.pone.0123628.

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–1291. http://dx.doi.org/10.1126/science.1208742.

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2014. Diversification practices reduce organic to conventional yield gap. Proc. R. Soc. London B Biol. Sci. 282.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W.E., 2010. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25, 345–353. http://dx.doi.org/10.1016/j.tree.2010.01.007.

Ramankutty, N., Rhemtulla, J., 2012. Can intensive farming save nature? Front. Ecol. Environ. 10http://dx.doi.org/10.1890/1540-9295-10.9.455. (455-455.).

Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. Nat. Plants 2, 15221. http://dx.doi.org/10.1038/nplants.2015.221.

Ricketts, T.H., Daily, G.C., Ehrlich, P.R., Michener, C.D., 2004. Economic value of tropical forest to coffee production. Proc. Natl. Acad. Sci. U. S. A. 101, 12579–12582. http://dx.doi.org/10.1073/pnas.0405147101.

Ricketts, T.H., Regetz, J., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Bogdanski, A., Gemmill-Herren, B., Greenleaf, S.S., Klein, A.M., Mayfield, M.M., Morandin, L.A., Ochieng', A., Potts, S.G., Viana, B.F., 2008. Landscape effects on crop pollination services: are there general patterns? Ecol. Lett. 11, 499–515. http://dx.doi.org/10.1111/j.1461-0248.2008.01157.x.

Saturni, F.T., Jaffé, R., Metzger, J.P., 2016. Landscape structure influences bee community and coffee pollination at different spatial scales. Agric. Ecosyst. Environ. 235, 1–12. http://dx.doi.org/10.1016/j.agee.2016.10.008.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232. http://dx.doi.org/10.1038/nature11069.

Steffan-Dewenter, I., Kuhn, A., 2003. Honeybee foraging in differentially structured landscapes. Proc. R. Soc. B Biol. Sci. 270, 569–575. http://dx.doi.org/10.1098/rspb.2002.2292.

Sustainable Agriculture Network, 2010. Sustainable Agriculture Standard.

Tuck, S.L., Winqvist, C., Mota, F., Ahnström, J., Turnbull, L.A., Bengtsson, J., 2014. Land-use intensity and the effects of organic farming on biodiversity: a hierarchical meta-analysis. J. Appl. Ecol. 51, 746–755. http://dx.doi.org/10.1111/1365-2664.12219.

Vaissière, B.E., Freitas, B.M., Gemmill-Herren, B., 2011. Protocol to Detect and Assess Pollination Deficits in Crops: and Assess Pollination Deficits in Crops. FAO, Rome, Italy.

Vergara, C.H., Badano, E.I., 2009. Pollinator diversity increases fruit production in Mexican coffee plantations: the importance of rustic management systems. Agric. Ecosyst. Environ. 129, 117–123. http://dx.doi.org/10.1016/j.agee.2008.08.001.

Winfree, R., Aguilar, R., Vázquez, D.P., LeBuhn, G., Aizen, M.A., 2009. A meta-analysis of bees' responses to anthropogenic disturbance. Ecology 90, 2068–2076. http://dx.doi.org/10.1890/08-1245.1.