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RESEARCH PAPER

Phenology leads to different wild bees with different traits pollinating spring- and summer-blooming crops

Joanna W. Greenwood[a,*], Katherine J. Turo[a,b], Katherine R. Urban-Mead[c], Neelendra K. Joshi[d], Heather Grab[e], David J. Biddinger[f], Rachael Winfree[a]

[a] Department of Ecology, Evolution, and Natural Resources, Rutgers University, 14 College Farm Rd, New Brunswick, NJ 08901, USA
[b] Department of Biological Sciences and the Louis Calder Center—Biological Field Station, Fordham University, 31 Whippoorwill Rd, Armonk, NY 10504, USA
[c] The Xerces Society for Invertebrate Conservation, 1971 Jacksonville Jobstown Rd, Columbus, NJ 08022, USA
[d] Department of Entomology and Plant Pathology, University of Arkansas, 495N Campus Walk, Fayetteville AR 72701, USA
[e] Department of Entomology, The Pennsylvania State University, 453 Shortlidge Rd, University Park, PA 16802, USA
[f] Department of Entomology, Fruit Research and Extension Center, The Pennsylvania State University, 290 University Dr, Biglerville, PA 17307, USA

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ABSTRACT

Wild bees are crucial crop pollinators, but our ability to manage this ecosystem service is limited by lack of attention to which wild bee species are key pollinators of which crops. Flower visitation to a given crop is typically dominated by just a few bee species, and this information could be used to develop targeted, crop-specific management. To identify the dominant wild bees visiting crops in northeastern North America, we compiled 29 datasets of wild bee visits to crop flowers. We summarized the identities and traits of dominant wild bees in each dataset and evaluated how the taxonomic and functional composition of wild bee visitors shifted with the season in which a crop bloomed. Of 265 wild bee species observed on crops, we identified 52 dominant species, defined as species providing $\geq$5% of visits to at least one crop. On average across datasets, dominant visitors comprised only 16% of the observed bee species yet performed 71% of crop visitation. Critically, the dominant bee species differed between crop species, and much of the variation in dominant species identities and functional traits was explained by phenology. In our study region, wild bee crop visitation broadly shifted from a spring suite of solitary, soil-nesting species with short flight seasons, to a summer suite of social species with long flight seasons. Thus, targeted pollinator management strategies should differ between spring- and summer-blooming crops to meet the resource needs of these distinct sets of species, with particular attention to conserving and restoring habitats that provide floral resources throughout the flight seasons of the dominant visitors. While our particular findings are specific to our study region, phenological turnover of wild bee communities is a general phenomenon that is likely to be useful for informing targeted pollinator management in other regions as well.

Introduction

The global food supply relies heavily on pollination by insects, with about three-quarters of crops requiring animal pollination to maximize production (Klein et al., 2006). Recent global analyses estimate that insufficient pollinator visitation currently limits the yields of between one and two-thirds of crop systems, and that increasing visitation rates could meaningfully increase yields (Turo et al., 2024). Therefore, development of effective pollinator management is crucial for maintaining adequate food production for a growing global population (Aizen et al., 2019). Wild insects, especially bees, contribute roughly half of crop visitation globally (Reilly et al., 2024), so improved management strategies for wild bees are important for safeguarding crop production (Garibaldi et al., 2014).

The majority of crop pollination is accomplished by a small number of numerically dominant pollinator species (Kleijn et al., 2015; Winfree et al., 2015). Although species vary in how much pollen they deposit per flower visit (or pollination efficiency; King et al., 2013), differences in pollination efficiency can be overwhelmed by differences in total visitation rate because some species visit flowers so much more frequently

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* Corresponding author.
E-mail addresses: joanna.greenwood@rutgers.edu (J.W. Greenwood), turo@fordham.edu (K.J. Turo), kass.urban-mead@xerces.org (K.R. Urban-Mead), nkjoshi@uark.edu (N.K. Joshi), heathergrab@psu.edu (H. Grab), djb134@psu.edu (D.J. Biddinger), rachael.winfree@rutgers.edu (R. Winfree).

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than others (Vázquez et al., 2005). As a result, variation in pollination services may be driven by the abundance of dominant pollinators, rather than pollinator diversity (Balvanera et al., 2005; Winfree et al., 2015). For example, Kleijn et al. (2015) found that only 2% of wild bee species provided 80% of the flower visits in a global collection of crop visitation datasets. Focusing on these dominant pollinators could provide cost-effective management of pollination services. Yet the great majority of papers on crop pollination have focused on total pollinator abundance or species richness (Dainese et al., 2019), leaving a research gap with respect to the identities of the species that contribute most to crop pollination (Pisanty & Mandelik, 2015).

The identities of dominant pollinators are likely to differ between crops (Hutchinson et al., 2021), particularly for crops blooming at different times of year. Both bees and crops have distinctive phenologies, and phenological turnover of wild bees will determine which species are potentially available as pollinators when a crop is in bloom (Sáez et al., 2023). The observation that crops blooming at different times will have different pollinators is by no means surprising. However, despite substantial literature on phenological turnover of plant-pollinator interactions in non-agricultural contexts (CaraDonna et al., 2017; Ogilvie & Forrest, 2017), the relationship between phenology and crop pollinator identity has been largely overlooked to date (Sáez et al., 2023). The phenology of dominant pollinators should be a central consideration for pollination management, as any resources provided to support crop pollinators must correspond to their flight seasons (Wood et al., 2018).

Together with their phenology, the functional traits of dominant wild bee pollinators can inform what resources they need (Williams et al., 2010) and therefore what management actions will support them (Garratt et al., 2014). In addition to flight season, three traits with relevance for pollinator management are habitat association, nesting habit, and sociality. First, different bee species use different habitats (Smith et al., 2021), and such habitat associations likely are key determinants of the best approach for supporting a species. For example, a meadow-like wildflower planting may not benefit bee species associated with forest habitat (Wood et al., 2018). Second, bees have diverse nesting strategies, and without appropriate nesting habitat, floral resource supplementation may have no effect (Westrich, 1996). Lastly, the sociality of dominant bees may inform management practices because social bees require floral resources at larger spatial and temporal scales than solitary bees (Ogilvie & Forrest, 2017).

If phenological turnover of bee communities leads to differences in the identities and functional traits of the dominant pollinators for different crops, this could provide a phenology-based framework to inform crop-specific best practices for promoting pollinator visitation. In this scenario, management for wild crop pollinators should not be the same across crops but should instead consider the phenology and specific resource needs of each crop's dominant pollinators. While studies have addressed targeted management based on pollinator identities and traits for individual crop systems (e.g., Garratt et al., 2014; Pisanty & Mandelik, 2015), we are not aware of any study that has used phenology as an organizing framework across a large region (but see Rondeau et al. (2022) and Hutchinson et al. (2021) for large-scale summaries of crop visitor identities). To demonstrate the possibility of informing targeted pollinator management using dominant species' identities and traits, we examine the wild bee communities visiting crops in northeastern North America. Specifically, we ask:

1. Which wild bee species are dominant visitors to which crops?
2. What are the flight seasons, habitat associations, nesting habits, and sociality of the dominant visitors?
3. How do the identities and traits of the dominant wild bee crop visitors differ between spring- and summer-blooming crops?

Materials and methods

Crop datasets

To gather datasets of dominant wild bee visitation to crops in northeastern North America, we conducted a Web of Science literature search in March 2025. We filtered datasets by the following criteria. (1) We used datasets collected in northeastern North America, which was broadly defined as eastern Canada and the Midwest, Mid-Atlantic, and New England regions of the USA. (2) We used datasets of bees observed or netted directly from crop flowers because passively-sampled bees may not reflect the community visiting crop flowers (Gibbs et al., 2017b). (3) We used datasets with ≥100 wild bee specimens, with ≥95% identified to species. (4) We used datasets on crops that benefit from animal pollination according to Klein et al. (2006) and Aizen et al. (2009). In addition to datasets identified via the literature search (six of which were published by the authors of this study), the authors provided another six unpublished datasets. For literature search details, see Supplementary Methods 1 and Figure S1.

Which wild bee species are dominant visitors to which crops in northeastern North America?

We follow Kleijn et al. (2015) in defining dominant crop visitors as species that contribute at least 5% of flower visits in a dataset. To determine the sensitivity of our results to our choice of a 5% threshold for defining dominance, we performed sensitivity analysis by running all analyses with a range of thresholds (Supplementary Methods 2). For datasets collected across multiple sites and/or years, we combined data before identifying dominant species. This is conservative with respect to how many species are considered dominant because there may be turnover of dominant species between locations and years, such that more species would be considered dominant if we applied the 5% threshold to individual study sites and years separately (Lemanski et al., 2022; Winfree et al., 2018). We chose not to subset out data in this way because, in addition to making our findings less conservative, the smaller samples sizes from individual sites would increase the influence of sampling stochasticity on dominant species identity. Some crop species were represented by multiple datasets from different studies, which were kept separate. We defined spring-blooming crops as those blooming in June or earlier and summer-blooming crops as those with bloom periods including July or later, which is consistent with the biological transition between spring and summer in our study region.

Although many other insects contribute to crop pollination—including non-bees and nocturnal insects (Buxton et al., 2022; Rader et al., 2016)—we focused on characterizing communities of crop-visiting wild bees because they are among the most important crop pollinators and are the focus of many management efforts (Rondeau et al., 2022; Zamorano et al., 2020). While managed honey bees (*Apis mellifera*) are also valuable pollinators for the crops we consider (Reilly et al., 2024), they are a non-native, domesticated species in our study region, and we therefore excluded them from analyses. Additionally, wild pollinators often increase crop production independently of honey bees, such that they provide added benefit even when honey bee visitation is high (Garibaldi et al., 2013).

What are the flight seasons of dominant wild bee crop visitors?

We used two data sources independent of the crop visitation datasets to define and visualize the flight seasons of the dominant crop visitors: (1) a database of wild bees collected in the years 2003–2018 in the northeastern USA by the senior author's laboratory, with 66,345 individual records of the dominant crop visitors we identify and (2) bee specimen records from the American Museum of Natural History, with 3897 records of the dominant species collected from the northeastern USA in the years 2000–2011 (Bartomeus et al., 2013).

In temperate regions, bees' phenologies broadly fall into three categories: short spring flight seasons, short summer flight seasons, and long flight seasons spanning spring and summer (Simpson et al., 2025; Wood et al., 2018). Spring- and summer-flying bees are generally solitary species, while long-season bees include both social and multivoltine species. We defined the start, end, and duration of species' flight seasons as the 1% quantile, 99% quantile, and 98% interquantile range of collection dates, respectively. We classified species as long-season if their flight seasons last >100 days. We classified short-season species as spring bees if their flight seasons start on May 15 or earlier and summer bees if their flight seasons start on June 15 or later.

We created a phenogram to visualize the bloom periods of the crops and the flight seasons of their dominant wild bee visitors. Specifically, for the 10 crop species with the largest sample sizes, we plotted the phenology curves of the top four bee species visitors (or fewer, if only 2–3 species were dominant). To plot a bee species' phenology curve, we first calculated its abundance in a 14-day moving window from March to October. We then fitted a generalized additive model for each species with date as the predictor variable and abundance as the response, and we used the fitted values to plot a smoothed phenology curve. We plotted approximate crop bloom periods based on information from agricultural extension centers at major universities in the study region, as well as the authors' knowledge of crop bloom phenology in the region. We omitted lowbush blueberry from the phenogram because the bee phenology data do not cover the areas where this crop is grown commercially.

What are the habitat associations, nesting habits, and sociality of dominant wild bee crop visitors?

Habitat associations were primarily from Smith et al. (2021), who categorized bee species collected throughout the northeastern USA as associated with forest ("forest-associated"), with anthropogenic habitat ("synanthropic"), or as generalists that use both types of habitat ("habitat generalists"). Five additional bee species not in Smith et al. (2021) were classified based on results in Winfree et al. (2014) and Collado et al. (2019) .

Nesting and sociality traits were compiled from the literature (Gibbs et al., 2017a; Wolf & Ascher, 2008). Belowground-nesting species were classified as soil-nesting if they excavate burrows and belowground cavity-nesting if they use existing soil cavities. Aboveground-nesting species were classified as wood-nesting if they excavate burrows in dead wood, hole-nesting if they use existing cavities in wood, and stem-nesting if they create nests in pithy stems. Each species' sociality was classified as solitary, facultatively social, or social.

The traits we consider are not independent—for example, all belowground cavity-nesters in our data are social *Bombus* species. We do not consider this problematic because our goal was explicitly to identify phenologically-correlated trait syndromes to inform pollinator management.

How do the identities and traits of the dominant wild bee crop visitors differ between spring- and summer-blooming crops?

To evaluate how dominant species composition varies with crop bloom phenology, we ran a permutational analysis of variance (PERMANOVA) on Raup-Crick dissimilarities among the communities of dominant species for each dataset, with collection date midpoint (an estimate of the middle of the crop bloom period) as a predictor. We visualized the results using nonmetric multidimensional scaling (NMDS). We used the package vegan in R to calculate dissimilarities and run the PERMANOVA and NMDS (Oksanen et al., 2022).

To determine how the habitat associations, nesting habits, and sociality of the crop-visiting wild bee community change with time of year, we constructed a multinomial logistic regression model for each of these three traits. The response data are the trait values of each bee specimen collected from a crop, and the models estimate the influence of predictors on the probability that a given wild bee crop visitor will have a particular trait value. In this case, the predicted probability of a visitor having a particular trait is equivalent to the predicted proportion of visits performed by bees with that trait. The predictor variable for each regression was the midpoint of the range of bee collection dates for each dataset, which we used as a measure of crop phenology. Each model also included a random effect for dataset to account for non-independence of specimens from the same dataset. For the habitat association model, we noted that two highly dominant species—*Bombus impatiens* and *Andrena miserabilis*—had high leverage on the results. Therefore, to determine the sensitivity of the results to these species, we re-ran the habitat association model after removing all records of these species from the data. We fitted multinomial logistic models using the mclogit package (Elff, 2022) and made predictions from models using the emmeans package (Lenth & Piaskowski, 2025). All analyses were conducted in R version 4.2.2 (R Core Team, 2025).

Results

Which wild bee species are dominant visitors to which crops in northeastern North America?

We compiled 29 crop visitation datasets comprising 51,501 wild bee records on 18 crop species (Table S1, Figure S2), including 19 datasets on spring-blooming crops (apple, apricot, highbush blueberry, lowbush blueberry, peach, pear, plum, raspberry, strawberry, sweet cherry, and tart cherry) and 10 on summer-blooming crops (alfalfa, cranberry, cucumber, muskmelon, pumpkin, tomato, and watermelon). Twelve of the 29 datasets were collected by the authors of this study. Out of roughly 725 wild bee species known to occur in northeastern North America (Ascher & Pickering, 2014), 265 species occurred in the compiled datasets. Of these, 52 were identified as dominant for at least one crop, using the "at least 5% of flower visits" threshold; thus, 20% of the observed species and approximately 7% of the regional species pool were dominant crop visitors. The mean number of dominant species per dataset was 5.3 (range 2–8). The dominant species constituted, on average, 16% of the species in a dataset (range 5%–33%) and performed an average of 71% of the flower visits (range 34%–98%). As indicated by these metrics, datasets consistently had a few abundant species and many species with low abundance. This pattern was generally more exaggerated for later-blooming crops, which therefore had fewer dominant species (Figs. 1, S3). For sensitivity analysis on the choice of a 5% threshold, see Supplementary Methods 3.

Of the 52 dominant species, 26 were dominant for more than one crop species. *Bombus impatiens* was dominant for the largest number of crops (11/18). Species in the subgenus *Melandrena* were especially dominant in spring, contributing one or more dominant species for 8/18 crops. Other frequently dominant species included *Andrena miserabilis* (seven crops) and *Ceratina calcarata* (six crops; Table S2).

What are the flight seasons of dominant wild bee crop visitors?

Spring bees were 48% of the dominant species, summer bees were 8%, and long-season bees were 42% (Table S2). The dominant wild bees for spring-blooming crops included both spring bees and long-season bees, while summer-blooming crops were dominated by long-season bees (Fig. 2, Table S2). Summer bees were infrequently dominant (Fig. 2), and two of the four dominant summer bees were specialists on the crop(s) for which they were dominant (*Melitta americana* on cranberry and *Eucera pruinosa* on cucurbits).

What are the habitat associations, nesting habits, and sociality of dominant wild bee crop visitors?

The dominant species were 23% forest-associated, 27%

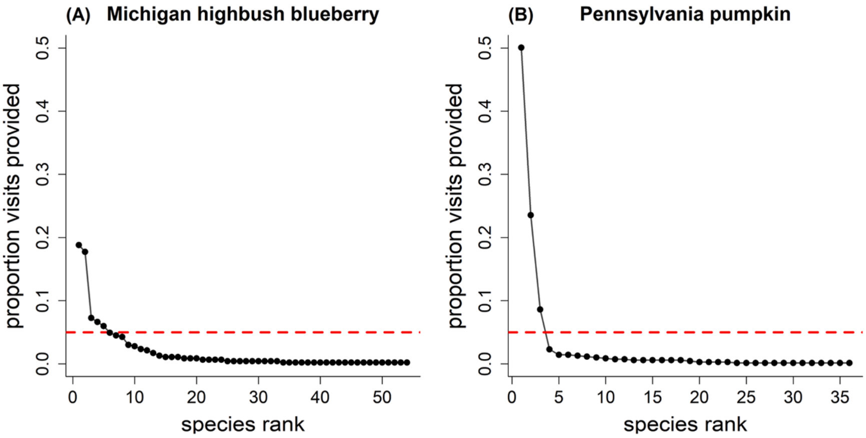

Fig. 1. Examples of rank abundance curves for (A) a spring-blooming crop—highbush blueberry in Michigan (Wood et al., 2018), and (B) a summer-blooming crop—pumpkin in Pennsylvania (McGrady et al., 2020). Each point represents one species and the proportion of visits it provided. Points above the dashed line indicate species that exceed the 5% dominance threshold.

synanthropic, 23% habitat generalists, and habitat associations were unknown for 27% (Fig. 3A). Dominant species were 75% soil-nesting, 12% belowground cavity-nesting, 8% stem-nesting, and 6% hole-nesting (Fig. 4A). Dominant species were 61% solitary, 29% social, and 10% facultatively social (Fig. 5A). The trait composition of all dominant species was fairly stable with dominance thresholds between 2% and 15% (Table S3).

How do the identities and traits of the dominant wild bee crop visitors differ between spring- and summer-blooming crops?

The 42 dominant species visiting the 11 spring-blooming crops were primarily in the families Andrenidae (55% of spring dominant species) and Apidae (28%), along with two species in Colletidae (5%) and several in Halictidae (12%; Fig. 6A). The 18 dominant species visiting the 7 summer-blooming crops were in the families Apidae (44% of summer dominant species) and Halictidae (50%), plus one species in Melittidae (6%; Fig. 6B). Our PERMANOVA showed that the composition of dominant species changed significantly with time of year ($p = 0.001$, $R^2 = 0.399$; Fig. 7), and this result was robust to changes in the dominance threshold (Table S5).

With increasing day of year, the proportion of visits by forest-associated bees increased, the proportion of visits by habitat generalist bees decreased, and the proportion of visits by synanthropic bees did not change significantly (Fig. 3B–D, Table 1). However, two species had high leverage on these regression results. The increase in forest-associated bee visitation with day of year was driven by increasing relative abundance of *B. impatiens* at later dates. Likewise, the lack of trend in synanthropic bee visitation was driven by one species—*Andrena miserabilis*—that was dominant for seven spring-blooming crops. If these species are removed, forest-associated bee visitation decreases and synanthropic bee visitation increases with day of year (Fig. 3E–G, Table 1).

The proportion of visits by soil-nesting bees decreased with day of year, while the proportion by belowground cavity-nesting bees increased (Fig. 4, Table 1). Because all cavity-nesting species in our data are *Bombus*, the increase in cavity-nesting bee visitation is equivalent to the increase in *Bombus* visitation. Similarly, the high visitation by soil-nesting bees in early spring was driven by the prevalence of *Andrena*. Visitation by wood-nesting, stem-nesting, and hole-nesting bees was low and did not change across seasons (Table 1).

Solitary bees provided a large majority of visits in spring and few visits in the summer, while social bees provided most summer visits (Fig. 5, Table 1). This was because solitary *Andrena* dominated spring crop visitation, while social *Bombus* and *Lasioglossum* dominated summer crop visitation (Fig. 6). Visitation by facultatively social species did not change across seasons (Table 1).

Discussion

By focusing on overall abundance and species richness, many past studies on crop pollination have overlooked the identities and traits of dominant pollinators. We identified the species that provide the majority of wild bee visitation to crops in northeastern North America. In keeping with past research (Kleijn et al., 2015), we found that a small subset of dominant species performed most of the crop visitation. On average, 16% of observed bee species performed 71% of crop flower visitation, and the dominant species across all crops represented only about 7% of the regional bee fauna.

Complementing the already-established fact that relatively few species perform most crop pollination services, we contribute a simple yet underappreciated observation: different bee species are dominant visitors for different crops, and these species have different traits corresponding to different resource requirements. This suggests that there is no one-size-fits-all management approach that will best support pollinators for all crops (Garratt et al., 2014). Rather, management should consider the resource needs of the focal crop's dominant visitors (Pisanty & Mandelik, 2015). Furthermore, we found that phenology strongly predicted dominant species identities and traits. While detailed knowledge on the natural history of specific dominant visitors is valuable, crop growers are unlikely to have that knowledge (Park et al., 2020), and our results suggest that they do not need to. Instead, simply knowing when a crop blooms is sufficient to guide wild pollinator management.

Seasonal organization of crop-visiting wild bees' identities and traits

In our study region, we found that the dominant wild bees visiting spring- and summer-blooming crops were taxonomically distinct (Figs. 6–7), leading to differing trait composition (Figs. 3–5). *Andrena*—in which all species are solitary soil-nesters (Danforth et al., 2019)—was the most dominant wild bee genus for spring-blooming crops (Fig. 6, Table S2). Therefore, spring crop visitation was dominated by solitary, spring-flying, soil-nesting bees (Figs. 4–6). Species in the subgenus *Melandrena* were particularly dominant. These species tend to be either forest-associated or habitat generalists (Smith et al., 2021), contributing to the high proportion of visits by these habitat association types in the spring (Fig. 3). Because solitary bee flight seasons are brief (Danforth et al., 2019), these spring-flying species drop out of the crop-visiting community at later dates.

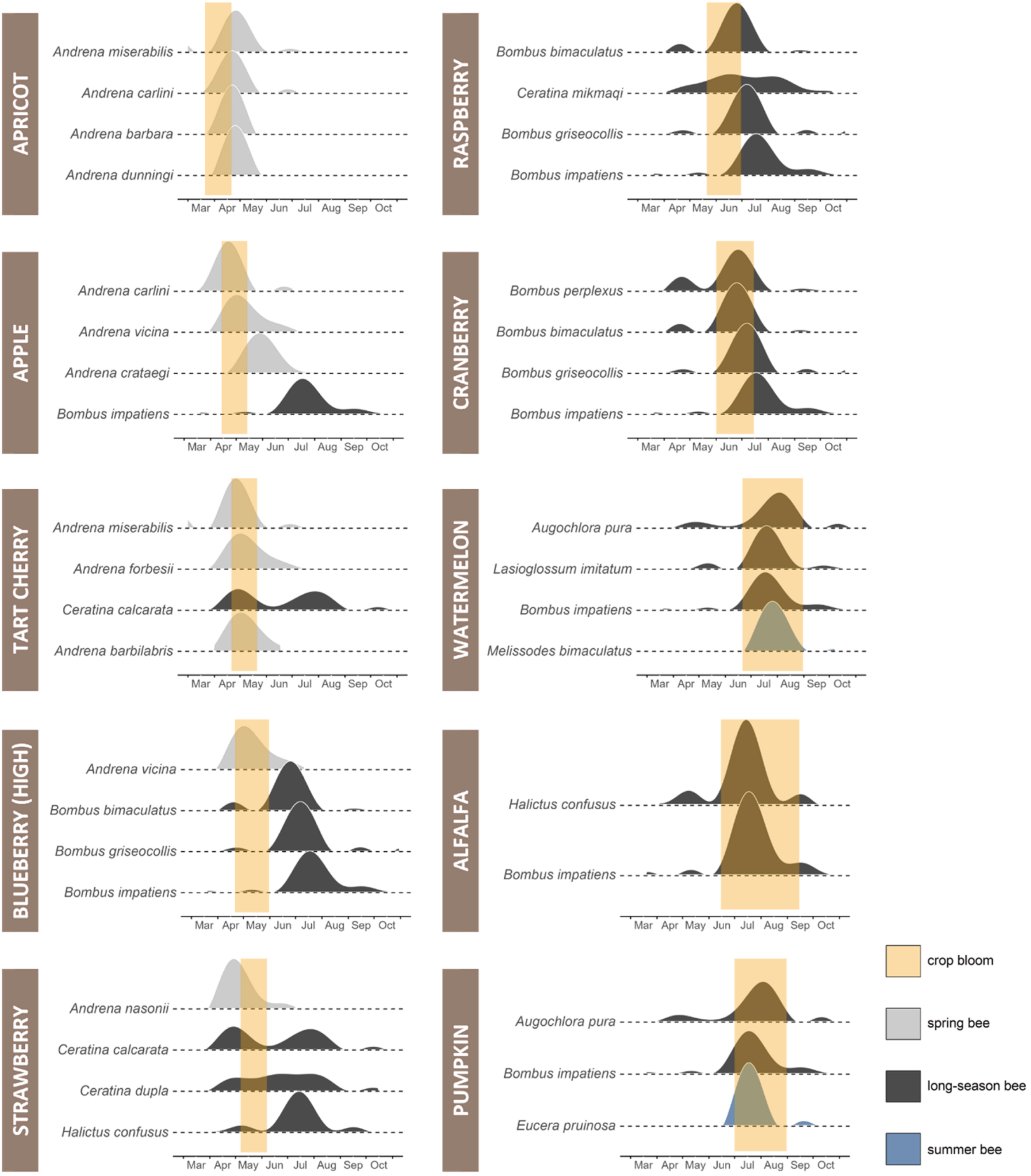

Fig. 2. Phenogram displaying the approximate bloom times of ten crops and phenology curves of up to four dominant wild bee visitors for each crop. Crops are organized chronologically by bloom phenology from top to bottom and left to right, and bees in each panel are organized chronologically by flight season start.

In contrast, summer crop visitation was dominated by the genus *Bombus* (bumble bees) and the family Halictidae (Fig. 6, Table S2). All non-kleptoparasitic *Bombus* are social, and the species in our datasets tend to nest in belowground cavities. The dominant Halictidae species were mainly social and soil-nesting. Thus, summer crops were visited mainly by social bees (Fig. 4), some soil-nesting and some belowground cavity-nesting (Fig. 5). Social bees have long flight seasons, with colonies started by one foundress and growing larger as workers are produced, so although their flight seasons usually begin in the spring, they become far more abundant later in the year (Fig. 2). Increasing relative abundance of social bees later in the growing season is a general phenomenon for temperate regions (Graystock et al., 2020; Ogilvie & Forrest, 2017), so the finding that social bees are more dominant for summer-blooming crops is likely to be true beyond northeastern North

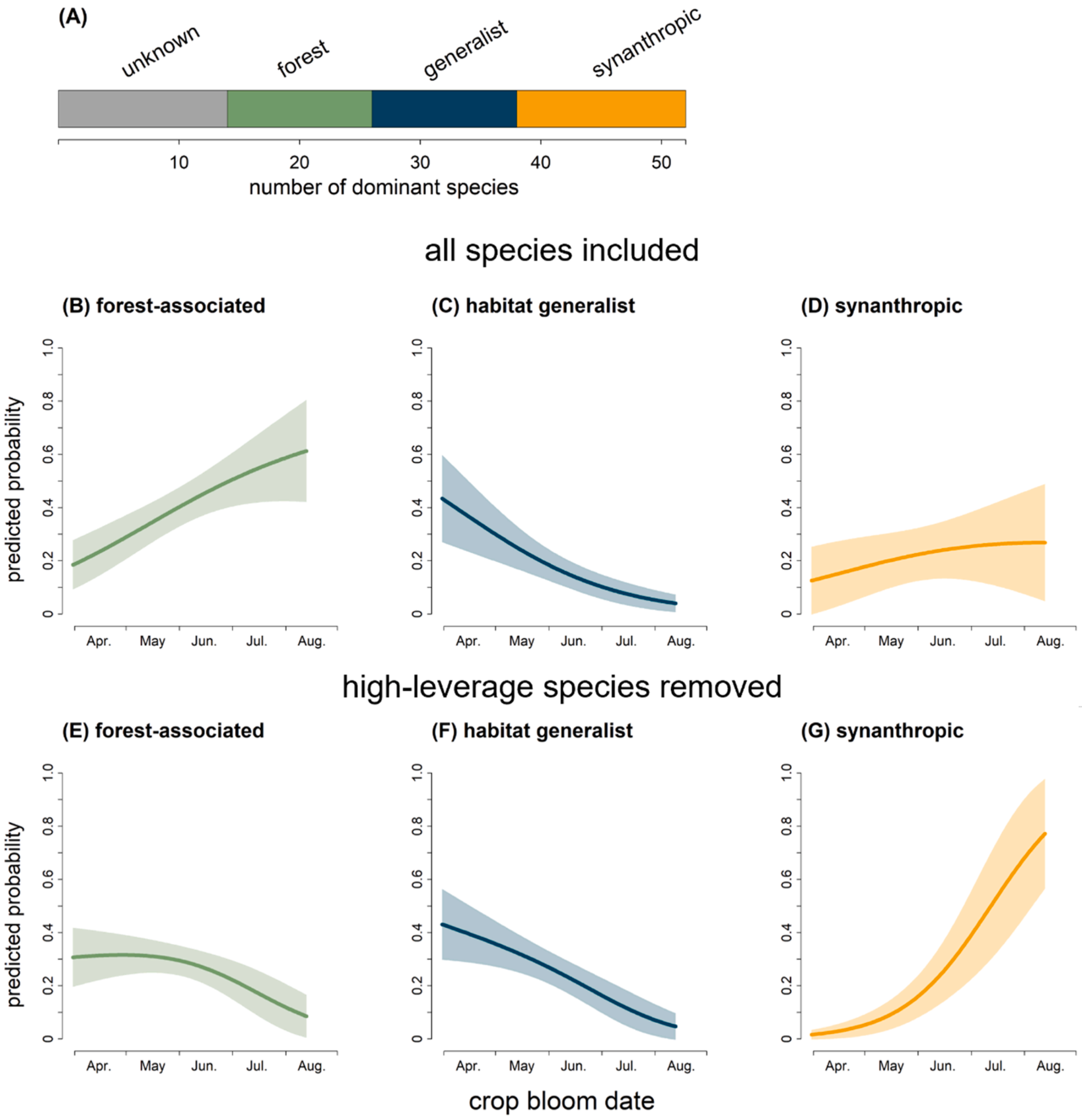

Fig. 3. (A) Number of dominant wild bee species with each habitat association. (B–D) Relationships between time of year and the probability that a given wild bee visiting a crop will belong to a species with each habitat association. (E–G) The same relationships when two high-leverage species (*Bombus impatiens* and *Andrena miserabilis*) are removed. Lines are predictions from multinomial logistic regression, and polygons are 95% confidence intervals.

America. Interestingly, the percentage of social species among dominant crop visitors (29%) is substantially higher than the overall percentage of social species in temperate regions generally (~10%; Danforth et al., 2019).

Our findings on the seasonal changes in habitat associations of crop-visiting bees were unexpected. Past research shows that bees in the northeastern USA primarily use forest habitat in spring and open, anthropogenic habitat in summer (Harrison et al., 2018). Therefore, we expected visitation to be dominated by forest-associated bees in spring and synanthropic bees in summer. Instead, we found greater forest-associated bee visitation in summer and no trend in synanthropic bee visitation (Fig. 3). However, this was driven by two high-leverage species whose habitat associations are atypical, given their phenologies: *Bombus impatiens*, which was dominant in 66% of datasets, and *Andrena miserabilis*, which was dominant in 28% of datasets. *B. impatiens*—by far the most abundant bumble bee in eastern North America—is active from early spring to fall and can persist in many habitats, yet is classified as forest-associated based on its relative abundance in different habitats (Smith et al., 2021). This is likely because forest habitat supports key parts of its life history, particularly nesting and spring foraging (Mola et al., 2021; Pugesek & Crone, 2021). *A. miserabilis* emerges very early in the spring yet is classified as synanthropic, likely due to its tendency to nest in disturbed habitats (Michener & Rettenmeyer, 1956). The unusual habitat association of

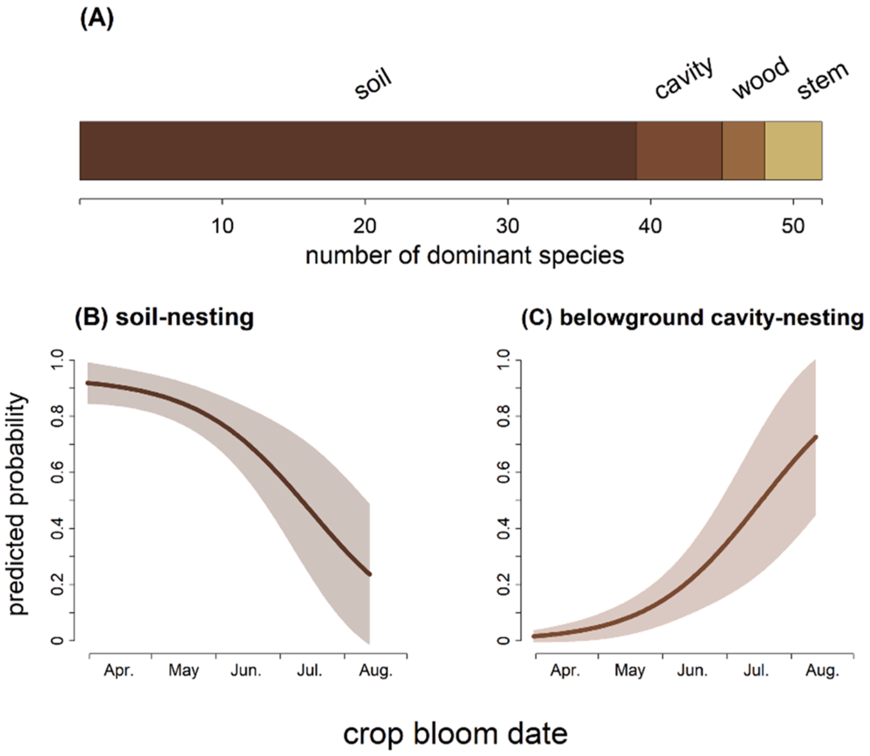

Fig. 4. (A) Number of dominant wild bee species with each nesting habit. (B–C) Relationships between time of year and the probability that a given wild bee visiting a crop will be soil-nesting or belowground cavity-nesting. Lines are predictions from multinomial logistic regression, and polygons are 95% confidence intervals.

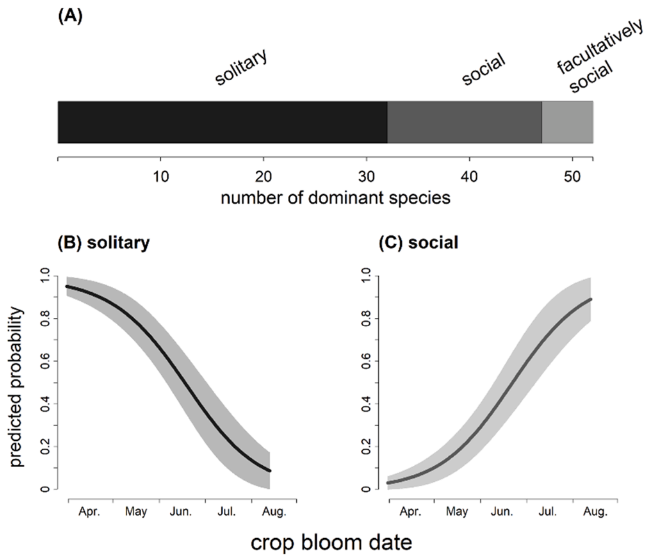

Fig. 5. (A) Number of dominant wild bee species with each sociality type. (B–C) Relationships between time of year and the probability that a given wild bee visiting a crop will be solitary or social. Lines are predictions from multinomial logistic regression, and polygons are 95% confidence intervals.

A. miserabilis among spring-flying *Andrena* may make it a particularly valuable spring pollinator in areas without intact forest patches. The unique natural histories of these two species highlight the value of understanding the taxon-specific ecology of dominant crop pollinators whenever possible (Garratt et al., 2014).

A limitation of our study is that we were unable to assess whether the identities of dominant crop visitors in our results were influenced by the landscape composition around the crop fields where datasets were collected. For example, if crop phenology were incidentally related to surrounding landscape composition in our datasets, this could influence our findings regarding changes in visitor traits with crop bloom time. Landscape effects on dominant crop visitor identity would be a valuable area of future research, as this is understudied compared to landscape effects on pollinator abundance and diversity (Kennedy et al., 2013).

Management implications

To date, management aimed at increasing wild pollinator visitation to crops has had mixed results. For example, meta-analyses have found that wildflower plantings in crop margins only increase crop visitation at field edges and have no consistent effect on crop yield (Lowe et al., 2021; Zamorano et al., 2020). Pollinator management is generally intended to promote the entire pollinator community, whereas crop pollination is mostly accomplished by a small subset of species (Kleijn et al., 2015). Thus, management for crop pollination may be more effective if targeted to the resource requirements of a crop’s dominant floral visitors (Garratt et al., 2014). We found that crop bloom season predicts the identities of dominant visitors (Figs. 6–7), decreasing the need to design targeted management for each crop separately. Here, we identify generalizable considerations for wild pollinator management that stem from the phenomenon of seasonal turnover of dominant pollinators. We then explore how these considerations play out for spring- and summer-blooming crops in our study region.

Management aimed at increasing wild bee visitation should first consider the focal crop’s bloom season because crops that bloom at different times of year can have different dominant pollinators. Phenological turnover of bees and floral resources is a general phenomenon (CaraDonna et al., 2017; Ogilvie & Forrest, 2017), so this is likely to be true regardless of geographical location. Second, regardless of crop bloom season, management should consider the full flight seasons of the dominant pollinators (Sáez et al., 2023). Specifically, it is important to assess whether floral resources are available near crop fields for the entirety of the key pollinators’ flight seasons, especially outside of crop bloom (Guezen & Forrest, 2021; Heller et al., 2019). This may require

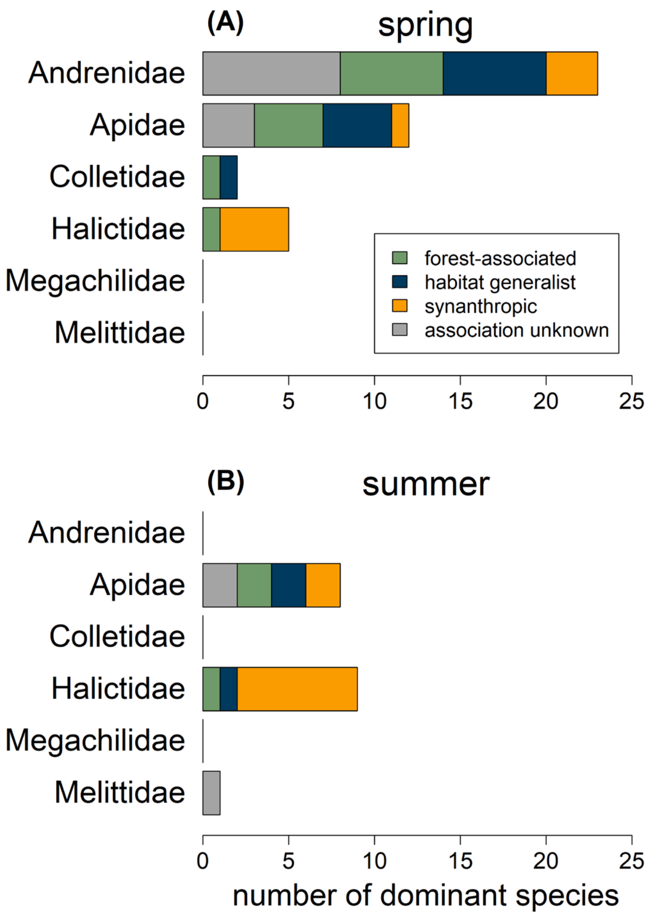

Fig. 6. Families and habitat associations of dominant wild bee visitors of (A) spring-blooming and (B) summer-blooming crops in northeastern North America.

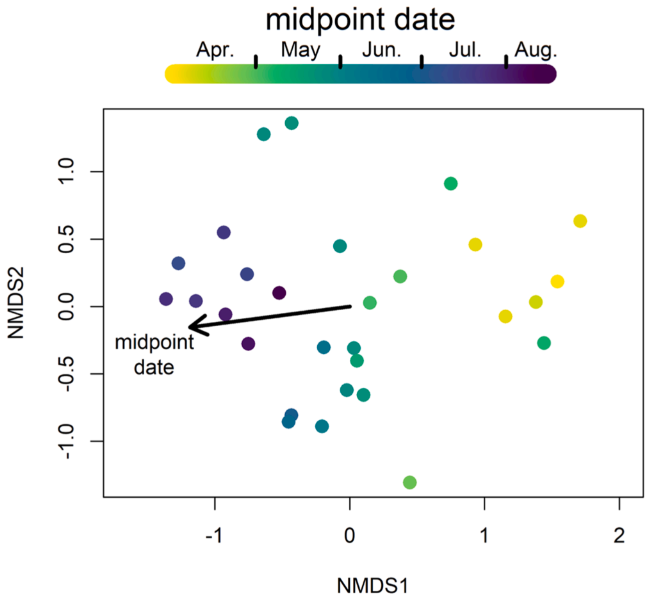

Fig. 7. NMDS scores for the dominant species community of each crop dataset, colored according to the midpoint date of bee collection for each dataset, which serves as an estimate for the middle of crop bloom because bees were only collected from blooming crop flowers. NMDS dimensions = 2, stress = 0.144.

Table 1

Predicted trait probabilities from multinomial regression models for one date in spring (May 1) and one date in summer (July 15) and Nagelkerke’s pseudo-R^2 as a measure of model fit. Values in parentheses are 95% confidence intervals.

trait	predicted probability on May 1	predicted probability on July 15	Nagelkerke's pseudo-R^2
habitat association model			0.542
forest-associated	0.29 (0.21–0.37)	0.54 (0.42–0.67)	
habitat generalist	0.3 (0.2–0.4)	0.08 (0.03–0.12)	
synanthropic	0.18 (0.06–0.29)	0.26 (0.11–0.42)	
habitat association model (high-leverage species removed)			0.596
forest-associated	0.32 (0.24–0.39)	0.18 (0.09–0.26)	
habitat generalist	0.36 (0.27–0.44)	0.12 (0.05–0.19)	
synanthropic	0.05 (0.01–0.09)	0.52 (0.31–0.72)	
nesting habit model			0.866
soil-nesting	0.88 (0.81–0.95)	0.48 (0.25–0.71)	
hole-nesting	0.02 (0–0.03)	0.01 (0–0.01)	
wood-nesting	0.03 (0.01–0.06)	0.04 (0.01–0.08)	
belowground cavity-nesting	0.05 (0–0.09)	0.47 (0.22–0.71)	
stem-nesting	0.02 (0–0.04)	0.01 (0–0.02)	
sociality model			0.696
social	0.1 (0.03–0.17)	0.71 (0.56–0.86)	
facultatively social	0.03 (0.01–0.06)	0.04 (0.01–0.07)	
solitary	0.87 (0.79–0.94)	0.25 (0.11–0.39)	

multiple complementary approaches to ensure resource continuity, such as summer-blooming herbaceous wildflower plantings combined with spring-blooming enhancements such as hedgerows. Third, targeted management should consider the full suite of habitats required by dominant pollinators; while crop fields can provide some resources, most species will need additional habitats for nesting and foraging (Bartholomée et al., 2020; Westrich, 1996). In many parts of the world, the most important habitats may vary with crop phenology because habitat types tend to vary in floral phenology (Bertrand et al., 2019; Simpson et al., 2025). Lastly, management should consider dominant visitors’ nesting requirements whenever possible; however, bee nesting ecology is understudied (Antoine & Forrest, 2021), so it is often unclear how to tailor management to specific nesting guilds. The specific actions resulting from these broad management considerations will vary among regions, but they are potentially important everywhere.

For spring-blooming crops in northeastern North America, these management considerations would lead to a greater emphasis on providing spring floral resources and conserving forest habitat, and reduced focus on later-blooming wildflower plantings. We found that spring crop visitation was dominated by solitary bees that are active only in spring (Figs. 2, 5). In our study region, spring flowers are primarily found in forests (Harrison et al., 2018; Smith et al., 2021) and are not present in standard wildflower strips such as those encouraged by the U.S. Conservation Reserve Program, which bloom in summer (Quinlan et al., 2021; Wood et al., 2018). Therefore, preserving forest remnants and planting spring-blooming trees and shrubs should promote bee visitation to spring-blooming crops more effectively than typical herbaceous, summer-blooming flower plantings (Bertrand et al., 2019). Most of the spring crop visitation was by soil-nesting bees (Fig. 4, Table S2), so creating bare ground for nesting and leaving field margins with undisturbed soil may be beneficial, though more research is needed on these practices (Garratt et al., 2023; Williams et al., 2010). We also note that the lack of aboveground-nesting species on crops, relative to the regional spring bee fauna, may result from a lack of aboveground nesting habitat in agricultural landscapes (Williams et al., 2010). Thus, providing dead wood and plants with pithy stems for nesting may improve visitation by these species (Hyjazie & Forrest, 2024).

For summer-blooming crops in northeastern North America, the management considerations we identify would lead to focusing on habitat heterogeneity and temporal continuity of floral resources, with summer-blooming herbaceous plantings as one component. We found that summer crop visitation was dominated by long-season social bees

(Figs. 2, 5). Although these bee species become more dominant later in the year (Graystock et al., 2020), resources at the start of their flight season are critical for kickstarting colony growth (Becher et al., 2024; Malfi et al., 2021). Therefore, while summer-blooming wildflower strips cover part of these species' food requirements, special attention should also be paid to early spring resources. Similarly, habitat heterogeneity will be especially important for supporting pollinators of summer-blooming crops because long-season bees must forage on many plant taxa in multiple complementary habitats to find resources over their entire flight season (Mandelik et al., 2012; Ogilvie & Forrest, 2017). Because summer-blooming crop visitation was mostly by belowground-nesting species, undisturbed field margins may be valuable (Purvis et al., 2020), but some crop visitors probably rely on adjacent non-agricultural habitats for nesting (Pisanty & Mandelik, 2015). Similarly to our conclusions for spring-blooming crops, our findings suggest that summer-blooming wildflower plantings will be insufficient on their own to support the dominant visitors of summer-blooming crops, because these visitors are also active in the spring. Unlike our conclusions for spring-blooming crops, we expect that summer floral resources will nevertheless be an important component of pollinator management for summer-blooming crops in order to provide continuous resources for long-season bees.

Conclusion

The majority of crop pollination is accomplished by a small number of dominant species, a fact with important implications for managing this ecosystem service. Using data on wild bee crop visitation in northeastern North America, we establish a related yet previously overlooked fact: dominant pollinators differ between crops, with phenology of both bees and crops as a driving factor. Seasonal turnover in dominant crop pollinator identity—which is likely to occur in other regions as well—suggests that best pollination management practices may differ depending on crop phenology. Our approach to studying this phenomenon by summarizing dominant species identities and traits across crops is simple yet powerful. Because pollinator fauna and floral resource landscapes differ geographically, this approach should be applied at a regional scale by researchers familiar with the natural history of the regional pollinators. For our study region, the results suggest that current standard practices for wild pollinator management (i.e., summer-blooming flower plantings) are unlikely to provide sufficient resources for the dominant visitors of many crops.

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CRediT authorship contribution statement

Joanna W. Greenwood: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Katherine J. Turo:** Writing – review & editing, Visualization, Data curation, Conceptualization. **Katherine R. Urban-Mead:** Writing – review & editing, Data curation, Conceptualization. **Neelendra K. Joshi:** Investigation, Data curation. **Heather Grab:** Investigation, Data curation. **David J. Biddinger:** Investigation, Data curation. **Rachael Winfree:** Writing – review & editing, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Supplementary Methods 1: Literature search

To identify datasets of wild bees visiting crop flowers in northeastern North America, we first created a list of crops grown in this region using information from the United States Department of Agriculture (USDA Farm Service Agency, 2024) and Statistics Canada (Statistics Canada, 2022a, 2022b, 2022c). From this list, we removed crops that do not benefit from animal pollination, according to information from (Aizen et al., 2009; Klein et al., 2006). Using the common and scientific names of the remaining list of crops, combined with the names of states and regions in the study area, we searched the Web of Science Core Collection on March 7, 2025 using the following search terms:

> (“wild bee” OR “wild bees” OR “native bee” OR “native bees” OR pollinator* OR “flower visitors” OR “crop visitors”) **and** (“northeastern North America” OR “eastern Canada” OR “northeastern United States” OR “northeastern U.S.” OR Midwest OR Mid-Atlantic OR “New England” OR New Brunswick OR Nova Scotia OR Ontario OR Prince Edward Island OR Quebec OR Connecticut OR Delaware OR Indiana OR Illinois OR Kentucky OR Maine OR Maryland OR Massachusetts OR Michigan OR New Hampshire OR New Jersey OR New York OR Ohio OR Pennsylvania OR Rhode Island OR Vermont OR Virginia OR West Virginia OR Wisconsin) **and** ("Brassica alba" OR mustard OR "Brassica nigra" OR "Brassica juncea" OR "Brassica napus" OR canola OR "oilseed rape" OR "Citrullus lanatus" OR watermelon* OR "Cucumis melo" OR cantaloupe* OR melon* OR muskmelon* OR "Cucumis sativus" OR cucumber* OR "Cucurbita maxima" OR pumpkin* OR squash* OR zucchini* OR "Cucurbita mixta" OR "Cucurbita moschata" OR "Cucurbita pepo" OR "Fagopyrum esculentum" OR buckwheat OR "Glycine max" OR soy* OR "Gossypium hirsutum" OR cotton OR "Helianthus annuus" OR sunflower* OR "Malus domestica" OR apple* OR "Medicago sativa" OR alfalfa OR "Prunus armeniaca" OR apricot* OR "Prunus avium" OR cherr* OR "Prunus cerasus" OR "Prunus domestica" OR plum* OR "Prunus persica" OR peach* OR nectarine* OR "Prunus spinosa" OR "Pyrus communis" OR pear* OR "Solanum melongena" OR eggplant* OR "Vaccinium angustifolium" OR "Vaccinium corymbosum" OR blueberr* OR "Vaccinium macrocarpon" OR cranberr* OR "Vicia faba" OR "broad bean" OR "faba bean" OR "field bean" OR Fragaria OR strawberr* OR Rubus OR blackberr* OR raspberr* OR caneberr* OR Amelanchier OR saskatoon* OR serviceberr* OR Ribes OR currant* OR "Lonicera caerulea" OR haskap* OR honeysuckle)

This search returned 603 unique publications, to which we added an additional 12 unique publications from a list of datasets on wild bee visitors of North American crops in Rondeau et al.

(Rondeau et al., 2022). Of the 615 publications identified, 490 were excluded while screening titles and abstracts for relevance to our study. Of the remaining 124 publications, 18 met the criteria described in the manuscript in section 2.1 (Figure S1). Note that publications were frequently excluded under the “<95% of bees identified to species” reason because the data consisted of floral visitation observations, with visitors visually identified to morphogroup. Some accepted publications included data on wild bee visitors to multiple crops, resulting in 23 unique crop visitor datasets. In addition, the authors of this study provided six previously unpublished datasets, for a total of 29 datasets (Table S1).

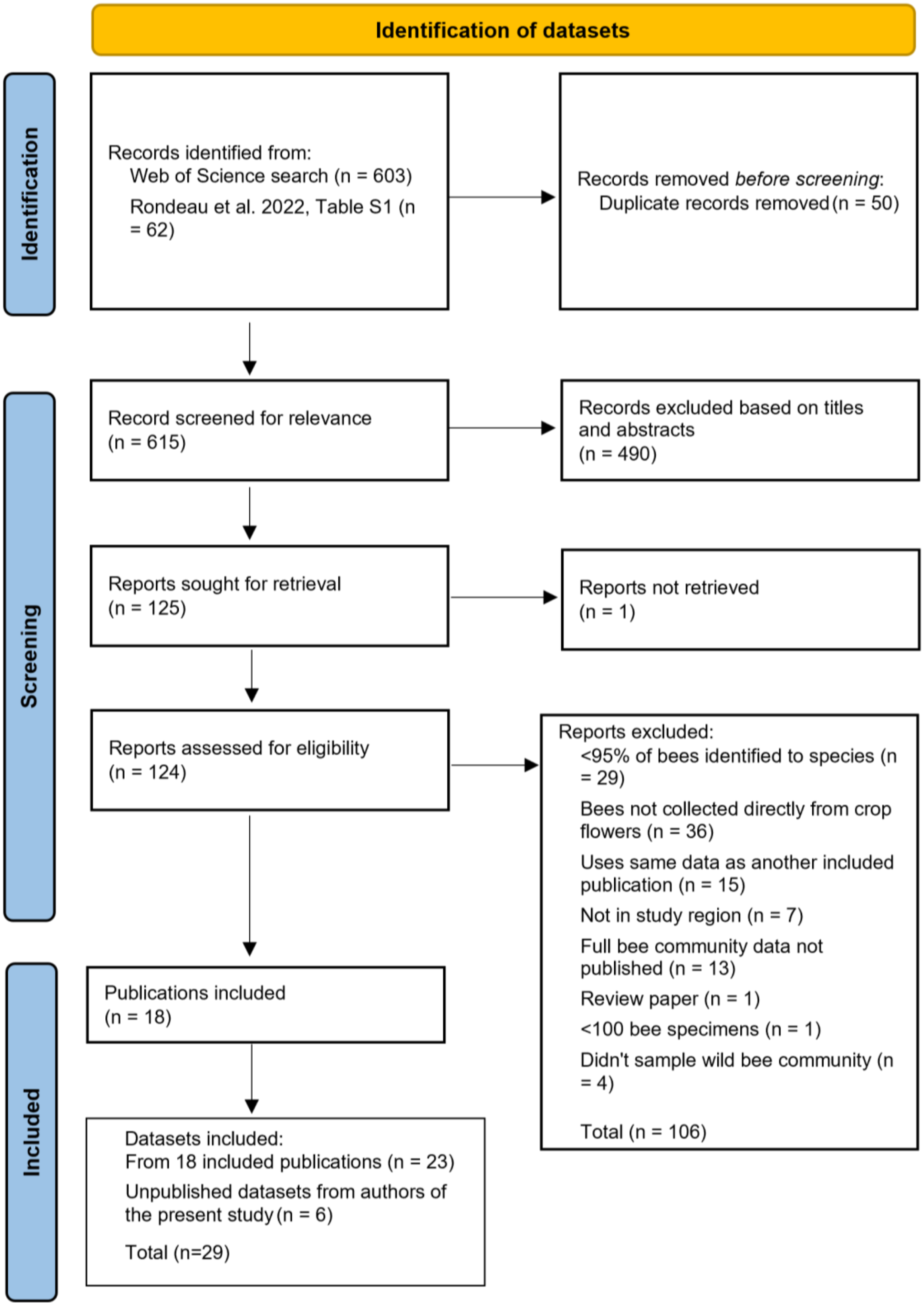
Supplementary Methods 2: Dominance sensitivity analysis

To assess the sensitivity of our results to the "contributes at least 5% of all crop flower visits in a dataset" threshold for considering a species a dominant crop visitor, we calculated several metrics for the following dominance thresholds: 2%, 4%, 5%, 6%, 8%, 10%, 15%, 20%, 25%, and 30%. For the complete set of dominant species across all datasets, we determined the total number of dominant species, the percentage of all observed species that were dominant, and the percentage of dominant species with certain trait values (forest-associated, synanthropic, soil-nesting, cavity-nesting, solitary, and social). For each individual dataset, we determined the percentage of observed species that were considered dominant and the percentage of visits performed by the dominant species. Lastly, we ran PERMANOVAs evaluating the influence of date on dominant species composition at each dominance threshold.

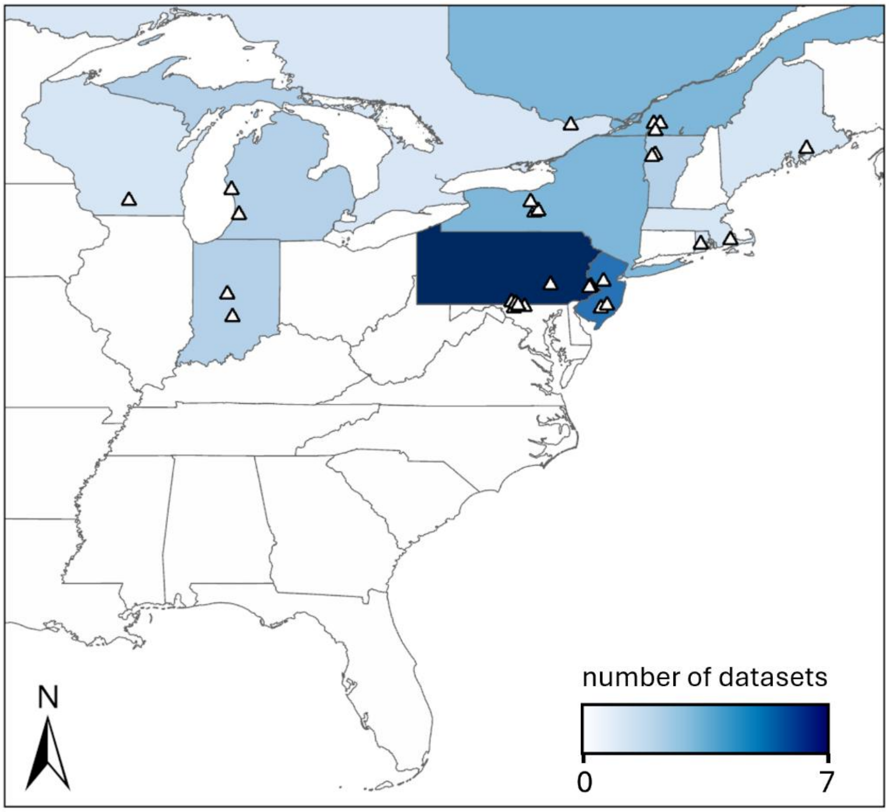
Obviously, the number of dominant species and the percentage of observed species considered dominant decrease as the threshold for dominance is increased (**Table S3**). At a "contributes at least 2% of visits" dominance threshold, there are 74 dominant species (28% of observed species). At a 30% dominance threshold, there are 4 dominant species (1.5% of observed species). The percentages of dominant species with different trait values are fairly stable for dominance thresholds ranging from 2% to 15%. Within that range, percentages of dominant species belonging to the trait groups evaluated change by, at most, 11%. At higher dominance thresholds, the trait composition of the dominant species changes more because very few species are considered dominant (≤10 species, <5% of species). At these high thresholds, the dominant species include a higher percentage of synanthropic species, cavity-nesting species, and social species

Unsurprisingly, at the level of individual datasets, the percentage of species considered dominant and the percentage of visits done by dominant species both decline as the threshold for dominance is increased (**Table S4**). At the 2% threshold, a large percentage of species are considered dominant in many datasets; this would make the designation of “dominant species” less useful for designing targeted management strategies. At thresholds of 10% and higher, some datasets have no species that qualify as dominant, again making the designation unhelpful from a management perspective.

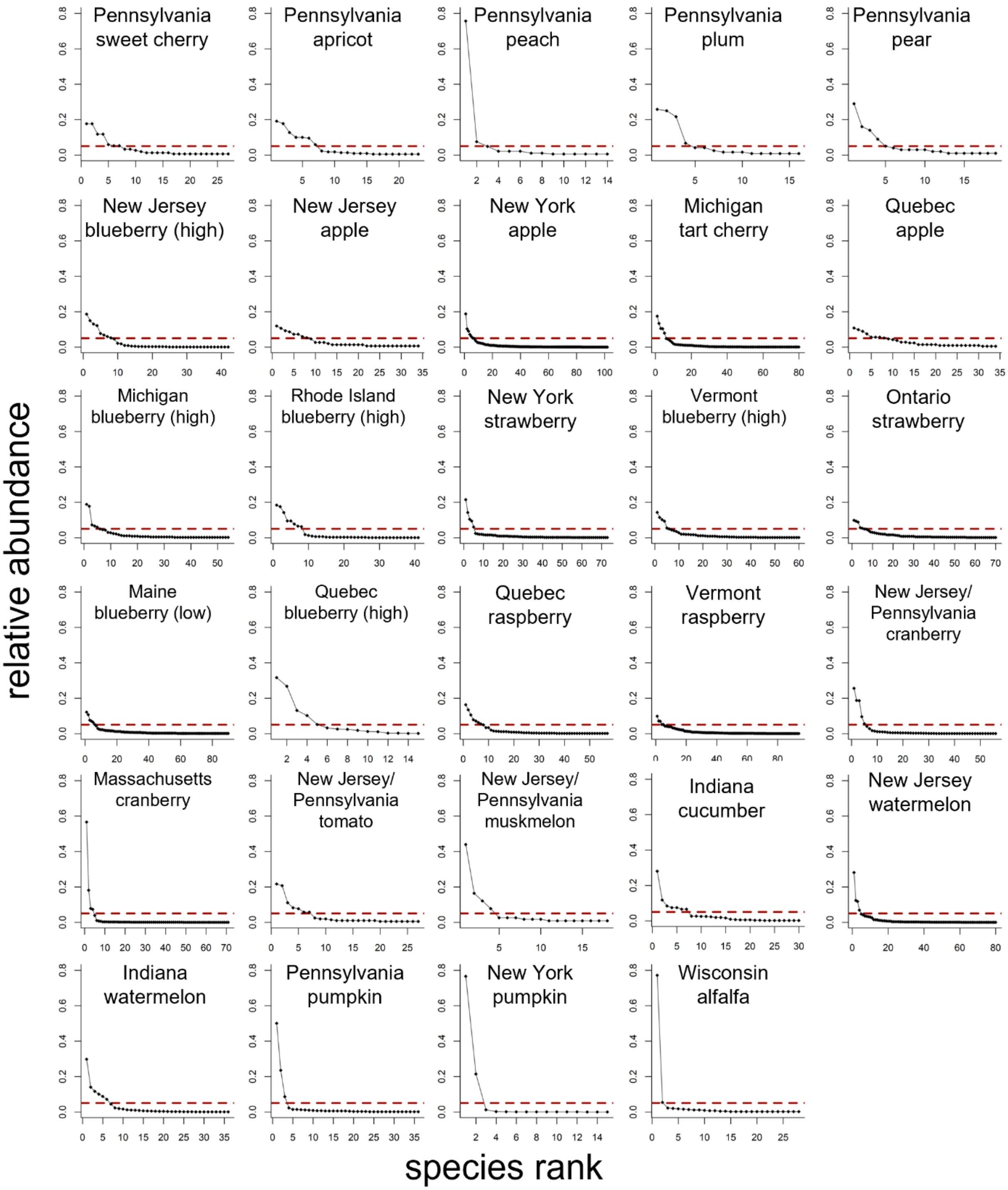
PERMANOVA results were robust to changes in the dominance threshold (**Table S5**). Midpoint collection date was a significant predictor of dominant species composition at all but the highest threshold (30%). That is, unless species had to be extremely dominant to qualify as dominant, there was a significant shift in composition with date. Even at this highest threshold, the PERMANOVA result was marginally significant (p = 0.093). R^2 values became lower as the threshold for dominance increased, suggesting that the set of dominant species becomes more similar across crops as the dominance threshold becomes more restrictive.



Supplementary figure 1. Literature search process to identify datasets on wild bee visitors of crops in northeastern North America.



Supplementary figure 2. Locations of datasets used in analysis. Each white triangle corresponds to one dataset. Points are jittered when multiple datasets come from similar locations. States and provinces are shaded according to the number of datasets from each.



Supplementary figure 3. Rank abundance curves for all datasets, organized chronologically by bloom date from left to right and top to bottom. Each point represents one species and the proportion of visits it provided. Points above the dashed red line indicate species that exceed the 5% dominance threshold.

Supplementary table 1. Details of the 29 crop datasets used for analysis. Sample size refers to the number of bee specimens collected from crop flowers.

Crop	Location	Years of collection	Sample size	Source
Alfalfa (*Medicago sativa*)	WI, USA	2018	447	Boyer et al., 2020
Apple (*Malus domestica*)	NJ, USA	2004-06	151	*unpublished data*
Apple (*Malus domestica*)	NY, USA	2008-13	7200	Russo et al., 2015
Apple (*Malus domestica*)	Quebec, Canada	2012	214	Martins et al., 2018
Apricot (*Prunus armeniaca*)	PA, USA	2012-2013	220	*unpublished data*
Cranberry (*Vaccinium macrocarpon*)	MA, USA	2007-09, 2011-13, 2014, 2016	8062	Averill et al., 2018
Cranberry (*Vaccinium macrocarpon*)	NJ, USA	2009-10	3668	Cariveau et al., 2013
Cucumber (*Cucumis sativus*)	IN, USA	2009	560	Smith et al., 2013
Highbush blueberry (*Vaccinium corymbosum*)	Quebec, Canada	2012	658	Martins et al., 2018
Highbush blueberry (*Vaccinium corymbosum*)	VT, USA	2016-17	708	Nicholson et al., 2021
Highbush blueberry (*Vaccinium*	NJ, USA	2010-2012	1085	Benjamin et al., 2014

corymbosum)				
Highbush blueberry (*Vaccinium corymbosum*)	RI, USA	2014-15	1083	Scott et al., 2016
Highbush blueberry (*Vaccinium corymbosum*)	MI, USA	2013-2017	468	Wood et al., 2018
Lowbush blueberry (*Vaccinium angustifolium*)	ME, USA	2012-2013	827	Venturini et al., 2017
Muskmelon (*Cucumis melo*)	NJ and PA, USA	2004	116	Winfree et al., 2008
Peach (*Prunus persica*)	PA, USA	2012-2013	185	*unpublished data*
Pear (*Pyrus communis*)	PA, USA	2012-2013	100	*unpublished data*
Plum (*Prunus domestica*)	PA, USA	2012-2013	120	*unpublished data*
Pumpkin (*Cucurbita pepo)*	NY, USA	2008-2009	7739	Artz et al., 2011
Pumpkin (*Cucurbita pepo*)	PA, USA	2013-2015	697	McGrady et al., 2020
Raspberry (*Rubus idaeus*)	VT, USA	2016-17	1713	Nicholson et al., 2021
Raspberry (*Rubus idaeus*)	Quebec, Canada	2012	803	Martins et al., 2018
Strawberry (*Fragaria x ananassa*)	NY, USA	2013-2015, 2018	894	Grab et al., 2018 (bees collected

				2013-2015); *unpublished data* (bees collected 2018)
Strawberry (*Fragaria x ananassa*)	Ontario, Canada	2019	790	MacInnis et al., 2020
Sweet cherry (*Prunus avium*)	PA, USA	2012-2013	153	*unpublished data*
Tart cherry (*Prunus cerasus*)	MI, USA	2013-2017	2702	Wood et al., 2018
Tomato (*Solanum lycopersicum*)	NJ and PA, USA	2004-05	208	Winfree et al., 2008
Watermelon (*Citrullus lanatus*)	NJ, USA	2004-05, 2007-08, 2012-12	6504	Rader et al., 2013
Watermelon (*Citrullus lanatus*)	IN, USA	2018-2020	3352	Pecenka et al., 2023

Supplementary table 2. For each wild bee species identified as a dominant crop visitor, summary of traits and crops for which it was dominant. Habitat associations are derived from Smith et al. (2021) unless a different source is cited in the table.

Species	Family	Phenology type	Habitat association	Sociality	Nesting habit	Crops
Andrena barbara	Andrenidae	spring	generalist	Solitary	soil	apricot, pear
Andrena barbilabris	Andrenidae	spring	unknown	Solitary	soil	tart cherry
Andrena bisalicis	Andrenidae	spring	unknown	Solitary	soil	peach, sweet cherry
Andrena bradleyi	Andrenidae	spring	forest (Winfree et al., 2007)	Solitary	soil	highbush blueberry
Andrena carlini	Andrenidae	spring	forest	Solitary	soil	apple, apricot, highbush blueberry, lowbush blueberry, pear, plum, sweet cherry
Andrena carolina	Andrenidae	spring	unknown	Solitary	soil	highbush blueberry
Andrena commoda	Andrenidae	spring	unknown	Solitary	soil	apricot, raspberry
Andrena crataegi	Andrenidae	spring	unknown	Solitary	soil	apple, raspberry, tart cherry

Andrena dunningi	Andrenidae	spring	generalist	Solitary	soil	apple, apricot, pear
Andrena forbesii	Andrenidae	spring	generalist	Solitary	soil	sweet cherry, tart cherry
Andrena hippotes	Andrenidae	spring	synanthropic	Solitary	soil	apple, sweet cherry
Andrena imitatrix	Andrenidae	spring	generalist	Solitary	soil	pear, plum, sweet cherry
Andrena milwaukeensis	Andrenidae	spring	forest	Solitary	soil	apple
Andrena miserabilis	Andrenidae	spring	synanthropic	Solitary	soil	apple, apricot, peach, pear, plum, sweet cherry, tart cherry
Andrena morrisonella	Andrenidae	spring	unknown	Solitary	soil	apple
Andrena nasonii	Andrenidae	spring	generalist	Solitary	soil	apple, strawberry
Andrena nuda	Andrenidae	spring	unknown	Solitary	soil	apple
Andrena perplexa	Andrenidae	spring	forest (Winfree et al., 2014)	Solitary	soil	apple
Andrena pruni	Andrenidae	spring	unknown	Solitary	soil	sweet cherry

Andrena regularis	Andrenidae	spring	unknown	Solitary	soil	apple
Andrena rugosa	Andrenidae	spring	forest	Solitary	soil	apple
Andrena vicina	Andrenidae	spring	forest	Solitary	soil	apple, highbush blueberry, raspberry
Andrena wilkella	Andrenidae	not classified*	generalist	Solitary	soil	raspberry
Augochlora pura	Halictidae	long-season	forest	Solitary	wood	cucumber, muskmelon, pumpkin, tomato, watermelon
Augochlorella aurata	Halictidae	long-season	synanthropic	Eusocial	soil	cucumber, lowbush blueberry, strawberry, tomato
Bombus bimaculatus	Apidae	long-season	generalist	Eusocial	cavity	cranberry, highbush blueberry, raspberry
Bombus griseocollis	Apidae	long-season	unknown	Eusocial	cavity	cranberry, highbush blueberry, raspberry
Bombus impatiens	Apidae	long-season	forest	Eusocial	cavity	alfalfa, apple, cranberry, cucumber, highbush blueberry, lowbush blueberry, muskmelon, pumpkin, raspberry, tomato, watermelon
Bombus perplexus	Apidae	long-season	forest	Eusocial	cavity	cranberry, highbush blueberry

Bombus ternarius	Apidae	long-season	unknown	Eusocial	cavity	highbush blueberry, lowbush blueberry
Bombus vagans	Apidae	long-season	forest	Eusocial	cavity	lowbush blueberry
Ceratina calcarata	Apidae	long-season	generalist	facultatively social	stem	apple, apricot, cucumber, muskmelon, raspberry, strawberry, tart cherry
Ceratina dupla	Apidae	long-season	generalist	facultatively social	stem	strawberry
Ceratina mikmaqi	Apidae	long-season	synanthropic	facultatively social	stem	raspberry
Ceratina strenua	Apidae	long-season	generalist	facultatively social	stem	apricot
Colletes inaequalis	Colletidae	spring	generalist	Solitary	soil	apple, highbush blueberry
Colletes validus	Colletidae	spring	forest (Winfree et al., 2014)	Solitary	soil	highbush blueberry
Eucera pruinosa	Apidae	summer	synanthropic	Solitary	soil	muskmelon, pumpkin
Habropoda laboriosa	Apidae	spring	forest	Solitary	soil	highbush blueberry

Halictus confusus	Halictidae	long-season	synanthropic	facultatively social	soil	alfalfa, strawberry
Lasioglossum cressonii	Halictidae	long-season	forest	Eusocial	wood	lowbush blueberry
Lasioglossum hitchensi	Halictidae	long-season	synanthropic	Eusocial	soil	tomato
Lasioglossum imitatum	Halictidae	long-season	synanthropic	Eusocial	soil	watermelon
Lasioglossum oceanicum	Halictidae	long-season	generalist	Eusocial	soil	tomato
Lasioglossum pilosum	Halictidae	long-season	synanthropic	Eusocial	soil	watermelon
Lasioglossum tegulare	Halictidae	long-season	synanthropic	Eusocial	soil	strawberry
Lasioglossum versatum	Halictidae	long-season	synanthropic	Eusocial	soil	cucumber, strawberry, tomato, watermelon
Lasioglossum weemsi	Halictidae	long-season	synanthropic	Eusocial	soil	tomato
Melissodes bimaculatus	Apidae	summer	synanthropic	Solitary	soil	cucumber, watermelon

Melitta americana	Melittidae	summer	unknown	Solitary	soil	cranberry
Triepeolus remigatus	Apidae	summer	unknown	Solitary	soil	cucumber
Xylocopa virginica	Apidae	long-season	unknown	Solitary	wood	highbush blueberry, plum

*This species—which is nonnative in our study region—does not meet our criteria for any of the three flight season types. Its phenology is unusual compared to the native bee fauna, falling between the phenologies of spring- and summer-flying species.

Supplementary table 3. Metrics on dominant species for dominance thresholds ranging from 2% to 30%. The dominance threshold is the minimum percentage of flower visits a bee species must provide in a dataset for it to be considered dominant. Values in this table are calculated for the complete set of species across all datasets, rather than separately for individual datasets.

Dominance threshold	**Total number of dominant species**	**% observed species dominant**	**% dominant species forest-associated**	**% dominant species generalist**	**% dominant species synanthropic**	**% dominant species soil-nesting**	**% dominant species cavity-nesting**	**% dominant species solitary**	**% dominant species social**
2%	74	28%	24%	20%	24%	77%	11%	62%	28%
4%	58	22%	21%	26%	28%	78%	10%	59%	31%
5%	52	20%	23%	23%	27%	75%	12%	62%	29%
6%	44	17%	25%	23%	25%	73%	14%	64%	27%
8%	37	14%	16%	24%	30%	76%	11%	65%	24%
10%	31	12%	16%	26%	29%	71%	13%	65%	26%
15%	17	6%	24%	24%	35%	71%	18%	71%	24%
20%	11	4%	27%	27%	36%	64%	27%	64%	36%
25%	8	3%	38%	12%	38%	50%	38%	62%	38%
30%	4	2%	25%	25%	50%	50%	50%	50%	50%

Supplementary table 4. Metrics on dominant species in each dataset for dominance thresholds ranging from 2% to 30%. The dominance threshold is the minimum percentage of flower visits a bee species must provide in a dataset for it to be considered dominant. Values in this table were calculated separately for each of the 30 datasets. The ranges in the table are the minimum and maximum values across all datasets, and the values in parentheses are the mean across all datasets.

Dominance threshold	% of observed species considered dominant	% of visits performed by dominant species
2%	7–67% (mean = 26%)	63–98% (mean = 84%)
4%	6–38% (mean = 18%)	47–98% (mean = 76%)
5%	5–33% (mean = 16%)	34–98% (mean = 71%)
6%	3–27% (mean = 13%)	24–98% (mean = 65%)
8%	1–27% (mean = 10%)	10–98% (mean = 57%)
10%	0–27% (mean = 8%)	0–98% (mean = 51%)
15%	0–19% (mean = 5%)	0–98% (mean = 37%)
20%	0–19% (mean = 3%)	0–98% (mean = 26%)
25%	0–13% (mean = 2%)	0–77% (mean = 22%)
30%	0–8% (mean = 1%)	0–77% (mean = 14%)

Supplementary table 5. Results of PERMANOVA analyzing change in dominant species composition with time of year for dominance thresholds ranging from 2% to 30%. R^2 is the proportion of variance in dominant species composition explained by the predictor variable (midpoint collection date), and p-values <0.05 indicate that dominant species composition changed significantly with date.

Dominance threshold	**R^2**	**p-value**
2%	0.464	0.001
4%	0.415	0.001
5%	0.399	0.001
6%	0.366	0.001
8%	0.318	0.001
10%	0.300	0.001
15%	0.248	0.001
20%	0.310	0.001
25%	0.283	0.004
30%	0.282	0.093

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