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**The Role of Space and Time in the Interaction of  
Farmers' Management Decisions and Bee  
Communities - Evidence from South India**

by Linda Steinhübel, Arne Wenzel, Prashant Hulamani,  
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**Title:** The Role of Space and Time in the Interaction of Farmers' Management Decisions and Bee Communities - Evidence from South India

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**Date:** July 1, 2021

**Abstract:** 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. 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 abundance and richness on 127 agricultural plots in the rural-urban interface of Bangalore, India. To capture temporal and spatial scaling in the relationship of agricultural management systems and bee populations, we explicitly model the effects of present, past, and neighboring agricultural management decisions in our empirical analysis. We find statistically significant negative spillover of pesticide use on both bee abundance and richness. Furthermore, smallholders' decisions to use chemical fertilizers and pesticides on their own plots significantly decrease the number of observed bees. A history of intensive past management reduces both bee abundance and richness.

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

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## 1. Introduction

Pollinator communities make important contributions to agricultural production and food security (Kleijn et al., 2015; Tschamntke 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 most staple crops do not rely on animal pollination, many fruit and vegetable crops do (Klein et al., 2007) and they often figure prominently in efforts to improve the incomes and living standards of smallholders in low-income countries. The commercialization of such high-value production systems allows for the participation in national and international agricultural value chains and is, thus, seen as critical tools of 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 other factors amplifying the transformation from extensive to more intensified agricultural management systems in large parts of Africa and Asia (Steinhübel & Cramon-Taubadel, 2020; Vandecasteele et al., 2018).

Despite the economic benefits for smallholders in poorer regions, there is a flipside to the greater use of modern agricultural technologies such as chemical fertilizers or pesticides. These can harm pollinator populations, with negative implications for the economic performance of production systems in the future (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. Reasons are manifold, among others the account of existing pollinator species in these countries is often patchy, and collecting pollinators in (sub-)tropical climates brings own—often practical—challenges. However, since farming

systems can differ greatly between high and low-income countries, we cannot simply transfer the results from the existing literature to fully understand farm-pollinator interactions in low-income countries. For example, agricultural plots in low-income countries are often much smaller, climate and crop choices differ, and most relevant for this study, smallholders normally dependent exclusively on wild pollinator population. These have been shown to substantially increase yields of pollination dependent crops (Garibaldi et al., 2016) and once gone, smallholder might not have the resources to bring in managed bee populations to substitute missing pollination services.

Another challenge to analyzing farm-pollinator interactions is the combination of ecological and economic concepts and 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, however, 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 fragmented landscapes 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 seasons or growing cycles (i.e. it is rather short-term) (Steinhübel et al., 2020); whereas ecological studies emphasize that pollinator

communities are likely affected by the sum of subsequent management decisions through nesting and foraging possibilities (Kremen et al., 2007; Schwarz et al., 2020).

The motivation of our study is, therefore, twofold. First, we want to contribute new evidence to the literature on farm-pollinator interactions in low-income countries by analyzing primary data on bee communities and farm management on 127 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) Do management decisions taken by one farmer affect bee communities on other farmers' plots – i.e., 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 simultaneously 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). Although it 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), the rural-urban interface 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 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.<sup>6</sup> 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.<sup>7</sup> 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.

For the pan traps experiments, 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 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, and all traps were installed and collected between the hours of 10 am and 2 pm. This is a standard sampling method to record pollinator communities (Meyer et al., 2015; Westphal et al., 2008). 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

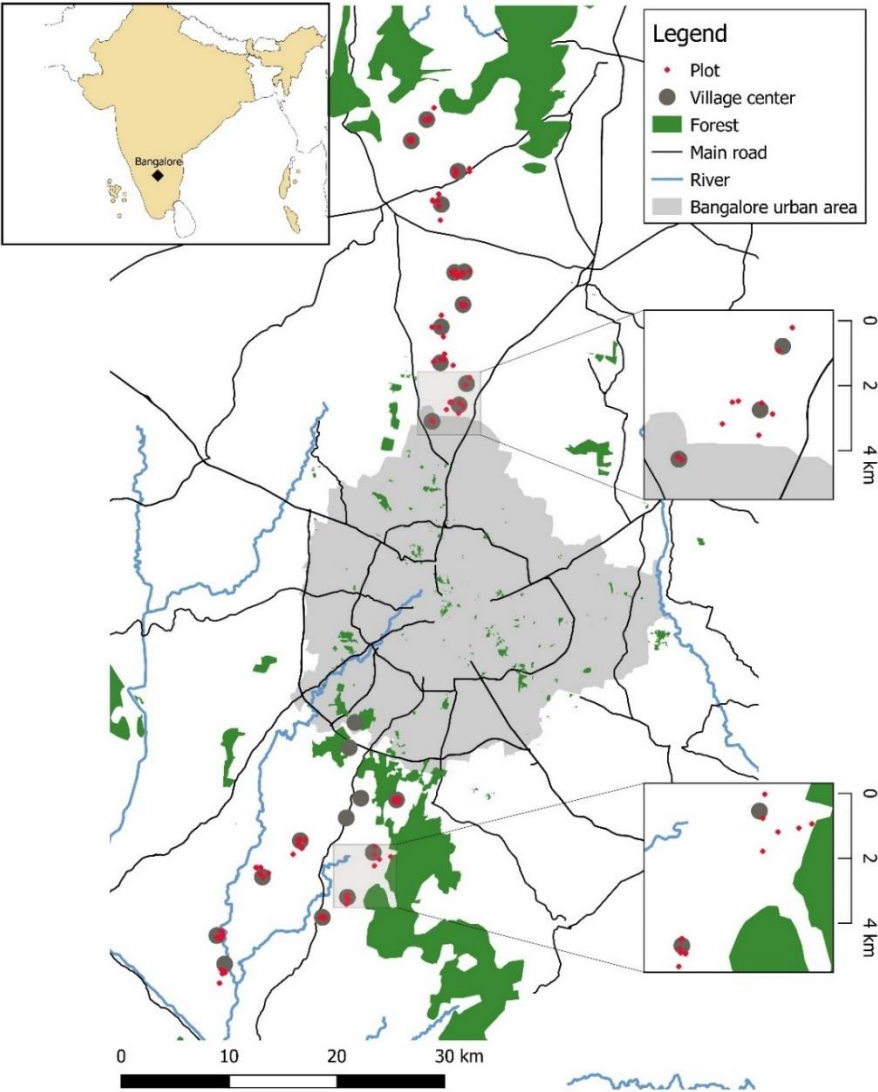
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<sup>6</sup> Because only few agricultural households are located in the urban stratum, we excluded the 20 villages in this stratum from the subsample.

<sup>7</sup> 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 the empirical analysis of this study.



analysis to control for the number of successful traps per plot (see Table A.1). Pan traps were placed in the field only on sunny, windless, and dry days. Collecting took place from January 9 to February 11, 2018, and thus during the winter months.



**Fig. 1.** Research area and location of sampled villages and plots along the rural-urban interface of Bangalore, South India ( $N = 127$ ).

*Note:* 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*.

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 colonies.

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 pollination services 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) to account for the count data of the dependent variables—abundance and richness—and we were mainly interested in how they 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; Vandecasteele et al., 2018), whereas pesticides do not only signal intensification but can be directly harmful to bees (Brittain et al., 2010; Tuell & Isaacs, 2010). To incorporate the different spatial and temporal scales discussed

before, we do not only estimate the effects of farm practices used on the plot under observation but also past management of the plot and farm practices used on plots in the neighborhood.<sup>8</sup> Therefore, bee abundance or richness  $y$  on plot  $i$  are given by the predictor  $\eta_i$ :

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

where  $\mathbf{z}_i$  is a row vector of dummies for irrigation, chemical fertilizer, and pesticide use on plot  $i$  in 2018 (*present management*)<sup>9</sup>;  $\mathbf{p}_i$  is the number of years either of the three inputs have been used on plot  $i$  since 2012 (*past management*);  $\mathbf{h}_i$  is the agricultural management of plots in the neighborhood of plot  $i$  in 2018 (*neighboring management*); and  $\mathbf{x}_i$  is a set of control variables including a constant (i.e. first element equals 1). The parameter vectors  $\boldsymbol{\alpha}$ ,  $\boldsymbol{\gamma}$ ,  $\boldsymbol{\theta}$ , and  $\boldsymbol{\beta}$  are to be estimated. Technically speaking  $\mathbf{h}_i$  in equation (1) can be understood as spatially lagged (SLX) variables of  $\mathbf{z}_i$ . That means that we used so-called (non-negative) spatial weight matrices  $\mathbf{W}$  of dimension  $n \times n$  to define interactions between plot  $i$  and any plot  $j$  in its neighborhood. We dropped  $\mathbf{W}$  in equation (1) for a simpler notation ( $\mathbf{h}_i = \mathbf{w}_i\mathbf{Z}$ ). Since  $\mathbf{h}_i$  is only concerned with the neighborhood of plot  $i$ , the main diagonal of  $\mathbf{W}$  (when  $i = j$ ) was set to zero. Thus, the weight matrix was composed of known scalars that represent *a priori* assumptions about the spatial

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<sup>8</sup> 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.

<sup>9</sup> 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. When surveying the producers in our sample, we did not collect data on the quantities of inputs used in past years because these 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.

interdependence between observations  $i$  and  $j$  where  $i, j \in \{1, \dots, N\}$  (Lee, 2004). We can assume that spatial interdependence ends beyond a certain distance, i.e. the corresponding weights in  $\mathbf{W}$  equal zero. In the present case, this cut-off distance was determined by the bee foraging distance, i.e. which other plots could a bee have visited that was caught on plot  $i$ . Previous studies indicate bee foraging distances up to several kilometers (Zurbuchen et al., 2010). Accordingly, we created a weight matrix with a two-kilometer<sup>10</sup> and one with a four-kilometer cut-off. To model the strength of interdependence (i.e. the weights in  $\mathbf{W}$ ) between different plots we tested two approaches. One is the simple share of neighboring plots using a respective agricultural input. A value of 1 in  $\mathbf{W}$  simply indicates that a plot is within the cut-off distance and  $\mathbf{W}$  was normalized by the row sums of  $\mathbf{w}_i$ . 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  $\mathbf{h}_i$  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 either of the two specifications of  $\mathbf{h}_i$ . Since all other parameter estimates were robust to the two different specifications, for reasons of simpler interpretation only the  $\mathbf{h}_i$  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.

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<sup>10</sup> Unfortunately, we only have data from 127 plots. That means, 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 neighboring plots of every plot  $i$  are observed. 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).

176 **Table 1** Descriptive statistics for the dependent variables and agricultural input use ( $n = 127$ )

| Variable                                       | Mean | Std. Dev. | Min  | Max  |
|------------------------------------------------|------|-----------|------|------|
| <b>Dependent variables</b>                     |      |           |      |      |
| 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   |
| <b>Agricultural input use</b>                  |      |           |      |      |
| 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 |

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

Considering the 127 observations in our sample, including all explanatory variables likely leads 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 and discussion

Overall, we caught 613 bee individuals and identified 31 species belonging to three different families (Apidae, 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.<sup>11</sup> Moreover, 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.

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<sup>11</sup> 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 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 on the mean rate of bee abundance and richness to facilitate interpretation.

### *3.1 Effects of agricultural input use on bee communities*

Our results show a general pattern 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 significantly decreases bee abundance by about 20 percent. Also, the use of pesticides by other smallholders in the 2-kilometer neighborhood has a significantly negative association with the bee abundance on the plot under observation. With every additional percent of pesticide use in a smallholder's neighborhood (=0.01 share), the number of bee individuals on his/her plot decreases by 0.68 percent. Considering that on average 25 percent (maximum of 80 percent) of neighboring farmers apply pesticides (Table A.1), other smallholders' management decisions (in particular regarding pesticides) seem to be just as important to bee abundance as those of the smallholder managing the plot. 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. 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-value<0.001)), we decided to drop one of them to avoid issues with multicollinearity. Consequently, the effect of past irrigation should rather be interpreted as an effect of past intensity of agricultural management. For the relationship between agricultural management and bee richness, we find similar results, except for the effect of the present use of chemical fertilizers and pesticides. These do not show any statistically significant associations with bee richness. In



contrast, past and neighboring agricultural management show significant negative effects on bee richness of nearly the same magnitude as for bee abundance.

**Table 2** Estimation results ( $n = 127$ )

| Variable                                                       | Effects as percentage changes |               |
|----------------------------------------------------------------|-------------------------------|---------------|
|                                                                | Abundance                     | Richness      |
| <b><i>Agricultural input use</i></b>                           |                               |               |
| Chemical fertilizer – on plot <sup>a</sup>                     | -22.2 (0.026)                 | -4.9 (0.709)  |
| Pesticides – on plot <sup>a</sup>                              | -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) |
| <b><i>Landscape scale</i></b>                                  |                               |               |
| Distance to Bangalore (km)                                     |                               | 2.4 (0.001)   |
| Southern transect (dummy)                                      | -29.7 (0.001)                 |               |
| Village build-up area (percentage)                             | -4.7 (<0.001)                 |               |
| <b><i>Local / Plot scale</i></b>                               |                               |               |
| 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) – ref. 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, <sup>a</sup>not chosen by the selection algorithm in the *Richness*

model.

Since abundance and richness are common indicators of pollination services in the literature (Holzschuh et al., 2007; Kremen et al., 2004), we might also suspect that these negative effects

hold for biodiversity and ecosystem services like pollination. Such a negative relationship has been highlighted in the literature before (Matson, 1997; Tilman et al., 2002; Winfree et al., 2009). However, since we did not measure outcomes such as fruit set, we cannot draw direct conclusions but rather 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, bee communities (in terms of abundance and richness) in our research area are susceptible to negative spatial spillovers of 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, Kremen et al. (2004) and Shuler et al. (2005) do not find any interactions. 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, i.e. different agricultural inputs. 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 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). Note that 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 farmers managing small landholding. In our study, the average plot size is about 1.33 acres (Table A.1). This means that a bee community in Bangalore is likely to be affected by more individual agricultural management decisions than a bee population in Europe or North America, for example.

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 since natural vegetation is reduced compared with extensively managed plots. 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 we might just not have enough spatial variation of chemical fertilizer use in our sample to detect spillovers.

### *3.2 Other factors influencing bee communities*

Looking at the control variables, it requires more explanatory variables to explain the variation in bee abundance than richness, particularly on the local scale. 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 installing the pan trap (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. This strong association is logical as bees feed on flowers and has been shown in the literature before (Motzke et al., 2016).

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 away from the city, bee richness increases by 2.4 percent. In contrast, bee abundance is negatively associated with build-up area, which is an indicator of urbanization as well. However, it is not necessarily connected to a continuous rural-urban gradient such as the distance to Bangalore. In the vicinity of Bangalore, several smaller towns produce urbanization patterns as well (Steinhübel & Cramon-Taubadel, 2020). Thus, the negative effect of build-up area on bee abundance is not necessarily located only around Bangalore but can also occur around smaller towns. 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) or reduction of habitat size and connectivity (Faeth et al., 2011; Pickett et al., 2011; Turrini & Knop, 2015). Furthermore, Banaszak-Cibicka and Zmihorski (2012), for example, show that ground-nesting pollinators have bigger problems with urbanization than cavity-nesting species. This might explain why we find that bee richness is affected by larger-scale patterns, whereas bee abundance is rather influenced by local factors. Further evidence of such local influence on bee abundance is provided by the statistically significant effects of adjacent plot use. A road or building reduces bee abundance by 18.2 and 16.5 percent respectively, whereas a forest right next to an agricultural plot leads to an increase of more than 35 percent. Especially the

positive relationship between forests and pollinator communities or benefits from silvoarable 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).

#### **4. Conclusion 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 considers 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 the two proxies. 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 necessity to consider 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 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 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.

Our study shows that there are negative interactions between increasing agricultural intensification and wild bee communities in low-income countries. To ensure sustainable agricultural and economic growth in these regions, we need more and larger samples from different countries in the Global South. This will increase the statistical validity and precision of the estimates that we report. Furthermore, 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, research is required that measures 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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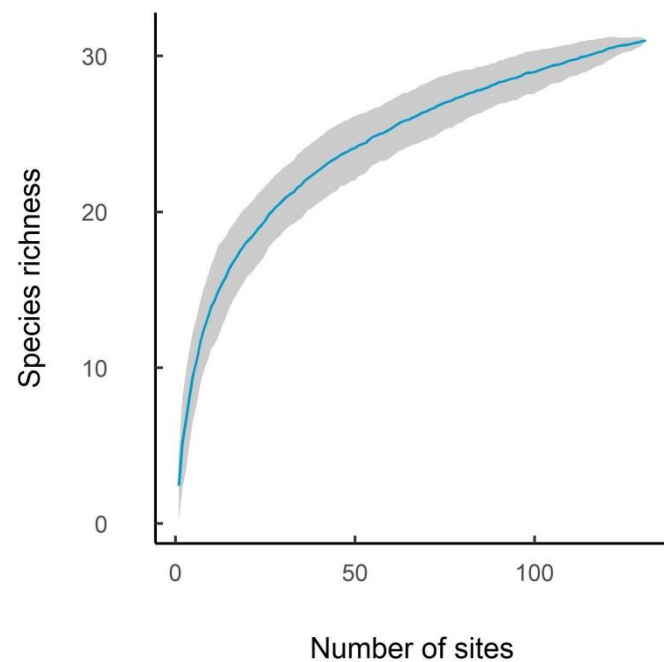
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**Appendix**



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

552 **Table A.1** Descriptive statistics for the control variables ( $n = 127$ )

| Variable                                                                                 | Mean         | Std. Dev. | Min   | Max   |
|------------------------------------------------------------------------------------------|--------------|-----------|-------|-------|
| <i>Landscape scale</i>                                                                   |              |           |       |       |
| 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 |
| <i>Local / Plot scale</i>                                                                |              |           |       |       |
| 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) <sup>a</sup>                                                         | 0.04         |           |       |       |
| Fruit crop (dummy) <sup>a</sup>                                                          | 0.19         |           |       |       |
| Staple crop (dummy) <sup>a</sup>                                                         | 0.77         |           |       |       |
| Tree crop (dummy) <sup>a</sup>                                                           | 0.05         |           |       |       |
| Vegetable crop (dummy) <sup>a</sup>                                                      | 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      |       |       |

553 *Note:* <sup>a</sup>See Table A.3 for corresponding crops; for dummies and categorical variables shares, are  
554 presented.



555 **Table A.2** Estimation results, 2<sup>nd</sup> approach for neighborhood construction, ( $n = 127$ )

| Variable                                                       | Effects as percentage changes |               |
|----------------------------------------------------------------|-------------------------------|---------------|
|                                                                | Abundance                     | Richness      |
| <b><i>Agricultural input use</i></b>                           |                               |               |
| Chemical fertilizer – on plot <sup>a</sup>                     | -23.4 (0.019)                 | -4.4 (0.741)  |
| Pesticides – on plot <sup>a</sup>                              | -24.4 (0.037)                 | -16.9 (0.250) |
| Irrigation since 2012 (years) <sup>b</sup>                     | -8.2 (<0.001)                 | -7.4 (0.008)  |
| Pesticides – neighborhood (weighted by inverse distance)       | -95.3 (0.191)                 | -39.6 (0.845) |
| <b><i>Landscape scale</i></b>                                  |                               |               |
| Distance to Bangalore (km)                                     |                               | 2.3 (0.002)   |
| Southern transect (dummy)                                      | -23.6 (0.013)                 |               |
| Village build-up area (percentage)                             | -3.1 (0.005)                  |               |
| <b><i>Local / Plot scale</i></b>                               |                               |               |
| 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) |

556 *Note:* p-values given in parentheses, <sup>a</sup>not chosen by the selection algorithm in the *Richness*

557 model.

558 **Table A.3** Observed crops sorted by functional groups.

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

559

560 **Table A.4** Total number of individuals per bee species sorted by family.

| Family       | Species                   | Author    | Abundance | Number of plots<br>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<br>heiroglyphica | Smith     | 6         | 5                                |
|              | Ceratina<br>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                                |

561