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Woody flowering plants support early-spring pollinators in urban greenspaces

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Online Resource 1 – supplemental analyses and data

1.1 Information on studied plant taxa

Table S1. Plant taxa included in this study. *Prunus* and *Viola* taxa are each separated into native and ornamental taxa; *Viburnum* taxa are separated based on flower morphology (i.e., open flowers permitting pollinator access, versus flowers with narrow corollas restricting pollinator access). Exotic *Lamium amplexicaule* and native *Viola bicolor* occur as non-managed lawn weeds.

Plant taxon	**Common name**	**Growth form**	**Native status**
Amelanchier sp.	Serviceberry	Woody (tree)	Native
Cercis canadensis	Eastern redbud	Woody (tree)	Native
Chaenomeles spp.	Flowering quince	Woody (shrub)	Exotic
Citrus sp.	Citrus	Woody (tree)	Exotic
Forsythia sp.	Forsythia	Woody (shrub)	Exotic
Ilex sp.	Holly	Woody (shrub)	Native
Kerria japonica	Japanese rose	Woody (shrub)	Exotic
Lonicera fragrantissima	Winter honeysuckle	Woody (shrub)	Exotic
Prunus angustifolia	Chickasaw plum	Woody (shrub)	Native
Prunus caroliniana	Laurelcherry	Woody (tree)	Exotic
Prunus spp. (ornamental)	Plum; cherry	Woody (tree)	Exotic
Pyrus calleryana	Callery pear	Woody (tree)	Exotic
Rhododendron sp.	Azalea	Woody (shrub)	Exotic
Syringa sp.	Lilac	Woody (shrub)	Exotic
Viburnum spp. (open)	Viburnum	Woody (shrub)	Exotic
Viburnum spp. (restricted)	Viburnum	Woody (shrub)	Exotic
Euphorbia myrsinites	Myrtle spurge	Herbaceous	Exotic
Galanthus sp.	Snowdrop	Herbaceous	Exotic
Hyacinthoides spp.	Blue bell	Herbaceous	Exotic
Hyacinthus spp.	Hyacinth	Herbaceous	Exotic
Lamium amplexicaule	Henbit deadnettle	Herbaceous	Exotic
Muscari spp.	Grape hyacinth	Herbaceous	Exotic
Narcissus spp.	Daffodil	Herbaceous	Exotic
Tulipa spp.	Tulip	Herbaceous	Exotic
Viola bicolor	Field pansy	Herbaceous	Native
Viola spp. (ornamental)	Pansy	Herbaceous	Exotic

1.2 Summary of sample sizes and pollinator taxa associated with studied plant taxa

Table S2. Summary of sample sizes and pollinator taxa associated with studied plant species. *N* exceeds the number of botanical gardens ("No. sites") in cases where a species was surveyed at the same garden in both March and April. "No. poll." corresponds to the total number of pollinator individuals observed visiting each plant taxon. "HB" corresponds to the observed number of honey bees (*Apis mellifera* L.), "MB" to mason bees (*Osmia* spp.), "STB" to short-tongued bees (families Andrenidae, Colletidae, and Halictidae), "BB" to bumble bees (*Bombus* spp.), "CB" to carpenter bees (*Xylocopa virginica* L.), "Wasp" to winged non-bee Hymenoptera, "HF" to hover flies (family Syrphidae), and "OF" to all other flies (non-Syrphidae Diptera).

Plant taxon	No. sites	*N*	No. poll.	HB	MB	STB	BB	CB	Wasp	HF	OF
Amelanchier sp.	1	1	44	16	1	15	0	2	2	6	2
Cercis canadensis	3	3	54	4	24	13	4	0	0	1	8
Chaenomeles spp.	1	2	3	0	1	1	0	0	0	0	1
Citrus sp.	2	3	53	32	3	8	2	0	1	3	4
Forsythia sp.	1	1	37	0	2	8	0	0	6	1	20
Ilex sp.	1	1	71	39	2	11	3	0	8	0	8
Kerria japonica	2	3	19	3	0	10	0	0	4	1	1
Lonicera fragrantissima	2	2	92	26	45	15	0	0	2	1	3
Prunus angustifolia	1	1	52	13	6	13	0	0	1	2	17
Prunus caroliniana	1	1	54	13	0	28	0	0	1	5	7
Prunus spp. (ornamental)	3	4	98	11	42	34	0	0	4	0	7
Pyrus calleryana	3	5	48	16	0	22	0	1	0	7	2
Rhododendron sp.	2	2	16	0	3	2	6	0	4	0	1
Syringa sp.	1	2	17	6	1	0	0	0	1	8	1
Viburnum spp. (open)	2	3	93	43	9	26	0	1	1	5	8
Viburnum spp. (restricted)	1	1	0	0	0	0	0	0	0	0	0
Euphorbia myrsinites	1	2	82	11	0	31	0	0	1	6	33
Galanthus sp.	3	4	0	0	0	0	0	0	0	0	0
Hyacinthoides spp.	1	2	6	1	0	5	0	0	0	0	0
Hyacinthus spp.	1	1	10	2	4	3	0	0	0	0	1
Lamium amplexicaule	1	1	12	1	0	0	0	0	0	11	0
Muscari spp.	1	2	2	2	0	0	0	0	0	0	0
Narcissus spp.	1	1	6	0	0	3	0	0	0	1	2
Tulipa spp.	1	1	9	2	0	2	0	0	0	0	5
Viola bicolor	1	1	1	0	0	0	0	0	0	0	1
Viola spp. (ornamental)	1	1	0	0	0	0	0	0	0	0	0
			Total	**241**	**143**	**250**	**15**	**4**	**36**	**58**	**132**

1.3 Removing an influential outlier modifies the relationship between a plant taxon's garden-level flower abundance and its patch-level pollinator visitation rate

The plant taxon that had the highest recorded garden-level flower abundance was *Viburnum* with narrowed flowers restricting pollinator access. Since this taxon received no visitation from hymenopteran or dipteran pollinators (see Fig. 1 of main text), it constituted an influential outlier in our models (see Fig. S1 of Online Resource 1.4, below). Thus, we constructed alternate versions of our models with this plant taxon excluded to examine the degree to which this outlier may have influenced our conclusions.

The alternative model for the 1-m^2 patch level yielded results consistent with the full model in most respects. Namely, as in the full model, pollinator visitation was higher in woody than in herbaceous plants (Z = 3.67, P < 0.001), positively correlated with each plant taxon's $\log_{10}$-transformed patch-level flower abundance (Z = 2.66, P = 0.008), and unrelated to native status (Z = 0.32, P = 0.75) and survey round (Z = 0.10, P = 0.92). However, unlike in the full model, there was no effect of each plant taxon's scaled garden-level flower abundance (Z = 0.03, P = 0.98), demonstrating that the significant effect of garden-level flower abundance in the full model was driven by this outlier plant taxon.

In contrast, the alternative model for the single-flower level yielded results that were wholly consistent with the full model from a qualitative standpoint. Here, pollinator visitation was higher in woody than in herbaceous plants (Z = 2.28, P = 0.02), negatively correlated with each plant taxon's scaled garden-level flower abundance (Z = 2.07, P = 0.039), and unrelated to native status (Z = 0.55, P = 0.59) and survey round (Z = 0.20, P = 0.85).

The outputs of these alternative models are visualized in Fig. S2 of Online Resource 1.4, below.

1.4 Visualization of model outputs

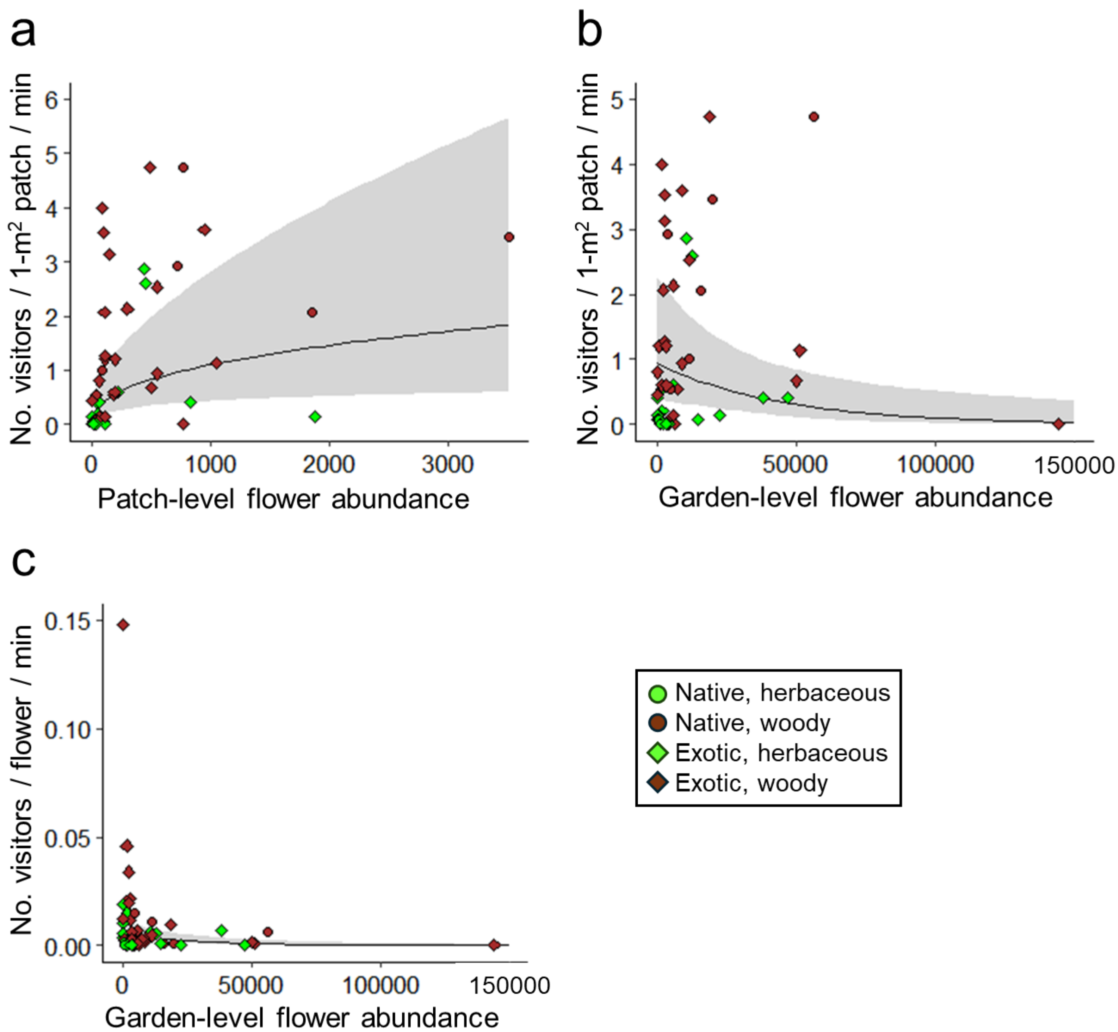

Figure S1. Visualization of outputs of full models reported in the main text. Panels (a) and (b) show effects of patch- and garden-level flower abundance on patch-level pollinator visitation; panel (c) show effects of garden-level flower abundance on per-flower pollinator visitation rate. Data points depict unique combinations of plant taxon, studied garden, and survey round. Solid lines indicate predicted values (with responses averaged over all levels of other predictor variables included in the model); gray bands depict 95% confidence intervals; circles depict native and diamonds depict exotic taxa; and green shapes depict herbaceous and brown shapes depict woody taxa. Predicted values and 95% confidence intervals were generated using R package *emmeans* (Lenth 2024).

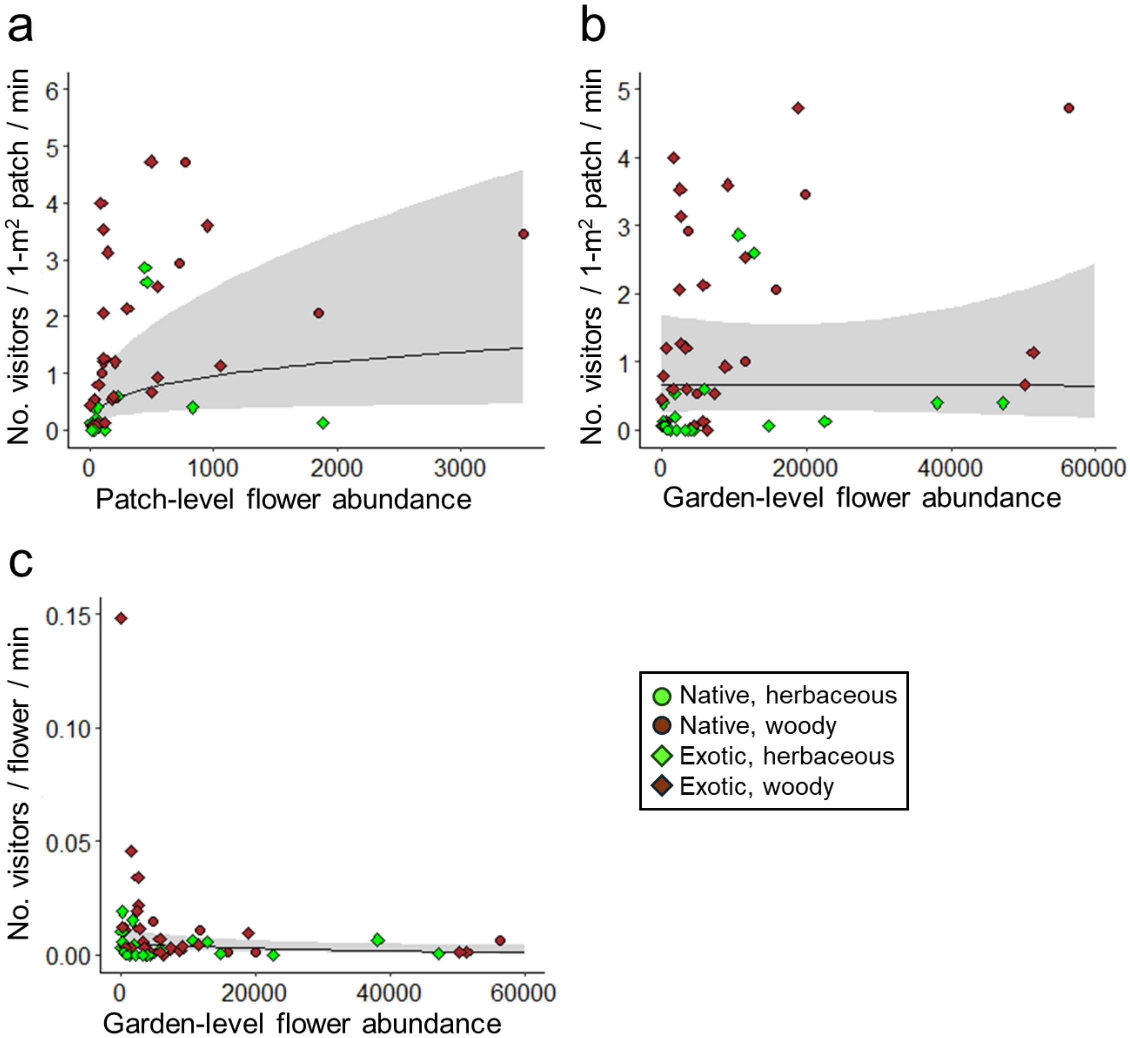

Figure S2. Visualization of outputs of models with the outlier *Viburnum* removed (see Online Resource 1.3, above). Panels (a) and (b) show effects of patch- and garden-level flower abundance on patch-level pollinator visitation; panel (c) show effects of garden-level flower abundance on per-flower pollinator visitation rate. Data points depict unique combinations of plant taxon, studied garden, and survey round. Solid lines indicate predicted values (with responses averaged over all levels of other predictor variables included in the model); gray bands depict 95% confidence intervals; circles depict native and diamonds depict exotic taxa; and green shapes depict herbaceous and brown shapes depict woody taxa. Predicted values and 95% confidence intervals were generated using R package *emmeans* (Lenth 2024).

References

Lenth R (2024). *emmeans*: Estimated Marginal Means, aka Least-Squares Means. R package version 1.10.0. URL: https://CRAN.R-project.org/package=emmeans

1.5 Factors influencing non-honey bee pollinator visitation to studied plant species

The non-native honey bee was the single most abundant pollinator species we observed in our study (Table S1)—as a category, short-tongued bees outnumbered them, but the short-tongued bees included members of three families, represented at least by genera *Andrena* (Andrenidae), *Colletes* (Colletidae), and *Lasioglossum* (Halictidae). Since non-native honey bees may exhibit divergent host-plant preferences compared to native pollinators as a whole, may be distributed unevenly across our studied botanical gardens in the form of managed colonies, and is not a species targeted in native pollinator conservation efforts in North America, we constructed additional GLMMs to verify that this numerically dominant group did not unduly influence our findings. The GLMMs were structured identically to the two models presented in the main text, except honey bees were excluded from the dataset, resulting in a dataset with 638 pollinators—most of which we presumed to be native. Additionally, in the model for visitation at the single-flower level, garden identity was included as a fixed effect instead of a random effect to facilitate model convergence.

When honey bees were excluded from the dataset, visitation at the 1-m^2 observation patch level remained higher in woody than in herbaceous plants (Z = 3.10, P = 0.002), positively correlated with each plant taxon's log_{10}-transformed patch-level flower abundance (Z = 2.82, P = 0.005), and negatively correlated with each plant taxon's scaled garden-level flower abundance (Z = 2.48, P = 0.013); there was no effect of native status (Z = 0.71, P = 0.94) or survey round (Z = 0.27, P = 0.81). Visitation at the single-flower level also remained higher in woody than in herbaceous plants (albeit marginally so; Z = 1.87, P = 0.062) and negatively correlated with each plant taxon's scaled garden-level flower abundance (Z = 3.82, P < 0.001); and there was no effect of native status (Z = 0.29, P = 0.77) or survey round (Z = 0.42, P = 0.68).

1.6 Relationship between growth form and patch-level flower abundance

Woody plant taxa in our study had a greater tendency to present densely packed inflorescences that offered many flowers in a small amount of space. To formally test this observation, we constructed a linear mixed-effects model in which the number of flowers blooming in a 1-m^2 observation patch (log_{10}-transformed to facilitate model fitting) was the dependent variable, growth form was the independent variable, and plant taxon identity was included as a random-intercept effect. This model revealed that woody plant taxa indeed had higher numbers of blooming flowers at the observation patch level ($t_{21.0} = 2.21$, $P = 0.038$).

We also constructed two additional generalized linear mixed-effects models (GLMM), structured similarly to the first negative binomial GLMM presented in the main text, except with either growth form or log_{10}-transformed patch-level flower abundance excluded, to compare the degree to which these two correlated variables predicted pollinator visitation rates when modeled separately from each other. We found that growth form was positively correlated to pollinator visitation rates ($Z = 3.43$, $P < 0.001$), as was log_{10}-transformed patch-level flower abundance ($Z = 3.22$, $P = 0.001$); but the former model had a higher conditional R^2 value (trigamma $R^2_c = 0.89$) and lower AIC score (AIC = 367.3) than the latter (trigamma $R^2_c = 0.82$; AIC = 368.2). Additionally, despite the correlation between growth form and log_{10}-transformed patch-level flower abundance, the full model exhibited variance inflation factors that did not suggest problematic multicollinearity among fixed effects (VIF = 1.08 for native status; 1.25 for log_{10}-transformed patch-level flower abundance; 1.17 for growth form; 1.14 for scaled garden-level flower abundance, and 1.04 for survey round).

Besides the R packages used to construct models (reported in the main text), we used package *MuMIn* (Bartoń 2023) to calculate conditional R^2 values and package *car* (Fox and Weisberg 2019) to calculate variance inflation factors.

References

Bartoń K (2013) *MuMIn*: Multi-Model Inference. R package version 1.47.5. URL: https://CRAN.R-project.org/package=MuMIn

Fox J, Weisberg S (2019) An R companion to applied regression, 3rd edition. Sage, Los Angeles.