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REVIEW

# Progress Towards Integrating Forests Into North American Pollinator Conservation: New Insights, Past Findings, and Future Directions

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**Abstract**
Managed forests comprise a significant portion of the North American land base and have potential to contribute to pollinator conservation, yet our understanding of how forest management influences insect pollinators is limited. In this paper, we highlight the twelve articles comprising this special issue on forest insect pollinators, summarize research evaluating management impacts on this group within North America, and outline productive avenues for future research. The new articles published here make great strides towards improving our understanding of the diversity, flower associations, and sensitivities of forest insect pollinators, including their responses to management practices. Nevertheless, this group remains unstudied in much North America, including Mexico, Canada, and many US states. Additionally, past studies have largely been descriptive, of short duration, focused on a limited set of topics, and distributed unevenly across forest types. Existing knowledge gaps call for studies aimed at (1) determining which pollinator taxa are forest-dependent, (2) developing management guidelines specific to conifer and broadleaf forests, (3) assessing the value of older forests to insect pollinators, (4) investigating the responses of individual species, and (5) quantifying the effects of less-studied management practices. We encourage new investigations on these topics, especially those that leverage silvicultural practices as a priori manipulative experiments to provide strong inference regarding how management activities influence insect pollinators. Such research will add to our growing knowledge base and help shape future management aimed at maximizing forest ecosystem health, including the conservation of pollinators reliant on these areas.

**Keywords** Bees · Forest management · Insect pollinators · North America · Silviculture

Animal pollinators play a crucial role in enhancing agricultural food production and supporting the functioning of a wide range of terrestrial ecosystems (IPBES 2016).

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Long-term pollinator declines have led to much interest in this group, as such declines can negatively influence pollination services in both managed and natural settings (Potts et al. 2010; Dicks et al. 2021). Although research on pollinators has expanded over time (Rahimi and Jung 2025), the settings in which this work has been undertaken is notably uneven. For example, many investigations of pollinators focus on their role in managed agricultural settings and their link to crop production and human food security. In contrast, other systems have received far less attention and remain relatively unstudied, including forests (Ulyshen et al. 2023). That our understanding of pollinators in forested settings remains particularly limited is somewhat surprising considering that forests make up nearly a third of the global land base (FAO 2024) and they continue to be converted to other land uses, degraded, or managed for a variety of forest products. Nevertheless, this has led to sizable knowledge gaps regarding which pollinators are found within managed forest landscapes, how they respond to natural disturbances, and how different types of forest management activities influence this group (Rivers et al. 2018). Therefore, additional research undertaken on pollinators is needed to improve our understanding of how they are impacted by land management activities, and to evaluate the extent to which managed forests contribute to broader pollinator conservation efforts.

Flower-visiting animals – which we refer to as pollinators for simplicity, while recognizing that many flower visits by animals do not lead to pollination – are a globally diverse group that may represent upwards of 300,000 species (Kearns et al. 1998). In temperate forest ecosystems, insects are the dominant pollinator group, comprised largely of bees and wasps (Hymenoptera), flies (Diptera), moths and butterflies (Lepidoptera), and beetles (Coleoptera). Although species within all of these groups visit flowers to obtain floral rewards (i.e., nectar, pollen, and/or floral oils), their varied life histories lead to differences in the extent to which they interact with flowering plants. For example, moths and butterflies, as well as some species of flies, are characterized by a life cycle in which adults visit flowers to obtain nectar, yet as larvae they consume a diversity of non-floral rewards including live plants, decaying organic matter, and even other insects. In contrast, bees are obligate flower visitors and feed upon floral rewards throughout entire their life cycle, consuming pollen to support growth and development during the larval stage and nectar to fuel their activities as adults (Michener 2010). The diet of bees, coupled with their diversity and abundance, makes them the most significant pollinators in most terrestrial systems (Danforth et al. 2013; Almeida et al. 2023). In addition to their consumption of floral rewards, insect pollinator populations require other resources including nesting areas and oviposition sites and, in some species, areas to overwinter. Thus, understanding insect pollinators in forested settings requires a focus on all of these key resources and how they are influenced by local conditions and land management.

In this manuscript, we have three related objectives. First, we introduce a dozen new research studies published in this special issue and provide context for how they expand upon our current understanding of forest insect pollinators and their response to management activities in forests. Second, we review the published literature on insect pollinators in managed forests of North America to provide a summary of research to date, reporting study components such as the geographic region in which investigations have taken place, the management activities they have evaluated, and the taxa on which they have focused. Finally, we draw upon our review of the literature to highlight topics for which our understanding is most limited at the current time and suggest areas in which new research will provide the greatest advances in this field of study.

## The Contributions of a Dozen New Papers in this Special Issue

This special issue comprises the first published compilation of research studies whose focus is on understanding forest insect pollinators within North America. Given the modest, albeit growing, number of investigations delineated by our literature review (see below), the new studies in this issue collectively provide a substantial advance of the science of forest insect pollinator ecology and conservation within temperate forests. Throughout the rest of this section, we describe the key findings of each paper and provide context for its broader contribution to the field, with papers grouped into six topical areas.

### Disturbances as Creating Habitat

Disturbances are a hallmark for maintaining biodiversity within forest landscapes, and those that occur in closed canopy forests and cause a substantial reduction to the canopy can have strong effects on insect pollinator communities. Disturbances can be broadly classified into those that occur primarily through anthropomorphic means (e.g., timber harvest) or by natural processes (e.g., wildfire). Wildfire – and the use of prescribed fire as a management tool – has been the focus of a sizable proportion of previous studies of forest pollinators (see below), but two studies in the special issue add new dimensions regarding how this disturbance can influence pollinating insects in forests. In the first, Fulton et al. (2025) used an experimental approach to assess how the frequency of prescribed fire influenced ground-nesting bees and wasps in longleaf pine (*Pinus palustris*) forests of northern Florida, and they found that bee and wasp communities benefited by more frequent fire (i.e., areas burned on 1- and 2-year cycles). Because intermediate fire frequencies supported the most diverse spring bee communities, the authors argued that a mosaic of fire frequency should support the greatest diversity of habitat elements for ground-nesting bees and wasps in their region.

Frank et al. (2025) also investigated the response of bee communities to fire; however, their assessment focused on wildfire and included a contrast to commercial timber harvest across a 20-y chronosequence. Results from this study, which was conducted in mixed conifer forests of southern Oregon, mirrored previous investigations by showing that early seral forests supported diverse bee communities, but with subtle differences between fire-origin and harvest-origin stands (Frank et al. 2025). Specifically, bee abundance and richness were greater in fire-origin stands initially, with a shift across time such that these measures were greater in harvest-origin stands towards the end of the early seral period (~20 years post-harvest).

Solitary nesting species that require dead wood as nest sites (e.g., *Osmia* spp.) were documented more often in fire-origin stands, highlighting the importance of dead wood as a nesting resource in stands that develop after large-scale disturbance.

The last paper related to the theme of disturbance comes from Brown et al. (2025), who evaluated the effect of thinning treatments in mid-seral stands on wild bees and their parasites relative to stands of early seral forest and unthinned mature conifer forest in western Oregon. Whereas previous work has shown that early seral conifer forest in this region hosts a diversity of native bee species (Rivers and Betts 2021; Zitomer et al. 2023), Brown et al. demonstrated that thinned mature stands can also provide suitable habitat for bees, although they noted that the bee community in thinned stands was less diverse than those in early seral stands up to 6 years after harvest. Additionally, the study reported that the prevalence of the common parasite genus *Crithidia* was not strongly linked to floral or bee communities, indicating that the foraging areas provided by thinned stands did not promote elevated rates of disease transmission.

## Floral Resource Use

Insect pollinators are united in their use of floral resources to support populations and maintain diverse communities. Despite this, assessments of pollinator use of floral resources in forests are rare, so the paper by Weinman et al. (2025) stands as an important contribution in this regard. The authors documented floral visitation and pollen use by > 100 bee species in deciduous forests in the upper Midwest. Weinman et al. found that the distribution of floral visits by bees was unequal across flowering plant species, and that shrubs and trees comprised a sizable proportion of the pollen from hand-netted bees. This study demonstrates that bees in deciduous forests are not restricted to using flowering plants in the understory, and that woody vegetation can play an important role in providing food resources to pollinators within these landscapes.

Working in a notably different system – post-fire mixed conifer forests of southwestern Oregon – Rivers et al. (2025) also demonstrated the importance of woody plants for the blue orchard bee (*Osmia lignaria*) when provisioning its offspring within recently burned forest. The authors assessed the flowering plant species composition of fecal pellets that were obtained from bees reared across a gradient of wildfire severity four years after wildfire. They found that woody species were often used by nesting bees when feeding their offspring, in addition to other flowering plants found in the understory. However, the number of pollen types of flowering plants provisioned to bee offspring did not vary with fire severity because the woody plants favored by bees were present across the fire severity gradient. Rivers et al. also found no evidence that measures of overwinter survival or body size were impacted by the number of pollen types provisioned to young, ostensibly because provisioned pollen was not limited in the nutrients needed for larval growth and development. Although examining fecal pellets to delineate larval diet has been used sparingly in the past, this study showed it is useful for directly linking fitness proxies to larval floral diets, and this approach can serve as an alternative to destructive sampling of fresh pollen stores from nest cells for researchers interested in quantifying larval diet.

Breland et al. (2025) examined patterns of flower visitation by several insect groups – including flies, beetles, wasps, bees, butterflies, moths, and true bugs – in restored pine (*Pinus* spp.) stands of a western South Carolina forested landscape that was previously used for agriculture. They found that creation of open canopy conditions enhanced the diversity and abundance of floral communities and their insect visitors; however, sites that were not previously subjected to agriculture had more specialized flower-insect interactions. Such findings demonstrate that contemporary restoration of forests can enhance insect pollinator communities, and that agricultural legacies can influence floral-insect interactions decades after agricultural abandonment. As the development of forests following agricultural abandonment is a global phenomenon, these results have important implications for understanding how forest pollinators are influenced by past land use change throughout North America and beyond.

Working in the moist forests of western Oregon, Galbraith et al. (2025) also studied the interactions between insect visitors and their floral hosts but in this case the research was undertaken in Douglas-fir (*Pseudotsuga menziesii*) stands managed intensively for timber production. Galbraith et al. found that bees represented > 75% of the recorded flower visitors and that only one of the five most commonly visited flowers was a native flowering plant. They also found that even though plant and insect taxa changed as stands aged, the amount of time since harvest had a limited influence on several bee-floral networks characteristics, including network modularity, connectance, and robustness. The study by Galbraith et al. reinforces the notion that pollinator communities within intensively managed moist conifer forests occur for a relatively short period of time, and that insect pollinator conservation measures undertaken in this system will have the greatest impact if they are conducted soon after timber harvest occurs. This study also demonstrated that bee-flower interactions in intensively managed forests are closely linked to non-native species during the period of stand regeneration, raising questions about how floral communities and the insects they support may be altered with changes in management intensity.

The aforementioned studies focused on insect pollinator use of floral resources, but what can managers do if floral resources of interest are not present, particularly after a high-severity disturbance? Although seeding of flowering plants to enhance floral resources for insect pollinators has become widespread in managed agricultural settings, the investigation by McDonald et al. (2025) offers a novel take on this topic by applying this methodology to post-fire conifer stands in Oregon. These authors quantified the response of 20 sown plant species across three years in conifer stands that had undergone high-severity wildfire, and they found that areas where slash piles were recently burned were effective in supporting seeded plants for multiple years. Interest in bolstering pollinator habitat by seeding flowering plants is high for many landowners, including those in the forestry sector, so this study suggests that the return on investment for large-scale seeding efforts may be high, at least in areas where the burning of piled slash is a common practice.

## Variation in Forest Types

As more studies of forest insect pollinators are undertaken, patterns are beginning to emerge between different forest types, perhaps none stronger than the contrast between the ecology of insect pollinators inhabiting eastern deciduous forests and western coniferous forests in North America (Ulyshen et al. 2024b). Nevertheless, even within regions there exist forest types that are ostensibly similar, yet they have local factors that exert strong and divergent organizing effects on pollinator communities. One such example is the investigation by Mitchell et al. (2025) that evaluated pollinator communities in dry and moist forest types of the inland Pacific Northwest. These authors found strong differences in bee communities between the two forest types; bees were twice as abundant in dry, warm forests as compared to moist forests, and their composition diverged between these forest types. Floral resources also varied by season and forest type, and were more abundant and diverse as the degree of canopy cover decreased. Taken in its entirety, this study is a reminder that insect pollinator communities can vary markedly even across relatively small spatial scales, and that such differences are often mediated by local forest conditions and linked to variation in flowering plant communities.

## Demographic Measures

Many of the previous studies of forest insect pollinators have focused on assessing the response of communities to disturbances, with fewer studies evaluating vital rates and demographic measures that underly population dynamics. Thus, the work by Dodge and Davis (2025) in this special issue serves as an important contribution to assessing wild bee demographic response to land use change. Working in north-central Colorado, these authors evaluated how landscape composition and disturbance type (i.e., wildfire or thinning) influenced provisioning behavior of nesting blue orchard bees, as well as nest parasitism by a kleptoparasitic beetle (*Tricrania stansburyi*). Dodge and Davis found that neither disturbance type nor landscape composition influenced blue orchard bee nest provisioning, although kleptoparasitic beetle abundance was reduced with increasing urban cover. These findings indicate that some solitary bees nesting in forests may be less affected by landscape composition than their kleptoparasites, and they raise new questions about how other factors that constrain bee populations (e.g., predators) are influenced by contrasting landscape scenarios and disturbance types.

## Effects of Silvicultural Treatments

Whereas much of the work to understand forest pollinators in managed forests has included assessments that focused on ecological aspects of this group, studies that explore how silvicultural treatments influence pollinators are rarer, making the work by Mayfield et al. (2025) a notable contribution to the field. In their study, Mayfield et al. took advantage of ongoing treatments intended to increase the resilience of eastern hemlock (*Tsuga canadensis*) against the hemlock woolly adelgid (*Adelges* *tsugae*) by assessing the consequences of this management tool to forest bee communities. The authors worked in Virginia and North Carolina and found that the creation of small (~0.06 ha) canopy gaps led to improved health of focal hemlock trees 2–3 y after treatments were implemented, and sites with canopy gaps harbored greater bee abundance and richness relative to control sites, where hemlock health declined. Thus, Mayfield et al. demonstrates that canopy gap creation to improve hemlock health has the added benefit of enhancing local bee communities, and this work highlights the value of managers and scientists working together to evaluate the effects of silvicultural practices on insect pollinators in managed forests.

### Guidelines for Managers

In some regions, adequate information has been amassed about insect pollinators that researchers can translate their findings into guidelines for managers; for example, Cunningham-Minnick et al. (2024) recently summarized best management practices for bee openings in the Great Lakes region. In this issue, Ulyshen (2025) similarly provides practical guidelines for forest managers in the southeastern US who are interested in integrating pollinator conservation measures with their management activities. Ulyshen reported that because insect pollinators in the southeastern US vary in their life history requirements, having heterogeneity in habitat is important for providing the broadest support to this group. He also noted that fire – a common management tool in southeastern US forests – can have both positive and negative consequences for insect pollinators, and therefore managers should avoid a one-size-fits-all mindset when approaching habitat management for forest pollinators. This paper concluded by highlighting the need for managers to expand beyond a focus solely on floral resources for insect pollinators, to one that incorporates other key habitat elements, such as nesting and oviposition sites.

## Summary of Previous Research on Forest Pollinator Management

To provide an overview of the type of research undertaken on forest pollinator management to date and to help identify existing knowledge gaps, we reviewed existing peer-refereed studies (1) whose focus was aimed at advancing our understanding of forest insect pollinators and (2) which provided information that could be used by managers to meet forest management objectives. We started by conducting a literature search using standard keyword combinations for our topic (e.g., “forest management AND pollinator”) but this led to an overabundance of papers that were irrelevant, and it also resulted in some key papers being missed. We reasoned that such an approach was unlikely to be productive, so we instead based our review on direct examination of papers – and the literature they cited – that have been published in relevant peer reviewed journals in the fields of animal ecology and forest management. We constrained our search to studies that took place in North America, were undertaken primarily in forests, and were focused on insect pollinators. We did not consider reviews, syntheses, unpublished theses/dissertations, or studies that quantified pollinator habitat elements (e.g., floral resources) without also quantifying insect pollinators in some manner. Because there has been so little work done on this topic in North America, we feel confident that no critical papers were overlooked using this approach.

Our literature survey identified 60 studies in North America, including several appearing in this special issue (Table S1), and it revealed a marked increase in the number of studies published since 2018 (Fig. 1). Although this important body of work serves as a basis for understanding the relationship between managed forests and insect pollinators, they collectively have limitations that prevent a comprehensive understanding of insect pollinators in managed forests at the current time. For example, the location of where studies have taken place in North America is notably uneven (Fig. 2); only six studies have been conducted outside of the US, two in Mexico and four in Canada (the latter restricted to Alberta and British Columbia). In addition, more than half of the studies conducted within the US are restricted to a small number of states: Florida and/or Georgia (15), Oregon (9), Colorado (7), and North Carolina (5). Of note, we found no peer-referred publications on forest pollinators in the states with the greatest levels of bee diversity (e.g., Arizona) and we located only one such study that was conducted in California. Similarly, forest insect pollinators remain unstudied in Alaska despite it having the greatest total of forest land area of any US state. Thus, insect pollinators remain unstudied across large areas of North American forests, including many

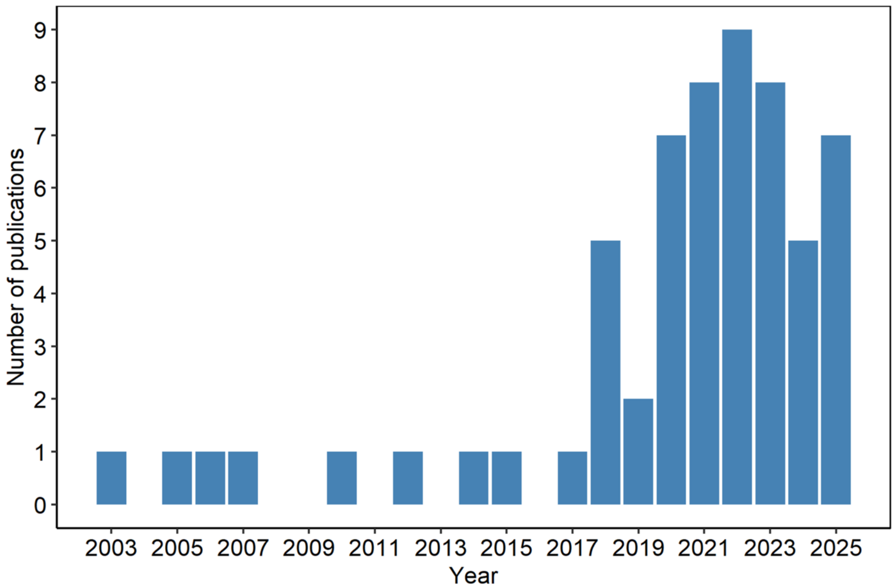


**Fig. 1** The number of peer-refereed publications reporting management-relevant information about forest insect pollinators in North America has grown substantially over the last two decades. Note that we included only one publication from study locations where multiple research projects were conducted. Because multiple research projects from a single study location were more prevalent in recent years, the increase in publications over time is therefore a conservative estimate

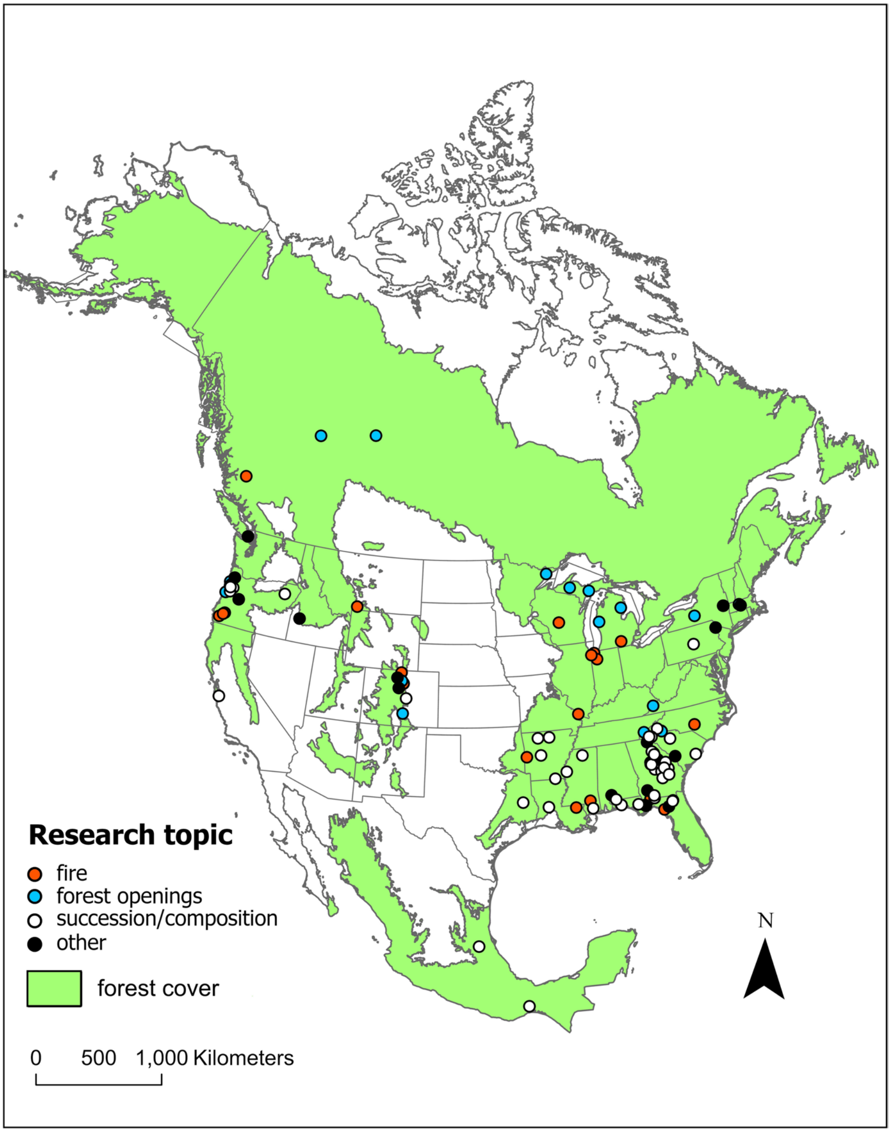


**Fig. 2** Geographic extent of peer-refereed publications reporting management-relevant information about forest insect pollinators in North America relative to the coverage of forest (green) and the study's focal topic, including wildfire/prescribed fire (red circles), forest openings (blue circles), succession/composition (white circles), or other (black circles). For studies whose sampling footprint covered > 50 km – 20% of the total – we plotted multiple points to show the broader coverage by data sampling efforts. Thus, the number of study sites plotted as points on this map greatly exceed the number of studies located via our literature review

regions of the US where forests dominate the landscape and forest management is prevalent.

The limitations of our current understanding are further revealed by considering the topics that have been investigated to date, as well as the spatial and temporal extents of past studies. Topical areas of study have focused heavily on fire – both the timing and severity of wildfire and prescribed fire – as well as forest openings, and the succession and/or composition of stands (Table 1). Of the 60 studies we identified, ~ 78% had a sampling footprint that covered < 50 km, indicating most field-based studies have been conducted on relatively small spatial scales. When considering temporal scales, ~ 85% of studies were two years or less in duration. Most studies have been undertaken as field experiments (45.0%), followed by natural experiments (23.3%), or a combination of both (8.3%); it is noteworthy that we classified only 3 studies (5%) as manipulative experiments (see Table 1 for how studies were classified). As for the focal taxonomic group being investigated, more than three quarters of studies focused solely on bees, with only ~ 17% surveying multiple insect groups simultaneously (Table 1). Finally, most studies involved passive trapping (especially colored pan traps and blue vane traps), whereas less than a third of studies involved sampling insects directly from flowers (Table 1).

Our literature review has revealed some noteworthy patterns regarding past investigations of insect pollinators in North American forests. For instance, it has been established for decades that insect populations are dynamic and can experience strong annual fluctuations (Huffaker et al. 1999), a pattern also characteristic of bees (Williams et al. 2001). Yet, only a small minority of the studies we located were undertaken for > 2 years and therefore unlikely to document the full extent of population variation across time. We suspect this is due, in part, to an artifact of research funding being available for relatively short time periods and is therefore beyond the control of scientists. Nevertheless, the need for long-term studies is as great as ever given concerns about global insect declines (Wagner et al. 2021), as well as large-scale reductions in populations of some previously widespread pollinating insects in North America (e.g., *Bombus occidentalis* in western North America; Graves et al. 2020). Another finding that emerged from our review is that many studies have shown strong, positive responses by insect pollinator communities to disturbances within closed canopy forests. Although these findings are important and useful to managers, community-scale studies do not typically focus on the response of individual species to disturbance or evaluate their fitness consequences. Despite this, new studies at the population level are needed to know which species are “winners” and “losers” in response to disturbance for informed forest management. Additionally, because a key aspect of disturbances in forests are the biological legacies that remain (Seidl et al. 2017), how forests are managed after a disturbance is likely to have far-reaching consequences for insect pollinators. That makes the dearth of studies evaluating the short-term response of insect pollinators to anthropogenic disturbance – such as reforestation, salvage logging, and herbicide application – particularly noteworthy and emphasizes the need for studies that address these responses at the population level. In addition to these points, which emphasize how we can improve upon

**Table 1** Summary of characteristics of 60 peer-refereed publications reporting management-relevant information about forest insect pollinators in North America. Note that some study classifications do not add up to 100% due to rounding error

| Study characteristic | Classification | # of studies (%) | Study characteristic | Classification | # of studies (%) |
|---|---|---|---|---|---|
| **Experimental design** | Field experiment[1] | 27 (45.0%) | **Topical area** | Fire | 19 (31.7%) |
| | Natural experiment[2] | 14 (23.3%) | | Succession/composition | 13 (21.7%) |
| | Observational[3] | 11 (18.3%) | | Forest openings | 9 (15.0%) |
| | Natural & field experiment | 5 (8.3%) | | Fire & forest openings | 2 (3.3%) |
| | Manipulative experiment[4] | 3 (5.0%) | | Post-fire salvage logging | 2 (3.3%) |
| **Sampling approach** | Pan traps | 16 (26.7%) | | Fire and succession/ composition | 1 (1.7%) |
| | Blue vane traps | 11 (18.3%) | | Other[9] | 14 (23.3%) |
| | Blue vane & pan traps[5] | 4 (6.7%) | **Focal pollinating group(s)** | Bees | 46 (76.7%) |
| | Netting | 8 (13.4%) | | Flower visitors[10] | 5 (8.3%) |
| | Netting & passive[6] | 10 (16.7%) | | Butterflies | 4 (6.7%) |
| | Pan trap & other[7] | 2 (3.3%) | | Bees & butterflies | 4 (6.7%) |
| | Emergence[8] | 2 (3.3%) | | Bees & wasps | 1 (1.7%) |
| | Nest traps | 1 (1.7%) | **Forest type** | Conifer | 35 (58.3%) |
| | Visual surveys | 5 (8.3%) | | Hardwood | 16 (26.7%) |
| | White bucket traps | 1 (1.7%) | | Mixed (conifer-hardwood) | 7 (11.7%) |
| | | | | Tropical | 2 (3.3%) |

[1] *Studies were classified as field experiments if they quantified insect pollinator response to changes that occurred through forest management actions but such actions were not implemented* a priori *to assess pollinator response (e.g., harvest at different points in time)*

[2] *Studies were classified as natural experiments if they quantified insect pollinator response to changes that occurred naturally (e.g., response to wildfire severity) but were not implemented* a priori *to assess pollinator response*

[3] *Studies were classified as observational if they quantified insect pollinator response to existing conditions (e.g., gradients in stand age)*

[4] *Studies were classified as manipulative experiments if they quantified insect pollinator response to a specific factor(s) that was altered* a priori *with the intention of understanding insect response to the factor(s) of interest*

[5] *Includes one study that used pan traps, blue vane traps, and visual surveys*

[6] *Passive traps comprised pan traps, blue vane traps, and/or fruit traps*

[7] *Includes one study that combined pan traps with Malaise traps, and one study that combined pan traps with visual surveys*

[8] *Includes one study that combined emergence traps with netting*

[9] *Includes investigations focused on timber harvest, biofuel removal, use of log landings, invasive shrub removal, response to beetlekill, and herbicide intensity*

[10] *Flower visitors includes sampling for multiple taxa: bees, flies, butterflies, and/or beetles*

past studies, below we outline several areas for new research that is expected to advance our understanding of the ecology and management of insect pollinators in managed forests.

## Important Knowledge Gaps that Remain

Collectively, the new studies in this special issue add to the relatively limited literature available on insect pollinators in North American forests, and the findings they report are expected to enhance our management and conservation of insect pollinators within this setting. Nevertheless, information about how insect pollinators are influenced by forest management has lagged behind other animal groups despite calls for more work in this area (Hanula et al. 2016, Rivers et al. 2018), and much research remains to be undertaken. Below we briefly summarize what we consider to be five of the most important knowledge gaps that remain with respect to our understanding of the ecology and management of insect pollinators in managed forests.

First, there is a need for research focused on determining which pollinator species are forest specialists (i.e., species that require resources that are restricted to forests), as such information is critical for aligning management practices to support forest-dependent pollinators. This is important because the needs of such species should be given greater priority than those of habitat generalists which are, by definition, able to persist in non-forested ecosystems. To date, only two efforts have been made to delineate forest-dependent bee species in North America, one from the northeast (Smith et al. 2021) and a second from Florida (Ulyshen et al. 2024a). In contrast, no such efforts have been made in the western half of the US, Mexico, and Canada, nor have studies been undertaken on less-studied insect pollinator groups, despite the value of this information for management and conservation.

Second, best management practices for forest insect pollinators are needed that are tailored to different geographic regions and forest types. The forests of North America are incredibly diverse, and this diversity complicates efforts to develop general approaches to pollinator conservation and management in forests. With such strong differences in forest structure, composition, and age across the continent (Ulyshen et al. 2024b), it is clear there can be no single best management practice that works in all forests. It is also clear that although the ideal scenario would involve local research guiding local management, this is infeasible at the current time for much of North America because of the dearth of published research. Nevertheless, some progress can be made by developing management guidelines separately for conifer- and broadleaf-dominated forests in well-studied regions as a first step towards more spatially refined best practices. For example, although the benefits of canopy reduction to insect pollinators in conifer systems is well-established, less is known about the effects of this practice in broadleaf forests, with virtually no studies regarding how forest-specialist bees in the canopy are influenced by canopy reduction. This is a necessarily coarse starting point, but we expect new studies will emerge that build on these differences iteratively over time and eventually allow for best management practices to be tailored to appropriate scales.

Third, research incorporating a wider range of forest ages would be of great benefit. A number of studies have documented changes in pollinator diversity from early seral habitats to young closed-canopy stands (Mathis et al. 2021; Zitomer et al. 2023). However, limited work has addressed the diversity and composition of pollinators in older forests which tend to be more open, have greater age class diversity, and are characterized by more canopy gaps than forests at earlier stages of succession. Canopy gaps in closed canopy forests are expected to have conditions that could support some insect pollinators (see Brown et al. 2025 in this special issue), and insect pollinator communities may be expected to be more diverse when older forests are embedded in a matrix of young age classes, such as some conifer forest landscapes of the Pacific Northwest. Thus, evaluating insect pollinators across a broad range of forest ages will help refine where conservation actions should be targeted.

Fourth, a greater emphasis should be placed on quantifying the responses of individual species. To date, many studies of forest insect pollinators have focused on community-level responses such as total abundance, species richness, and a range of diversity metrics. Although valuable, these studies do not allow for evaluating how individual species may be impacted by management activities. In contrast, studies at more basal levels of biological organization – such as evaluating population demographic rates and the behavior of individuals (Dorian et al. 2024) – allow for delineating factors that underlie population changes and assessing their fitness consequences. Many community-scale studies have documented dozens of co-occurring insect pollinators, so selecting a model species – such as the blue orchard bee as studied by both Rivers et al. (2025) and Dodge and Davis (2025) in this special issue – may be useful for providing inference to other species that are closely related and share similar life history traits. Studies that simultaneously evaluate several co-occurring species that differ in their life histories (e.g., nesting sites, social organization) may also improve our understanding of how broader insect pollinator communities are influenced by forest management. Thus, we view a combination of new studies that are undertaken at the community scale, as well as those investigating demographic drivers and individual behaviors, as needed for a stronger, more complete understanding of how forest management activities impact insect pollinators.

Finally, and as highlighted by our literature review, most studies to date have focused on a rather narrow set of topical areas, such as how pollinators respond to fire (both wildfire and prescribed fire) or changes in vegetation composition and structure after disturbance. Nevertheless, there remains a wealth of topics central to the management of forests that have been largely ignored. For example, secondary roads are critical infrastructure in working forest landscapes that provide access for harvest operations, telecommunications, and aid in the control of wildfire. Yet our understanding of how roads influence insect pollinators is poor (Hanula et al. 2016), including such topics as the creation of new roads, which may provide new pollinator habitat but may also spread non-native plant species, and road maintenance practices, which using herbicide spraying to reduced noxious weeds that may be of benefit to native pollinators. Likewise, forest herbicides are used in many parts of the world to control competing vegetation during stand regeneration, and this practice has strong potential to influence pollinator communities by changing abiotic conditions and flowering plant communities. However, very few studies have been undertaken on this topic despite its importance (but see Kormann et al. 2021; Briggs et al. 2024). We note that road creation and herbicide use are just two of many contemporary land management activities implemented in forests globally that are expected to have consequences on insect pollinators; studying these and others will improve our knowledge about the effects of forest management on insect pollinators.

## Conclusion

The investigations presented in this special issue will expand our knowledge base of forest insect pollinators, and we anticipate this body of work will be impactful on shaping how forest management practices are undertaken when insect pollinators are considered. Although research on forest insect pollinators has expanded over time, particularly within the last decade, our understanding of how management influences this group remains limited. Past investigations have typically been limited to relatively short periods of time, focused on a subset of topical areas and taxa, and have largely investigated responses at the community level. Thus, the many topics that remain stand to improve our understanding of insect forest pollinators and how they are influenced by management activities, including some most common and widespread practices that take place when managing our forests. Against this backdrop, we note that there is immense value for scientists in working with forest managers to leverage planned silvicultural treatments to evaluate their influence on insect pollinators. Adopting such partnerships can allow for implementing studies that are designed as manipulative experiments and therefore have an a priori focus on measuring pollinator response, an approach that provides stronger inference than most of the investigations that have been undertaken to date. Therefore, we urge scientists to develop partnerships with land managers at the onset of research projects to maximize the amount of information gained. Doing so will not only strengthen our understanding of how forest management influences insect pollinators, but it will also provide opportunities to improve management to benefit insect pollinators and solidify the role that managed forests plays in supporting broader conservation efforts for this group.

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## Declarations

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