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Inspiring citizens and municipalities to initiate pollinator conservation: the urban pollinator matrix modeling tool

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Abstract

Anthropogenic impacts like climate change, pollution, and habitat loss represent ominous environmental threats that can seem insurmountable to concerned citizens. Habitat loss through urbanization presents a particularly acute threat to insect pollinators, which are essential to human agricultural systems and human well-being. Herein, we introduce a user-friendly online modeling tool, The Urban Pollinator Matrix, that predicts how actions initiated by citizens and municipalities can benefit pollinators in backyards and across local communities. The Urban Pollinator Matrix applies a fuzzy interaction web approach to qualitatively model how backyard and community-scale actions can increase pollinator populations. We demonstrate an application of this tool by contrasting how cultivating native flowering plants vs. discontinuing traditional lawn care (i.e., lawn mowing and broadleaf herbicide use) in Missoula, MT, USA, might affect urban pollinators. Our model predicts that reducing traditional lawn care by 50% would increase pollinators modestly, with generalists like honeybees (*Apis mellifera*) benefiting most. In contrast, increasing native landscaping to levels comparable with ornamental landscaping (60% of the community), with no constraints on lawn care, was predicted to generate substantial increases in pollinator abundance, particularly for sensitive groups like bumblebees (*Bombus* spp.) and other native bees. These predictions suggest that cultivating native plants can achieve far greater benefits for important pollinator groups than less socially acceptable actions like discontinuation of traditional lawn care. The Urban Pollinator Matrix provides a modeling template for citizens and municipalities around the globe to incorporate pollinator conservation into urban planning for the betterment of the planet.

Keywords Conservation modeling · Fuzzy interaction web · Pollinators · Native plants · Rewilding · Urban conservation

Introduction

Anthropogenic impacts like climate change, pollution, and habitat loss pose severe threats to ecosystems and the ecosystem services they provide for humanity (Mantyka-Pringle et al. 2012; Oliver and Morecroft 2014; Habibullah et al. 2022). These global threats can seem insurmountable to concerned citizens wishing to effect change for the betterment of their families and futures. In some cases, individuals and local communities can take action to address these daunting threats, but they may lack the tools to understand which actions can help and how best to deploy them. In this paper, we introduce and demonstrate an online modeling tool designed to allow citizens and municipalities to plan conservation actions that can benefit pollinator populations in urban settings. Our intent is to provide a user-friendly and readily accessible template that can be replicated across municipalities around the globe for the betterment of pollinator conservation and human welfare.

Insects are foundational to terrestrial and aquatic food webs around the world, and they provide key ecosystem services for humans (Potts et al. 2016; Wagner et al. 2021). Pollinating insects are essential for the maintenance of terrestrial plant communities (Ollerton et al. 2011), and they support over 35% of global food crops (Klein et al. 2007). The range of services

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insects provide have direct implications for human health and well-being. Insect pollinators support human populations not only through their contributions to agriculture but also via maintenance of biological diversity, plant-based medicines, and open spaces, which measurably benefit human mental health, especially in urban areas (Shepley et al. 2019; Garibaldi et al. 2022).

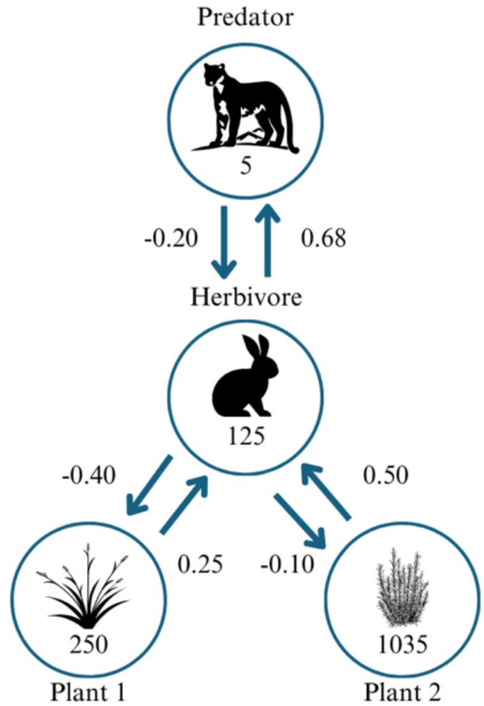
Urban expansion poses a particularly pernicious threat to insects and other biodiversity (McKinney 2008; Van Klink et al. 2020). Compared to natural systems, urban environments are characterized by landscape-scale change, including increased impervious surfaces (pavement, roads, driveways, buildings, sidewalks), drastically reduced plant diversity, and extensive replacement of native vegetation with exotic plant species, all of which can negatively affect wildlife (Cardoso and Gonçalves 2018; Liang et al. 2023). The increase in impervious surfaces has multiple detrimental effects on pollinators. For example, impervious surfaces inhibit water absorption and plant growth, reduce available habitat for ground-nesting native pollinator species, and contribute to increased urban heat, which can be a physiological barrier for some insect species (Ayers and Rehan 2021). Green spaces within urban areas are dominated by non-native grasses and horticultural plants, which affect pollinators in several ways. First, grasses, which rely on wind for pollination, provide minimal resources for pollinating insects. Additionally, many beneficial insects have specialized relationships with native plant species that are often lost from urban environments, leading to reductions in important pollinator groups (Nason and Eason 2023). Finally, urban green spaces are often intensively managed using practices such as mowing and pesticide applications, which can further reduce insect richness and abundance (reviewed in Baldock 2020).

Despite these broadscale negative effects of urbanization on insects, urban spaces can serve as refugia for some pollinator species (Baldock 2020; Hall et al. 2017; Theodorou et al. 2020), and there is potential to manage urban spaces to increase benefits to pollinators (Baldock 2020). For example, adding community gardens or increasing their size or floral diversity can benefit a range of pollinator species (Quistberg et al. 2016; Nason and Eason 2023). In a recent global review of urban pollinator conservation, Baldock (2020) proposed numerous potential "opportunities" or management strategies for benefiting urban pollinators. One of these involves a reduction of traditional lawn care in the form of reduced mowing. This conservation action has since become popularized and advocated for its environmental benefits through the "No Mow May" movement (e.g., Sharma 2023; Ahn et al. 2024). While reduced mowing can benefit pollinators (e.g., Lerman et al. 2018), it is also controversial (Hagerty 2023; Ahn et al. 2024), and it is unclear how effective this strategy is relative to other conservation opportunities. Having readily accessible tools for modeling the efficacy of different management strategies could help focus conservation actions on the most efficacious approaches.

Fuzzy interaction webs (FIW) are a qualitative modeling approach adapted for conservation management (see Fig. 1; Hobbs et al. 2002; Ramsey and Veltman 2005) from fuzzy cognitive maps developed in the social sciences and engineering fields (Kosko 1992; Özesmi and Özesmi 2004). FIWs have recently been vetted against known ecological case studies and shown to provide reasonably accurate qualitative predictions for complex ecological systems (Clark-Wolf et al. 2022) that can help to improve conservation management. FIWs are a powerful tool for modeling complex ecological systems because they can combine high-resolution data with less precise qualitative data and even expert opinion (Ramsey and Veltman 2005). These attributes are invaluable for modeling complex ecological systems where high-resolution quantitative data required for traditional quantitative models are rarely available for all nodes in a network (Pearson and Clark-Wolf 2023), and they are increasingly being used in conservation applications (Hobbs et al. 2002; Ramsey and Veltman 2005; Hunter et al. 2015; Baker et al. 2018). Moreover, having originated in the social sciences, these models can readily incorporate living and non-living ecological elements like plants, insects, and rainfall, along with social constructs and management actions. In sum, this approach holds great potential for addressing conservation management in urban ecosystems, particularly when the mathematics underlying the modeling are integrated into an accessible, user-friendly interface.

In this paper, we introduce a FIW for modeling outcomes of pollinator conservation actions within an urban setting. We designed our model as a template and user's guide for adaptation to other municipalities around the globe. To ensure that individuals without modeling skills can use the tool, we have embedded it within a user-friendly interface (https://matrix.mpgranch.com/#/) accessible online to anyone with a computer and access to the internet. We illustrate the functionality of the model within our system by contrasting predicted outcomes of two alternative management actions that individuals can apply to increase pollinator populations in backyard settings. In one scenario, we predict the effects of reducing traditional lawn care on pollinator populations - defined here as periodic lawn mowing combined with broadleaf herbicide applications commonly used to reduce flowering weeds and maintain grass monocultures. In the other case, we predict the effects of introducing native flowering plants into the backyard setting with no constraints on traditional lawn care. These two scenarios are intended as examples of the many potential modeled management actions that could be explored.

a.



b.

	Plant 1	Plant 2	Herbivore	Predator
Plant 1			0.25	
Plant 2			0.50	
Herbivore	-0.40	-0.10		0.68
Predator			-0.20	

Node	Abundance
Plant 1	250
Plant 2	1035
Herbivore	125
Predator	5

Fig. 1 Depiction of (**a**) a graphical representation of a basic fuzzy interaction web (FIW) and (**b**) a community interaction matrix and a species abundance vector. The basic elements of a FIW include the nodes (species, abiotic factors, or concepts), linkages (connections between two nodes reflecting direct effects of one node on the other [note that these can be unidirectional or bidirectional in FIWs]), linkage directionality (the sign for each linkage indicating a positive or negative effect of one node on the other), linkage interaction strengths (a coefficient indicating the strength or relative strength of node interactions), and node abundances (an estimate of node abundance). The community interaction matrix and abundance vector can be combined mathematically to predict how perturbations or management actions alter community outcomes, i.e., changes in abundance or relative abundance of network nodes. Icon images from Canva

Materials and methods

Study area

We developed our pollinator matrix for the city of Missoula, Montana, which resides in the Northern Rocky Mountain region of the western United States. This city of approximately 75,000 people is located in a large mountain valley within intermountain grasslands surrounded by montane forests. The city is reflective of many smaller US cities in that it has a mix of urban and suburban zones, with the former comprising a mix of businesses and apartment complexes with reduced green space and the latter comprising houses with lawns often accompanied by landscaping and gardens. The city also has numerous city parks and natural areas that provide green spaces along with a few community gardens, the latter of which are rented by citizens for growing food, complemented by ornamentals for esthetics.

Creating the urban pollinator matrix

Deriving from community ecology and network theory (May 1972; Wootton 1994; Godoy et al. 2018), there are five basic elements required to fully describe and hence model an ecological community and its response to perturbations or management actions (Pearson et al. 2022; Clark-Wolf et al. 2022). These are the species or nodes in the network; the linkages connecting the species via interactions like herbivory, predation, competition, or facilitation; the sign indicating the nature of these linkages (i.e., does species A positively or negatively affect species B); the interaction strength associated with each linkage; and the abundance of each species or node. In FIWs, nodes can extend beyond species to represent abiotic factors like precipitation and management actions, thereby allowing for the integration of ecological and human processes. Collectively, these elements can be incorporated into a graphical representation of an ecological network (Fig. 1a) and a corresponding community interaction matrix and abundance vector (Fig. 1b), which can be used to model community responses to perturbations (*sensu* May 1972). The mathematics underlying FIWs are described elsewhere (see Kosko 1992; Ramsey and Veltman 2005; Papageorgiou 2011; Clark-Wolf et al. 2022), and a detailed explanation of the MPG Matrix user interface (https://matrix.mpgranch.com/#/) for applying FIWs is described and vetted by Clark-Wolf et al. (2022) and Pearson and Clark-Wolf (2023) and demonstrated for grizzly bear (*Ursus arctos*) conservation by Gorczynski et al. (in review). Here, we focus on (1) introducing an end-user tool built onto the MPG Matrix that is designed as a template for modeling urban pollinator conservation and (2) providing the basic understanding necessary to adapt this tool to other municipalities (Appendices A-C).

Our urban pollinator matrix (https://matrix.mpgranch.com/#/matrices/7fa1a4) consists of 22 nodes with 69 linkages spread over four organizational levels (Fig. 2): a basal level representing urban habitats relevant to pollinators (8 nodes), a primary consumer level that is focused on key pollinator groups of interest (5 nodes), a secondary consumer level reflecting native birds (1 node), and, lastly, anthropogenic factors representing human actions that influence urban pollinators (8 nodes). The identity of the nodes, their abundance estimation, and the determination of their linkages will vary across urban settings and as a function of conservation objectives (human action nodes). However, our pollinator matrix provides a starting point and template for developing matrices specific to other cities.

In our scenario, each of the eight basal nodes reflects key urban habitats that can positively or negatively influence pollinator abundance. Many of these habitats are common across urban settings. However, in our system, open space comprised of natural areas is an important pollinator habitat that may not be available in all systems. To estimate the abundance for each basal node, we identified the city limits and estimated the proportion of each of our identified habitats present within that boundary using the online i-Tree Canopy tool (https://canopy.itreetools.org/) and the Beescape tool (https://beescape.psu.edu/). Hence, the node values for this level reflect percentages of the landscape for each class and sum to approximately 100. Other web-based tools may also be helpful in defining habitats and estimating cover values, such as the USDA Cropland-CROS tool (Appendix F). Importantly, even if the same habitat classes we used apply to another municipality, the specific node abundance values would need to be estimated for the specific setting using tools like those identified above.

For our pollinator guilds, we identified five categories that reflect commonly recognized pollinator classes (Fig. 2). We assigned relative abundances for each pollinator node as a percentage of the total abundance across all five pollinator nodes (the totals add to approximately 100), as described below. To parameterize the abundance values, we first searched for pollinator survey data from our city. Since we could find no survey results from our municipality, we searched for studies that have published urban pollinator survey results for our pollinator guilds, starting with the most proximal and extending out from there within North America. Given the absence of community-specific data, an ideal data source would derive averaged estimates across all of our pollinator guilds (ideally, all five groups would be simultaneously quantified in each survey) from several nearby cities representing similar environments. However, we only found two North American studies that estimated the

Fig. 2 A depiction of the nodes for an urban pollinator network for the city of Missoula, Montana, USA. Only nodes and node abundances are shown for simplicity because there are 69 linkages in the network (see Appendix D for linkages and interaction coefficients). Unless otherwise noted, photography is from Getty Images via Canva.com. Bumblebees @Myriams-Foto via Canva.com; Honeybees @Ralphs_Fotos via Canva.com; MonoLawns @TimmHill via Canva.com; Open Space @KellyvanDellen via Canva.com; Traditional Lawn Care @Michal Collection via Canva.com

required parameters for Portland, Oregon, USA (Anderson et al. 2022) and Ottawa, Canada (Fukase and Simons 2016). Hence, we first averaged the specific abundance estimates between the two studies for the overlapping groups of bees (note that the category of native bees was described as solitary bees and may include some introduced species), honeybees, and bumblebees (e.g., for each overlapping group, Portland value+Ottawa value=sum/2). We used the unaveraged estimates for other insects and butterflies from the Ottawa study since the Portland study did not quantify these groups. Finally, we summed the values across the groups to get the total pollinator abundance and divided each group by the total to assign a percentage or relative abundance to each node. While these data sources are less than ideal (indicating critical gaps in the literature), they should provide approximations of the relative abundance categories (rank ordering of abundances) sufficient to obtain reasonable qualitative projections from the model. FIWs have been demonstrated to provide fairly robust qualitative predictions using such qualitative data (Clark-Wolf et al. 2022), emphasizing the strength of this tool for real-world conservation challenges. Nonetheless, as data are refined, model outputs can be improved by updating parameter estimates.

As general guidance, we note that nodes can represent individual species or guilds at any trophic level. The degree to which one will break out nodes will depend on the scale at which the system is evaluated (i.e., coarse vs. fine resolution) and the degree to which the organisms may differ with regard to their interactions with other nodes and their responses to system perturbations. For our pollinators, we created four nodes that reflect guilds and one that reflects a species: honeybees. We built our model this way for two reasons: (1) surveys did not provide species-level information to work with except for honeybees, and (2) honeybees behave differently than other pollinators in that they are subsidized by beekeepers, known to be more generalist foragers than many natives, and documented to compete with native pollinators (Torné-Noguera et al. 2016; Ropars et al. 2019). Hence, we wished to reflect on the rather different ways that this node interacts with other nodes and responds to the treatments. While other species in our system no doubt differ to varying degrees in their ecologies, we did not have specific abundance data for them, and we felt that interspecific interactions among them were likely relatively weak compared to other factors driving this system like habitat abundance, pesticides, etc. With sufficient data, one could break out our matrix to reflect more species-specific nodes or more refined guilds (e.g., ground nesting, solitary, bees). The decision regarding the specificity of nodes will be subjective based on data availability and the resolution the observer wishes to depict.

We identified native bird abundance as an important secondary consumer node that we wished to track in our system. This node was estimated using eBird (https://ebird.org/home) observations documented in the Missoula city limits from December 2014 to November 2024. From the reported observational data over this window, we calculated the mean abundance of native passerine birds (summed across all native passerine species) recorded on a standard survey as a general estimate of native bird abundance for the city.

Finally, for our anthropogenic factors, we identified eight key human actions that commonly occur in urban environments that can positively or negatively influence pollinator abundances (Fig. 2). Parameterizing the abundances and interaction strengths for these nodes was more challenging than many of the above nodes, because, for example, unlike the urban habitat categories, there is no simple data source such as GIS information to provide clear estimates for each category. This situation increases the subjectivity associated with assigning parameters, but parameters should never be arbitrarily assigned. Efforts should be made to derive the best understanding and, hence, estimates possible for each node in the network. Model predictions will only be as good as the model structure and parameterization allow. Accordingly, we derived the best approximations of values for each node that we could by primarily using survey data from the United States census and other surveys (Table 1). For example, for the traditional landscaping node, we used results from the 2023 Angie survey of American lawn care (https://www.angi.com/articles/american-lawns-survey.htm), which evaluated how much importance Americans placed on green grass in their yards. We assumed that responses of extremely (23%), very (37%), and moderately (23%) important would provide a reasonable index that such people were likely to maintain green lawns. Hence, we summed these response categories to get an estimate of 73% for this node, which we feel provides a reasonable approximation of city-wide efforts toward the creation of green grass monocultures in backyards, golf courses, city parks, business parks, etc. in our city. We used a similar approach to parameterize other node values as delineated in Table 1.

After providing abundance or effort values for each node, we identified the critical linkages between nodes and determined the nature and strength of those linkages based on natural history information and relevant literature. For example, in our model native bees are positively influenced by open space (1.0), native landscaping (1.0), domestic gardens (0.25), pollinator lawns (0.15), and community gardens (0.25) via the positive effects of floral resources and habitat, weighted by the interaction strengths (in parentheses) reflecting the relative benefit of each of these habitats for native bees (e.g., Frankie et al. 2009; Pardee and Philpott 2014; Banaszak-Cibicka et al. 2016; Quistberg et al. 2016; Larson et al. 2014; Tallamy 2017; Lerman et al. 2018; Lowenstein et al. 2019; Ballare et al. 2019; Rihn et al. 2023; see interaction coefficient matrix Appendix D). For example, very strong interactions of 1 are assigned to the linkage

Table 1 Anthropogenic nodes. This table provides the measurement metric, justification, and sources underlying the parameterization of each of the anthropogenic factors in our matrix. Following US census definitions, homes are defined as an isolated single-unit dwelling where people can have yards, gardens, etc. Households are defined as any dwelling, such as an apartment, house, etc., that a family unit (including a single person) can occupy. We defined populus as the whole population across the City (homes, businesses, etc.)

Node	Measurement	Justification	Sources
Native Planting	Percentage of homes in the study area practicing native planting.	We used the Rhin et al. 2023 survey of attitudes toward native plants to estimate cultivation for Missoula. We took the US census statistics for the proportion of Missoulians that live in a single-unit detached dwelling (i.e., a home where homeowners have space to plant). We multiplied that value times the numbers from the Rhin et al. survey for the category of people responding that native plants are "extremely important" (16%) as follows: The last US Census says 61% of the US, 70% of MT, and 50% of Missoula are single-unit detached dwellings. Hence, 16% responded that native plants are extremely important x 50% of homes in Missoula = 8% that conservatively plant some natives.	https://www.researchgate.net/publication/369008091_Greater_Appeal_of_Native_Plants_for_Environmentally_Conscious_Consumers https://awaytogarden.com/state-of-the-native-plant-movement-with-rebecca-mcmackin/ https://www.census.gov/acs/www/about/why-we-ask-each-question/rooms/
Traditional Landscaping	Percentage of homes in the study area practicing traditional landscaping.	Using the 2023 Angie survey for the US, if we add the lawn care responses of extremely (23%), very (37), and moderately important (23) together, we get 73% of Americans emphasizing traditional lawn care. Given the high proportions of housing in Missoula with traditional lawns, we included the categories of very and moderately important. We applied this value citywide (i.e., to all households and businesses) because apartment complexes, university landscapes, golf courses, and businesses with lawns also apply this approach.	*American Lawns: How Do U.S. Residents Maintain Their Lawns? | Angi* https://www.sciencedirect.com/science/article/abs/pii/S1618866724002589 https://academic.oup.com/jue/article/7/1/juab015/6308279 https://finance.yahoo.com/news/american-homeowners-agree-having-good-130000832.html
Herbicide Application	Percentage of households in the study area using herbicides.	Using the 2023 Angie survey for the US, if we add the lawn care responses of extremely, very, and moderately important together, we get 73% of Americans emphasizing traditional lawn care. Assuming the category of "moderately important" responses does not all religiously apply herbicide, we estimate that 60% of Missoula households use herbicide periodically.	*American Lawns: How Do U.S. Residents Maintain Their Lawns? | Angi* https://www.beyondpesticides.org/assets/media/documents/lawn/factsheets/LAWNFACTS%26FIGURES_8_05.pdf
Domestic Gardening	Percentage of homes in the study area practicing domestic or backyard gardening.	The 2020 estimate of domestic gardening in the United States is 39% of households. We apply this value to homes or single-unit dwellings that can accommodate gardens) within our study area. $0.39 \times 0.50 = 0.20$ for Missoula.	https://www.statista.com/statistics/716538/us-vegetable-gardening-participation/ https://spectrumlocalnews.com/nc/charlotte/news/2024/04/18/more-people-growing-food-at-home-as-grocery-costs-remain-high
Land Development	Percentage of land within city limits that changes from other categories to impervious surfaces each year.	After an extensive review of city planning documents, we found that projections for our rapidly growing region are all based on expanded city limits. Because we wished to project effects within the current city limits, we made the best guess as to how current development and infill affect pollinator resources. We set this value at 4% for the current transformation rate of other habitats into impervious surfaces, as current infill rates are very high.	*Montana Free Press: Missoula Releases Draft of Land Use Plan to Guide Growth Over the Next 20 Years* *Engage Missoula: Growth Policy Update*
Community Gardening	Percentage of effort put into community gardening as a reflection of the current land used for this activity.	Here, we simply use the value reflecting how much land is currently assigned to community gardening as the effort put into it ~ 1%	https://static1.squarespace.com/static/593a9008e6f2e1d2faf911ad/t/66d2282d988b852688743f36/1725048886414/Impact+Report+2023-web.pdf
Ornamental Landscaping	Percentage of the populus in the study area practicing ornamental landscaping.	Estimates obtained here indicate that ornamental planting is generally a good deal higher than vegetable gardening but perhaps slightly lower than traditional monolawns (i.e., some folks with monolawns do not add horticultural plantings). We set the value at 60% (somewhat below traditional lawn care and well above vegetable gardening) of the populous, as many businesses and apartment complexes apply horticultural practices.	https://www.rubyhome.com/blog/gardening-stats/

Table 1 (continued)

Node	Measurement	Justification	Sources
Insecticide Application	Percentage of households in the study area using insecticides.	We could not find estimates of outdoor insecticide application as a per-household metric, so we used Robbins and Birkholtz's 2003 estimate of a 3:1 herbicide-to-insecticide ratio and projected this value across Missoula homes: 0.33×0.6 (our estimate of homes applying herbicides) = 0.20.	https://pmc.ncbi.nlm.nih.gov/articles/PMC2946087/

between native bees and open space because this is their primary habitat, and most native insects have specialized relationships with native host plants (Tallamy 2017). Likewise, a value of 1 is assigned to native landscaping, which provides many of the same resources, but a much lower value of 0.25 is assigned to domestic gardens because surveys indicate that native bees use domestic gardens (Frankie et al. 2009; Pardee and Philpott 2014) but many species are less abundant there than in natural vegetation, presumably because critical host plants may be lacking (Frankie et al. 2009). We likewise linked native bees negatively to insecticides (-0.50), which directly kill them, to native birds (-0.05), which consume them, and to honeybees, which compete with them (-0.05) according to the relative strengths of these interactions (i.e., insecticides kill insects far more effectively than native birds depredate them; e.g., Godfray et al. 2015; Ropars et al. 2019). Importantly, only direct effects are explicitly modeled (Appendix B). Indirect effects arise from the modeling process as a function of additive and synergistic effects of multiple direct interactions. For example, the negative effects of insecticides are directly linked to native bees because they directly kill them, but negative effects of herbicides on native bees arise through indirect interactions as herbicides directly reduce the abundance of flowers in pollinator lawns, which reduces pollinator resources and hence pollinators.

The initial parameter values for interaction strengths are based on published studies and natural history knowledge (Appendix D). However, these values are refined through a model tuning process (Appendix C) wherein interaction strengths are modified iteratively by rerunning the model until the model equilibrates such that node abundances closely reflect real-world data values (we recommend that final node values equilibrate to with 2–5% of the raw abundance estimates; see Clark-Wolf et al. 2022). The justification for this approach is that node abundances can be reasonably well approximated through the processes described above (e.g., using geographic information system-based tools to estimate the relative abundance of the different habitats and using survey methods to estimate pollinator abundance), but interaction strengths are extremely difficult to estimate even for two-way interactions (Wootton and Emmerson 2005; Kleinhesselink et al. 2022). Moreover, within a community context, interaction strengths can change as a function of complex system dynamics (Kleinhesselink et al. 2022). Hence, this tuning process emphasizes more robustly determined matrix elements (the nodes and their linkages, directionality, and abundances) to refine estimates for the more difficult-to-define parameters - the interaction strengths (see Clark-Wolf et al. 2022). Once this tuning process is completed, the final model will closely approximate the real-world system under current conditions, and the model can be used to predict outcomes of perturbations and management actions.

The above process can be executed using the MPG Matrix user interface by either copying the Urban Pollinator Matrix (UPM) into a new matrix for editing or building a new matrix from scratch (Appendix B). To copy and edit the UPM, go to https://matrix.mpgranch.com/#/, create an account or login using a Google login or other login info, choose the Gallery tab, and then open the UPM. Next, go to the Duplicate Matrix icon in the upper right; you can rename this matrix and click OK to create a copy of the UPM template in your private gallery. From there, you can readily edit the matrix by adding/deleting nodes and linkages and altering node abundances and interaction strengths as needed. A new matrix can also be built from scratch by logging into MPG Matrix and going to the Gallery tab. Click Private, then New Blank Matrix, and follow the step-by-step guide to building a matrix. User guides are available at various points within the MPG Matrix to help you navigate these processes.

Modeling pollinator conservation scenarios

To demonstrate an application of the UPM, we contrasted outcomes predicted for two hypothetical pollinator conservation actions that could be executed by individual citizens (see Baldock 2020 for these and other potentially beneficial management actions). These actions were (1) a 50% reduction of Traditional Lawn Care, which we defined as periodic lawn mowing and herbicide applications widely applied in North America to maintain traditional lawn monocultures, and (2) increased cultivation of native flowering plants (dicots) with no constraints on traditional lawn care. The first scenario was modeled by simultaneously reducing by 50% the action values for the traditional lawn care node and the herbicide node. To model the second scenario, we increased the value of the Native Plant Cultivation node from 8 to 60%. This change reflects an increase in the cultivation of native flowering plants comparable to our estimated level of ornamental landscaping across the city. This scenario was deemed plausible under the assumption that the proportion of the community that already cultivates ornamental plants might be encouraged to add or switch to native flowering plants for landscaping. After running each model, we conducted a sensitivity analysis to determine how sensitive the model predictions were to our specified parameter inputs (see Gorczynski et al. in review). This was done by varying the interaction strengths for linkages between the altered node(s) and all other connected nodes by up to 50% in either direction (the range is sometimes bounded to less than 50% by values of zero or one) over 1000 permutations drawn from uniform distributions and calculating the resulting 95% confidence intervals.

These experiments can be recreated, and the sensitivity analyses can be conducted by logging into the MPG Matrix user interface, copying the UPM into a private gallery, and then selecting the Create Experiment tab to generate a modification of the UPM that can be compared to the original base matrix. Once the new experiment is created, the matrix can be modified to reflect the experimental settings by selecting the Edit Matrix icon in the upper right to change to editing mode. Click Create Experiment, name the experiment (e.g., Decreased Traditional Lawn Care and Herbicides), and select OK. Navigate to the Traditional Lawn Care node and click the edit icon in the upper right corner. Select the Population/Abundance tab, use the slider to reduce the abundance by 50%, and hit ok. Repeat this action for the Herbicide node, and the full experiment will be created. Next, to conduct the sensitivity analysis, select the Edit/Analyze button and select Sensitivity Analysis. Within the sensitivity analysis panel, select the nodes to analyze for sensitivity analysis, in this case, Traditional Lawn Care and Herbicide and select the interactions to be assessed, in this case, select Import All Connections for each node. Select Run Analysis and the resulting charts and tables for the sensitivity analysis will be output below. This whole process can then be repeated for the alternative experiment where the Native Plant Cultivation node value is increased from 8 to 60.

Results

Our modeling efforts predicted that both of our proposed management actions, reducing traditional lawn care and cultivating native plants, would likely increase the abundance of all pollinator classes (95% confidence intervals [CIs] did not overlap zero; Fig. 3). However, the overall strength of the effect was predicted to be stronger in response to cultivating native plants, particularly for more specialized species like native bees, butterflies, and bumblebees, which showed significantly higher increases under native plant cultivation than reduced lawn care (corresponding CIs from the different models do not overlap for these groups, except very slightly for native bees). In contrast, reducing traditional lawn care was predicted to increase generalist honeybees more than other pollinator groups (corresponding CIs do not overlap) and more than native planting (although these CIs overlapped somewhat but did not include the means). The differences in these outcomes were driven by the underlying processes and the resulting indirect effects transmitted through the network. For example, the models predicted that abandoning traditional lawn care practices would greatly reduce monoculture lawns dominated by grasses and replace them with pollinator lawns (lawns with common flowering weeds), which would presumably provide generalist pollinators with floral resources from cosmopolitan plants like dandelions (*Taraxacum* spp.), clovers (*Trifolium* spp.), and other weedy species. Hence, abandoning traditional lawn care is predicted to elevate pollinators, particularly generalist pollinators, by shifting monoculture lawns to pollinator-friendly lawns that provide generic pollinator services, but these benefits are modest for most species. In contrast, cultivating native plants was predicted to modestly reduce monolawns and pollinator lawns due to a portion of these habitats being transformed into native flower beds that directly support a range of native pollinators. The larger boost to native pollinator groups arose from the stronger interaction coefficients linking the native floral resources to more specialized hosts. Finally, both actions were predicted to generate small increases in native birds driven primarily by food subsidies to insectivorous and granivorous birds but also via benefits of increased habitat in the form of native shrubs and trees in the case of increased native plantings.

Discussion

Diversity declines arising from anthropogenic impacts spreading across the globe can seem overwhelming to individual citizens in their daily lives. However, there are actions that people can take in their backyards and local communities that can reduce diversity declines and benefit humans. Here, we introduce a user-friendly, internet-based tool, the Urban Pollinator Matrix (UPM), that can be used to predict how different management actions may increase pollinator populations in urban and suburban settings to reduce pollinator diversity declines and increase pollinator services. The tool renders complex modeling procedures accessible to people lacking modeling skills, and the graphical interface illustrates management outcomes using visual aids to

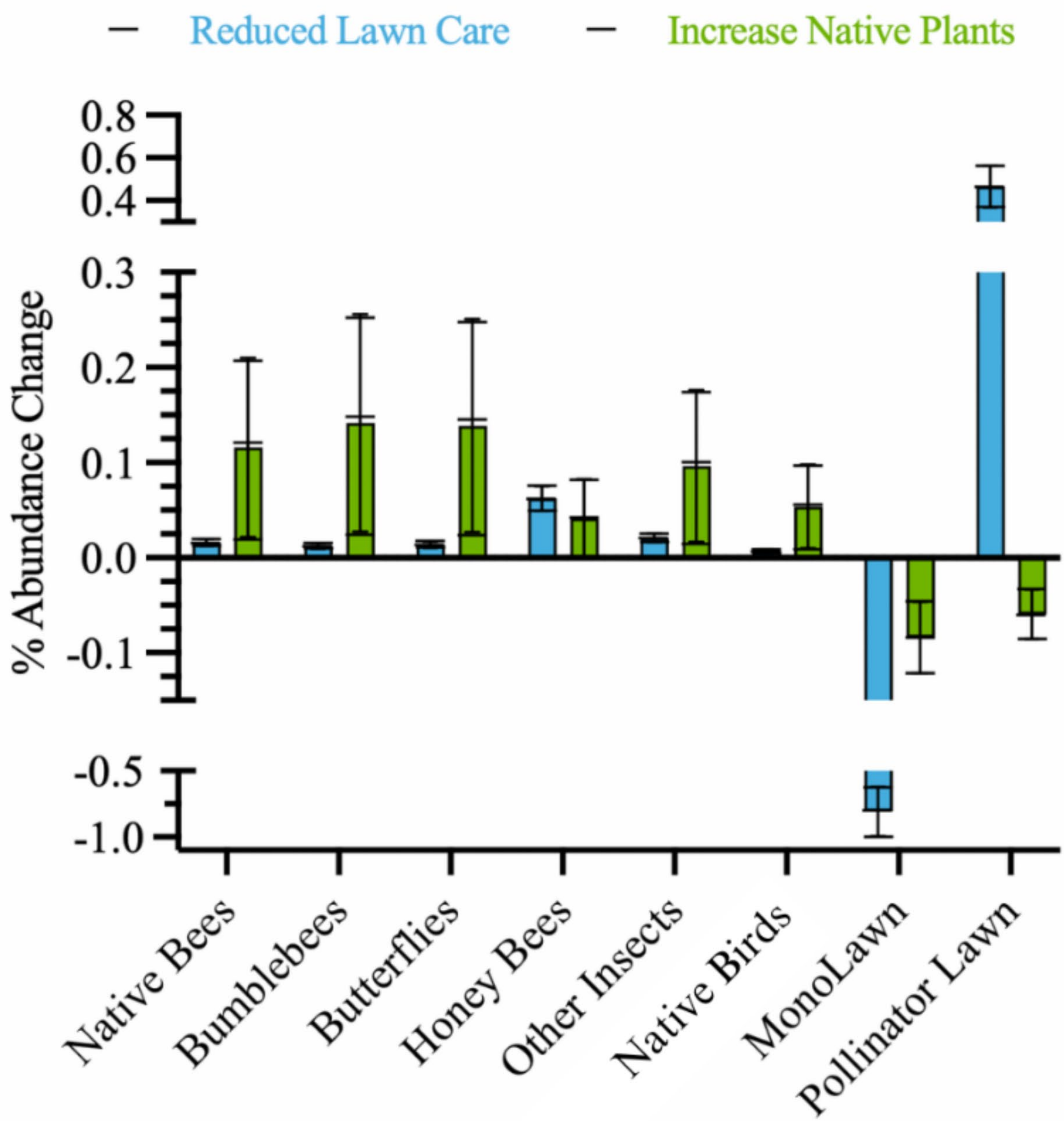


Fig. 3 Output from modeling the effects of two potential conservation actions that citizens could take to benefit urban pollinators in Missoula, MT, USA. These actions were (1) reduced lawn care (by 50%), which we defined as periodic lawn mowing and herbicide applications, and (2) increased cultivation of native flowering plants to the level of ornamental landscaping with no constraints on traditional lawn care. The results reflect the predicted percent change in node abundances from prior to the action with 95% CIs based on sensitivity analyses (see Methods for details). Created with Prism 10 software

enhance communication in ways that can motivate individuals and municipalities toward effective conservation goals. Importantly, the tool is designed as a template that can be adapted to other municipalities using the methods described herein. Finally, the user interface and the underlying fuzzy modeling framework are highly flexible and can be adapted to a range of urban and wildland conservation problems that extend far beyond pollinators (e.g., Hobbs et al. 2002; Ramsey and Veltman 2005; Hunter et al. 2015; Baker et al. 2018).

Our modeled scenario demonstrates how the UPM can be used to explore proposed or competing conservation actions to maximize conservation benefits. While both of our proposed actions were predicted to increase the abundance of all of our pollinator guilds, it is encouraging that the most beneficial action was also the most socially acceptable. The reduction of traditional lawn care practices can benefit pollinators (Wastian et al. 2016; Yang et al. 2019), and this approach has been endorsed as an option for pollinator conservation (Baldock 2020) that has recently been widely popularized by the "No Mow May" movement (Sharma 2023; Ahn et al. 2024). However, many individuals and homeowner associations will likely reject the broad-scale implementation of this strategy (Hagerty 2023; Ahn et al. 2024). Hence, while some individuals may effectively execute this approach on their properties, it does not seem to warrant a major community-level campaign, given the modest benefits derived from even a wholesale community implementation.

In contrast, increasing cultivation of native plants generated substantial benefits to pollinators, particularly the more threatened pollinator groups. Our proposal to increase native plant cultivation to levels comparable with estimated ornamental gardening efforts in our community seems a reasonable goal, given that such a proportion of the community is already familiar with and interested in plant cultivation. Importantly, our model predictions were consistent with studies that have quantified greater pollinator abundance associated with native plant cultivation (Burghardt et al. 2009; Pardee and Philpott 2014; Lowenstein et al. 2019). An added bonus is that even small additions of native plants can increase important pollinator groups, particularly if highly beneficial species are used (Lowenstein et al. 2019). Hence, native plant cultivation can be readily integrated into a variety of landscapes with minimal disruption and arguably substantial aesthetic benefits by simply incorporating native plants into flower gardens, creating native flower borders, and/or adding pots of native plants around yards, on decks, or apartment balconies. Moreover, our model predicted that these effects could also benefit native birds, consistent with empirical studies (Burghardt et al. 2009; Narango et al. 2020). Nonetheless, we caution that model predictions are just that, predictions. The quality of the predictions is determined by the accuracy of the model structure (whether the critical nodes are present and properly linked) and parameter estimates (whether abundance and interaction strength estimates are sufficiently accurate) relative to real-world conditions. We encourage the testing of model predictions when possible and refining of model inputs as data improves to hone model outputs.

FIWs can be valuable tools for evaluating the efficacy of different management actions and for identifying potentially complex, unintended ecological outcomes of well-intentioned management actions (Pearson et al. 2022; Clark-Wolf et al. 2022). While our modeled scenarios did not predict any particularly complex outcomes, we were pleasantly surprised that the treatments were predicted to increase native bird abundance. While this outcome is not shocking, given that it reflects a simple food chain, this result does illustrate how multiple drivers can generate less obvious outcomes via cumulative effects. In this case, the birds increase because they benefit from three simultaneous direct effects: (1) increased insects mean increased foods, (2) increased native plants, which include forbs, trees, and shrubs in our system, mean increased habitat for cover, nesting, roosting, etc., and (3) increased native plants provide plant foods in the form of seeds and fruits. In general, the degree to which FIWs are likely to predict unexpected outcomes to occur will depend on system and model complexity. Complex systems with longer chains and strong interactions can set up unintended consequences because longer chains link to indirect effects, and stronger interactions propel direct effects further through the network (Clark-Wolf et al. 2022). Overall, urban models are less likely to predict unexpected outcomes than more complex models for natural systems. However, as we demonstrate here, FIWs are valuable for (1) assessing which management actions generate more effective outcomes, (2) how combined management actions can increase efficacy (e.g., increasing native plant cultivation and reducing insecticide use may further increase pollinator abundance), and (3) how applying different strategies and/or refining actions can increase efficacy or focus efficacy for different target groups (e.g., exploring how specific native plant species, adding pollinator habitats or cultivating native plants that represent broader flowering phenologies might benefit more pollinator species or specific pollinators). The potential for exploring the relative benefits of different strategies for different objectives are largely constrained by the imagination.

We developed our UPM so that it can be applied to other municipalities to explore a variety of pollinator conservation strategies. Additional questions that communities might consider include evaluating the effects of specific native plant species, native plant phenology, and pollinator habitat attributes like nesting habitat. Current work suggests that some native plants provide pollinator services to far more species than others (Lowenstein et al. 2019; Glenny et al. 2022; Anderson et al. 2022). Moreover, cultivating native plants with different flowering phenologies can be critical for providing season-long services for pollinators (Russo et al. 2013; Wray and Elle 2015; Glenny et al. 2022). Some pollinators also require specific nest site conditions, which vary across pollinator groups and may be reduced in urban settings (Neame et al. 2013; Bennett and Lovell 2019). Baldock (2020) provides an excellent review of urban pollinator threats along with a variety of actions that might be employed to benefit pollinators in urban settings. These ideas can be explored by adapting our UPM to these specific questions and other municipalities. Finally, this tool can be used to explore how altering human landscapes may affect other wildlife like birds, as we demonstrate here, and it can be adapted to address even more disparate questions regarding how greenspace affects human well-being and crime (e.g. Shepley et al. 2019). We hope that this tool will be adopted by various communities around the globe to benefit plant and animal diversity and human welfare in urban and suburban settings.

Conclusions

In conclusion, FIWs provide a flexible tool for examining a great variety of resource management scenarios in wild and urban settings. Importantly, prior efforts at vetting this modeling approach suggest that it can give fairly accurate qualitative predictions with high-quality data and generate reasonable approximations about the general abundance and directionality of node changes with fairly crude data. Finally, the user-friendly interface and templates make this powerful tool readily available to conservation practitioners who may lack modeling skills to expand and improve resource conservation.

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Author contributions MK initiated the idea for this work in conjunction with AD. DEP developed the Pollinator Matrix Model in conjunction with extensive inputs from MK and AD. All authors developed supporting materials. AD drafted the user's guide with input from MR and DEP. DEP drafted the initial manuscript, and all authors edited and contributed to writing.

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Data availability Data generated from this study are located at https://matrix.mpgranch.com/#/gallery and analyses can be replicated there following the Methods and Supplementary material in this article.

Declarations

Competing interests The authors declare no competing interests.

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