REVIEW ARTICLE

J. For. 116(6):563–572
doi: 10.1093/jofore/fvy052
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forest ecology

A Review of Research Needs for Pollinators in Managed Conifer Forests

James W. Rivers, Sara M. Galbraith, James H. Cane, Cheryl B. Schultz, Michael D. Ulyshen, and Urs G. Kormann

Managed conifer forests in temperate regions are critical for supplying wood products, but little is known about their potential for pollinator conservation. We hosted a workshop for Pacific Northwest managers and biologists to identify perceived information gaps regarding pollinators in managed conifer forests; we also undertook a literature review on this topic to assess gaps in the primary literature. The most important gaps identified by workshop participants were a need for baseline data on pollinators in managed conifer forests, and for determining how forest management influences pollinators. Our literature review found a dearth of pollinator studies in managed conifer forests, which were limited to few regions and a subset of taxa. Given these findings, we developed a research agenda that targets identified knowledge gaps, including the need for documenting fundamental aspects of pollinator ecology in managed conifer forests and testing how pollinators and their habitats are influenced by management activities.

Keywords: bees, flies, forest management, managed conifer forest, Pacific Northwest, pollinators

Managed conifer forests, defined here as forested areas in temperate regions that have undergone management, at least in part, for wood products, can contribute to the conservation of forest biodiversity and support critical ecosystem services (Hartley 2002, Carnus et al. 2006, Brockerhoff et al. 2008, Paquette and Messier 2010, Irwin et al. 2014). Despite their potential value, however, few studies have quantified the extent to which these habitats support wild pollinator populations. This is perhaps surprising given that (1) managed conifer forests are essential for the production of wood and fiber needed by society (Carle and Holmgren 2008, FAO 2016); (2) pollinators are critical to human health and global food security (Klein et al. 2007, Gallai et al. 2009); and (3) some conifer forests provide floral resources, nesting substrates, and favorable thermal microhabitats that are required for sustaining wild pollinators (Taki et al. 2013, Rubene et al. 2015a, Hanula et al. 2016, Rodriguez and Kouki 2017). Although a recent review has indicated that some managed conifer forests support wild pollinator populations (Hanula et al. 2016), much remains to be learned about the diversity of pollinators that inhabit conifer forests managed for wood production in different regions and contexts, including the extent to which contemporary forest-management practices influence members of this group and their associated ecosystem services. Thus, empirical research is needed by resource managers to choose among available management prescriptions and practices, yet it is largely unavailable.

Given the current state of knowledge regarding pollinators in managed conifer forests, we organized a 1-day workshop at Oregon State University (Corvallis, Oregon, USA) titled "Pollinators in Managed Forest Landscapes," to provide a venue for discussing current and future pollinator research undertaken in managed conifer forests of the Pacific Northwest region of the United States (hereafter Pacific Northwest). This

Received July 3, 2018; accepted October 8, 2018.

Affiliations: *James W. Rivers (jim.rivers@oregonstate.edu), Sara M. Galbraith (sara.galbraith@oregonstate.edu), Urs G. Kormann (urs.kormann@oregonstate.edu), Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR. James H. Cane (jim.rivers@oregonstate.edu), USDA-ARS Pollinating Insect Research Lab, Utah State University, Logan, UT. Cheryl B. Schultz (schultzc@wsu.edu), School of Biological Sciences, Washington State University, Vancouver, WA. Michael D. Ulyshen (mulyshen@fs.fed.us), USDA Forest Service, Southern Research Station, Athens, GA. Urs G. Kormann (urs.kormann@oregonstate.edu), Forest Biodiversity Research Network, Oregon State University, Corvallis, OR. Urs G. Kormann (urs.kormann@oregonstate.edu), Bern University of Applied Sciences, School of Agricultural, Forest and Food Sciences HAFL, Zollikofen, Switzerland.*

Acknowledgments: *We thank all of the participants of the Pollinators in Managed Forest Landscapes Workshop for sharing the valuable thoughts and insights; we also thank B. Beene, S. Sahnow, S. Tesch, and the many workshop facilitators for their logistical support. Funding that supported this work was provided by the Bureau of Land Management, the Mealey/Boise Cascade/Boone and Crockett/Noble Endowment Fund from the College of Forestry at Oregon State University, the Fish and Wildlife Habitat in Managed Forests Research Program in the College of Forestry at Oregon State University, and a USDA National Institute of Food and Agriculture grant (AFRI-2018-67013-27535).*

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region is a global leader in conifer timber production and contains forests that are dominated by several economically important native tree genera including *Pseudotsuga*, *Pinus*, *Abies*, and *Thuja*, with regeneration approaches and management activities that vary depending on forest type and geographic location. The Douglas-fir (*Pseudotsuga menziesii*) forests of the Pacific Northwest, particularly those found in the coastal forests of Oregon and Washington, can often be subjected to intensive management activities, such as planting genetically improved stock, applying herbicides during the period of stand initiation, and harvesting stands on a short rotation age (Talbert and Marshall 2005). Thus, workshop participants were drawn from a temperate region where managed conifer forests dominate the landscape and forests experience a range of management actions to meet diverse objectives across federal, state, and private ownerships.

The goals of our workshop were twofold; first, we sought to provide participants with an overview of basic pollinator ecology and inform them of recent research being undertaken within managed conifer forests. Second, we held a facilitated discussion to identify perceived knowledge gaps of workshop participants as they related to pollinators within managed conifer forests. This approach allowed us to understand both the working knowledge and information needs of resource managers who implement management practices that impact pollinators and their habitat. After quantifying perceived information gaps by workshop participants, we then reviewed the primary literature to evaluate the extent to which the knowledge gaps highlighted by workshop participants were concordant with real research gaps. Finally, we used our findings to assemble a scientifically based research agenda that provides a framework for future study of pollinators within managed conifer forests. This agenda was developed for scientists conducting empirical studies aimed at improving our understanding of pollinators in managed conifer forests, as well as forest managers, conservation practitioners, and policymakers that seek to balance forest-management activities with the conservation of pollinators and their habitats. Although the starting-point for our agenda is the Pacific Northwest, the global footprint of managed conifer forests, including intensively managed plantations, makes our research agenda widely applicable and relevant worldwide.

Materials and Methods

Workshop for Forest Managers and Scientists

To better understand the perceived research needs of forest managers and scientists, we held our workshop on March 30, 2017 at Oregon State University in Corvallis, Oregon, USA. The free workshop was advertised widely to maximize the number of forest managers, scientists, and other interested parties, and of 114 registrants, 90 attended. The affiliations of workshop participants were broad and represented the range of entities that own, manage, and/or work within managed conifer forests of the Pacific Northwest, including government agencies, private industry, nonprofit organizations, and academic researchers. At the time of registration, each individual was surveyed to provide information regarding the organization with which they were affiliated, as well as the depth of their understanding of pollinator ecology.

The workshop consisted of distinct morning and afternoon sessions; the morning session comprised short (20-min) presentations by a group of researchers conducting recent research on pollinators within managed forest landscapes (i.e., the authors of this article), with breaks for informal discussion and networking. In contrast, the afternoon session was designed as a facilitated discussion in which participants were placed into predetermined groups of approximately 10 individuals; groups were intentionally created so that they contained members with a range of affiliations to facilitate the sharing of diverse perspectives during discussion. Once in their discussion group, each participant was asked to provide responses to three questions related to pollinators in managed conifer forests as follows:

Question 1. Are there any apparent knowledge gaps that prevent you from making management decisions that consider pollinators?

Question 2. What are the management activities your group undertakes that may impact floral resources and nesting habitat for pollinators?

Question 3. What barriers exist for implementing management that supports pollinator populations in the areas in which you work?

These questions were provided to workshop participants at the start of the morning session so responses could be considered prior to the afternoon discussion.

Workshop Data Collection

Each afternoon discussion group was joined by a trained facilitator who recorded the responses of individuals onto a group whiteboard to encourage all group members to provide input. The facilitator did not provide their own responses to the questions being posed, but they did work with group members to ensure clarity of individual responses. Each group had approximately 1 h to share individual responses to the

Management and Policy Implications

Animal pollinators play a pivotal role in the production of food used by human and wildlife populations, but the extent to which managed conifer forests support pollinators in temperate regions remains largely unknown. We held a day-long workshop with land managers and biologists from the Pacific Northwest to review perceived knowledge gaps regarding pollinators in managed conifer forests, and we conducted a literature review of published studies from the primary literature. We found clear and extensive knowledge gaps regarding pollinators in managed conifer forests, with both a lack of baseline information about pollinators in these habitats and a dearth of studies that have evaluated the impact of forest-management activities on pollinators. Given increased concerns about pollinator health in response to human-induced changes in land use, our study highlights an urgent need for new investigations that evaluate the relationships between pollinator diversity, management activities, and the ecosystem services that pollinators provide within managed forest ecosystems. Filling the knowledge gaps we have identified through empirical studies will be critical for generating new information needed by forest managers, conservation practitioners, and policymakers seeking to enhance pollinator populations in light of contemporary forest-management practices.

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three discussion questions, after which they were asked to come to a consensus and rank their top three responses to each of the three focal questions. After a short break, participants reconvened for a workshop-wide discussion where one participant from each group reported the top three responses to the first question posed (above), as our overall goal was to work towards a detailed list of perceived knowledge gaps as identified by participants. The workshop-wide discussion was led by a single facilitator to clarify statements made by group representatives, and each new response was added to a running list that all participants could view during the reporting process.

After the group discussion ended yet prior to close of the workshop, we provided each participant with a short questionnaire where we asked them to list their work affiliation and provide a response to the following question: "In your opinion, what are the top three knowledge gaps related to pollinators in your managed forest landscape?" Although the wording of this questionnaire was very similar to the first question posed in the group discussion, we felt it was important to survey individuals at the end of the workshop for two reasons. First, we wanted to ensure that all participants were exposed to as many topics as possible prior to providing a response, including perspectives that may have not been raised within their group-level discussion. Second, we wanted respondents to feel free to list topics that they thought were most important, including those that they might have not been willing to share within a group setting.

Workshop Data Analysis

We transcribed responses that were recorded during workshop discussions, and then developed a codebook to identify general themes among responses (Weston et al. 2001). To ensure consistent interpretation of the responses, three of the authors (JWR, SMG, UGK) independently applied the codebook to a subset of responses, calculating an inter-rater reliability agreement coefficient after each iteration (Kurasaki 2000). We then revised the coding until we reached a minimum reliability coefficient of 0.90 (Krippendorff 2004). Because workshop participants were not randomly chosen, we restrict our data presentation related to the workshop to basic summary statistics.

Literature Review Data Collection

We used Web of Science (v5.29) to search for research publications in the primary literature that were focused on pollinator research in managed conifer forests. Although ours was not an exhaustive search of available literature, it does represent an unbiased sample of the available literature on our focal topic. We constrained our search to published studies of managed conifer forests in temperate regions using the following combinations of terms, which resulted in 15 individual searches undertaken on 14 May 2018: pollinator AND forest management, bee AND forest management, fly AND forest management, pollinator AND managed forest, bee AND managed forest, fly AND managed forest, pollinator AND agroforestry, bee AND agroforestry, fly AND agroforestry, pollinator AND timber harvest, bee AND timber harvest, fly AND timber harvest, pollinator AND temperate forest, bee AND temperate forest, fly AND temperate forest. We elected to focus our search using "pollinator," "bee," and "fly" because these terms were considered to represent the best-studied pollinator groups in general and thus would be most likely to identify relevant literature conducted in managed conifer forests.

As a first step towards identifying relevant literature, one of us (JWR) evaluated titles, abstracts, or both for each publication identified from the literature search to determine whether it was relevant to pollinator research in managed conifer forests. In the event that our initial review was inconclusive regarding its relevance to managed conifer forests, we adopted a conservative approach and included the publication as one that was potentially relevant to our literature search. Next, we closely examined the remaining pool of publications (i.e., those relevant, and those whose relevance was inconclusive) by reviewing the actual publication to determine whether it was germane to managed conifer forests and ensure that it included some measure of pollinator(s) at either the population or community level. Through this two-step approach, we identified three types of publications: empirical studies that directly evaluated pollinator responses to effects of forest management in conifer forests, empirical studies of pollinators that were conducted within managed conifer forests but were driven by questions of an ecological nature, and a single literature review of pollinator research in forests whose focus included managed conifer forests (i.e., Hanula et al. 2016). For each study we deemed relevant, we report its location, conifer forest type, focal pollinator group(s), and the management-related topic(s) that the study addressed.

Results

Workshop Responses to Pollinator Research Knowledge Gaps

The majority of workshop registrants (52 percent) were affiliated with some branch of government (e.g., federal, state, city); other affiliations include research universities (15 percent), forest industry (13 percent), nongovernment organizations (NGOs; 5 percent), and small private timber companies (1 percent). Interested members of the public comprised the remaining 14 percent of registrants. When polled on their understanding of pollinator ecology prior to the workshop, respondents were variable: 5 percent reported very good, 33 percent reported good, 47 percent reported fair, 13 percent reported poor, and 2 percent reported very poor.

Basic aspects of pollinator ecology was the most common apparent knowledge gap perceived by workshop groups within the context of managed conifer forests (Table 1). This included information regarding the nesting habitat requirements, preferred floral resources, and foraging range of pollinators. For example, when outlining perceived knowledge gaps, one group asked "What bees are present?" whereas another group listed "Habitat needs for species—how much is enough?" Management-related impacts, or the influence of forest management on pollinators and pollination, was the second most common category of apparent knowledge gaps. Other knowledge gaps comprised less than 20 percent of the responses; examples included: monitoring methods and training (e.g., "Standardized long-term monitoring of rehabilitation success"), reasonable targets for restoration (e.g., "What is restoration success and how to get there"), extension, outreach, and communication (e.g., "More education on basic pollinator concepts within and among industries and organizations"), and

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Table 1. Categorization of responses by small discussion groups to the question: Are there any apparent knowledge gaps that prevent you from making management decisions that consider pollinators?

Theme	Examples	Number of related statements	Percentage of responses
Pollinator ecological information	Pollinator foraging range Flower preferences Nesting habitat	41	47
Management-related impacts	Impacts from various management activities Baseline information for comparison	27	31
Monitoring methods and training	Pollinator identification Systematic sampling of pollinators	8	9
Reasonable targets for restoration	Species/plant-pollinator interactions representing a "restored" system	3	3
Extension, outreach, and communication	Key messages for public Education strategies within industries and organizations	2	2
Costs and benefits of supporting pollinators	Economic tradeoffs of adjusting management to support pollinators	2	2
Other		5	6

costs and benefits of supporting pollinators (e.g., "Costs/benefit analysis of invasive species and pollinators").

Overall, 46 participants filled out the individual questionnaire at the end of the workshop. Most respondents were associated with government agencies (n = 24), but individuals representing NGOs (n = 5), timber industry, private landowners, and academia also responded (n = 4 each). Five participants did not provide any information about their professional affiliation. In total, 110 perceived knowledge gaps were recorded; one answer was excluded, as it related to lack of funding rather than to a perceived knowledge gap, and three participants did not include knowledge gaps in their responses. Reported knowledge gaps were most commonly considered to be associated with *Management-related Impacts* (n = 46 answers) and *Ecology and Distribution of Pollinators* (n = 38; Table 2, Figure 1), followed by *Training and Monitoring* (n = 10), *Extension and Outreach* (n = 7), along with *Policy and Regulations* and *Cost-Benefit of Interventions* (n = 4 each). *Ecology and Distribution of Pollinators* and *Management-Related Impacts* were the most commonly listed top knowledge gaps, with 52 percent of all participants placing both topics in their top three responses, and 88 percent of all participants listing at least one of these topics. This pattern was apparent across almost all professional groups except private landowners (Figure 1), as they most frequently listed the *Cost and Benefit of Supporting Pollinators* as an important knowledge gap.

Workshop Perspectives to Management Activities and Perceived Barriers

Approximately half of the workshop groups were of the opinion that ongoing management activities, such as invasive-species management and prescribed burning, influenced pollinator habitat (Table S1). Some examples provided by respondents included the restoration or maintenance of riparian areas and buffers, meadow management for wildlife, and wetland restoration. Approximately a third of the groups listed silvicultural techniques, such as the use of sheet mulching and the spraying of herbicides after planting, that were thought to affect the quality of pollinator habitat. Harvesting timber, which was viewed as changing the amount of light penetration and includes varying degrees of soil compaction, debris retention, and tree removal, was also listed by many groups. Responses reported by <10 percent of the groups were the creation and maintenance of infrastructure (e.g., roads, power lines), nontimber use of public lands (e.g., grazing), and human dimensions related to forest management (e.g., public educational activities).

Most respondents reported that management to support pollinator populations was impeded by a lack of support (Table S2). For example, several groups listed little or no funding as a major hindrance. Groups also reported that these activities were not supported in regard to priorities for their time, available oversight, and opportunities to undertake projects with uncertain outcomes. Education and awareness were also listed as barriers for participants, including informing the public to garner support on public lands, and education to guide managers in creating quality pollinator habitat and measuring the success of such projects. Other responses related to conflicting management goals, particularly in areas managed for timber production. For example, participants reported that managers were unable to prioritize pollinator habitat in production landscape if it reduced resource production in the short-term. Collaboration and communication comprised another common theme among respondents, including communication between researchers and managers, between different agencies, between researchers and land managers, and between land managers and the public. For example, one group reported that the "Need for collaboration between large-scale organizations, community organizations, and private landowners" was a barrier to managing habitat for pollinators. Policy conflicts, particularly policies that require certain types of reforestation, were also viewed as barriers if they limited manager freedom to prioritize pollinator habitat. Uncertainty of outcomes, including the "Lack of incentives to accept high uncertainty", was also reported by multiple groups, along with statements noting the lack of specific goals (e.g., number of species) against which to measure restoration success.

Literature Review on Pollinators in Managed Conifer Forests

Our literature searches identified 1,261 unique papers that we subsequently evaluated based on their title, abstract, or both. Of this total, 66 papers were considered to have potential to contain information

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Table 2. Categorization of responses by individual workshop participants to the question: In your opinion, what are the top three knowledge gaps related to pollinators in your managed forest landscape?

Theme	Examples	Number of related statements	Percentage of responses
Pollinator ecological information	Pollinator foraging range Flower preferences Nesting habitat requirements	38	35
Management-related impacts	Impacts from management activities Baseline information for comparison	46	42
Monitoring methods and training	Systematic sampling of pollinators Pollinator identification	10	9
Extension, outreach, and communication	Key messages for public Education strategies within industries and organizations	7	6
Costs and benefits of supporting pollinators	Economic tradeoffs of adjusting management to support pollinators	4	4
Understanding of policy and regulations	Landowner restrictions for pollinator support Legal grounds to enforce pollinator support	4	4

regarding pollinators in managed conifer forests and were further evaluated by close review of the publication. However, only 15 of the 66 papers that we examined were ultimately deemed relevant to pollinators in managed conifer forests (Table 3). After excluding the lone review paper that did not present new empirical data, we determined that the remaining 14 papers were limited to only four countries (i.e., United States, Japan, Finland, and Sweden). These studies focused primarily on bees (n = 11 studies) and were undertaken in a range of conifer forests, particularly those composed of pine (*Pinus*, n = 8 studies) and/or spruce (*Picea*, n = 5 studies; Table 3). With respect to management activities, timber harvest was the most commonly encountered management-related topic that was addressed (n = 11 studies), with fewer studies quantifying pollinator response to prescribed fire (n = 6), stand age (n = 6), or vegetation control measures (n = 4; Table 3). We note that although stand age is not a management action per se, we included studies that addressed this topic because stand age is linked to changes in the amount of habitat suitable for pollinators, and it is under control of forest managers with respect to the timing of harvest.

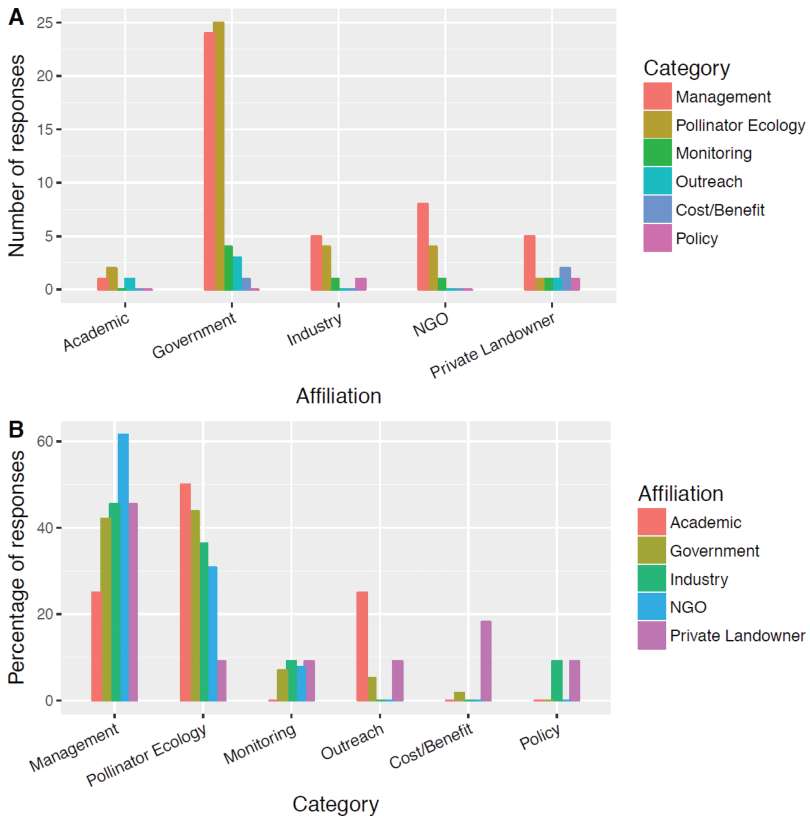

Figure 1. Distribution of responses by workshop participants when asked the question: *In your opinion, what are the top three knowledge gaps related to pollinators in your managed forest landscape?* Responses were placed into six distinct categories of knowledge gaps and assembled to illustrate (A) the number of responses to each category of knowledge gap as a function of professional affiliation and (B) the relative percentage of responses to each knowledge gap as a function of professional affiliation.

Discussion

The results from of our workshop indicate that forest managers and biologists perceived sizable knowledge gaps regarding pollinators within managed conifer forests. Both discussion groups and individuals reported similar responses overall, which is noteworthy because these priorities were similar in respondents regardless of their diverse professional affiliations. It is important to note, however, that >60 percent of participants rated their knowledge of pollinator ecology as fair, or worse, prior to attending the workshop, so there was potential for workshop participants to not fully appreciate how forest-management activities may impact pollinators. For example, a growing body of literature indicates that the abundance and diversity of pollinators within some conifer-dominated landscapes respond positively to timber harvest (Taki et al. 2013, Hanula et al. 2016, Rodriguez and Kouki 2017). Thus, harvest operations that commonly take place within managed conifer forests (e.g., thinning, clearcut harvest) may serve to support pollinator

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Table 3. Summary of published studies relevant to pollinators in temperate managed conifer forests as revealed by a literature search using search terms as outlined in the Methods.

Author(s)	Location	Forest type	Focal taxa	Management-related topics addressed			
				Timber harvest	Vegetation control	Prescribed fire	Stand age
Bried and Dillon 2012	USA (New York)	*Pinus*	Bees	Mowing	Herbicide	No	No
Brousil et al. 2015	USA (Washington)	*Pseudotsuga*, *Tsuga*	Beetles	Yes	No	No	No
Hanula et al. 2015	USA (Georgia)	*Pinus*	Bees	Thinning	No	No	Yes
Hanula et al. 2016*	Multiple	Multiple	Multiple	Yes	Herbicide	Yes	Yes
Maeto et al. 2002	Japan	*Cryptomeria*, *Chamaecypress*	Beetles	No	No	No	Yes
Rodriguez and Kouki 2015	Finland	*Pinus*, *Picea*	Bees, hoverflies	Yes	No	Yes	No
Rodriguez and Kouki 2017†	Finland	*Pinus*, *Picea*	Bees, hoverflies	Yes	No	Yes	No
Rubene et al. 2015a	Sweden	*Pinus*, *Picea*	Bees, wasps	Yes	No	Yes	No
Rubene et al. 2015b‡	Sweden	*Pinus*, *Picea*	Bees, wasps	Yes	No	Yes	No
Rudolph and Ely 2000	USA (Texas)	*Pinus*	Butterflies	No	No	Yes	No
Taki et al. 2010	Japan	*Cryptomeria*, *Chamaecypress*	Multiple	Yes	No	No	Yes
Taki et al. 2013	Japan	*Cryptomeria*, *Chamaecypress*	Bees	Yes	No	No	Yes
Taki et al. 2018	Japan	*Larix*	Bees	No	Weeding	No	No
Westerfelt et al. 2015	Sweden	*Pinus*, *Picea*	Bees, wasps	Yes	No	No	Yes
Yamaura et al. 2012	Japan	*Larix*	Bees	Yes	Weeding	No	No

*Review article that summarized empirical studies regarding pollinators in managed temperate conifer forests but did not present new data.
†Study conducted within same study system as reported in Rodriguez and Kouki (2015).
‡Study conducted within same study system as reported in Rubene et al. (2015a).

populations on the landscape, yet some participants may have not viewed this management action as being potentially beneficial to pollinators.

Our review of the primary literature found that there were very few published studies focused on pollinators in managed conifer forests throughout the world. Indeed, our review identified only 14 publications that presented new empirical data on pollinators in managed conifer forests, with most published studies being restricted to a small number of countries and focusing on wild bees. Of the pool of studies we identified, there were two instances where a pair of published studies addressed different research questions but were conducted at the same study sites (i.e., Rubene et al. 2015a,b; Rodriguez and Kouki 2015, 2017), further reducing the number of distinct locations that have been studied. Thus, the literature is especially sparse regarding pollinator studies undertaken in managed conifer forests, and available studies are limited with respect to their geographic and taxonomic scope. The dearth of studies as determined by our formal literature review was concordant with perceived knowledge gaps of workshop participants; thus, it appears that the lack of information apparent to managers is indeed because of scant information per se, as opposed to issues related to the communication of available information to resource managers. Nevertheless, we find it promising that many workshop participants expressed strong interest in supporting pollinator research within managed conifer forests, and this has led to the development of several empirical studies now under way in the Pacific Northwest (Rivers et al. in 2018; Galbraith et al., in review; Kormann et al., unpub. data).

A Research Agenda for Pollinators in Managed Conifer Forests

The results from the workshop, combined with our review of published studies from the primary literature, indicate sizable knowledge gaps and information shortfalls regarding pollinators within the context of managed conifer forests. Given the extensive distribution and substantial acreage devoted to managed conifer forests globally and the ongoing concerns about pollinator conservation (e.g., Allen-Wardell et al. 1998, NRC 2007, Potts et al. 2010, Pollinator Health Task Force 2015), these findings provide compelling reasons to prioritize research on this topic, not only in the Pacific Northwest but also in conifer-production regions throughout the world. In particular, our analysis revealed that three topical areas are both understudied by scientists and perceived by managers to be highly relevant to the management of conifer forests. The first area is focused on general aspects of pollinator ecology within managed conifer forests, such as spatial and temporal variation in pollinator communities and the factors that regulate populations. The second area focuses on the direct and indirect effects of forest-management activities on pollinators, and the final area is aimed at understanding the consequences of actions that occur after natural disturbance. We therefore expand our discussion of these three identified knowledge gaps to describe, in our view, the types of new studies that will have the greatest potential to broaden our understanding of pollinators within managed conifer forests.

We have strived to make our research agenda relevant to managed conifer forests in the temperate zone, but we recognize that such forests can vary greatly among regions because of differences in climate and species composition, among others. Whereas some conifer forests of the Pacific Northwest are characterized by abundant rainfall and develop relatively closed-conditions as they age, those growing in more fire-prone regions often have much more open canopies at maturity. For example, the longleaf pine (*Pinus palustris*) forests of the southeastern United States are maintained by some of the most frequent fires regimes in North America (burning every 2–3 years; Guyette et al. 2012) and have such wide spacing between trees that they are sometimes referred to as savannas (Varner and Kush 2004). Thus, given the dearth of information from all regions, the broad priorities outlined below aim to provide a starting-point for researchers, with the characteristics of each major forest type being an important consideration that can also

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be incorporated in the development of new empirical studies.

Theme 1. Establish Contemporary Baseline Patterns of Spatial and Temporal Variation in Pollinator Communities

Many fundamental questions regarding pollinator communities have received far more attention in agricultural systems, open-country habitats, and native deciduous forests than in managed conifer forests. For example, few studies are available that provide baseline characterization of fundamental aspects of pollinator communities (e.g., relative abundance, species diversity) and assess how these components change through time and across space, particularly with respect to changes in forest age. Nevertheless, this topic is important because the ways in which pollinator communities vary temporally and spatially within managed conifer forests are likely to be fundamentally different from those within agricultural landscapes, where general disturbances occur more frequently (e.g., tillage, regular insecticide application) yet the landscape remains as farmland across years. In contrast, changes within managed conifer forest landscapes occur across longer timescales, with a patchwork of suitable habitat available to pollinators that varies depending on harvest frequency and site productivity. Changes in pollinator communities with forest succession will likely differ strongly depending on regional differences in climate and stand composition. For example, bee diversity is expected to increase with forest age in regions where fire-managed forests become more open as they mature (Hanula et al. 2015), but the opposite pattern might be expected in forests that develop more closed canopies over time.

Given that pollinator conservation efforts in managed conifer forests are unlikely to be implemented in a way that benefits all pollinator species present, managers need information about which pollinator groups within forested landscapes are most important, particularly for the maintenance of nonconiferous native plants. Bees are a natural starting-point for this topic because they are the most important pollinators in many settings (Michener 2007), although other pollinator groups merit investigation (Gittings et al. 2006, Deans et al. 2007, Ibbe et al. 2011, Blixt et al. 2015). New studies are also needed that describe how pollinator communities change as a function of fundamental characteristic of managed forests, such as forest type and stand age, and how key taxa in these communities are linked to the elements of the flowering plant communities of these forests. For example, conventional wisdom holds that managed conifer forests are more valuable to pollinators as young forests (i.e., precrown closure, Hanula et al. 2016), but as mentioned above it remains largely unknown how often this is true and for which pollinator taxa, as well as how such relations may vary within landscapes or across regions (Sobek et al. 2009, Ulyshen et al. 2010, Hanula et al. 2015, 2016). Finally, studies that broaden our understanding of pollinators by incorporating a landscape-scale approach will be especially valuable (Hadley and Betts 2012, Beduschi et al. 2018) because the high mobility of many pollinators does not restrict them to a single type of habitat (Kremen et al. 2007, Blitzer et al. 2012), and because forest management is ultimately implemented within a landscape context (Ohmann et al. 2007). New studies should also aim to determine how the value of managed conifer forests to pollinators changes with forest succession from immediately postharvest to mature stands, and the minimal habitat needed to maintain important pollinator groups within larger managed forest landscapes that may experience fragmentation (Hadley and Betts 2012). Insights gained from past studies of habitat fragmentation on pollinator in other systems (Cane et al. 2005, 2006, Kormann et al. 2015) will help guide the development of new studies on this topic in managed conifer forests, and such investigations will help to establish whether pollinators respond similarly to fragmentation across different habitat types.

Theme 2. Assessing the Influences of Direct and Indirect Effects of Forest-Management Activities

Forest-management activities can impart changes that influences pollinators directly or indirectly within managed conifer forests. Timber harvest and prescribed fire are two of the most widespread management activities regularly undertaken, and both can create a favorable habitat for pollinators (Hanula et al. 2016). For example, clearcut harvest creates conditions favorable to many pollinators (Korpela et al. 2015, Roberts et al. 2017) and their flowering hosts (e.g., water, sunlight; Cartar 2005, Pengelly and Cartar 2011, Proctor et al. 2012, Neill and Puettmann 2013), and removal of forest residuals may provide previously inaccessible nesting sites to some groups (e.g., ground-nesting bees; Cane and Neff 2011, Rivers et al. in press). One important exception is managed conifer forests where broad spacing of trees allows for light penetration and the development of a robust understory maintained by regular prescribed fire, such as the longleaf pine forests of the southeastern United States (Hanula et al. 2015). Although pollinators may benefit from timber harvest that opens up closed-canopy forest, postharvest management activities, such as herbicide application, have the potential to negatively influence pollinator diversity through a reduction in floral resources (Kormann et al., unpub. data). Therefore, we view comparing pollinator responses to contrasting management actions that coincide with harvest activities as a priority, including quantifying changes in overall abundance, patterns of similarities and diversity, gaps in seasonal use or availability of floral resources, and availability of other habitat features that are necessary for the persistence of pollinator populations (e.g., oviposition and nesting sites).

In addition to forest-management activities proper, vast networks of unpaved secondary roads typify managed conifer forests (Gucinski et al. 2001), and the creation and maintenance of such roads are also likely to be influential on pollinator communities (Wojcik and Buchmann 2012). An important yet unaddressed question is the extent to which pollinators use such roads for foraging, nesting, or dispersal, and whether roadside areas benefit pollinators relative to other habitats within forested landscapes. In heavily forested areas, unpaved secondary roadsides may provide the only open habitat for pollinators, offering sunlit ground, warmer temperatures, channeled runoff, and more regular disturbance relative to unroaded sections of mature forests (Hanula et al. 2016). These factors should also favor some forage plants and nesting opportunities (Trombulak and Frissell 2000); however, these apparent benefits may be offset by the role roads can play in facilitating spread of exotic plant species (Christen and Matlack 2009). Even though such plants may be used as food resources

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(Powell et al. 2011, Stout and Tiedeken 2017), legal mandates require some federal managers to control noxious weeds with herbicides to curtail their spread (e.g., Haug 2017). How these mandates may influence pollinators remains unknown given the limited data available, so field studies that compare impacts of different roadside vegetation management activities on pollinators are sorely needed to identify best management practices in managed conifer forests. There can also be more subtle effects from roads that are also poorly understood at the current time; one example is the recent finding that fine dust emanating from roadsides can interfere with flower reproduction (Waser et al. 2017), which may have negative consequences for pollinators as well. Thus, effects that arise from operations and infrastructure that support forest-management activities, such as the creation and maintenance of forest roads, may also influence plant and pollinator communities and therefore should be considered important for future work.

Theme 3. Quantifying Effects of Forest-Management Activities that Follow Natural Disturbances

Natural ecological disturbances that can occur within forests include wildfire, windstorms, and tree mortality caused by pathogens and insects (Attiwill 1994), all of which have a strong potential to influence pollinator communities through the creation of early-successional forest (Swanson et al. 2011). In many cases, these disturbances are likely to have beneficial effects on pollinator communities. For example, patches of forests that were salvage-harvested in response to southern pine beetle (*Dendroctonus frontalis*) infestation were found to support some of the highest numbers of bees relative to other forest types compared in the southeastern United States (Hanula et al. 2015). Habitat remediation may be necessary after severe disturbances, which can include broadasting seeds of fast-growing plants to stabilize soils and revegetate bare areas during the immediate postdisturbance period. However, the value of the seed mixes to pollinators in other habitats can be variable, and the cost and/or insufficient availability of native seed mixes often favors the use of cheaper alternatives that are of little use to pollinators (Cane and Love 2016). Currently, it is unclear whether large-scale production of native plants useful to pollinators could be developed in a way that produces affordable seed mixes. Given that restoration activities may be legally mandated in some areas, research that provides science-based guidance for seed choices should help managers to make restoration efforts more conducive to pollinator conservation (Cane and Love 2016). Postdisturbance management can include removal of dead and dying trees following fire, windstorms, and insect-driven mortality (i.e., salvage logging; McIver and Starr 2001, Lindenmayer et al. 2008); thus, the same research topics outlined above for assessing the consequences of timber harvest are also germane to enhancing our understanding of how postdisturbance salvage logging may influence pollinators (Heil and Burkle 2018).

Conclusions

Interest in conservation of native pollinators remains high (Allen-Wardell et al. 1998, Potts et al. 2010, Gonzalez-Varo et al. 2013, Pollinator Health Task Force 2015), and new threats continue to emerge (e.g., pesticides [Rundlof et al. 2015] and diseases [Furst et al. 2014]). It is clear that managed conifer forests can and do harbor pollinators that are expected to contribute to native plant community diversity in these ecosystems. It is also evident that forest-management actions can alter local pollinator populations and their habitats. What is less clear is the magnitude and, in some cases, the directionality of these effects on particular pollinator groups, as well as the extent to which management actions may act synergistically with one another. Therefore, new empirical studies are urgently needed to address these and other sizable knowledge gaps by collecting data that allow for an improved understanding of the ecology of forest pollinators and the effect of forest-management actions on this group. Importantly, new investigations must take into account the realities of forest management if it is to inform and guide better management practices that ultimately benefit pollinators and their habitats. From our workshop, it was evident that many people associated with or responsible for managed conifer forests of the Pacific Northwest are motivated to learn about native pollinators and are willing to explore practical, dependable means of managing forests in ways that may benefit pollinators. Therefore, the next step is to begin implementing components of this research agenda to provide new information about pollinators in the managed conifer forests in the Pacific Northwest and beyond, and then share findings with the resource professionals who are ultimately responsible for making decisions about how such forests are managed.

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