

## Research paper

# Enhancing pollination supply in an urban ecosystem through landscape modifications



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## HIGHLIGHTS

- We test the pollination module of InVEST in an urban environment (Chicago, USA).
- The model predicts 46% of the native bee richness ( $p = 0.008$ ,  $n = 14$ ).
- The model suggests that pollination supply is highly variable across Chicago.
- We model various land cover change scenarios' effect on pollination supply.
- Of the scenarios tested, increasing floral resources around urban agriculture sites is best.

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## ABSTRACT

Although urban agriculture is growing in popularity, little is known about the distribution of insect pollinators across urbanized landscapes. We used the pollination module of InVEST (a suite of software models used to map and value ecosystem services), along with fine-scale land cover data and empirical data on bee distributions, to assess different scenarios of urban pollinator management in Chicago, Illinois (USA). Specifically, we simulated the partial conversion of lawn/turf-grass to floral resources in city parks only, in gardens managed by individual households only, and in any available turf grass within buffer distances of 250–1000 m of urban farms, community gardens, and home gardens across Chicago. We found that the output of InVEST's pollination model was significantly related to empirical measures of bee richness (explaining 46% of the variation) but not bee abundance in Chicago. To increase pollination supply at urban farms and community gardens, our results indicate that, out of the scenarios presented here, the best strategy for the City of Chicago would be to concentrate floral resources nearby (within a 250 m buffer rather than within a 1 km buffer). In contrast, for home gardens, the model indicates that it may be better to increase floral resources throughout the city. This discrepancy may be due to the smaller size of home gardens and their more dispersed spatial arrangement throughout the city. Generally, our results indicate that converting turf grass to a more florally-rich land cover would support increased supply of pollinators and urban agriculture.

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## 1. Introduction

In recent years, interest in residential food gardens, community gardens, and urban farms, aka urban agriculture, has been growing (Tornaghi, 2014). The crops grown in these gardens may increase urban sustainability and food security (Colasanti, Hamm,

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& Litjens, 2012). However, many urban crops, such as cucumbers and squash, depend on pollination services provided by insects (Matteson and Langellotto, 2009), and several studies have shown not only a decrease in pollinator diversity with urbanization or human population density (Ahrne, Bengtsson, & Elmqvist, 2009; Bates et al., 2011; Matteson, Grace, & Minor, 2013) but also a shift in species composition (Banaszak-Cibicka & Żmihorski, 2012; Cane, Minckley, Kervin, Roulston, & Williams, 2006). Other research suggests that pollination services and seed set may be limited (Leong, Kremen, & Roderick, 2014; Pellissier, Muratet, Verfaillie, & Machon, 2012) or variable (Lowenstein, Matteson, & Minor, 2015) in urban areas, possibly due to the distribution of floral resources or to low pollinator abundance. Efforts to conserve urban pollinators could also boost productivity of urban agriculture.

Wild insects can be highly effective pollinators of agricultural crops (Garibaldi et al., 2013). Studies from rural systems indicate that high quality habitat in the surrounding landscape benefits the wild pollinator community (Kennedy et al., 2013; Ricketts et al., 2008). Nearby floral resources and nesting sites have been linked to increased pollinator diversity (Potts, Vulliamy, Dafni, Ne'eman, & Willmer, 2003; Potts et al., 2005) and pollination services (Blanche, Ludwig, & Cunningham, 2006; Holzschuh, Dudenhöffer, & Tscharnke, 2012). In urban areas, wild bees are often more abundant than honey bees (Leong et al., 2014; Lowenstein et al., 2015), but high quality bee habitat may be scarce or distributed in ways that do not benefit urban agriculture. For instance, Matteson and Langellotto (2010) found that only 10–32% of the landscape surrounding urban gardens in New York City had vegetation of any type, with most of this being sparsely distributed street-trees, heavily-managed gardens, or urban parks. However, bee diversity in heavily developed landscapes may be maintained to some degree by ornamental flowers in urban gardens and other managed habitats (Fetridge, Ascher, & Langellotto, 2008; Frankie et al., 2005; Lowenstein, Matteson, Xiao, Silva, & Minor, 2014; Matteson & Langellotto, 2011). Increasing floral resources may provide an important mechanism for counteracting the negative impacts of urban development on pollinators. One common land cover which could be potentially modified to provide increased floral resources is turf grass or lawns.

Turf grass is a common land cover in residential, commercial, industrial, and recreational areas in U.S. cities. Turf grasses cover approximately 163,800 km<sup>2</sup> (+/– 35,850 km<sup>2</sup>) of the conterminous U.S., an area three times larger than that of any irrigated crop (Milesi et al., 2005). In Franklin County, Ohio (USA), residential lawns were estimated to cover 23% of the county (Robbins & Birkenholtz, 2003). If a small amount of turf grass was modified or converted to floral resources, the benefits to urban bees and pollination services could be substantial (Blackmore & Goulson, 2014).

Using information on pollinator nesting resources and floral resources, Lonsdorf et al. (2009) predicted the relative abundance of pollinators available to pollinate farm crops. This approach, based on the suite of software models used to map and value ecosystem services called *InVEST* (Sharp et al., 2014), has not been tested in urban systems. However, it could potentially provide a useful approach for evaluating scenarios and developing land-use plans that promote and improve urban agriculture. We used *InVEST* to examine the potential for converted urban lawns to enhance pollination supply in Chicago, Illinois (USA). We first tested whether the *InVEST* pollination model (Sharp et al., 2014) can predict pollinator abundance and richness in an urban area and validated the spatially explicit model output against empirical field data. We then modeled the supply of pollination provided to approximately 4000 urban farms, community gardens, and home food gardens within the city limits. With different scenarios and spatial configurations, we converted areas of turf grass to flower gardens and evaluated the effect on pollination supply. The scenarios mimic three differ-

ent management approaches by which to increase floral resources in the city. The first scenario mimics a city-led effort which focuses on city parks, the second scenario targets private yards managed by individual households, and the third is a combination of the first two but is a scale-dependent assessment. These scenarios were intended to evaluate the success of various strategies for enhancing urban pollination supply in Chicago, Illinois, USA.

## 2. Methods

### 2.1. Study area

Chicago, Illinois is the third largest city in the United States, with just over 2.5 million residents (2010 U.S. Census). Approximately 21.3% (126 km<sup>2</sup>) of the city is covered by turf grass (Fig. 1). Turf grass in this study refers to intensely managed grass that is treated with insecticides and herbicides and mowed frequently (e.g., most golf courses) as well as lawns that contain lawn weeds such as dandelions (*Taraxacum officinale*) and white clover (*Trifolium repens*) which provide floral resources for pollinators in urban areas (Larson, Kesheimer, & Potter, 2014). Common lawn species in this area include Kentucky bluegrass (*Poa pratensis*), perennial ryegrass (*Lolium perenne*), and fine and tall fescues (multiple species including *Schedonorus arundinaceus*), although these vary depending on specific management.

We used the location of urban farms, community gardens, and home food gardens as identified from Google Earth imagery by Taylor and Lovell (2012). In their study, Taylor and Lovell differentiated between various types of urban agriculture, e.g., urban farms, community gardens, and home gardens, among others. An urban farm was defined as a “large garden comprising more than one vacant lot, with no apparent internal divisions except those created by crops, suggesting unified management by a single gardener/farmer or group”; while a community garden was defined as “a garden apparently divided into individual plots” (Taylor & Lovell, 2012). In the present study, we consider community gardens and urban farms as one type of urban agriculture (larger in extent), as opposed to residential food gardens which are smaller and managed by individual households. The distribution of these two garden types (community/urban gardens versus residential gardens) across Chicago can be seen in Fig. 1. We assumed that these various types of urban agriculture grow similar crops and thus would have similar per area pollination requirements, and that they did not keep honey bee (*Apis mellifera*) hives on the premises.

### 2.2. Field work for model validation

Pollinator specimens were collected at 15 community gardens across Chicago (Fig. 2). The sites were chosen opportunistically, based on the garden manager's interest in the project, accessibility of the garden, and presence of an open area to set up the sampling grid. We have no reason to think that the gardens we studied were significantly different from other gardens in terms of floral resources or pollinators. We collected pollinators at each garden using pan traps (4 oz. soufflé cups painted white, yellow, or blue and filled with a detergent solution) placed on the ground in a 3 m x 3 m grid, with all pan traps one meter apart and not immediately adjacent to a pan trap of the same color. The grid placement was based on the available space in the garden and located away from footpaths when possible. Floral resources were not measured at the gardens. One of the sites bordered a golf course and the bee bowls were placed near tree canopy. Very low bee abundance and richness were observed at this site and it was removed from subsequent modeling (n = 14).

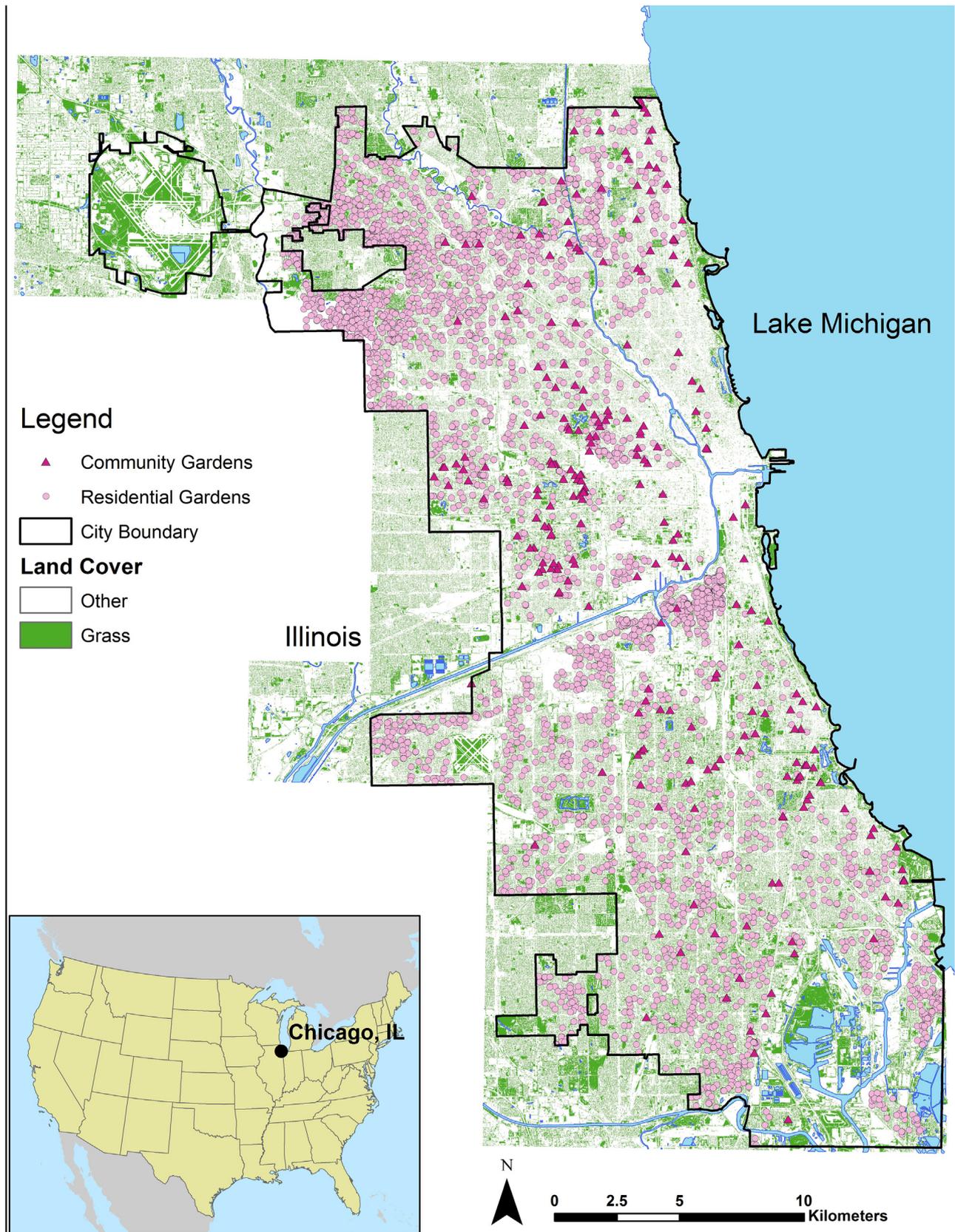


Fig. 1. Study area (Chicago, Illinois) with inset of United States.

Collections were performed once per month during July, August, September, and October of 2009, and each collection was performed at all sites within a three-day span. The grid of pan traps

was left out for one daylight cycle on a sunny, calm day, either being set up and collected within the same day (set up in the morning, collected in the evening) or left out for a 24-hr period. This method

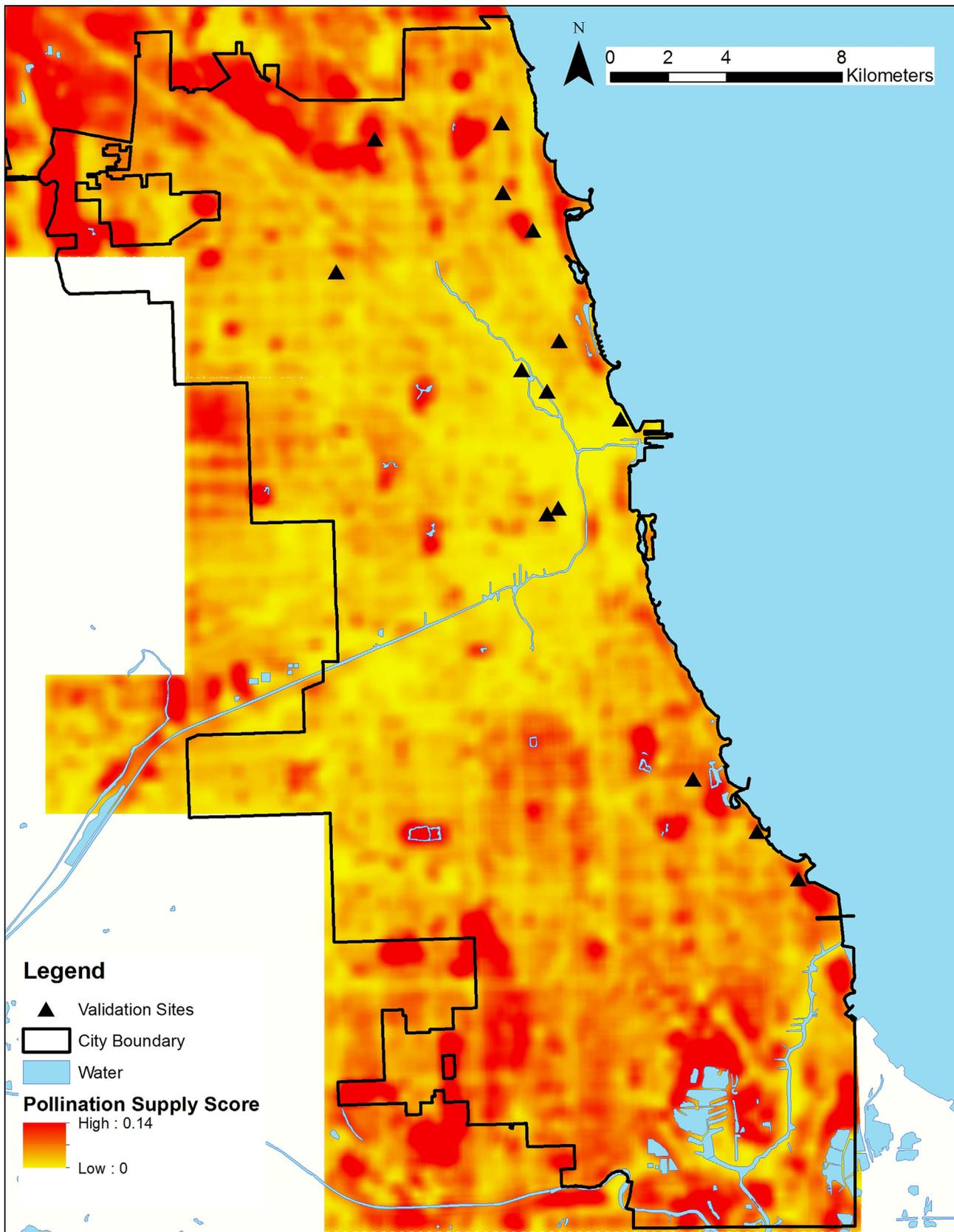


Fig. 2. Map of pollination supply score and location of sites used for model validation, i.e. sites where bees were collected.

**Table 1**

Land cover composition for the study area in square kilometers and as a percentage of the land within city limits. The last three columns contain the expert estimates of nesting and floral resources for each land cover. The last column gives the estimates of floral resources under landscape modification scenarios. These values are needed to run InVEST's pollination model.

Land cover type	Land cover (km <sup>2</sup> )	Land cover (%)	Nesting availability	Floral abundance	Floral abundance for scenarios
Trees	160.1	16.5	0.5	0.25	0.25
Water	130.5	13.4	0	0	0
Impervious	456.9	47.0	0	0	0
Bare Soil	45.8	4.7	0.25	0	0
Grass	178.1	18.3	0.5	0.3	0.9

is adapted from the bee monitoring protocol outlined in Droege (2012).

After the collection period, the contents of all pan traps were strained, placed in a watertight bag, and preserved with 95% ethanol. The specimens were later pinned, labeled, and sent out for identification by two recognized experts (John Ascher and Sam Droege). Specimens in the Apoidea superfamily were identified to species level, and all other Hymenoptera specimens were identified to genus. We measured distance between wing bases (intertegular span) for all specimens, using methods adapted from Greenleaf et al. (2007). For small specimens, we used a measuring reticule in the ocular of microscope. For large specimens, we used a finely graduated (0.1 mm) ruler. All measurements were rounded to the nearest 0.1 mm.

### 2.3. Modeling pollination supply

Pollination supply was modeled across the landscape in a spatially explicit manner using the crop pollination module of InVEST 2.1 in ArcGIS 10.0 (ESRI). The mathematical model underlying the InVEST pollination model is described in Lonsdorf et al. (2009). The model uses expert estimates about nesting and floral resources across the landscape to create a map of source habitat for pollinators. Based on the distribution of source habitat and the foraging range of pollinators, the model then calculates a relative index of bee abundance for each location (here, a pixel) in the landscape. This spatially explicit map can be thought of as an index of pollination supply.

Model inputs include a land cover map, information about nesting and floral resources in each land cover type, and information about the pollinators in the area. We used a land cover dataset derived from Quickbird satellite imagery (4 spectral bands, 0.6 m spatial resolution) acquired during the summers of 2007 and 2008. The images were orthorectified and classified using automated feature extraction to obtain 7 original land cover classes, which were aggregated into 5 classes: impervious surface, water, bare soil, trees, and grass (Table 1). The 'grass' class contains heavily managed turf grass (such as on golf courses), weedy turf grass that might include clover or other small, herbaceous flowering plants, and land covered in forbs. Only the latter two vegetation types would be expected to provide floral resources. Our original land cover data did not include a separate class for flower beds, which were lumped into the 'grass' category, i.e. the grass land cover can really be thought of as any non-woody vegetated land cover. Due to computational limitations, we resampled the original data to 5 m spatial resolution using ArcGIS 10.0 (ESRI). The class that had the most coverage within the 5 m by 5 m pixel was assigned as the new land cover class for that pixel.

The model can be adjusted by season and region. In Lonsdorf et al. (2009), the model was tested using bee data from coffee farms in Costa Rica, as well as in semi-agricultural systems in New Jersey, Pennsylvania, and California. In that study, the authors modeled between two and four nesting guilds as well as three flight seasons (spring, summer and autumn). Additionally, the model has been validated with field data from 39 different studies across a

range of biomes including tropical and subtropical, Mediterranean, and other temperate biomes (Kennedy et al., 2013). The regional adjustments are made by changing the floral and nesting resource scores for the region of interest before running the model.

We assigned a value for pollinator nesting and floral resources to each land cover class (Table 1) based on Kennedy et al.'s (2013) work synthesizing floral resource values for standardized land cover types across 39 studies. Water and impervious surfaces (e.g. asphalt, rooftops) cannot provide nesting or floral resources for wild bees and therefore were assigned a score of zero. Bare soil does not contain any flowers (and consequently was assigned a score of zero for floral resources) but can provide nesting resources for ground nesting bees in particular. Bare soil pixels were thus assigned a score of 0.25 as a nesting substrate to match those reported in Kennedy et al., (2013). The grass class was assigned a nesting score of 0.5 because we combined the nesting scores for Grassland/Herbaceous score (0.64) and Pasture/fallow fields (0.36) from Kennedy et al. (2013). The floral resource index for 'grass' was set to 0.3 on a possible scale from zero to one, with zero being a land cover that provides no floral resources for bees (Table 1). This essentially means that in one 25 m<sup>2</sup> pixel of grass, 30% of the land would contain floral resources that are beneficial to bees during the months that bees are active. This corresponds to our personal observations of lawns and gardens in the region while doing field work for another study (Minor, Belaire, Davis, Franco, & Lin, 2016).

Other model inputs include information about the various bee guilds or species present in the area, such as their nesting substrates, preferred foraging season(s), and foraging range. For this study, we modeled a single representative, i.e. generic, pollinator species that characterizes all wild bee species in the area. The foraging range for this representative bee was calculated as 700 m, based on the mean intertegular span (Greenleaf, Williams, Winfree, & Kremen, 2007) of all the bee genera caught during field work (Table A1). The representative bee could nest both in the ground and in cavities. We also considered just one foraging season which represents the general quality of forage across seasons, i.e. while bees are active in the Chicago region.

### 2.4. Scenarios modifying floral resources

We increased floral resources in grassy areas to simulate scenarios of various stakeholders replacing existing grass cover with flowering plants that would be beneficial to pollinators. In Scenario 1, pixels in city parks that were classified as grass were converted to flower gardens. The flower garden would theoretically include multiple species of flowers that are attractive to pollinators and that (in combination) bloom throughout the bees' active season. This scenario simulates the decision by park managers to increase floral resources in their parks. In scenario 2, grass was converted to flower gardens only in residential (i.e. home) gardens; this simulates individual residents' decision to plant more pollinator-beneficial flowers in their yards. In scenario 3, existing grass was converted to flower gardens only if it was located within 250 m, 500 m, 750 m, or 1000 m of the community gardens identified by Taylor and Lovell (2012) and pictured in Fig. 1. Sce-

**Table 2**  
Summary of floral enhancement scenarios for simulations. CGs stands for Community Gardens.

Scenario identifier	Description of scenario
1	Change grass located only in city parks to flower gardens
2	Change grass located only in residential yards to flower gardens
3a	Change grass located only within 250 m of CGs to flower gardens
3b	Change grass located only within 500 m of CGs to flower gardens
3c	Change grass located only within 750 m of CGs to flower gardens
3d	Change grass located only within 1 km of CGs to flower gardens

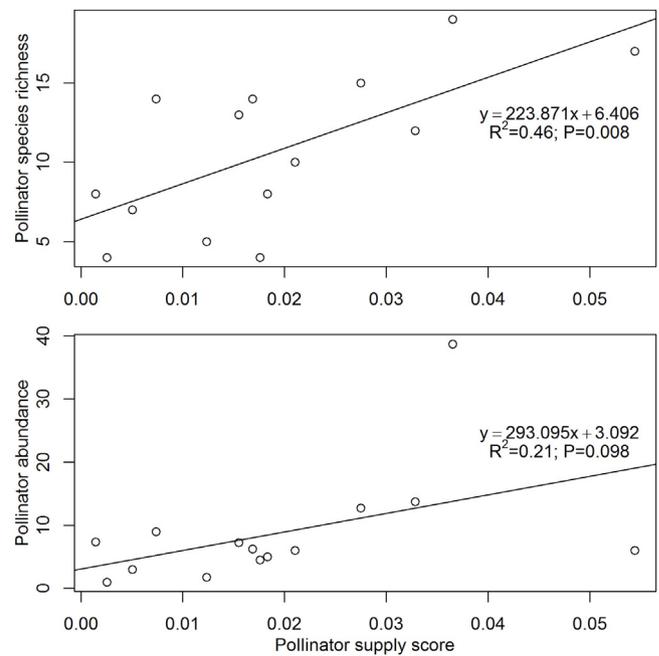
nario 3 thus consisted of 4 sub-scenarios where we varied the distance within which we concentrated the added floral resources. Any grass (whether in public parks or yards managed by individual households) was available for conversion in scenario 3. This last scenario simulates a situation where planting floral resources might be incentivized for residents who live around existing urban farms and community gardens and would also be increased in nearby public parks. This scenario might simulate urban farmers working with the neighboring community to enhance floral resources that are beneficial for pollinators. These scenarios are summarized in Table 2.

For each scenario, two levels of modification were modeled. The first level converted 1% of all grass in the city to flower gardens. The second level converted 5% of all grass in the city to flower gardens. A five percent conversion was considered the maximum possible because, in the parks scenario, it would leave approximately half of the grass acreage in parks for recreation. Given that Chicago parks are heavily used for activities such as soccer, baseball, and picnics, we felt it was necessary to leave a substantial portion of turf grass for such activities. For all scenarios, the percentage of grass pixels converted to flower gardens was calculated across the entire city, not per individual park or yard, and converted pixels were allocated randomly to existing grass pixels in the landscape (within the boundary conditions described above). For scenarios 2 and 3, randomly converting grass pixels to flower gardens is a reasonably realistic scenario, as a 5 m × 5 m pixel is roughly the size of a residential garden in our study area. The random allocation of these floral enhancements was done 20 times for each scenario (10 times for level 1 and 10 times for level 2) for a total of 120 output maps. We examined the impact of each scenario on pollination supply in residential gardens and community gardens separately.

### 3. Results

#### 3.1. Local bee community and model fit

We collected 433 individual bees, representing 14 genera (Table A1). The greatest abundance of bees was observed in the following genera: *Lasioglossum*, *Agapostemon*, and *Halictus*. The model predicted 21% of the variance in observed bee abundance ( $p = 0.098$ ,  $n = 14$ , Fig. 3) and 46% of the native bee richness ( $p = 0.008$ ,  $n = 14$ , Fig. 3). The spatially explicit map of the supply of pollination suggests that some areas of the city are likely to receive much more pollination than others (Fig. 2). Chicago's urban parks and forest preserves are seemingly 'pollination supply hotspots', as are the marshy areas on the south side of Chicago. Areas where pollination supply might be deficient are located around the south branch of the Chicago River, which is heavily industrialized, and the downtown area. In general, the index of pollinator supply increased with



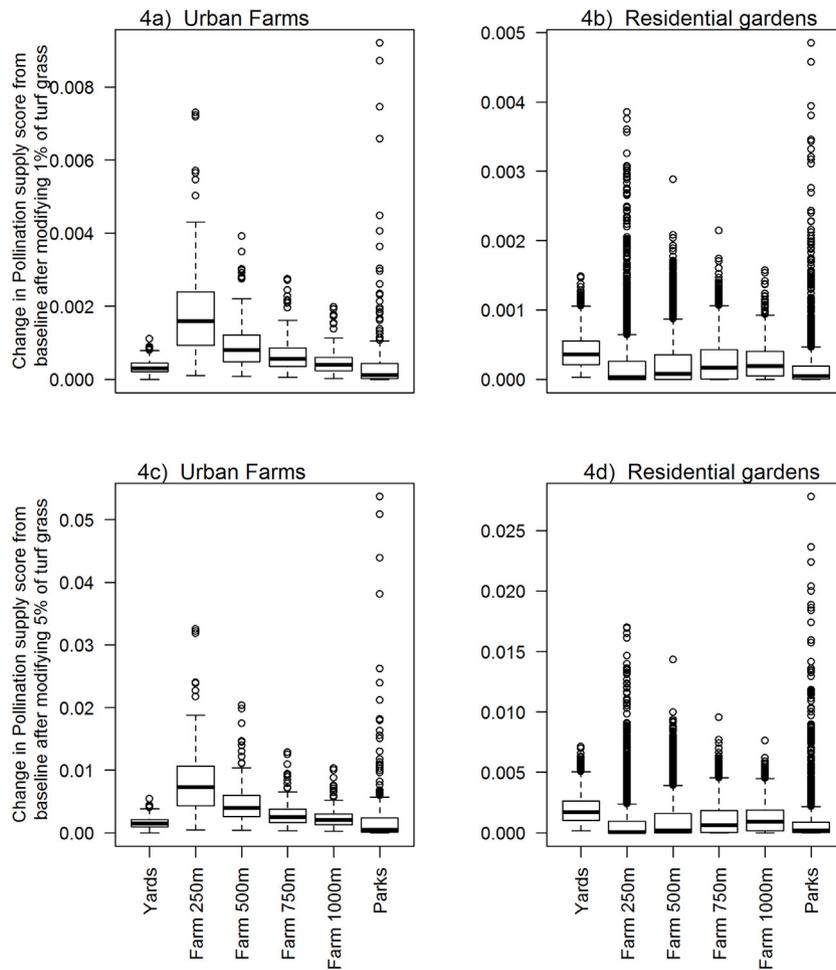
**Fig. 3.** InVEST pollination model validation (abundance and richness).

distance from downtown, which would indicate greater bee abundance and richness on the outskirts of the city.

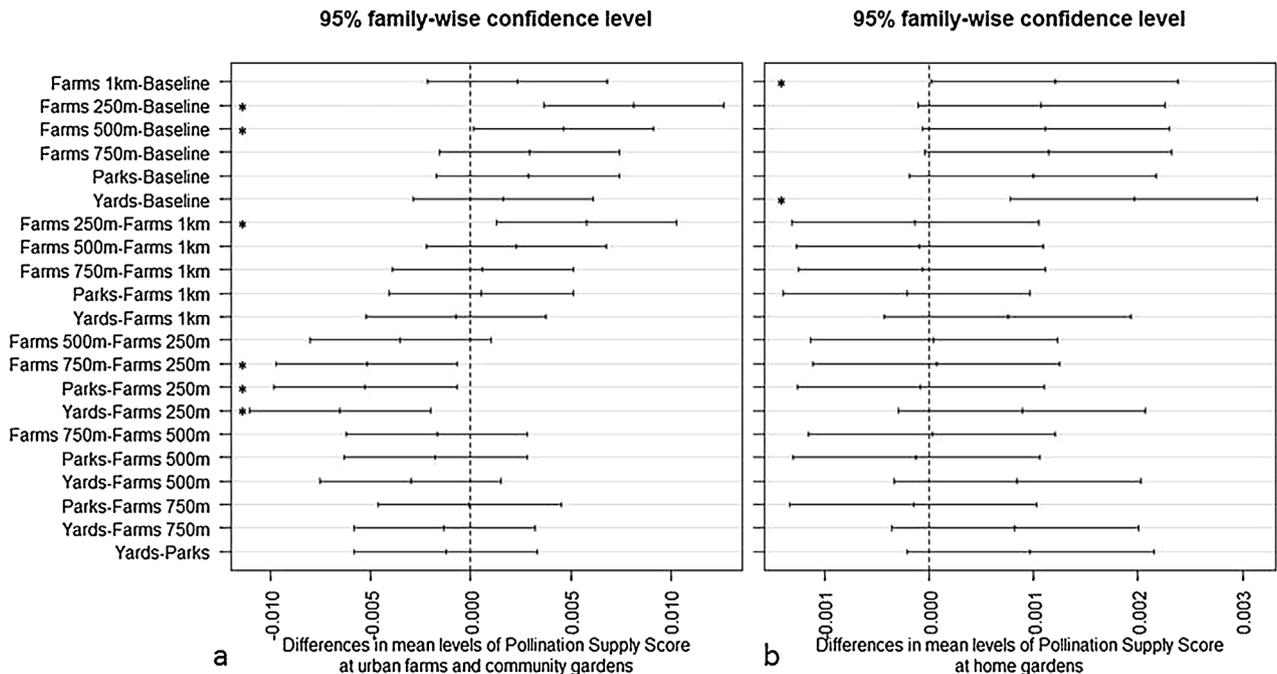
#### 3.2. Scenarios

In all cases, when only converting 1% of the city's grass to pollinator friendly flower gardens, there were no statistically significant differences in pollination supply scores between the baseline data and any scenario means as determined by one-way ANOVA ( $F(6,1682) = 0.262$ ,  $p = 0.95$ , for urban farms and community gardens, and  $F(6,14700) = 0.202$ ,  $p = 0.98$ , for residential gardens). Indeed, pollination supply score increases compared to the baseline were negligible in all the scenarios (Fig. 4 a and b; note that the range of the y-axes vary).

When converting 5% of grass in the study area to pollinator friendly flower gardens, one-way ANOVAs revealed statistically significant differences in pollination supply scores between scenario means for the urban farms and community gardens ( $F(6,1700) = 5.72$ ,  $p < 0.001$ ) as well as for the residential gardens ( $F(6,14700) = 4.08$ ,  $p < 0.001$ ). Post hoc comparisons using the Tukey HSD test indicated that, for the urban farms and community gardens (Fig. 5a), two scenarios differed from the baseline scenario ( $\bar{x} = 0.022$ ,  $sd = 0.014$ ): floral enhancements within 250 m ( $\bar{x} = 0.030$ ,  $sd = 0.019$ ) and within 500 m ( $\bar{x} = 0.026$ ,  $sd = 0.017$ ) from the urban farms (Fig. 4c, and see lines that are starred in Fig. 5a). Floral enhancements within 250 m of a farm resulted in significantly higher pollination supply scores than enhancements within 750 m of farms ( $\bar{x} = 0.025$ ,  $sd = 0.016$ ), within 1 km of farms ( $\bar{x} = 0.024$ ,  $sd = 0.016$ ), in parks ( $\bar{x} = 0.025$ ,  $sd = 0.020$ ), and in yards ( $\bar{x} = 0.023$ ,  $sd = 0.015$ , Fig. 5a). No other comparisons were significantly different. In contrast, for pollination supply scores in residential/home food gardens (Fig. 5b), enhancing floral resources in yards ( $\bar{x} = 0.021$ ,  $sd = 0.013$ ) or within 1 km of urban farms ( $\bar{x} = 0.020$ ,  $sd = 0.013$ ) are the only scenarios that differed significantly from baseline (Fig. 4d, and see lines that are starred in Fig. 5b). In all cases, the parks scenario has the most spatial variability due to some community gardens or residential gardens being fortuitously close to the parks where we increased floral resources (Fig. 4).



**Fig. 4.** Effect of landscape modification scenarios on pollination supply scores. Each circle represents a farm (residential or urban farm) within the study area. The different scenarios are on the x-axes. Y-axes represent change in pollination supply scores for each scenario compared to baseline, i.e. the original (non-modified) land cover. Note that each y-axis has a different maximum. The thick line for each box is the median change (increase) in pollinator supply score for that scenario.



**Fig. 5.** Results of Tukey HSD test for the 5% change in grassy landscapes for urban farms and community gardens (a), and residential gardens (b). If a confidence interval does not contain zero, the corresponding means are significantly different (these are also marked by a \* in the figure).

#### 4. Discussion

The goals of this study were to test the ability of InVEST's pollination model to predict pollinator abundance and richness in urban areas and to model various strategies for improving pollination supply for urban agriculture. While the model output was not significantly related to our empirical measures of bee abundance, it was significantly related to bee richness. As bee richness has been shown to be a predictor of pollination services (Lowenstein et al., 2015), InVEST's pollination model could help cities identify where pollination supplies are lacking and thus help them a) determine where efforts are needed to correct the deficiency and b) establish a plan to involve citizens and gardens, park, and open space managers to plant pollinator friendly plants in the green spaces they manage.

Our modeling results show that, out of the strategies tested here, the best strategy for increasing the supply of pollinators in Chicago will depend on whether the main focus is on home food gardens or on community gardens and urban farms. If the objective is to enhance pollination supply for home gardeners, then converting turf grass in people's yards to flower gardens or within 1 km of urban farms and community gardens would be beneficial. However, to enhance pollination at existing urban farms and community gardens in Chicago, the best strategy is to concentrate the increased floral resources close to the farms themselves. Since Taylor and Lovell (2012) found that community gardens and urban farms make up 25.3% of the area devoted to urban agriculture in Chicago, while residential gardens make up 45.1% (the rest being mostly cultivated in school gardens (1.1%) as well as vacant lots (27.2%)), increasing pollination supply for residents city wide instead of for urban farms and community gardens could arguably be more important if residential gardens are as productive as urban farms and community gardens on a per area basis.

To increase the diversity of bees visiting urban agriculture sites in Chicago, it is clear that concentrating floral resources around where the crops are being grown is the best option. Indeed, the two scenarios that concentrate the floral resources the most (i.e. in parks and in a 250 m radius from farms) are the ones with the largest increase in pollination supply score. These modeling results confirm recommendations from the literature; Brosi et al. (2008) suggest that to ensure sufficient levels of pollination (in an agricultural landscape) it is best to conserve bee habitat in small parcels throughout the landscape where pollination is needed. While some evidence suggests that urban farmers and community gardeners do modify the property's resources (i.e. the same parcel they are gardening) to attract bees (Pawelek, Frankie, Thorp, & Przybylski, 2009), the extent to which this strategy is used by urban "farmers" (both in home gardens and in community gardens) is unknown and would warrant further research. It is also interesting to note, that while there is increased interest in maintaining honey bee (*Apis mellifera*) hives in some cities, Lowenstein et al. (2015) found that the majority of pollinators visiting sentinel plants in an urban environment were wild, native bees. To our knowledge, none of the crops grown in Chicago rely exclusively on honey bees for pollination. Increasing floral resources could help promote a diversity of bees, thus decreasing reliance on a single species.

Additionally, the results of this modeling exercise should be independently verified via landscape manipulation experiments and field observations. Augmenting floral resources in different spatial arrangements throughout the city and measuring the effect not just on pollinator abundance and richness but also on seed set of pollinator-dependent plants would be informative. Blackmore and Goulson (2014) conducted a similar experiment (non-randomized) in an urban area in the United Kingdom (UK) and found that planting wildflower areas in what was previously turf grass significantly increased pollinator abundance, but they did not look at seed set

or test various spatial arrangements of the experimental increase in floral resources.

Changing the norms of what people consider an acceptable yard is difficult (Robbins, 2012). Gobster (1999) states the importance of the public's familiarity with plants that researchers want people to adopt. This might be achieved through educational campaigns and demonstration sites. We surmise that using similar strategies to prompt individuals to provide resources for pollinators could be successful. Research in the UK has indicated that the general public does support providing habitat for insects in public parks, and a majority of park visitors reported that their enjoyment of the park had either stayed the same or increased after half of the grass area in a 6 ha park was replaced with wildflowers (Garbuzov, Fensome, & Ratnieks, 2015). Similar studies in the U.S. are needed.

##### 4.1. Limitations

Our land cover layer only had five land cover classes and greatly simplified the Chicago landscape. More land cover classes, especially for the non-built environment (such as differentiating managed grass from herbaceous plants) would most likely improve the modeling efforts, as would taking into consideration habitat patch size and dynamics of bee populations over time.

Similarly, the spatial resolution (25 m<sup>2</sup> pixels) may be too coarse to detect the fine-scale variability in people's yards. Minor et al. (2016) surveyed 600+ yards in Chicago and showed that the structure of yards is complex and that most people (78%) had at least one flowering plant in their yard, i.e. the majority of people do not solely have turf grass or trees in their yard. While we attempted to account for this by assuming that 30% of the land classified as grass contains floral resources, finding many households that would be willing to convert a part of their lawn to a flower garden may be unrealistic, especially for families with children or dogs. On the other hand, just reducing the frequency of the mowing regimen of turf grass areas may be beneficial for pollinators (Garbuzov et al., 2015; Smith, Broyles, Larzleer, & Fellowes, 2015). Whether or not those changes would be more or less acceptable to homeowners compared to converting lawn area to flower beds, and how mowing affects bees in particular, need to be further investigated. Indeed, there may be several barriers to modifying people's yards, as grassy areas are well suited for recreation, and the planting and maintenance of flowering plants is more time consuming (and may require more knowledge) than simply mowing turf grass.

Our study only considered bees and did not examine other pollinators, although bees are generally considered to be the most important pollinators in eastern North America and they also are the most abundant pollinators in the city of Chicago (Lowenstein et al., 2015). However, it is important to note that the presence of bees in a location does not always translate to greater seed set (Leong et al., 2014) and that enhancing crop pollination services is only part of the solution to conserve pollinator diversity (Senapathi et al., 2015), so caution should always be used when interpreting results of models such as InVEST's pollination model.

Lastly, few validation sites were located in the more economically disadvantaged areas of south and west Chicago. Given the many lines of evidence for increased floral diversity with increasing income (Hope et al., 2003), the model, as we implemented it here, does not integrate this potentially important subtlety of yard management.

##### 4.2. Future research

Floral resources are not the only limitation bees face in urban or agricultural environments; nesting resources may be limiting as well. Running similar scenarios while modifying nesting resources (such as bare ground, or stems of trees and bushes; Potts et al.,

2005) could provide further insight into how to enhance pollination supply in an urbanized area. Similarly, given that urban plant communities are novel assemblages that affect the temporal dynamics of pollinators (Leong, Ponisio, Kremen, Thorp, & Roderick, 2016), an interesting follow up to this study would be to model seasonality as well. These types of analyses could also be conducted for the other ecosystem services that can be modeled with InVEST, such as carbon sequestration. This approach would enable the identification of tradeoffs and synergies between different ecosystem services in urban areas. Lastly, while we do not expect that different residents would intentionally aggregate their gardens to facilitate management, park managers (e.g. scenario 1) might want to aggregate these areas of converted lawns within each park, in which case random conversion of grass to flower gardens might not be completely realistic. Future work could examine the impact of different spatial patterns of lawn conversion.

## 5. Conclusions

Pollination supply varies greatly across Chicago and the benefits provided by Chicago's large urban parks, green boulevards, and forest preserves should not be understated. We found that augmenting floral resources in an urbanized environment such as Chicago can improve the supply of pollinators, but that those efforts should be concentrated around areas where pollinators are especially needed, such as residential/home gardens, urban farms and community gardens. More research is needed to determine how many bee species or what bee abundance is "sufficient" to provide adequate seed set for the variety of crops grown in highly urbanized environments.

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## Appendix A.

**Table A1**

List of genera, total number of individuals, and estimated foraging distances in meters for bees collected at the 14 validation sites across the City of Chicago, Illinois, USA. Foraging distances were estimated using measures of intertegular span and equations from Greenleaf et al. (2007). The last summary row of the table gives the total number of bees collected, and the mean estimated foraging distance (one per genus) in meters. This is not the mean estimated foraging distance weighed by number of individuals collected, which would be approximately 500 m.

Genera	Number of individuals collected	Estimated Foraging Distance (m)
<i>Agapostemon</i>	96	614
<i>Andrena</i>	3	293
<i>Anthidium</i>	6	898
<i>Apis</i>	14	2000
<i>Augochlora</i>	1	126
<i>Bombus</i>	9	1955
<i>Ceratina</i>	3	61
<i>Colletes</i>	1	915
<i>Halictus</i>	78	321
<i>Hoplitis</i>	1	259
<i>Hylaeus</i>	4	64
<i>Lasioglossum</i>	146	88
<i>Megachile</i>	14	1208
<i>Melissodes</i>	57	854
Summary	<b>433</b>	<b>690</b>

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