Received: 4 June 2024 | Accepted: 17 December 2024

DOI: 10.1111/icad.12806

SHORT COMMUNICATION

Insect Conservation and Diversity

Pollinator visits increase with bloom amount but decline with building height on extensive green roofs

Shannon M. Underwood[1] | **Nicholas Sookhan**[2] | **Keng-Lou James Hung**[2,3] | **J. Scott MacIvor**[1,2]

[1]Department of Biological Sciences, University of Toronto Scarborough, Toronto, Ontario, Canada

[2]Ecology and Evolutionary Biology, University of Toronto, Toronto, Ontario, Canada

[3]Oklahoma Biological Survey, University of Oklahoma, Norman, Oklahoma, USA

Correspondence
J. Scott MacIvor, Department of Biological Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON M1C 1A4, Canada.
Email: scott.macivor@utoronto.ca

Funding information
Department of Biological Sciences at UTSC; Natural Sciences and Engineering Research Council of Canada (NSERC), Grant/Award Number: RGPIN-2018-05660

Editor/Associate Editor: Manu Elinor Saunders

Abstract

- Green roofs provide foraging and nesting resources for pollinators that would otherwise be absent. However, green roofs are isolated from ground level, limiting habitat to only species that can reach them. In Eastern North America, green roof design often prioritises water conservation and plant survival, and so species in the genera *Sedum* and *Phedimus* (hereafter, stonecrops) that are hardy and drought tolerant are mainly planted.
- The purpose of this study was to investigate how building height and bloom amount shape flower-visiting insect communities on extensive green roofs (EGRs). Bees, wasps, and flies (hereafter, pollinators) were surveyed on five plant species (four non-native stonecrops: *Sedum acre*, *Sedum album*, *Phedimus kamtschaticus*, *Phedimus spurius*, and one native herbaceous plant: *Rudbeckia hirta*) from six EGRs and two replicated ground-level control sites in 2019.
- We identified 26 pollinator species and found that stonecrops and *Rudbeckia* showed distinct blooming periods, with the stonecrops flowering from June to August and *Rudbeckia* from August to September. Percent flowering stonecrops during the early bloom was significantly positively correlated with bee abundance and species richness. Pollinator communities determined from distinct stonecrop species were compositionally more alike to one another than *R. hirta*. The inclusion of *R. hirta* lengthened the bloom period of stonecrop-dominated EGRs and attracted five additional bee species. We further determined that pollinator abundance and species richness were negatively correlated with building height.
- Despite its limited scope, our data suggest that pollinator habitat design on EGRs should prioritise low-rise buildings and flowering species with abundant blooms that occur at different times than stonecrops, ensuring complementary flowering periods.

KEYWORDS

bees, green infrastructure, habitat creation, Hymenoptera, pollinators, *Sedum*, stonecrops, urban greening

---

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.
© 2025 The Author(s). *Insect Conservation and Diversity* published by John Wiley & Sons Ltd on behalf of Royal Entomological Society.

INTRODUCTION

Constructed green infrastructure is expected to play a growing role in supporting biodiversity and ecosystem services in cities (Filazzola et al., 2019). Green roofs are one example that have been adopted by cities worldwide, and much research has focused on the contribution of rooftop habitat to flower-visiting insects. These include bees (Hymenoptera: Anthophila) which provision offspring with collected pollen and nectar and are effective pollinators of many native and non-native plants, as well as select wasps (Hymenoptera) and flies (Diptera) which visit flowers to feed on nectar but also act as pollinators. These flower-visiting insects (hereafter, 'pollinators') are widespread, diverse, have a range of mobility, and could benefit from flowering vegetation on green roofs (Braaker et al., 2014; Dromgold et al., 2020; MacIvor et al., 2015). However, green roofs are difficult growing environments due to sun and wind exposure, which may negatively affect plant health and available water, and thus available resources to pollinators, depending on plants selected.

Extensive green roofs (EGRs) are the most common type of green roof installed because these are characteristically lightweight and have low substrate depths, meaning it can be retrofitted onto existing buildings (Li & Yeung, 2014; Oberndorfer et al., 2007). While deployment of EGRs has potential to support pollinators in cities, the plant communities used on EGRs are typically limited to drought-tolerant and shallow-rooting species. In Eastern North America, flowering succulent stonecrop species in the genera *Sedum* and *Phedimus* (Family: Crassulaceae) (hereafter, stonecrops) are widely used on EGRs, as these survive longer and in greater abundance than most other commonly used plant species (Vandegrift et al., 2019).

Nectar and pollen of stonecrops are valuable food resources for many types of pollinators including bees and hover flies (Diptera: Syrphidae) (Clausen, 1975). Several wild bee species have been recorded visiting stonecrops on EGRs in Toronto (MacIvor et al., 2015). However, stonecrop species commonly used on EGRs, at least in northeastern North America, bloom predominantly at the same time in the early summer; thus, stonecrop-dominated green roofs usually represent an ephemeral foraging opportunity for pollinators. Several studies report that bee communities respond positively to increases in floral availability and diversity in other types of urban and seminatural habitats (Birdshire et al., 2020; Frankie et al., 2009; Requier et al., 2020). One study showed that floristically diverse EGRs doubled the local abundance of bees compared to stonecrop-only EGRs (Brenneisen, 2005).

An additional barrier for pollinators is the vertical isolation of green roofs from ground level, which, depending on height, may influence the type and number of pollinators that can access them. Despite being highly mobile, many pollinators are limited in flight distances, which appear to be strongly correlated to body size (at least in bees, which are central-place foragers; Greenleaf et al., 2007). For example, smaller-bodied species may be unable to successfully reach a green roof regardless of the quantity or diversity of flowers. Some studies have shown similar bee communities between ground-level and green roof paired sites (Colla et al., 2009; Dromgold et al., 2020). However, others have reported lower diversity and abundance of bees on green roofs compared to ground-level green spaces (McNamara Manning et al., 2024; Tonietto et al., 2011). Much less is known for wasps and flies (Jacobs et al., 2023; Passaseo et al., 2020).

Decision-makers are often motivated to incorporate EGRs into urban greening initiatives due to their positive impact on biodiversity (see Williams et al., 2014). However, key data gaps persist. Here, we address a data gap by evaluating the effects of bloom amount and building height of EGRs on the abundance and diversity of pollinators. We hypothesise that pollinator abundance and richness would (1) increase with the total number of flowers in bloom, but also (2) decline with building height. We predicted that the addition of herbaceous flowering plants to stonecrop-dominated green roofs would attract unique pollinator species, implying that adding plant species to green roofs enhances urban pollinator conservation. Uncovering relationships between vertical isolation, green roof plant diversity, and the combined effects on urban pollinators will improve how constructed green infrastructure are implemented and managed in cities.

METHODS

Site description

Bees, wasps, and flies were sampled from June to September 2019 from eight identically planted sites across the University of Toronto Scarborough Campus in Toronto, Ontario, Canada. These were located on six distinct buildings varying in vertical height from ground level (between 6 and 20 m) and two set up on ground level as control sites (i.e., 0 m) (Table S1). Each extensive green roof consisted of 45 identically planted modules which were 41 cm × 60 cm × 10 cm (L × W × H) in size. At each EGR, modules were planted with four stonecrop species: *Sedum acre* (L.), *Sedum album* (L.), *Phedimus kamtschaticus* (Fischer), and *Phedimus spurius* (M.Bieb.) in 2017. In 16 of the modules randomly distributed among the 45, an additional five native perennial plant species were seeded in May 2018 (the same modules seeded again in May 2019), including four flowering species: *Allium cernuum* (Roth), *Achillea millefolium* (L.), *Rudbeckia hirta* (L.), *Symphyotrichum novae-angliae* (L. & G.L.Nesom) and one grass, *Festuca rubra* (L.). Of these species, only *R. hirta* flowered during our surveying year. Each EGR was irrigated weekly and in the same way for all sites.

Floral counts

At each site, bloom amount was recorded weekly for each flowering plant species over the sampling period and represented the proportion of modules that had at least one flowering individual of a species out of the total number of modules that were planted with that species. We observed that stonecrops reached full bloom and began to decline as *R. hirta* started blooming (Figure S1). This separation into distinct 'early' and 'late' blooming periods limited our interpretations

1752458, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

to the role of these flowering species on EGRs in extending the bloom period and shaping the temporal dynamics of the pollinator community (i.e., rather than assessing the effect of species identity). Furthermore, during data collection, the bloom amounts of *P. kamtschaticus* were mistakenly combined with those of *P. spurius*, which was significantly less common (MacIvor, personal observation). As a result, we were unable to evaluate the individual contributions of *P. kamtschaticus* and *P. spurius* bloom amounts to site-level differences in pollinator communities. Despite this, it was possible to identify the specific pollinator species and their abundances visiting *P. kamtschaticus* and *P. spurius* separately, as the identity of each flowering species was recorded in a separately conducted survey.

Pollinator sampling from flowers

Pollinators (i.e., all bees, wasps, and flies observed visiting flowers) were sampled from each green roof array on sunny and non-windy days between 10:00 AM and 4:00 PM, approximately once per week. We used targeted aerial netting to capture pollinators observed visiting one of the five flowering species during a 15-min sampling period at each site. We stopped the timer once a pollinator was collected and resumed after the specimen was transferred to a scintillation vial and given a unique ID that referenced the site, time of capture, and flower species. Pollinators were identified to species using reference collections available in the Biodiversity of Urban Green Spaces ('BUGS') lab at the University of Toronto Scarborough, where all specimens from this study are also curated, as well as specialised keys (*Ceratina*: Rehan & Sheffield, 2011; *Nomada*: Mitchell, 1962; *Halictus*: Mitchell, 1960; *Lasioglossum*: Gibbs, 2011; *Coelioxys* and *Megachile*: Mitchell, 1962; *Ammophila*: Menke, 1965: *Parancistrocerus* and *Vespula*: Buck et al., 2008; *Villa*: Kits et al., 2008; *Eristalis*: Dankowicz & Dankowicz, 2021; *Toxomerus*: Dankowicz, 2019; *Criorhina* and *Sphaerophoria*: Miranda et al., 2013).

Analysis

All statistical analyses were completed using R version 4.3.2 (R Core Team, 2023). Generalised linear mixed models (GLMMs) were used to evaluate the effect of (1) bloom amount and (2) a building height gradient on pollinator community richness and abundance. Site identity was included as a random factor. Independent GLMMs were divided across two distinct periods in our study, which we define as 'early' (date range (MM–DD): 06/17–07/28) and 'late' (07/28–09/22). The abundance of stonecrops was much greater than that of *R. hirta*, and peak flowering times did not overlap, and so analysis that collapsed season would limit any interpretation of the effect of *R. hirta* on this EGR plant-pollinator network. GLMMs were initially fit with the Poisson family and log link function. Model fits were assessed through visual inspection of simulated scaled residuals and the simulation-based diagnostic tests for dispersion developed in Hartig (2020). Individual GLMMs were re-fit with the negative binomial family if overdispersion occurred. Zero-inflation of model residuals was not detected in any of the constructed models according to a simulation-based zero-inflation test (Hartig, 2020).

The contribution of each flowering plant species to the pollinator community collected was calculated using Levin's niche breadth (*B*) in the package '*spaa*' (Zhang et al., 2016). Levins' niche breadth estimates the diversity of resources used by an organism (Feinsinger et al., 1981). A higher *B* value indicates a more diverse visiting pollinator community to that flowering species. We visualised *B* using plant-pollinator networks created with the '*bipartite*' package (Dormann et al., 2009). We calculated Bray–Curtis dissimilarity scores using the package '*vegan*' (Oksanen et al., 2007) to compare between the composition of pollinator communities observed on each of the flowering plant species.

RESULTS AND DISCUSSION

Pollinator communities

A total of 146 pollinators (59 bees, 18 wasps, 69 flies) were surveyed on flowers on EGRs and ground reference sites (Table S1 lists abundance and species richness per site, Table S2 lists species determinations). Of this total, 11.5% of pollinators ($N = 17$) were recorded from leaves or other surfaces and without flower visitation data (2 bees, 1 wasp, 14 flies). We identified 18 bee species belonging to four families: Halictidae ($N = 8$ species); Apidae ($N = 6$); Megachilidae ($N = 3$); Colletidae ($N = 1$). Five fly species belonging to two families were identified: Syrphidae ($N = 4$) and Bombyliidae ($N = 1$). Finally, three wasp species belonging to two families, Vespidae ($N = 2$) and Sphecidae ($N = 1$), were identified. The dominant species observed were, for each group, the non-native bee, *Anthidium oblongatum* (Illiger, 1806) (Megachilidae), which represented 30.5% of all bees captured ($N = 18$ individuals); the native wasp, *Parancistrocerus leionotus* (Viereck, 1906) (Vespidae) representing 77.8% of all wasps ($N = 14$); and the native hover fly, *Toxomerus marginatus* (Say, 1823) (Syrphidae), representing 92.8% of all flies ($N = 64$, and the most abundant pollinator in the study).

Bloom amount

Supporting our first hypothesis, we show that pollinator abundance and species richness were weakly positively correlated with stonecrop bloom amount. Analysed separately, it was apparent the trend was driven by bees, as only bee abundance and bee species richness were positively correlated with stonecrop bloom amount during the early period (Table 1). No pollinator taxon's abundance or species richness were correlated with stonecrop or *R. hirta* bloom amount during the late period. Sites did not significantly differ in the average bloom amount over the sampling period (Table 1). A total of 21 pollinator species visited stonecrop flowers on our roofs, while 10 species visited *R. hirta* flowers (Figure 1). In this study, we demonstrate that the

17524598, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 Results from GLMMs of pollinator abundance and richness regressed on building height (m) and bloom amount (%), separated by sampling period ('early' and 'late').

	Early			Late		
	Coefficient	**Abundance**	**Richness**	**Coefficient**	**Abundance**	**Richness**
Pollinator	Height (m)	−0.105*	−0.098*	Height (m)	−0.117*	−0.104*
	Stonecrop (%)	0.003	0.003	Stonecrop (%)	0.000	−0.006
				Rudbeckia hirta (%)	0.007	−0.005
	Site	0.110	0.000	Site	0.000	0.000
Bee	Height (m)	−0.158*	−0.135*	Height (m)	−0.122*	−0.113*
	Stonecrop (%)	0.019*	0.018*	Stonecrop (%)	0.006	0.006
				R. hirta (%)	0.006	0.002
	Site	0.401	0.000	Site	0.000	0.000
Fly	Height (m)	−0.068	−0.045	Height (m)	−0.053	−0.053
	Stonecrop (%)	−0.004	−0.004	Stonecrop (%)	−0.020	−0.020
				R. hirta (%)	−0.015	−0.015
	Site	0.252	0.000	Site	0.000	0.000
Wasp	Height (m)	−0.317*	−0.253*	Height (m)	−0.177	−0.177
	Stonecrop (%)	0.008	−0.001	Stonecrop (%)	−0.164	−0.164
				R. hirta (%)	−0.036	−0.036
	Site	0.000	0.000	Site	0.000	0.000

Note: Significant *p* values ($\alpha < 0.05$) are indicated with an asterisk.

inclusion of just one additional non-stonecrop flowering plant expanded the foraging pollinator community to include five unique bee species active in the late summer.

The Bray–Curtis dissimilarity index revealed that stonecrop species had more overlap in the visiting pollinator communities compared to *R. hirta* (Figure S2). Specifically, the pollinator communities visiting *S. acre* and *S. album* were the most similar in the study (BC = 0.31) whereas *P. kamtschaticus* was most like *P. spurius* (BC = 0.64), but more dissimilar to *S. acre* and *S. album* than to *R. hirta* (Figure S2). The *R. hirta* pollinator community was the most distinct, differing especially from all stonecrops, especially *S. acre* (BC = 0.90), *S. album* (BC = 0.85), and *P. spurius* (BC = 0.85).

Bees, wasps, and flies were recorded visiting each of the five flowering species in our study. Flies were the most abundant pollinators to *S. acre* and *S. album*, while bees were the most frequent visitors of *P. kamtschaticus*, *P. spurius*, and *R. hirta* (Figure 1). A greater range of pollinator species visited *P. kamtschaticus* (Levins' *B* = 5.45), followed by *P. spurius* (*B* = 5.41), *R. hirta* (*B* = 4.45), *S. album* (*B* = 2.92), and *S. acre* (*B* = 2.53) (Figure 1). The most abundant visitor to the stonecrops was the hover fly *Toxomerus marginatus*, except for *P. spurius*, which was visited most by the non-native bee species *Anthidium oblongatum*. *Rudbeckia hirta* was visited most by the bee species *Halictus ligatus* (Halictidae) (Figure 1).

The only seeded plant to germinate and bloom in our study was *R. hirta*, and it has been shown that established *Sedum* can reduce the germination of spontaneous plants that colonise EGRs (Schrieke et al., 2023; Vasl et al., 2017). This could explain the limited success of seeded plants establishing in our stonecrop-dominated EGRs and more work is needed to implement seed mixes suited to these environments (Walker & Lundholm, 2018).

Building height

Abundance and species richness of pollinators (all taxa summed) were weakly negatively correlated with building height during both the early period (Figure S3) and the late period (Figure S4), providing support for our hypothesis. A similar pattern was shown for bees when taxa were analysed independently, but no relationship was detected between building height and wasp or fly abundance (Table 1). No trend with wasps is likely due to too few individuals representing only 13% of the total sample. Flies, unlike bees and wasps, are not central place foragers that make nests and return to them following flower visitation, rather the movement of flies around the landscape is determined by environmental conditions and species-specific behaviours. Since most of the flies observed belonged to a single species, *T. marginatus* (92.7%), it is possible that the lack of nests and the limited influence of building height on their movement in this study could explain why no relationship was found between fly abundance and building height. No pollinators were recorded from flowers on the most isolated green roof in our study, at 20 m from ground level.

The distance an insect must travel from ground level to a foraging opportunity on a green roof, must represent less than the maximum foraging distance, which has been shown to be largely correlated with body size in bees (Greenleaf et al., 2007). Certain pollinators may increase foraging distance travelled for green

17524598, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

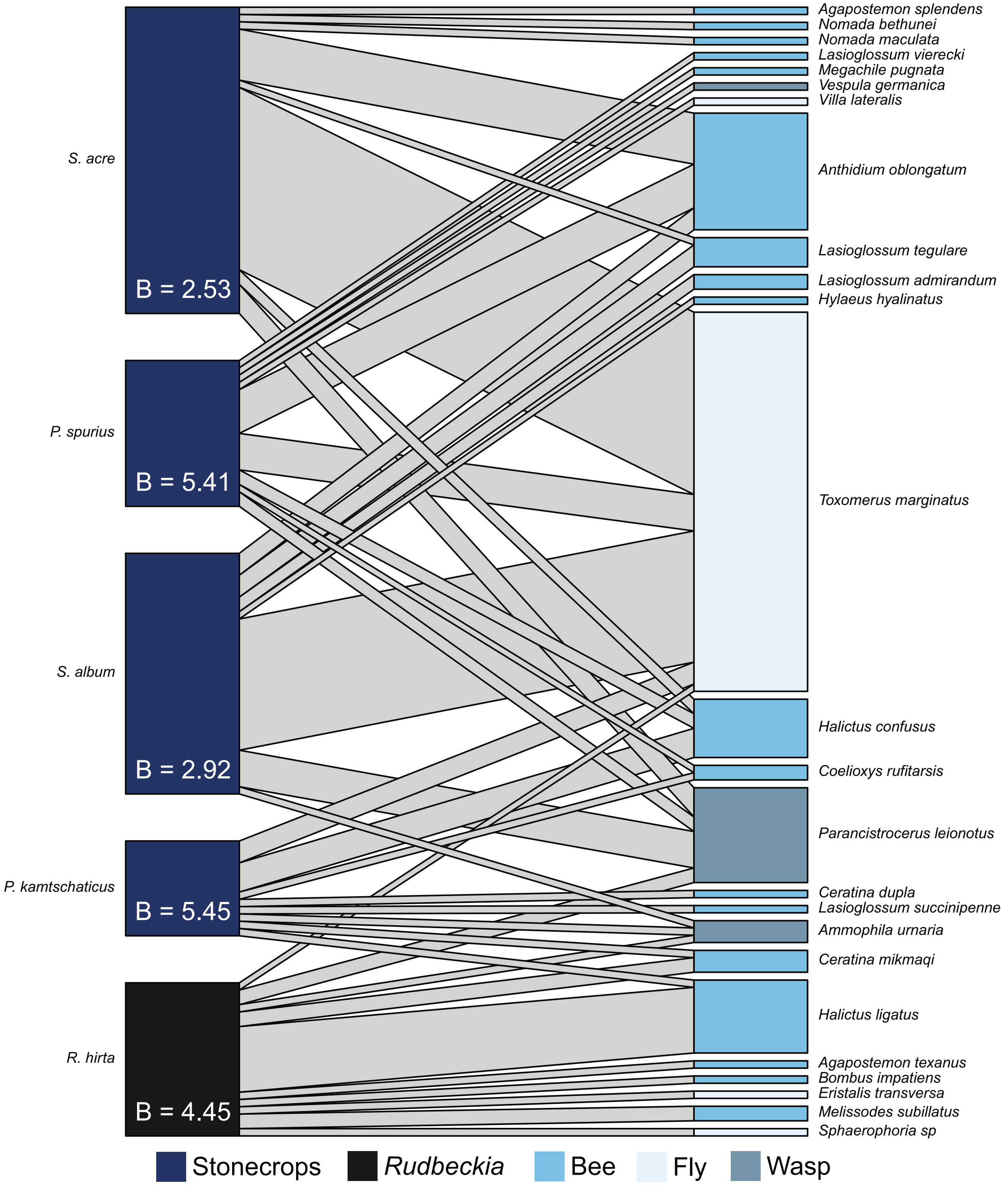

FIGURE 1 Plant–pollinator network of the five flowering plant species included in our extensive green roof arrays: *Sedum acre*, *Sedum album*, *Phedimus kamtschaticus*, *Phedimus spurius*, and *Rudbeckia hirta*. The range of pollinator species utilising each flower species was calculated using Levins' standardised niche breadth ('B'), where higher values indicate a wider range of species.

spaces that offer highly rewarding resources (Beekman & Ratnieks, 2000; Cresswell et al., 2000); however, solitary bees and wasps will aim to forage shorter distances to reduce foraging trip duration in order to maximise offspring production (Klein et al., 2004; Zurbuchen et al., 2010). Our understanding of reward-based foraging distances is based on horizontal distances, and more work is needed to disentangle the three-dimensionality of foraging resources in the built environment—where there are green roofs, green walls, balconies and other spaces where vegetation is present and isolated from ground level.

17524598, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Our study focuses on a temperate-region EGR plant community, involves only eight fully replicated roofs and ground-level sites, and identifies marginally significant relationships between pollinators, bloom amount, and building height. Despite these constraints, our findings align with existing literature. For instance, Kratschmer et al. (2018) showed that wild bees on nine green roofs were influenced by the temporal availability of floral resources. Similarly, positive links between bloom amount and pollinator diversity have been observed in other urban green spaces, such as home gardens (Quistberg et al., 2016) and community gardens (Frankie et al., 2009; but see Matteson & Langellotto, 2011). These results support the growing consensus that prioritising plant diversity and bloom abundance in green roof designs, especially stonecrop-dominated EGRs, can enhance pollinator habitats.

Conclusions

Green infrastructure supports wild pollinators in cities, and green roofs are no exception (Hofmann & Renner, 2018). Using a building height gradient, we find support that building height limits pollinators, but also that bloom amount was correlated with bee activity, and interplanting stonecrop-dominated EGRs with other drought-tolerant perennial taxa extended the blooming period and attracted pollinator taxa unique from those found visiting stonecrops.

With findings from our small study supporting those in other studies demonstrating the negative impact of building height and the positive influence of bloom amount on pollinators, we believe that EGRs implemented to provide habitat for pollinators should prioritise efforts on low-rise buildings and choose plant species that flower at different times than stonecrops to extend the blooming period on EGRs. These considerations should be integrated into design practices and recommended by municipal programs that incentivise the creation of EGRs.

AUTHOR CONTRIBUTIONS

Shannon M. Underwood: Investigation; writing – original draft; methodology; data curation. **Nicholas Sookhan:** Methodology; data curation; formal analysis; visualization; writing – review and editing; conceptualization. **Keng-Lou James Hung:** Writing – review and editing; methodology; data curation. **J. Scott MacIvor:** Conceptualization; methodology; data curation; investigation; funding acquisition; visualization; formal analysis; supervision; writing – review and editing; project administration.

ACKNOWLEDGEMENTS

We thank the University of Toronto Scarborough (UTSC) facility management and staff for cooperation and building access. We thank Julie Wang and Adriano Roberto for maintaining the green roof plant communities, Dr. Thomas Onuferko for assistance with *Nomada* species identification, and Professors Aarthi Ashok, Ivana Stehlik, and Terrence Chang for administering the BIOD98 course taken by the first author and developing the project. We acknowledge bellvania naomi argi pramana, Icogenix, Softscape, and Chehuna for creating icons used in the graphical abstract.

FUNDING INFORMATION

Funding was provided by the Department of Biological Sciences at UTSC through the undergraduate BIOD98 honours thesis program, and by an Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant awarded to JSM (RGPIN-2018-05660).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data used in the study are included in the Supporting Information.

ORCID

J. Scott MacIvor https://orcid.org/0000-0002-2443-8192

REFERENCES

Beekman, M. & Ratnieks, F.L.W. (2000) Long-range foraging by the honey-bee, *Apis mellifera* L. *Functional Ecology*, 14, 490–496. Available from: https://doi.org/10.1046/j.1365-2435.2000.00443.x

Birdshire, K.R., Carper, A.L. & Briles, C.E. (2020) Bee community response to local and landscape factors along an urban-rural gradient. *Urban Ecosystems*, 24, 689–702. Available from: https://doi.org/10.1007/s11252-020-00956-w

Braaker, S., Ghazoul, J., Obrist, M.K. & Moretti, M. (2014) Habitat connectivity shapes urban arthropod communities: the key role of green roofs. *Ecology*, 95, 1010–1021. Available from: https://doi.org/10.1890/13-0705.1

Brenneisen, S. (2005) *The natural roof (NADA)—Research project report of the use of extensive green roofs by wild bees*. Wädenswil, Switzerland: University of Wädenswil.

Buck, M., Marshall, S.A. & Cheung, D.K. (2008) Identification atlas of the Vespidae (Hymenoptera, Aculeata) of the northeastern Nearctic region. *Canadian Journal of Arthropod Identification*, 5, 1–492.

Clausen, R.T. (1975) *Sedum of North America north of the Mexican Plateau*, Vol. 1. New York, USA: Cornell University Press. https://cat.fsl-bsf.scitech.gc.ca/record=3192545~S6

Colla, S.R., Packer, L. & Willis, E. (2009) Can green roofs provide habitat for urban bees (Hymenoptera: Apidae)? *Cities and the Environment*, 2, 1–12. https://digitalcommons.lmu.edu/cate/vol2/iss1/4

Cresswell, J.E., Osborne, J.L. & Goulson, D. (2000) An economic model of the limits to foraging range in central place foragers with numerical solutions for bumblebees. *Ecological Entomology*, 25, 249–255. Available from: https://doi.org/10.1046/j.1365-2311.2000.00264.x

Dankowicz, E. (2019) Calligrapher Flies (Toxomerini): Common Species of Northeastern USA/Canada. Available from: https://docs.google.com/presentation/d/1be4kfvxrHqCQp085SIxyBozEEmze2Y3BJeDJtwan2nY/preview?slide=id.p [Accessed 11th December 2023].

Dankowicz, E. & Dankowicz, Z.R. (2021) Key to *Eristalis* of US & Canada. Available from: https://sites.google.com/view/flyguide/species-guides/syrphidae/eristalini/key-to-eristalis [Accessed 11th December 2023].

Dormann, C.F., Fründ, J., Bluthgen, N. & Gruber, B. (2009) Indices, graphs and null models: analyzing bipartite ecological networks. *The Open Ecology Journal*, 2, 7–24. Available from: https://doi.org/10.2174/1874213000902010007

Dromgold, J.R., Threlfall, C.G., Norton, B.A. & Williams, N.S.G. (2020) Green roof and ground-level invertebrate communities are similar and are

17524598, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

driven by building height and landscape context. *Journal of Urban Ecology*, 6, 1–9. Available from: https://doi.org/10.1093/jue/juz024

Feinsinger, P., Spears, E.E. & Poole, R.W. (1981) A simple measure of niche breadth. *Ecology*, 62, 27–32. Available from: https://doi.org/10.2307/1936664

Filazzola, A., Shrestha, N. & MacIvor, J.S. (2019) The contribution of constructed green infrastructure to urban biodiversity: a synthesis and meta-analysis. *Journal of Applied Ecology*, 56, 2131–2143. Available from: https://doi.org/10.1111/1365-2664.13475

Frankie, G.W., Thorp, R., Hernandez, J., Rizzardi, M., Ertter, B., Pawelek, J. C. et al. (2009). Native bees are a rich natural resource in urban California gardens. *California Agriculture*, 63(3).

Gibbs, J. (2011) Revision of the metallic *Lasioglossum* (Dialictus) of eastern North America (Hymenoptera: Halictidae: Halictini). *Zootaxa*, 3073, 1–216.

Greenleaf, S.S., Williams, N.M., Winfree, R. & Kremen, C. (2007) Bee foraging ranges and their relationship to body size. *Oecologia*, 153, 589–596. Available from: https://doi.org/10.1007/S00442-007-0752-9

Hartig, F. (2020) DHARMa: Residual diagnostics for hierarchical (multi-level/mixed) regression models. R package version 0.3.3.0.

Hofmann, M.M. & Renner, S.S. (2018) Bee species recorded between 1992 and 2017 from green roofs in Asia, Europe, and North America, with key characteristics and open research questions. *Apidologie*, 49, 307–313. Available from: https://doi.org/10.1007/s13592-017-0555-x

Jacobs, J., Beenaerts, N. & Artois, T. (2023) Green roofs and pollinators, useful green spots for some wild bee species (Hymenoptera: Anthophila), but not so much for hoverflies (Diptera: Syrphidae). *Scientific Reports*, 13, 1449. Available from: https://doi.org/10.1038/s41598-023-28698-7

Kits, J.H., Marshall, S.A. & Evenhuis, N.L. (2008) The bee flies (Diptera: Bombyliidae) of Ontario, with a key to the species of eastern Canada. *Canadian Journal of Arthropod Identification*, 6, 1–52. Available from: https://doi.org/10.3752/cjai.2008.06

Klein, A.M., Steffan-Dewenter, I. & Tscharntke, T. (2004) Foraging trip duration and density of megachilid bees, eumenid wasps and pompilid wasps in tropical agroforestry systems. *Journal of Animal Ecology*, 73(3), 517–525. Available from: https://doi.org/10.1111/j.0021-8790.2004.00826.x

Kratschmer, S., Kriechbaum, M. & Pachinger, B. (2018) Buzzing on top: linking wild bee diversity, abundance and traits with green roof qualities. *Urban Ecosystems*, 21, 429–446. Available from: https://doi.org/10.1007/s11252-017-0726-6

Li, W.C., & Yeung, K.K.A. (2014). A comprehensive study of green roof performance from environmental perspective. *International Journal of Sustainable Built Environment*, 3(1), 127–134. https://doi.org/10.1016/j.ijsbe.2014.05.001.

MacIvor, J.S., Ruttan, A. & Salehi, B. (2015) Exotics on exotics: pollen analysis of urban bees visiting *Sedum* on a green roof. *Urban Ecosystems*, 18, 419–430. Available from: https://doi.org/10.1007/s11252-014-0408-6

Matteson, K.C. & Langellotto, G.A. (2011) Small scale additions of native plants fail to increase beneficial insect richness in urban gardens. *Insect Conservation and Diversity*, 4, 89–98. Available from: https://doi.org/10.1111/j.1752-4598.2010.00103.x

McNamara Manning, K., Coffman, R.R. & Bahlai, C.A. (2024) Insect pollinator and natural enemy communities in green roof and ground-level urban habitats. *Urban Ecosystems*, 27, 977–991. Available from: https://doi.org/10.1007/s11252-023-01499-6

Menke, A.S. (1965) A revision of the North American *Ammophila* (Hymenoptera, Sphecidae). PhD Thesis, University of California, Davis. https://ou.on.worldcat.org/oclc/9542997

Miranda, G.F.G., Young, A.D., Locke, M.M., Marshall, S.A., Skevington, J.H. & Thompson, F.C. (2013) Key to the genera of Nearctic Syrphidae. *Canadian Journal of Arthropod Identification*, 23, 351. Available from: https://doi.org/10.3752/cjai.2013.23

Mitchell, T.B. (1960) Bees of the eastern United States (vol. I). Technical Bulletin Number 141. The North Carolina Agricultural Experiment Station.

Mitchell, T.B. (1962) Bees of the eastern United States (vol. II). Technical Bulletin Number 152. The North Carolina Agricultural Experiment Station.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N. et al. (2007) Green roofs as urban ecosystems: ecological structures, functions, and services. *Bioscience*, 57, 823–833. Available from: https://doi.org/10.1641/B571005

Oksanen, J., Kindt, R., Legendre, P., O'Hara, B., Simpson, G.L., Solymos, P. et al. (2007) The vegan package. *Community Ecology Package*, 10(631–637), 719.

Passaseo, A., Pétremand, G., Rochefort, S. & Castella, E. (2020) Pollinator emerging from extensive green roofs: wild bees (Hymenoptera, Anthophila) and hoverflies (Diptera, Syrphidae) in Geneva (Switzerland). *Urban Ecosystems*, 23, 1079–1086. Available from: https://doi.org/10.1007/s11252-020-00973-9

Quistberg, R.D., Bichier, P. & Philpott, S.M. (2016) Landscape and local correlates of bee abundance and species richness in urban gardens. *Environmental Entomology*, 45, 592–601. Available from: https://doi.org/10.1093/ee/nvw025

R Core Team. (2023) *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.

Rehan, S.M. & Sheffield, C.S. (2011) Morphological and molecular delineation of a new species in the *Ceratina dupla* species-group (Hymenoptera: Apidae: Xylocopinae) of eastern North America. *Zootaxa*, 2873, 35–50.

Requier, F., Jowanowitsch, K.K., Kallnik, K. & Steffan-Dewenter, I. (2020) Limitation of complementary resources affects colony growth, foraging behavior, and reproduction in bumble bees. *Ecology*, 101, e02946. Available from: https://doi.org/10.1002/ecy.2946

Schrieke, D., Williams, N.S.G. & Farrell, C. (2023) Response of spontaneous plant communities to *Sedum mexicanum* cover and water availability in green roof microcosms. *Land*, 12, 1239. Available from: https://doi.org/10.3390/land12061239

Tonietto, R., Fant, J., Ascher, J., Ellis, K. & Larkin, D. (2011) A comparison of bee communities of Chicago green roofs, parks and prairies. *Landscape and Urban Planning*, 103, 102–108. Available from: https://doi.org/10.1016/j.landurbplan.2011.07.004

Vandegrift, D.A., Rowe, D.B., Cregg, B.M., & Liang, D. (2019). Effect of substrate depth on plant community development on a Michigan green roof. *Ecological Engineering*, 138, 264–273. https://doi.org/10.1016/j.ecoleng.2019.07.032.

Vasl, A., Shalom, H., Kadas, G.J. & Blaustein, L. (2017) *Sedum*—annual plant interactions on green roofs: facilitation, competition and exclusion. *Ecological Engineering*, 108, 318–329. Available from: https://doi.org/10.1016/j.ecoleng.2017.07.034

Walker, E.A., & Lundholm, J.T. (2018). Designed habitat heterogeneity on green roofs increases seedling survival but not plant species diversity. *Journal of applied ecology*, 55(2), 694–704. https://doi.org/10.1111/1365-2664.12970.

Williams, N.S., Lundholm, J. & MacIvor, J.S. (2014) Do green roofs help urban biodiversity conservation? *Journal of Applied Ecology*, 51, 1643–1649. Available from: https://doi.org/10.1111/1365-2664.12333

Zhang, J., Ding, Q. & Huang, J. (2016) spaa: Species association analysis. R package version 0.2, 2, 33.

Zurbuchen, A., Landert, L., Klaiber, J., Müller, A., Hein, S. & Dorn, S. (2010) Maximum foraging ranges in solitary bees: only few individuals have the capability to cover long foraging distances. *Biological Conservation*, 143, 669–676. Available from: https://doi.org/10.1016/j.biocon.2009.12.003

17524598, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Summary of pollinator visitor richness and abundance (‘Abund’) on green roofs and ground-level sites in our study.

Table S2. Species-level abundances of captured specimens pooled by sampling period (‘Early’ and ‘Late’ period).

Figure S1. Time series of bloom amount across sampling weeks measured as the percent of modules occupied (% occupancy) by species in flower. Floral cover is shown for (A) stonecrop species (with *P. spurius* and *P. kamtschaticus* combined, here listed as *Phedimus* species) and (B) all stonecrops combined and *Rudbeckia hirta*. The solid lines indicate median weekly occupancy values, and the ribbons indicate the first to third quartile. The dotted line denotes the division between the ‘Early’ and ‘Late’ sampling periods.

Figure S2. Matrix of Bray–Curtis dissimilarity scores comparing the pollinator assemblages among the plant species examined. Darker shades indicating higher dissimilarity and lighter shades indicating greater similarity.

Figure S3. Scatterplots depicting the relationships between building height (m) or bloom amount (here ‘cover’ as measured as the proportion of modules in flower) and pollinator abundance or richness during the ‘Early’ sampling period. (A) Building height versus pollinator abundance, (B) building height versus pollinator richness, (C) stonecrop cover versus pollinator abundance, and (D) stonecrop cover versus pollinator richness. Solid curves depict effects estimated by the constructed GLMMs; only curves for significant effects ($\alpha < 0.05$) are displayed.

Figure S4. Scatterplots depicting the relationships between building height (m) or bloom amount (here ‘cover’ as measured as the proportion of modules in flower) and pollinator abundance or richness during the ‘Late’ sampling period. (A) Building height versus pollinator abundance, (B) building height versus pollinator richness, (C) stonecrop cover versus pollinator abundance, (D) stonecrop cover versus pollinator richness, (E) *Rudbeckia hirta* cover versus pollinator abundance, and (F) *R. hirta* cover versus pollinator richness. Solid curves depict effects estimated by the constructed GLMMs; only curves for significant effects ($\alpha < 0.05$) are displayed.

How to cite this article: Underwood, S.M., Sookhan, N., Hung, K.-L.J. & MacIvor, J.S. (2025) Pollinator visits increase with bloom amount but decline with building height on extensive green roofs. *Insect Conservation and Diversity*, 18(3), 438–445. Available from: https://doi.org/10.1111/icad.12806

1752458, 2025, 3, Downloaded from https://resjournals.onlinelibrary.wiley.com/doi/10.1111/icad.12806 by University Of Oklahoma, Wiley Online Library on [14/05/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License