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The role of space and time in the interaction of farmers' management decisions and bee communities: Evidence from South India

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Abstract

CONTEXT

Agricultural management systems of many smallholders in low and middle-income countries depend on services by pollinator populations. However, increased adoption of modern inputs and particularly the wide-spread use of agrochemicals threaten pollinators and smallholders' crop production. Understanding how farmers' use of modern inputs affects pollinator communities is, therefore, crucial for development efforts and the design and promotion of sustainable agricultural practices.

OBJECTIVE

We contribute to the still scarce literature on pollinator communities in low and middle-income countries by analyzing the link between the use of agrochemicals and wild bee populations in South India. Moreover, we capture temporal and spatial scaling in farm-pollinator relationships by explicitly analyzing effects of present, past, and neighboring agricultural management decisions on wild bee populations.

METHODS

Our empirical analysis is based on an interdisciplinary data set, combining information from pan trap experiments and a socio-economic survey of 127 agricultural plots in the rural-urban interface of Bangalore, India. We implemented a Poisson generalized linear model (GLM) to analyze factors influencing bee abundance and richness with a particular focus on the effects of farmers' management decisions. Present and past management were measured by the use of chemical fertilizers, pesticides, and irrigation in 2018 and during the previous years respectively. By setting up spatial weight matrices, we derived a proxy for neighboring management decisions and were able to estimate potential spillover effects.

RESULTS AND CONCLUSION

Our results suggest that agricultural intensification is associated with a decline of bee abundance and richness in our study area. Both time and space play important roles in explaining farm-bee interactions. We find statistically significant negative spillovers of pesticide use. With every addition percent of neighboring farmers using pesticides, bee abundance and richness decrease by up to 0.68 percent on the focal plot. Furthermore, smallholders' decisions to use chemical fertilizers and pesticides on their own plots significantly decrease the number of observed bees by about 20 percent. Also, every additional year of intensive past management reduces both bee abundance and richness by up to 8 percent.

SIGNIFICANCE

We provide new empirical evidence on farm-pollinator relationships in tropical low and middle-income countries. Based on our results, cooperative behavior among farmers and/or the regulation of agrochemical use seem to be crucial to moderate spatial spillovers of agricultural decision-making.

Also, a rotation of extensive and intensive management seems to be an appropriate way to mitigate negative effects of agricultural intensification on bee populations.

Keywords: Bee communities, India, pesticides, spillovers, temporal and spatial scales

1. Introduction

Pollinator communities make important contributions to agricultural production and food security (Kleijn et al., 2015; Tscharntke et al., 2012) and interest in this topic has increased with the so-called ‘pollinator crisis’, the fast decline of pollinator populations on a global scale (Tylianakis, 2013). While many staple crops do not rely on animal pollination, most fruit and vegetable crops do (Klein et al., 2007). These crops often figure prominently in efforts to improve the incomes and living standards of smallholders in low-income countries. The commercialization of high-value fruit and vegetable production systems allows for participation in national and international agricultural value chains and can therefore contribute to economic development (Maertens et al., 2012). As a consequence, agricultural policy strategies in many low-income countries focus on improving farmers’ access to modern inputs and technologies to achieve more commercialized agricultural systems (Jayne et al., 2018; Minten et al., 2013). Furthermore, improved infrastructure and better access to urban centers and markets are also amplifying the transformation from extensive to more intensified agricultural management systems in large parts of Africa and Asia (Steinhübel & Cramon-Taubadel, 2020; Vandercasteelen et al., 2018).

Despite the economic benefits for smallholders in poorer regions, the flipside to the greater use of modern agricultural technologies such as agrochemicals is that they can harm pollinator populations, with negative implications for future economic performance (Brittain et al., 2010; Goulson et al., 2015). Evidence on farm-pollinator interactions in higher-income countries is vast but a study by Wenzel et al. (2020) shows that there are only a few studies from lower-income countries and tropical regions. Reasons are manifold, and include the often-patchy understanding of pollinator species in these countries. Furthermore, collecting pollinators in (sub-)tropical climates can be a challenging undertaking. Since farming systems can differ greatly between high and low-income countries, we cannot simply extrapolate from the existing literature to fully understand farm-pollinator interactions in low-income countries or tropical localities. For example, agricultural plots in low-income countries are often much smaller, and climate and crop choices differ. Most relevant for this study, smallholders normally depend exclusively on wild pollinator populations, which have been shown to substantially increase yields of pollination-dependent crops (Garibaldi et al., 2016). When wild populations are not able to provide sufficient pollination services, farmers in high-income countries often bring in managed bee populations as a substitute, but this option is often not available or not affordable for smallholders.

Another challenge to analyzing farm-pollinator interactions is that it requires a combination of ecological and economic concepts and approaches. While several studies have called for increased interdisciplinary analysis (Bennett et al., 2015; Collins et al., 2011; Vanbergen & Initiative, 2013; Zhang et al., 2007), this is often difficult because the two disciplines work on different temporal and spatial scales. Most studies to date have been published by ecologists. In this literature, management decisions are often considered at the landscape scale in an aggregate fashion, e.g., home gardens versus natural forests (Blitzer et al., 2012; Motzke et al., 2016; Tscharntke et al., 2005; Tscharntke & Brandl, 2004). Aggregation at the landscape or habitat level is intuitive to ecologists because ecological and anthropogenic boundaries do not necessarily match – i.e., pollinators can move between agricultural plots. Thus, several articles demonstrate the importance of landscape scale in defining local pollination services to account for pollinator mobility and foraging ranges (Halinski et al., 2020; Kremen et al., 2007; Tscharntke et al., 2005). From an economic and policy perspective, in contrast, the landscape scale is of limited use because decision-making typically takes place at the household or farm level. Similarly, in the economic literature, agricultural decision-making is often associated with short-term seasons or growing cycles (Steinhübel et al., 2020), whereas ecological studies emphasize that pollinator communities are likely affected by the longer-term accumulation of management decisions that affect nesting and foraging possibilities or the exposure to pollutants and toxicants (Kremen et al., 2007; Schwarz et al., 2020).

The motivation of our study is, therefore, twofold. First, we aim to contribute new evidence to the literature on farm-pollinator interaction in topical, low-income countries by analyzing primary data on bee communities and farm management on 127 smallholder plots in South India. Second, in our empirical analysis, we address the spatial and temporal disconnect of ecological and economic perspectives. By specifically modeling the effect of present, past, and neighboring agricultural management choices on bee abundance and richness, we aim to answer the following research questions:

1) Which farmer management decisions affect bee communities, and to what extent?

2) How do management decisions taken by one farmer affect bee communities on other farmers' plots – i.e., to what extent do spillover effects of management decisions extend beyond the boundaries of management units?

3) How do past management decisions affect current bee communities?

By considering different scales and by looking into the use of different agricultural inputs, our results provide a detailed picture of farm-pollinator interactions. This can help to better target extension and policy measures to regulate the use of agricultural inputs that can harm bee communities, and ultimately support sustainable agricultural growth in low-income countries.

2. Methods

2.1 Study area and survey design

Our empirical analysis is based on data from two study areas that extend from urban Bangalore roughly 40 km into the surrounding rural-urban interface, one to the north and the other to the south and west. We refer to these areas as research transects (Fig. 1). The rural-urban interface is heavily influenced by the rapidly growing city of Bangalore; the last official census in 2011 recorded 9.6 million inhabitants and average yearly growth rates of about 8 percent (Directorate of Census Operations Karnataka, 2011). Nevertheless, it is dominated by smallholder agriculture and agricultural land use is highly fragmented. Bangalore and several satellite towns offer a variety of marketing possibilities to farmers and connect them to local, national, and even international markets. Expanding infrastructure also improves farmers' access to input markets, especially for chemical fertilizers and pesticides. As a consequence, agricultural production is becoming increasingly commercial and many farmers are shifting from subsistence production of staple crops to intensive high-input fruit and vegetable production. The agricultural production systems in the rural-urban interface of Bangalore thus exemplify the dilemma that we discuss in the introduction: smallholders are shifting to more pollinator-dependent production systems and simultaneously increasing the use of potentially pollinator-harming inputs.

To capture potential spatial heterogeneity induced by the urban center of Bangalore, the selection of farm households and plots for data collection followed a two-step approach. Based on the *Survey Stratification Index* (SSI) introduced by Hoffmann et al. (2017), all villages in the two research transects were classified into three strata (rural, peri-urban, urban). In the first step, ten villages were randomly selected in each stratum in each transect (60 villages in total). Using household lists provided by preschool teachers in the selected villages, we randomly drew an average of 20 households per village (weighted by village size). The resulting 1,275 households were subjected to a detailed baseline socio-economic survey that was carried out between December 2016 and May 2017. About half of these households (638) were farm households, i.e., they managed at least one plot in 2016. For these households, the baseline survey included data on agricultural management in the agricultural year 2016/2017 and recall data for the years 2012 to 2015.

In the second, step we drew a random subsample of 24 of the 40 villages located in the peri-urban and rural strata, twelve in each transect.[1] In these randomly selected villages, all households that had been identified as farm households in the first step (N=127) were selected for pan trap experiments (described below) and a second survey, which was carried out in February and March 2018.[2] This second survey covered information on agricultural management decisions in the 2017/18 season. Combining data from both surveys provided us with a continuous record of the management history of each of the 127 farm households extending back to 2012.

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[1] Because only few agricultural households are located in the urban stratum, we excluded the 20 villages in this stratum from the subsample.

[2] Robust inference on spatial spillovers among farm plots requires a sufficient number of observations (plots) within a potential interaction radius of one another. We therefore drew a random subsample of villages rather than households, to ensure that the individual observations (plots) are spatially clustered. See the zoomed-in areas in Fig. 1. Unfortunately, there were 4 villages in the peri-urban strata of the southern transect with only one farm household. These households were not considered in our empirical analysis.

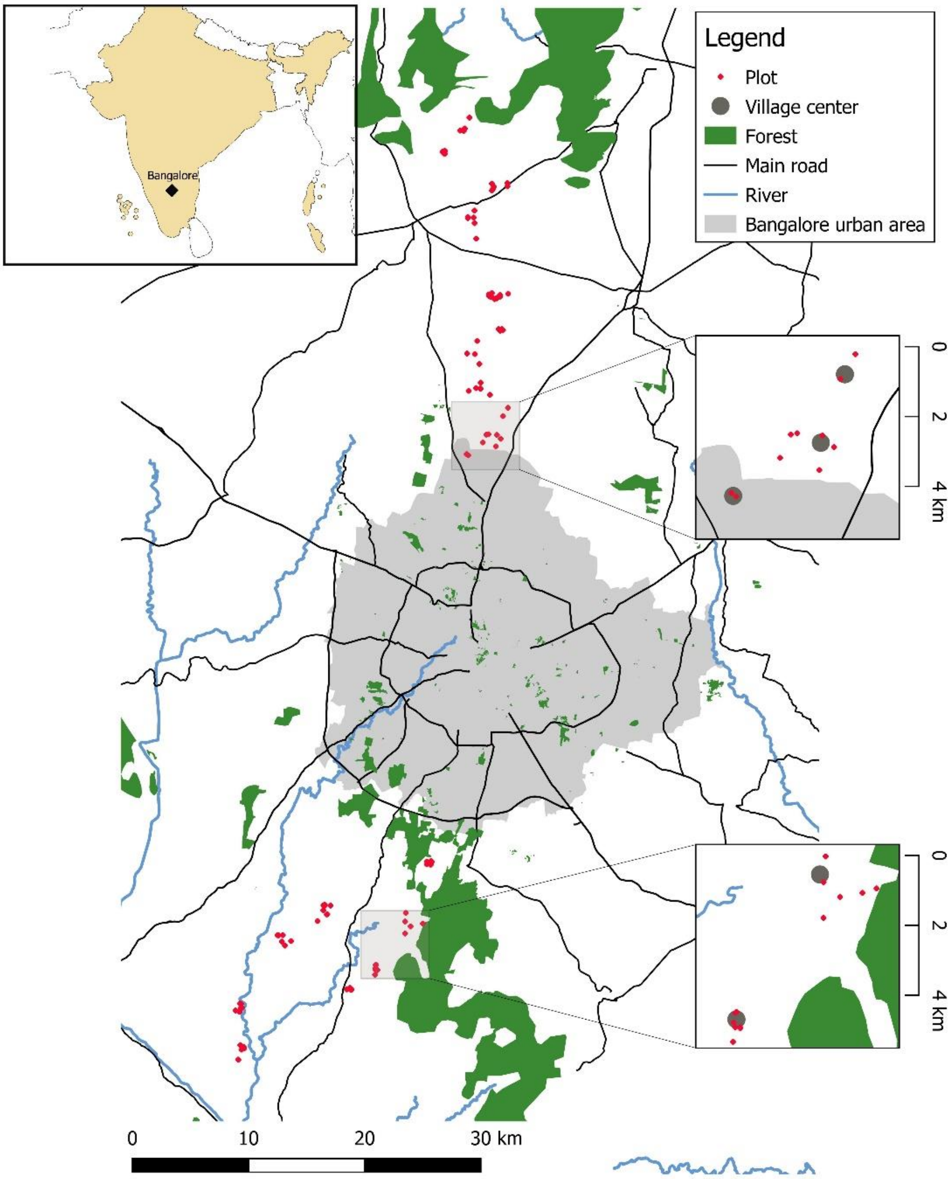

Fig. 1. Research area and location of sampled villages and plots along the rural-urban interface of Bangalore, South India ($N = 127$). Panels on the right show zoomed-in representations of the grey shaded squares in the large map. Village and plot coordinates were collected during the household survey in 2018. All other map features were downloaded from *OpenStreetMap* and visualized with *QGIS*.

To sample pollinators we applied pan trap experiments, a standard rapid sampling method to record pollinator communities (Meyer et al., 2015; Westphal et al., 2008). We randomly selected one plot from each of the 127 farm households in the subsample (Fig. 1). We collected information on the direct neighborhood of each selected plot, as well as the GPS-coordinates of its centroid. Four pan traps were placed on each of these plots. The pan traps were 500 ml bowls sprayed with yellow UV-bright color and filled with unscented soapy water to break surface tension. To ensure that we captured as many pollinators as possible, all four pan traps were placed near flower-rich patches, with a minimum distance of approximately 10 m between traps to minimize interactions between them. The traps were collected after 48 hours of exposure. Unfortunately, some traps failed; they spilled or were taken away by passers-by. As a consequence, some plots had fewer than four successful pan traps; we introduced dummy variables in our later analysis to control for the number of successful traps per plot (see Table A.1). Pan traps were placed in the field on dry, bright, and mostly calm days between the hours of 10 am and 2 pm. Collecting took place from January 9 to February 11, 2018.

After collection, all insects caught in the traps were treated with 70% ethanol, pinned, and identified to species or genus level. Most of the captured insects were bees along with a few other pollinating insect taxa (e.g., beetles, butterflies, flies, wasps). Since pollinator groups differ greatly in their ecological characteristics (Gagic et al., 2015), we decided to consider only bees in our analysis to avoid inconclusive results. In the remainder of this article ‘species’ refers to the lowest taxonomic rank identified. To the best of our knowledge, beekeeping is not common in the research transects. None of our sampled households reported keeping bees. Therefore, we assume that most of the bees caught in the pan traps originate from wild populations.

We used the number of bees caught per plot as a proxy for bee abundance and the number of different bee species as a proxy for bee richness. We are aware that these are only rough indicators for local bee diversity and that pan traps might oversample smaller species (see e.g. Baum & Wallen, 2011). Nevertheless, both are frequently used in the ecological literature (Holzschuh et al., 2007; Kremen et al., 2002, 2004) and hence our results can easily be compared with previous studies. Since bee abundance and richness are highly correlated in our sample ($\rho = 0.919$), we do not use both in the same model specification to avoid problems with multicollinearity.

2.2 Empirical analysis

We implemented a Poisson generalized linear model (GLM) with two dependent variables—counts of abundance and richness. Our main interest is how these counts are affected by the use of chemical fertilizers, irrigation, and pesticides. Chemical fertilizers and irrigation are commonly used to quantify the intensity of agricultural management in low and middle-income countries (see e.g. Asfaw et al., 2016; Vandercasteelen et al., 2018), whereas pesticides not only signal intensification but can reduce foraging resources, i.e. in case of herbicide applications, or be even directly harmful to bees (Brittain et al., 2010; Tuell & Isaacs, 2010). To incorporate the different temporal and spatial scales discussed before, we estimate the effects of current farm practices on the plot under observation, but also allow for the possible effects of past farm practices on the same plot as well as farm practices on plots in the neighborhood.[3] Therefore, bee abundance or richness y on plot i is given by the predictor η_i:

$$y_i \sim Po(\lambda_i),\ with\ log(\lambda_i) = \eta_i = \boldsymbol{z}_i\boldsymbol{\alpha} + \boldsymbol{p}_i\boldsymbol{\gamma} + \boldsymbol{h}_i\boldsymbol{\theta} + \boldsymbol{x}_i\boldsymbol{\beta} \tag{1}$$

where $\boldsymbol{z_i}$ is a row vector of dummies for irrigation, chemical fertilizer, and pesticide use on plot i in 2018 (*present management*)[4]; $\boldsymbol{p_i}$ is the number of years either of the three inputs have been used on plot i since 2012 (*past management*); $\boldsymbol{h_i}$ is the agricultural management of plots in the neighborhood of plot i in 2018 (*neighboring management*); and $\boldsymbol{x}_i$ is a set of control variables including a constant. The parameter vectors $\boldsymbol{\alpha}$, $\boldsymbol{\gamma}$, $\boldsymbol{\theta}$, and $\boldsymbol{\beta}$ are to be estimated. The $\boldsymbol{h}_i$ in equation (1) can be understood as spatial lags (SLX) of $\boldsymbol{z}_i$ ($\boldsymbol{h_i} = \boldsymbol{w_i Z}$), where $\boldsymbol{W}$ is a spatial weight matrix of dimension $n \times n$ that defines interactions between plot i and any plot j in its neighborhood. The weight matrix was composed of known scalars that represent *a priori* assumptions about the spatial interdependence between observations i and j where $i, j \in \{1, \ldots, N\}$ (Lee, 2004). First, the main diagonal of $\boldsymbol{W}$ (when $i = j$) was set to zero. Second, we assume that spatial interdependence ends beyond a certain distance, i.e. the corresponding weights in $\boldsymbol{W}$ also equal zero. In the present case, this cut-off distance was determined by the bee foraging distance, i.e. which other plots j could a bee have visited before it was caught on plot i. Previous studies indicate bee foraging distances up to several kilometers (Zurbuchen et al., 2010). Accordingly, we created two weight matrices; one with a two-kilometer cut-off,[5] and one with a four-

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[3] We also tested for spatial autocorrelation using Moran I tests. Test statistics were not significant and we, thus, did not include an autoregressive parameter in our model.

[4] For the years 2017 and 2018, we have data on quantities of fertilizer and pesticide applied on the sample plots. Nonetheless, we refrained from including input quantities as explanatory variables because we also wanted to include information on past plot management decisions in our analysis, and for earlier years (2012 to 2016) we only have data on the numbers of inputs used, not quantities. We did not collect data on the quantities of inputs used in past years because the surveyed producers rarely keep records and their recollection of the quantities of inputs used in past cropping seasons would be increasingly unreliable and possibly biased as the recall period grows. Furthermore, even if we had information on input quantities, it is not clear how to aggregate these without additional information on application concentrations and relative toxicities. Hence, we used dummies for consistency. We also did not differentiate between different types of pesticides (e.g. fungicides, herbicides) because pesticide use among farmers in our sample is still rare (Table 1).

[5] Since we only have data from 127 plots, we do not have data of the complete neighborhood of every plot. In order to still be able to capture the neighborhood of each plot, the minimum cut-off distance must be chosen such that at least a few surveyed neighboring plots of each plot i are included. Two kilometers is the minimum for our data set, where we have, on average, information on seven neighboring plots (min: 2, max:14). For the four-kilometer cut-off we observe an average of 13 neighboring plots (min: 4, max: 24).

kilometer cut-off. To model the strength of interdependence (i.e. the weights in $\boldsymbol{W}$) between different plots we tested two approaches. One is the simple share of neighboring plots using chemical fertilizers, pesticides, or irrigation. A value of 1 in $\boldsymbol{W}$ simply indicates that the respective agricultural input was used and that the plot is within the cut-off distance. $\boldsymbol{W}$ was then normalized by the row sums of $\boldsymbol{w}_i$. In the second approach, we assumed that the strength of spatial interdependence between plots i and j is proportional to the inverse distance between them. The calculation of $\boldsymbol{h}_i$ is the same as in the first approach only that the normalization is achieved by dividing by the maximum inverse distance. We estimated the model in equation (1) with both cut-off distances and both specifications of $\boldsymbol{h}_i$. Since all other parameter estimates were robust to the two different specifications, for reasons of simpler interpretation only the $\boldsymbol{h}_i$ based on the first approach was included in the subsequent analysis. However, estimation results for the second approach are included in Table A.2. Descriptive statistics for the dependent variables and the present, past, and neighboring management variables are presented in Table 1.

Table 1

Descriptive statistics for the dependent variables and agricultural input use ($n = 127$)

Variable	Mean	Std. Dev.	Min	Max
Dependent variables				
Bee abundance (number of bees per plot)	4.68	4.44	0	22
Bee richness (number of bee species per plot)	2.78	2.35	0	11
Agricultural input use				
Chemical fertilizer – on plot	0.78			
Irrigation – on plot	0.39			
Pesticides – on plot	0.26			
Chemical fertilizer since 2012 (years)	3.87	2.02	0	5
Irrigation since 2012 (years)	1.63	2.28	0	5
Pesticide use since 2012 (years)	0.35	1.19	0	5
Chemical fertilizer – 2km neighborhood (share)	0.78	0.19	0.36	1
Irrigation – 2km neighborhood (share)	0.38	0.25	0	1
Pesticides – 2km neighborhood (share)	0.26	0.24	0	0.8
Chemical fertilizer – 4km neighborhood (share)	0.77	0.13	0.5	1
Irrigation – 4km neighborhood (share)	0.38	0.18	0	0.71
Pesticides – 4km neighborhood (share)	0.26	0.13	0	0.57

Besides agricultural input use, we consider 25 control variables at the landscape and local scale (for a list and descriptive statistics see Table A.1). At the landscape scale, we used the GPS-coordinates of each plot to calculate its distance from Bangalore city center. This variable allows us to control for exogenous spatial heterogeneity induced by the rural-urban gradient. In addition, we included a dummy for the Southern transect to control for any transect-specific effects. Based on satellite images, we estimated the build-up area of every village, i.e., the area covered by infrastructure and, thus, habitat availability within a 1 km radius of the village center (for details see Hoffmann et al., 2017).

At the plot level, we used information on the direct neighborhood of each plot to create several dummies that describe the patterns of land use surrounding it. Furthermore, we included several variables that are related to the pan traps and their placement and might, therefore, influence bee abundance. These variables are the number of successful pan traps per plot and meteorological variables such as cloud cover, temperature, and wind conditions when the pan traps were in place. Since the cropping systems in the Bangalore area are very diverse, we also controlled for different crops. On the 127 pan trap plots, 40 different crops were grown. This crop diversity gives rise to two main issues. First, different crops serve bee communities in different ways and certain management practices might be strongly correlated with certain crops. Second, different crops have different growing schedules. As a consequence, some plots had already been harvested when the pan traps were placed, while others were at various earlier stages of development. Cropping seasons have become even more fluid with the increasing availability of irrigation, and there is no time of year when all agricultural plots are in a comparable state. We used different variables to test and control for these issues. We introduced a dummy variable that indicates whether the plot was already harvested and thus has been fallow for several weeks. In addition, we controlled for functional groups of crops, namely flowers, fruits, staples, tree crops, and vegetables on the plots (see Table A.3 for detailed information). We restrained from adding crop-specific dummies because given 40 different crops this would have severely reduced the degrees of freedom for estimation. We also created a dummy variable indicating whether a crop classifies as a forage crop for bees (i.e. pollen or nectar source); this variable represents the forage quality of the plot in the current season. Furthermore, we used the recall data from the baseline survey to measure the number of years since 2012 in which a plot had been planted with bee forage crops. Finally, we estimated the number of flowers of the focal crop on the plot when the pan traps were in place and the number of flowers within a 2 m radius of the pan traps.

Since our sample comprises only 127 observations, including all explanatory variables will likely lead to over-parametrization of the model (equation (1)). Therefore, we applied an adaptive selection algorithm based on the improved Akaike information criterion (iAIC), which evaluates the contribution of every term to the model fit. Variables that do not improve the model were dropped (for details see Belitz & Lang, 2008; Umlauf et al., 2015).

3. Results

Overall, we caught 613 bee individuals and identified 31 species belonging to three different families (Apidaea, Halictidae, and Megachile, Table A.4). The most abundant species were *Apis florea*, *Lasioglossum sp. 1*, and *Apis cerana* (160, 83, and 79 individuals respectively). *Chao 1* species richness estimators (Chao, 1984) indicate that we sampled 88 percent of the regional bee species pool, and the species accumulation curve in Fig. A.1 confirms that our sampling effort was sufficient to detect most bee species in the study region.[6]

Table 2 presents the results based on the selection algorithm and the estimation of the model in equation (1). We do not present coefficient estimates but calculated effects as percentage changes at the mean rate of bee abundance and richness to facilitate interpretation.

3.1 Effects of agricultural input use on bee communities

Our results provide evidence of a negative association between agricultural intensification and bee communities in the rural-urban interface of Bangalore. If a farmer applies chemical fertilizers or pesticides on his/her plot, this decreases bee abundance by about 20 percent ($p = 0.086$). Also, the use of pesticides by other smallholders within 2-kilometers of a plot reduces bee abundance on that plot. With every additional percent of pesticide use in the neighborhood of a plot (=0.01 share), the number of bee individuals on that plot decreases by 0.68 percent ($p < 0.001$). Considering that on average 25 percent (maximum of 80 percent) of neighboring farmers apply pesticides (Table A.1), pesticide use by neighboring smallholders can affect bee abundance on a plot just as strongly as pesticide use on that plot itself. As for the past management, we find that with every additional year of irrigation of the same plot, bee abundance on that plot decreases by 8.1 percent ($p < 0.001$). Originally, the selection algorithm suggested to include both past irrigation and pesticide use. However, since these two variables are strongly correlated ($\rho = 0.405$ ($p < 0.001$)), we decided to drop one of them to avoid multicollinearity. Consequently, the effect of past irrigation should rather be interpreted as an effect of past intensity of agricultural management. The results for the relationship between agricultural management and bee richness, are similar to those for bee abundance (Table 2). However, the present use of chemical fertilizers and pesticides does not have any statistically significant effects on bee richness. In contrast, past and neighboring agricultural management have significant negative effects on bee richness that are of nearly the same magnitude as those for bee abundance.

3.2 Other factors influencing bee communities

The selection algorithm only indicates three control variables that are positively associated with both bee abundance and richness. These are the dummy controlling whether a plot was already harvested before the pan trap was installed (only statistically significant for bee richness), the presence of flowers in the focal crop, and the plot size. Among these, the presence of flowers appears to be most important with relatively large effect size and high statistical significance.

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[6] Since all pan trap catches from a given plot were combined in the field for easier logistics, we are unable to present a species accumulation curve at the pan trap level.

Table 2

Estimation results ($n = 127$)

Variable	**Effects of explanatory variable as percentage changes on…** (e.g. $(e^{\widehat{\beta}} - 1) \times 100$)	
	Abundance	**Richness**
Agricultural input use		
Chemical fertilizer – on plot (dummy)[a]	-22.2 (0.026)	-4.9 (0.709)
Pesticides – on plot (dummy)[a]	-20.4 (0.087)	-12.9 (0.396)
Irrigation since 2012 (years)	-8.1 (<0.001)	-7.0 (0.011)
Pesticides – neighborhood (share)	-67.8 (<0.001)	-41.6 (0.043)
Landscape scale		
Distance to Bangalore (km)		2.4 (0.001)
Southern transect (dummy)	-29.7 (0.001)	
Village build-up area (percentage)	-4.7 (<0.001)	
Local / Plot scale		
Forest in direct neighborhood (dummy)	35.5 (0.037)	
Building in direct neighborhood (dummy)	-18.2 (0.086)	
Road in direct neighborhood (dummy)	-16.5 (0.046)	
Successful pan traps (number) – reference category is 4		
1	-20.1 (0.522)	
2	39.2 (0.034)	
3	46.4 (<0.001)	
Clouds at time of pan trap placement (Okta scale)		22.5 (0.071)
Plot fallow or harvested at time of pan trap placement (dummy)	16.3 (0.148)	22.6 (0.095)
Tree crop (dummy)	-40.3 (0.019)	
Vegetable crop (dummy)	-18.3 (0.031)	
Flowers present in focal crop 2018 (number, logarithmic scale)	29.4 (<0.001)	25.5 (<0.001)
Pollinator forage crops since 2012 (years)	-3.3 (0.065)	
Plot size (acre)	8.9 (0.003)	7.8 (0.028)
Intercept	668.8 (<0.001)	-56.5 (0.072)

Note: p-values given in parentheses, [a]not chosen by the selection algorithm in the *Richness* model.

Furthermore, the results in Table 2 show that a larger number of explanatory variables have a significant effect on bee abundance than on richness, particularly on the local scale. This includes statistically significant effects of the number of successful pan traps per plot implying that this is an important control variable in the model on bee abundance. Also, adjacent plot use appears to have a big influence on bee abundance. A road or building reduces bee abundance by 18.2 and 16.5 percent respectively, whereas a forest located next to an agricultural plot leads to an increase of more than 35 percent.

On the landscape scale, the distance to the urban center of Bangalore appears to be an important factor for the number of present bee species. With every additional kilometer distance from the city, bee richness increases by 2.4 percent. In contrast, bee abundance is negatively associated with build-up area, which is also an indicator of urbanization.

4. Discussion

The levels of bee abundance and species richness that we found in the rural-urban landscape around Bangalore are comparable to those found in other studies conducted in tropical agricultural landscapes (Hass et al., 2018; Hoehn et al., 2008). Still, the number of captured bee individuals was relatively small at the plot level. This might be due to unusually dry and hot weather conditions in early 2018. For longer sampling periods covering multiple seasons, catches might be higher. Nonetheless, as our design was strictly standardized (Meyer et al., 2015), we are confident that our bee data are robust and show sufficient variation for our study.

Bee or pollinator abundance and richness are common indicators of pollination services (Holzschuh et al., 2007; Kremen et al., 2004) and the negative effects of fertilizer and pesticide use on bee abundance and richness that we find might be expected to also hold for biodiversity and ecosystem services such as pollination. Such a negative relationship has been highlighted in the literature (Matson, 1997; Tilman et al., 2002; Winfree et al., 2009). However, since we did not measure direct pollination outcomes such as fruit or seed set, we cannot draw direct conclusions but can only deduce from other studies. A sufficient number of pollinators (abundance) is necessary to guarantee full pollination services (Kremen et al., 2002). Other studies highlight specialized plant-pollinator relationships and the importance of bee richness for a complete fruit set (Klein et al., 2003). Thus, effects on both indicators have to be taken into consideration in evaluating the effects of farmers' decision-making on pollination services.

Furthermore, we also find that the abundance and richness of bee communities in our research area are suffering from negative spatial spillovers of neighboring smallholders' management decisions, particularly from pesticide use. Several studies have analyzed the effect of pesticides on bee communities, but the results are not consistent. Whereas Tuell and Isaacs (2010) find significant negative effects for insecticides, Kremen et al. (2004) and Shuler et al. (2005) do not find any interactions between insecticide and overall pesticide use on wild pollinator populations respectively. However, these studies do not consider spatial scaling, which seems important in the light of our estimation results. Studies that consider spatial dimensions normally only consider effects of aggregated farming systems on bee populations of surrounding plots or the influence of distance to natural habitats (Holzschuh et al., 2007; Motzke et al., 2016). Therefore, a key advantage of our modeling approach is that it can identify spatial spillovers of specific farming practices such as agricultural input use. This enables us to quantify the link between a farmer's decision to use pesticides and resulting externalities on other plots. Even if a farmer was to reduce pesticide use to protect pollinator populations and their services, he/she might still face decreased provision of pollination services due to pesticide use by neighbors. In the worst case, the farmer could end up with only pests and no pollinators on his/her plots.

At the other extreme, a free-riding problem might arise. If only one farmer applies pesticides while all others refrain in an effort to protect pollinators, then this farmer will face lower pest rates and also benefit from largely intact pollination services. Thus, our results suggest that cooperative behavior among smallholders or other approaches such as pesticide regulations may be necessary to guarantee pollination services for all farmers. This is in line with other ecological studies (Goldman et al., 2007; Stallman, 2011) that refer to the prisoners' dilemma affecting pollinator maintenance (Rapoport, 1989). Also, this might be even more relevant in low-income countries. While in the global north intensified agriculture often takes place on large fields, in the global south agriculture is still dominated by smallholders. In our study, the average plot size is about 1.33 acres (Table A.1). This means that bee populations in Bangalore are more likely to be affected by different individual agricultural management decisions than a bee population in Europe or North America, for example. Note that, in the literature, fragmented or diverse landscapes are normally associated with positive effects on pollinator population (e.g. Krishnan et al., 2012). This, however, often refers to the influence of forest patches or other natural habitats between agricultural plots (Halinski et al., 2020; Priess et al., 2007), a positive association also present in our estimation results. What we talk about here are the consequences of a fragmentation of agricultural land use. In landscapes dominated by small-scale agriculture pollinator presence on an induvial farmer's plot depends to a great extent on management decisions of his/her neighbors.

Nevertheless, in contrast to our results for pesticides, the negative effects of chemical fertilizers and intensive past plot management are limited to the plot level and do not show any significant spillovers. Intensively managed plots likely offer less forage and nesting opportunities to bee populations than extensively managed plots, since they offer less natural vegetation. For instance, weeding is still often done through manual labor in the area, and its effects are as such not reflected by our pesticide variable. This explains the local negative effect of chemical fertilizer and past intensive plot management on bee populations. Furthermore, several authors have emphasized the importance of time in determining pollinators' access to species-specific forage and nesting resources (Kremen et al., 2007; Tuell & Isaacs, 2010). Note, however, that farmers applied chemical fertilizers on 78 percent of plots in our sample. Thus, we already observe a relatively high density of intensified agriculture and there might be insufficient spatial variation of chemical fertilizer use in our sample for detecting spillovers.

Regarding other factors influencing bee abundance and richness, our results suggest that the distance to the urban center of Bangalore is an important factor for the number of present bee species, whereas bee abundance is influenced by village build-up area. Urbanization does not follow a monotonic rural-urban gradient surrounding Bangalore; several smaller satellite towns influence urbanization patterns as well (Steinhübel & Cramon-Taubadel, 2020). In the vicinity of such towns build-up area and its negative effects can increase as one moves away from Bangalore center. These findings match previous literature on the linkage of urbanization and pollinator decline (Wenzel et al., 2020). Physical infrastructure can impede biodiversity and ecosystem services due to changes in physical parameters (e.g., temperature)reduction of habitat size and connectivity (Faeth et al., 2011; Pickett et al., 2011; Turrini & Knop, 2015), or light pollution (Altermatt & Ebert, 2016). Furthermore, Banaszak-Cibicka and Zmihorski (2012), for example, show that ground-nesting pollinators have bigger problems with urbanization than cavity-nesting species. This might be a sign that bee richness is rather affected by larger-scale patterns, whereas bee abundance is influenced by local factors. Further evidence of such local influence on bee abundance is provided by the statistically significant effects of adjacent plot use (e.g. road or building). Especially the positive relationship between forests and pollinator communities or benefits from agroforestry systems have been emphasized in the literature before and might be also useful insight for the Bangalore area (Motzke et al., 2016; Staton et al., 2019).

Finally, the other statistically significant control variables show that particularly bee abundance is subject to many influences. Among these, the presence of flowers and the number of successful pan traps appear to be most important with relatively large effect size and high statistical significance. This importance of flowers is plausible as bees feed on them and confirms results by Motzke et al. (2016). The loss of some pan traps due to passers-by or other influences is a good example of practical challenges in collecting pollinator data in tropical and low-income regions. Due to poor infrastructure and long ways, it is impossible to control traps while on the plots and other farmers or villagers might not be familiar with such experiments and think of the traps as trash. It makes sense that particular bee abundance depends on the number of successful traps and the significance of such a dummy should always be tested and if statistically significant included in future studies facing similar constraints.

5. Conclusions and policy implications

The goal of this study is to evaluate the effects of agricultural management practices on bee communities and to provide new evidence for low-income countries based on primary data from the rural-urban interface of Bangalore. In our empirical analysis, we considered both ecological factors at the landscape and local scale as well as farmers' decisions to use different agricultural inputs at the plot scale. To account for spatial and temporal scaling, we applied a model that allows for spatial spillovers and the effects of past plot management.

Overall, we find a statistically negative effect of agricultural intensification on the bee population in the Bangalore area. However, there are some differences between abundance and richness. While bee abundance is negatively affected by present, past, and neighboring farming decisions, bee richness only shows significant interactions with past and neighboring agricultural management. Thus, it seems that larger-scale patterns are more important in defining the pool of observed bee species. This also matches our results regarding urbanization effects on bee communities. For bee abundance, we find that local build-up area is an important factor decreasing the number of observed bee individuals, while for bee richness the overall rural-urban gradient of Bangalore is more relevant. This highlights the importance of considering spatial as well as temporal dimensions when analyzing farm-pollinator interactions.

Our results suggest that strategies to protect pollination services by wild bee communities could include the regulation of pesticide use, but also the provision of incentives for cooperative behavior among farmers to foster landscape-level improvements in pollinator habitats. This is particularly important in smallholder land-use systems, where plot sizes are relatively small and pollinator populations are affected by a multitude of interacting individual management decisions. In addition, extension services that increase farmers' understanding of the importance of pollinators and how to protect them could have positive effects. After all, we also show that an on-plot reduction of chemical fertilizer and pesticide use can benefit bee abundance. Since past plot management decisions affect current bee abundance and richness, rotation of intensive and extensive management practices might help to maintain sufficient forage and nesting opportunities to support healthy and diverse bee communities. In addition, protecting forest patches or agroforestry plots also holds the potential to promote bee populations.

Our study shows that increasing agricultural intensification has negative effects on wild bee communities in low-income countries. To increase the statistical validity and precision of these results as a basis for policy recommendations we need more and larger samples from different countries in the Global South. Data from other regions with fewer cultivated crops might reduce the correlation among variables and allow for more specific conclusions concerning the effects of different agricultural practices. Finally, to improve our understanding of economic implications and to inform the design of effective policies, we also require research on the relationships between bee abundance and richness on the one hand, and pollination outcomes such as fruit set on the other.

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Appendix

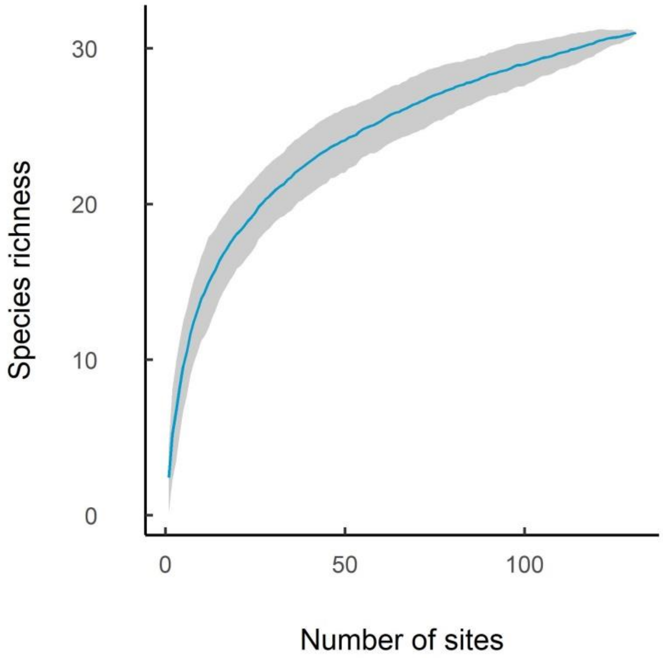

Fig. A.1. Species accumulation curve of bees: mean values (lines), and standard deviations (polygon) from 100 permutations of 127 sampled plots are shown.

Table A.1

Descriptive statistics for the control variables; for dummies and categorical variables shares, are presented, ($n = 127$)

Variable		Mean	Std. Dev.	Min	Max
Landscape scale					
Distance to Bangalore (km)		31.1	8.15	16.8	45.73
Southern transect (dummy)		0.45	0.5		
Village build-up area (percentage)		1.12	5.41	0.80	25.59
Local / Plot scale					
Agricultural plot in direct neighborhood (dummy)		0.85			
Fallow plot in direct neighborhood (dummy)		0.49			
Forest in direct neighborhood (dummy)		0.10			
Building in direct neighborhood (dummy)		0.28			
Road in direct neighborhood (dummy)		0.38			
Waterbody in direct neighborhood (dummy)		0.12			
Successful pan traps (number)					
	1	0.02			
	2	0.11			
	3	0.28			
	4	0.61			
Clouds at time of pan trap placement (Okta scale)		2.65	0.51	2	4
Temperature at time of pan trap placement (°C)		26.94	1.12	23	29
Wind at time of pan trap placement (Beaufort scale)		2.15	0.36	2	3
Plot fallow or harvested at time of pan trap placement (dummy)		0.47			
Flower crop (dummy)[a]		0.04			
Fruit crop (dummy)[a]		0.19			
Staple crop (dummy)[a]		0.77			
Tree crop (dummy)[a]		0.05			
Vegetable crop (dummy)[a]		0.50			
Pollinator forage crop (dummy)		0.81			
Flowers present in focal crop 2018 (number, logarithmic scale)		1.12	1.55	0	5
Flowers in 2m proximity of bowls (number, average all bowls per plot, logarithmic scale)		2.50	1.50	0	8
Pollinator forage crops since 2012 (years)		3.41	2.40	0	6
Plot size (acre)		1.33	1.37	0.001	10
Slope					
	1: Flat	0.23			
	2: Moderate	0.57			
	3: Steep	0.20			
Soil quality					
	1: Poor	0.05			
	2: Middle	0.46			
	3: Very good	0.49			

Note: The questionnaire of the socioeconomic survey can be found in the supplementary materials.

[a] See Table A.3 for corresponding crops.

Table A.2

Estimation results, 2nd approach for neighborhood construction, ($n = 127$)

Variable	**Effects as percentage changes**	
	Abundance	**Richness**
Agricultural input use		
Chemical fertilizer – on plot[a]	-23.4 (0.019)	-4.4 (0.741)
Pesticides – on plot[a]	-24.4 (0.037)	-16.9 (0.250)
Irrigation since 2012 (years)[b]	-8.2 (<0.001)	-7.4 (0.008)
Pesticides – neighborhood (weighted by inverse distance)	-95.3 (0.191)	-39.6 (0.845)
Landscape scale		
Distance to Bangalore (km)		2.3 (0.002)
Southern transect (dummy)	-23.6 (0.013)	
Village build-up area (percentage)	-3.1 (0.005)	
Local / Plot scale		
Forest in direct neighborhood (dummy)	39.5 (0.019)	
Building in direct neighborhood (dummy)	-26.7 (0.006)	
Road in direct neighborhood (dummy)	-15.2 (0.067)	
Successful pan traps (number) – *ref. 4*		
1	-18.7 (0.562)	
2	36.7 (0.044)	
3	48.7 (<0.001)	
Clouds at time of pan trap placement (Okta scale)		20.9 (0.094)
Plot fallow or harvested at time of pan trap placement (dummy)	22.0 (0.069)	28.0 (0.051)
Tree crop (dummy)	-44.1 (0.009)	
Vegetable crop (dummy)	-9.8 (0.263)	
Flowers present in focal crop 2018 (number, logarithmic scale)	31.5 (<0.001)	26.4 (<0.001)
Pollinator forage crops since 2012 (years)	-3.4 (0.062)	
Plot size (acre)	8.2 (0.008)	7.2 (0.043)
Intercept	375.0 (<0.001)	-59.9 (0.053)

Note: p-values given in parentheses, [a]not chosen by the selection algorithm in the *Richness* model.

Table A.3

Observed crops sorted by functional groups.

Categories	Crops
Vegetable and pulses	Avare/Lablab, Beans, Brinjal/Eggplant, Capsicum, Castor, Chilli, Coriander, Cowpea, Cucumber, Groundnut, Horse Gram, Ladiesfingers/Okra, Mustard, Spinach, Tomato, Tur/Arhar
Fruits	Banana, Coconut, Grapes, Guava, Jackfruit, Lemon, Mango, Ridge gourd, Sapota, Tamarind
Flowers	Chrysanthemum, Jasmine, Marigold, Rose
Staples and grasses	Jowar, Maize, Maize (Baby Corn), Mulberry/silk, Napier grass, Paddy, Ragi, Turf/grass
Tress	Eucalyptus, Neem

Table A.4

Total number of individuals per bee species sorted by family.

Family	Species	Author	Abundance	Number of plots where present
Apidae	Amegilla sp. 1		3	2
	Amegilla sp. 2		3	2
	Apis cerana	Fabricius	79	43
	Apis dorsata	Fabricius	16	11
	Apis florea	Fabricius	160	66
	Ceratina binghami	Cockerell	58	30
	Ceratina heiroglyphica	Smith	6	5
	Ceratina heiroglyphica	Smith	34	18
	Ceratina smaragdina	Smith	9	7
	Ceratina unimaculata	Smith	11	9
	Xylocopa latipes	Drury	1	1
	Xylocopa sp. 1		1	1
Halictidae	Austronomia sp. 1		2	2
	Hoplonomia sp. 1		1	1
	Lasioglossum sp.1		83	28
	Lasioglossum sp.2		39	20
	Lasioglossum sp.3		58	29
	Lasioglossum sp.4		22	14
	Lasioglossum sp.5		22	17
	Lasioglossum sp.6		15	9
	Lasioglossum sp.7		6	3
	Leuconomia sp. 1		1	1
	Nomia westwoodi	Gribodo	2	1
	Pachynomia sp. 1		2	2
	Seladonia sp. 1		29	18
	Seladonia sp. 2		17	11
	Sphecodes sp. 1		9	7
	Sphecodes sp. 2		3	2
Megachilidae	Coelioxys confusa	Smith	1	1
	Megachile disjuncta	Fabricius	1	1
	Megachile lanata	Fabricius	2	2

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Die Wurzeln der **Fakultät für Agrarwissenschaften** reichen in das 19. Jahrhundert zurück. Mit Ausgang des Wintersemesters 1951/52 wurde sie als siebente Fakultät an der Georgia-Augusta-Universität durch Ausgliederung bereits existierender landwirtschaftlicher Disziplinen aus der Mathematisch-Naturwissenschaftlichen Fakultät etabliert.

1969/70 wurde durch Zusammenschluss mehrerer bis dahin selbständiger Institute das **Institut für Agrarökonomie** gegründet. Im Jahr 2006 wurden das Institut für Agrarökonomie und das Institut für Rurale Entwicklung zum heutigen **Department für Agrarökonomie und Rurale Entwicklung** zusammengeführt.

Das Department für Agrarökonomie und Rurale Entwicklung besteht aus insgesamt neun Lehrstühlen zu den folgenden Themenschwerpunkten:

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- Betriebswirtschaftslehre des Agribusiness
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- Landwirtschaftliche Betriebslehre
- Landwirtschaftliche Marktlehre
- Marketing für Lebensmittel und Agrarprodukte
- Soziologie Ländlicher Räume
- Umwelt- und Ressourcenökonomik
- Welternährung und rurale Entwicklung

In der Lehre ist das Department für Agrarökonomie und Rurale Entwicklung führend für die Studienrichtung Wirtschafts- und Sozialwissenschaften des Landbaus sowie maßgeblich eingebunden in die Studienrichtungen Agribusiness und Ressourcenmanagement. Das Forschungsspektrum des Departments ist breit gefächert. Schwerpunkte liegen sowohl in der Grundlagenforschung als auch in angewandten Forschungsbereichen. Das Department bildet heute eine schlagkräftige Einheit mit international beachteten Forschungsleistungen.

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