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Roadside rights-of-way as pollinator habitat: a literature review

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16. Abstract (Limit 200 words)

This report includes a review of peer-reviewed academic and non-peer reviewed gray literature describing ROW management practices and their effects on pollinator populations, focusing on applications of these practices in landscapes similar to those found in Maine and the northeast United States; that is, landscapes that are heavily forested and interspersed with agriculture, developed areas, and wetlands. The literature consistently recommends these management practices to provide pollinator habitat in ROW and promote plant and pollinator diversity and abundance:

1) Reduce mowing frequency and time mowing to pollinator activity.
2) Target herbicide applications to undesirable plant species using backpack sprayers.
3) Plant native seeds, seedlings, or shrubs, leaving some exposed soil for nesting.

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Roadside rights-of-way as pollinator habitat: a literature review

Final Report to the Maine Department of Transportation

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SUMMARY

Pollination of crops and naturally-occurring flowering plants is a critical ecosystem service provided by managed and unmanaged animal pollinators. Insects are the most studied pollinators, particularly managed honey bees, unmanaged wild bees, and butterflies. Bees and butterflies thrive in early-successional habitat featuring grasses, exposed soil, wildflowers, and shrubs, which is consistently found within transportation and utility rights-of-way (ROW). However, intensive management of ROW can reduce the amount of high-quality pollinator habitat; such practices include frequent mowing, broadcast herbicide use, and planting non-native cool season grasses. Here, we review peer-reviewed academic and non-peer reviewed gray literature describing ROW management practices and their effects on pollinator populations, focusing on applications of these practices in landscapes similar to those found in Maine and the northeast United States; that is, landscapes that are heavily forested and interspersed with agriculture, developed areas, and wetlands. The literature consistently recommends these management practices to provide pollinator habitat in ROW and promote plant and pollinator diversity and abundance:

1) Reduce mowing frequency and time mowing to pollinator activity.

2) Target herbicide applications to undesirable plant species using backpack sprayers.

3) Plant native seeds, seedlings, or shrubs, leaving some exposed soil for nesting.

We considered threats to plants and pollinators associated with ROW, including traffic volume and mortality, noise, light, and air pollution, and habitat fragmentation. The literature suggests that these threats vary widely across road sizes, types, and landscape context, and the overall negative impacts do not outweigh the potential benefits of promoting pollinator habitat in ROW.

Landscape context also influences the composition of ROW plant and pollinator communities. In Maine, agriculture and grassland in the surrounding generally reduced bumble bee and butterfly abundance in Priority 1 ROW sites.

Many state Departments of Transportation have incorporated integrative vegetation management (IVM) principles into ROW management, and we summarize a number of case studies here. Restoration projects in high-visibility areas are common; further, these can lead to public support for additional pollinator habitat enhancement. Implementing new management practices can be difficult, therefore we discuss strategies to aid in successful adoption, including gathering public support, collaborations between public and private agencies, and innovative funding opportunities. While assessing vegetation management impacts on bee and butterfly communities in ROW is a rapidly expanding area of research, there are still many gaps in current knowledge. We conclude this report by addressing these gaps and provide suggestions for further study.

ACRONYMS

BMP: Best management practice, used to describe recommended management strategies.

CCAA: Candidate Conservation Agreement with Assurances, a voluntary conservation agreement between the U.S. Fish and Wildlife Service and one or more public or private parties that provides non-federal landowners incentives for participation through assurances that limit future conservation obligations.

DOT: Department of Transportation, a government agency that is devoted to transportation. DOTs exist at federal, state, and local levels.

FHWA: U.S. Federal Highway Administration, a division of the U.S. DOT that specializes in highway transportation.

IVM: Integrated vegetation management, a management scheme that aims to manage vegetation and the environment by balancing the benefits of cost, control, environmental quality, public health, and regulatory compliance.

IRVM: Integrated roadside vegetation management, an IVM scheme applied specifically to land associated with roadsides (Brandt et al. 2015).

PICO: An approach to outlining the scope of a literature search by defining Population, Intervention, Comparators, and Outcome criteria to develop an effective search strategy and collect the most relevant literature (Villemey et al. 2018).

ROW: Right-of-way, a type of easement granted or reserved over the land for transportation purposes, including maintenance and vegetation management.

USFWS: U.S. Fish and Wildlife Service, an agency of the US federal government within the US Department of the Interior dedicated to the management of fish, wildlife, and natural habitats.

TABLES AND FIGURES

1. Introduction

1.1. Pollinator services, biology, and conservation

Insect pollination is necessary for the reproduction of nearly 90% of flowering plants and two-thirds of crop plants globally (Klein et al. 2007, Ollerton et al. 2011). Crop pollination services contribute $34 billion to the United States economy annually (Jordan et al. 2021). Managed honey bee (*Apis mellifera*) hives provide much of this service, though unmanaged pollinators, including wild bees, butterflies, wasps, moths, and flies, are also significant contributors. Of these, most research has studied wild bees; much less is known about crop pollination by non-bee unmanaged pollinators (Rader et al. 2020). In the case of specialty crops grown in Maine and the northeastern United States, such as lowbush blueberries, cranberries, apples, and squash, wild bees can be more effective crop pollinators than honey bees (Garibaldi et al. 2013, Asare et al. 2017). Though honey bees can establish wild colonies and forage for food, beekeepers provide food and shelter for them, and the USDA classifies them as livestock (vanEngelsdorp and Meixner 2010). However, wild bees and other unmanaged insect pollinators require naturally-occurring food and shelter.

Maine is home to at least 278 wild bee species in six families of the order Hymenoptera, and at least 118 butterfly species in five taxonomic families within the insect order Lepidoptera, (Webster and deMaynadier 2005, Dibble et al. 2017). Both bees and butterflies, with some exceptions, are adults for a single growing season, during which they spend most of their energy on reproduction. Bees will establish nests, lay eggs, and provision those eggs with pollen and nectar to provide nourishment for the larval stage upon hatching. Bees and many butterflies overwinter as larvae or pupae and emerge the next spring as reproducing adults. A notable exception is the monarch butterfly (*Danaus plexippus*), which migrates south for the winter and overwinters as an adult. The following spring, overwintered adults migrate back north, laying eggs and producing multiple new generations of butterflies; these later generations reach the furthest north, reproduce, and the final generation of the season enters into reproductive diapause preceding the southward migration (Oberhauser and Solensky 2004). Bees consume pollen, and bees and many butterflies consume nectar from flowering plants. Flowering plants provide food and shelter for butterfly eggs and caterpillars. Wild bees nest either underground in exposed sandy soil or in cavities created by hollow twigs or rotting logs. Access to resources for both bees and butterflies is constrained by their maximum flight limits: wild bees typically fly 0.5 mi or less, while butterflies can fly up to 1.25 miles to find food (Greenleaf et al. 2007, Davis et al. 2007).

Pollinator habitat has been in steady decline for decades (Potts et al. 2010). This decline, along with increasing pesticide use, parasites, and pathogens, has contributed to drastic declines in insect pollinator populations (Goulson et al. 2015), including the regal fritillary (*Speyeria idalia*) and the rusty patched bumble bee (*Bombus affinis*), both of which were historically present in Maine. Maine currently has five state threatened and five state endangered insect pollinator species, and many others that are listed as species of Special Concern (Appendix A, this report; Maine State Wildlife Plan 2015). Recent surveys, including the Maine Butterfly Survey and Maine Bumble Bee Atlas, have updated or established baseline data on insect pollinator species distribution and relative abundance throughout the state (Webster and deMaynadier 2005, Bickerman-Martens et al. 2017).

1.2. Pollinator habitat along roadside rights-of-way

Roadside rights-of-way (ROW) are generally managed as early-successional habitat dominated by grasses, often featuring weedy flowering species. Roadside ROW managed following status quo practices (e.g., frequent mowing and widespread pesticide application) provide limited habitat resources for wild pollinators; non-native cool season grasses typical of these areas do not expose soil for nesting, allow shrubs to provide nesting or forage, or allow wildflowers to flourish. With adjustments to intensive management practices, roadside ROW could become a significant source of wild pollinator habitat.

A Presidential Memorandum issued by the White House in 2014 encouraged federal agencies to increase and improve existing pollinator habitat nationwide, and roadside ROW were specifically suggested as areas to explore expanding habitat (White House 2014). This was a crucial impetus for state Departments of Transportation (DOTs) to engage in pollinator conservation activity by adapting vegetation management practices along roadside ROW. DOTs manage 17 million miles of road with approximately 10 million acres of adjoining roadside land (Forman et al. 2002, Wojcik and Buchmann 2012), potentially providing a wealth of pollinator habitat. The Maine DOT manages approximately 2,023 ha (5,000 ac) of land within ROW (Campanelli et al. 2019). Roadside ROW restored to a prairie-like habitat condition have greater bee abundance and species richness than weedy roadsides, with bee communities that are similar to those in remnant prairie (Hopwood 2008). Butterflies also benefit from native wildflower plantings along roadsides (Feber et al. 1996, Valtonen et al. 2007). Reducing the frequency of mowing and pesticide application further promotes bee and butterfly communities in ROW (Feber et al. 1996, Zinnecker and Larsen 2011, Kuder 2019).

Roadside ROW are found across multiple landscapes; they run through forests, agricultural land, developed areas, and shrub or herbaceous-dominant natural habitat, including grasslands and wetlands. These types of land support distinct bee communities (Du Clos et al. 2020) and may influence the effectiveness of ROW management practices to support diverse and abundant wild pollinator populations. For landscapes with few habitat resources, ROW may serve as a source of wild pollinators (Berg et al. 2016). In low-intensity agricultural landscapes, roadsides can be a vital source of forage for bumble bees (Osgathorpe et al. 2012). In a study of multiple cover types in a mixed-use landscape of the United Kingdom, roadsides had the greatest percent cover and the richest assemblage of flowers, supporting the greatest abundance and diversity of bees, butterflies, and hoverflies (Cole et al. 2017).

Potential traffic-related threats associated with roadside habitat for wild pollinators include noise and air pollution, barriers to dispersal, and mortality via vehicle collision. The effects of these threats on pollinator communities vary with road size, traffic volume, roadside habitat quality, landscape context, and pollinator traits such as tongue length or body size (Hopwood et al. 2015a, Roberts and Phillips 2019). However, this variation and the amount of potential habitat available likely mitigates overall negative outcomes for ROW habitat restoration for pollinator communities (Phillips et al. 2020).

1.3 Research objectives

We conducted a literature search and review to assess the current body of information on roadside ROW vegetation management for wild pollinators. We reviewed existing best management practices (BMPs) and supporting literature to answer three research questions: 1) Are there specific ROW management practices that successfully enhance pollinator abundance and diversity? 2) Which insect pollinator taxa respond most significantly to common ROW management practices? 3) Are there elements of landscape context that affect the success of ROW management practices for pollinator conservation? We synthesized our findings and reviewed case studies to determine the effectiveness of recommended BMPs for wild pollinators. We also identified knowledge gaps in the literature where recommendations exist with few supporting scientific studies. Along with our review, we assessed landscape composition surrounding 10 ROW sites along Priority 1 roads in Maine. Plant and pollinator communities were surveyed at these sites in 2017.

2. Methods

2.1 Study scope

We outlined a study scope using the Population, Intervention, Comparator, Outcome (PICO) approach (Villemey et al. 2018) (Table 1). Our study population includes insect pollinator taxa of Maine and the northeastern US. Habitat types, pollinator communities, and landscape patterns in this region can be grouped together owing to overall similarity.

Table 1. Outline of study scope following the PICO approach (Villemey et al. 2018)

Population	Insect pollinator taxa
Intervention	ROW management practices
Comparators	Managed vs unmanaged habitat; Landscape context
Outcome	Change in pollinator population

To avoid gathering material from beyond our geographic scope, we framed our search strategy, inclusion criteria, and interpretation of results to the northeastern US. Our focal intervention is ROW management practices, including mowing, seeding, herbicide use, burning, and grazing. Although roadside ROW are the primary focus of this study, we considered information on similar ROW types including railways, power lines, and field edges or margins when conducting our search to ensure collecting a comprehensive body of information. Our comparators to assess effectiveness of ROW management practices for pollinator communities are 1) managed vs unmanaged habitat and 2) landscape context. Studies that provide this information present comparisons that we can interpret and apply to ROW management in Maine and the northeastern US. Lastly, our focal outcome is a change in insect pollinator abundance or diversity owing to

ROW management practices. We used our PICO variables to frame our search strategy and develop criteria for papers to include in our review.

2.2 Search strategy and protocol

We conducted an initial scoping search through previously gathered literature to a) aid in refining our PICO variables and developing search keywords and b) create a test list to compare to results from initial database searches. We gathered peer-reviewed literature by first searching our reference manager using a series of ROW-related keywords, and then we conducted two Google Scholar searches for papers citing foundational papers on ROW management for pollinators (Hopwood 2008, Wojcik and Buchmann 2012). We gathered gray literature not published in peer-reviewed sources and other non-academic information by conducting a Google search for “roadside vegetation management.” We gathered all relevant results using our PICO variables to test their relevance to and comprehensiveness of existing knowledge on ROW management for pollinators.

Following this initial search, we developed an *a priori* search protocol for our full literature search. The protocol began with a comprehensive search keyword list, with words generated in several subcategories of each PICO variable (Appendix B). We developed a set of inclusion criteria to determine which search results were kept or rejected. We chose three sources for our database searches, selecting Web of Science to gather peer-reviewed literature owing to its comprehensive collection of journals and supplementing Web of Science with Google Scholar to gather pre-prints, very recently published articles, and gray literature. We also chose to conduct a series of Google searches specifically for gathering gray literature from non-academic sources.

We began the full literature search by testing keyword combinations on Web of Science with the goal of building a comprehensive keyword phrase that incorporated our PICO variables and produced highly relevant search results, using truncation symbols, quotation marks, and Boolean operators. We assessed performance of keyword combinations by 1) the alignment of search results to the initial paper collection and 2) the number of duplicate results from previous test searches. The most comprehensive keyword phrase had three sections: ROW type, organism, and management practice, each represented by a keyword combination. We tested keyword phrases with a fourth section containing outcome-based keywords; however, all results from these searches were duplicates. Therefore, the final keyword phrase contained three sections. Each section was tested with multiple keyword combinations to exhaust our keyword list and to obtain the widest breadth of literature. Many search results were dominated by duplicates and provided few new articles, providing support for the comprehensiveness of our best-performing keyword phrase. Specifying type of organisms beyond "pollinators" (e.g., "bees," "bumble bees" or "butterflies") often provided more new results than modifying other sections of the keyword phrase. We tested various land cover type and landscape context keywords along with the management practice keywords; none of these searches returned new results. Our final best performing keyword in Web of Science was (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND pollinators AND (manag* OR conserv* OR enhanc* OR restor*).

We modified the best-performing keyword from Web of Science for the Google Scholar search, as Google Scholar does not recognize truncation symbols, by expanding the organismal term to list multiple types of pollinators and using the full words referenced in the management term. We conducted five searches in Google Scholar, each featuring a unique ROW search term with the modified organismal and management terms. We further modified the search term for our general Google search. We conducted searches for road and rail ROWs, omitting power lines owing to relevance in previous searches. We tested each management term with road and rail, finding "management" to be the most relevant result; therefore, we used only "management" when testing organismal terms. We tested eight organismal terms with "road management" and retained four of them to search with "rail management."

We conducted searches in Web of Science and Google Scholar in the summer of 2018 and again in the fall of 2019. In Google Scholar, the 2019 searches were conducted with the "since 2018" box checked to avoid redundancy in the results. In sum, we conducted 120 searches using 105 keyword combinations. All keyword combinations are listed in Appendix C.

2.3 Initial screening and cataloguing

We screened the titles of each search result to determine suitability for initial collection and gathered papers that mentioned a pollinator or pollinated plant and a type of ROW (including other linear landscape features such as field edges, margins, and hedgerows) within the title, rejecting all those that did not meet these two criteria. If the title was ambiguous, we read the abstract to find our two title criteria and made our decision on inclusion from that text.

We cataloged each reference we collected with a detailed entry in an Excel spreadsheet, assigning each reference, whether peer-reviewed or non-peer-reviewed/gray literature, a unique ID number based on its source: WOS#### (Web of Science), GS#### (Google Scholar) or GO#### (Google). We recorded many details for each reference when applicable, including the publishing journal, year published, DOI, focal organisms, focal ROW type, study variables (dependent and independent), comparators, study approach, language, and location, downloading PDF files of all available documents for full-text screening.

2.4 Full-text screening, critical appraisal, and data extraction

After the initial reference collection, we reviewed each entry in detail, reading the full-text to determine its suitability for inclusion in our review. We created an *a priori* set of inclusion criteria for each entry to meet based on relevance to our focal questions and, if applicable, study design. Criteria for full-text screening were extensive, including geographic location (USA, Canada, and Europe; we aimed to capture similar environmental and climatic conditions) and restrictions on the type of ROW and pollinators or plants. For example, while we gathered information about a variety of ROW in our initial screening, only roadside and railway ROW were included after full-text screening owing to the amount of relevant information collected. This led to the exclusion of references on field edges/margins, hedgerows, power lines, gas lines, solar or wind arrays, and others. Additionally, only bees, butterflies, moths, and hoverflies were included after full-text screening, leading to the exclusion of references on wasps, ants, and non-insect pollinators including birds, bats, and small mammals. All inclusion criteria used for full-text screening are listed in Appendix D.

Assessing details on study design, including clarity of methods and avoidance of bias, is called critical appraisal; this is a crucial component of conducting a thorough and unbiased literature review. When conducting reviews, a critical appraisal can be done separately from full-text screening; however, we chose to conduct these steps concurrently in the interest of efficiency. While reading the full text of each reference, we recorded a series of variables related to study design, including the type of study, control and experimental habitat types, any habitat manipulation or management, how sites were selected, distance between sites, spatial replication of sites, length of study in years, number of sampling occasions per year, and if the study assessed landscape context or threats associated with ROW habitat. We further assessed the susceptibility to bias of each reference, assigning a high, medium, or low bias ranking based on experimental design using a protocol from an ROW review conducted by Villemey et al. (2018). Contributing factors to susceptibility to bias included absence of replications, insufficient description of methods, major confounding factors, and unclear procedures for plot location selection.

We chose Hedge's d as our measure of effect size for a meta-analysis (Koricheva et al. 2013). If references reported sufficient quantitative data to calculate effect size via Hedge's d, met the requirements of critical appraisal, and had low or medium bias, we extracted all potentially relevant data for meta-analysis. Data required to calculate Hedge's d are a mean, sample size, and variance for two groups (typically a control and a treatment); we extracted these when reported. Other statistics can be used to approximate Hedge's d, including Z-scores, t-tests, and chi-squared tests; therefore, if these were reported, they were also extracted. Lastly, we chose the correlation coefficient as an alternate measure of effect size; if a reference reported results from F-tests, we recorded those (Koricheva et al. 2013). Full details on critical appraisal, bias assessment, and data extraction are provided in Appendix E.

2.5 Spatial analysis

We assessed any influence of the surrounding landscape on pollinator communities in Maine ROW vegetation, by analyzing the landscape composition surrounding ten sites along Priority 1 roads in five geographic regions across Maine (Figure 1). Plant and pollinator communities were surveyed at these sites in the early, mid-, and late growing season in 2017 (Drummond 2018). Groff et al. (2016) combined the 2004 Maine Landcover Dataset (https://www.maine.gov/megis/catalog/metadata/melcd.html) with ancillary data on roads (MEDOTPUBRDS), railroads (RAILROUTESYS; https://www.maine.gov/geolib/catalog.html), and wetlands http://www.fws.gov/wetlands/NWI/Index.html) to create a statewide land cover map with 5 m^2 (16 ft^2) pixel resolution and seven land cover classes representing different floral and nesting resources for wild bees: agriculture/pasture, consisting of small diversified farms, orchard crops, or pasture; coniferous forest; deciduous/mixed forest; deciduous/mixed forest edge; emergent wetland, an aggregation of forested wetland and scrub-shrub land cover; wetlands/water; and urban areas. We measured the percentage of each land cover type (PLAND; McGarigal et al. 2012) in the 1 km (0.6 mi) surrounding the survey sites on this map, as landscape variables at this scale are likely to most strongly influence bumble bee and butterfly abundance and species richness (Steffan-Dewenter et al. 2002, Davis et al. 2007).

We conducted all statistical analyses in R v.4.0.3 (R Core Team 2020). We evaluated annual and seasonal differences in bumble bee and butterfly abundance and species richness with Kruskal-Wallis tests, then determined post-hoc seasonal differences with the conservative Dunn's test of multiple comparisons using package dunn.test (Dinno 2017). We tested for spatial autocorrelation with Mantel tests on bumble bee and butterfly abundance and species richness with package ade4 (Dray and Dufour 2007). The Mantel tests compare matrices of geographic distance to matrices of data distance, determining if the data are related based on their geographic location (Dray et al. 2012). We assessed differences in bumble bee and butterfly communities in ROW owing to landscape composition over the entire growing season and at each sampling period with generalized linear models (GLMs) calculated with base R or package MASS (Venables and Ripley 2002). We determined significant relationships with post-hoc analysis of deviance. Models of bumble bee and butterfly abundance had negative binomial error distributions owing to overdispersion, whereas, with the exception of early season bumble bee species richness, models of species richness had Poisson error distributions.

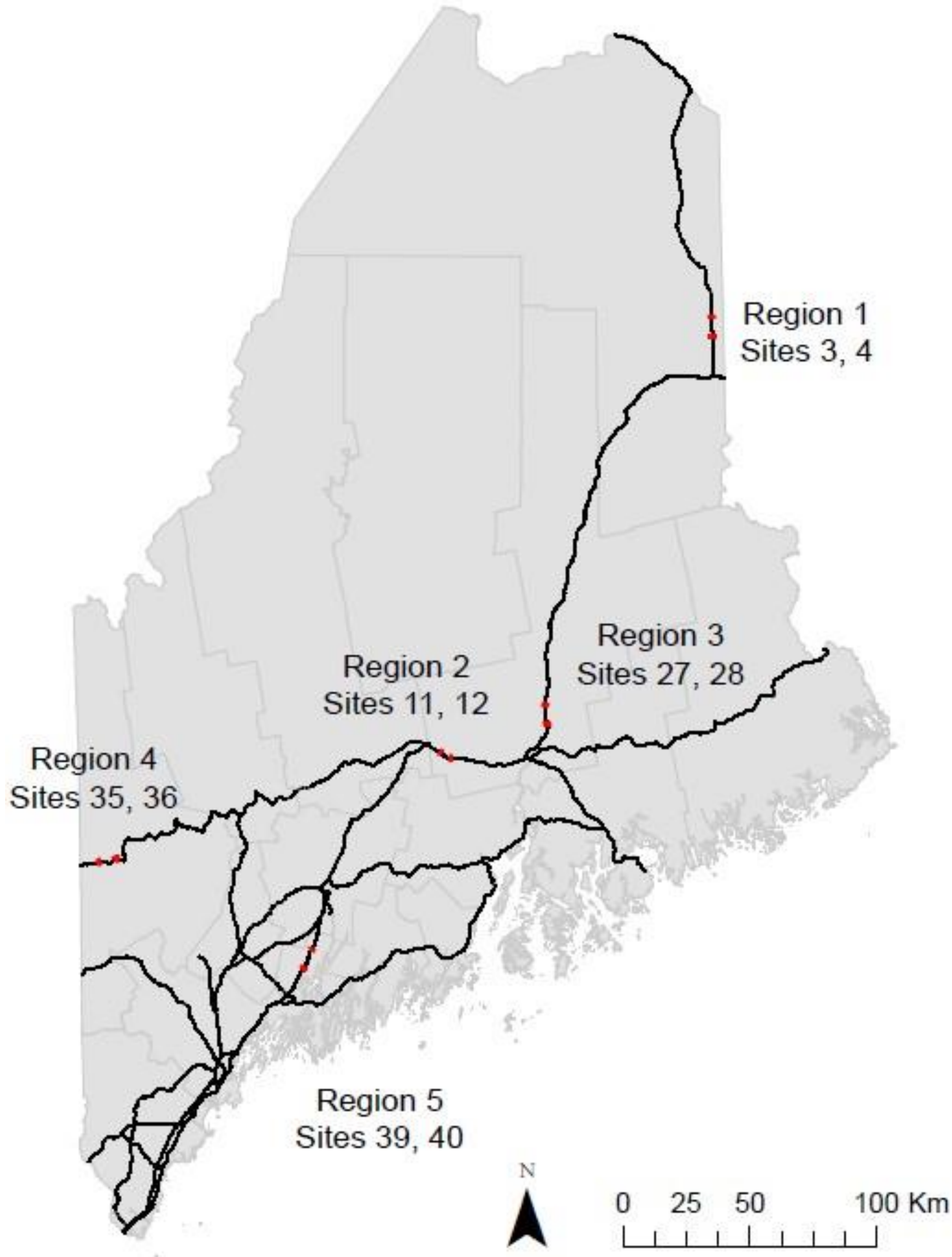

Figure 1. Locations of 10 ROW sites along Priority 1 roads in Maine where plant and pollinator communities were surveyed in 2017 by F. Drummond. 100 km = 62 mi.

3. Results

3.1 Summary of reference collection

We gathered 3,708 total references from the initial scoping search and full literature search. The initial scoping search returned 98 references; the full literature search returned 3,610 references across Web of Science, Google Scholar, and Google (Figure 2). The vast majority of search results were duplicates. Many results did not meet our search criteria through title and abstract screening, and a small number of results were not available in full-text; these were all rejected for full-text screening. Of all returned results, 555 met the criteria for full-text screening for inclusion in the narrative synthesis. Full-text screening and critical appraisal excluded 350 results; therefore, 205 results were ultimately used in our narrative synthesis (Appendix F).

This body of literature has grown rapidly over the recent decade; nearly half (47.3%) of the results included in our narrative synthesis were published after 2015, while almost three quarters (74.6%) were published after 2010. Only 1.4% of our included results were published before 2000 (Table 2). Geographically, more than half of our results (61.5%) came from peer-reviewed and non-peer-reviewed/gray literature sources in North America, while 34.1% came from Europe and 4.4% had a global focus. Most of the results included in the narrative synthesis focused solely on roadsides (63.4%) or railways (7.3%). The remainder of the included results assessed multiple types of rights-of-way. The results we included in the narrative synthesis were fairly evenly split by type of reference: 52.2% were peer-reviewed academic journal articles, while 47.8% were gray literature. The bulk of the gray literature came from our general Google search and included NGO webpages and reports, news articles, technical documents from local, state, and federal government agencies, industry and consultant reports, and academic gray literature, which consists of book chapters, conference proceedings, and Extension publications.

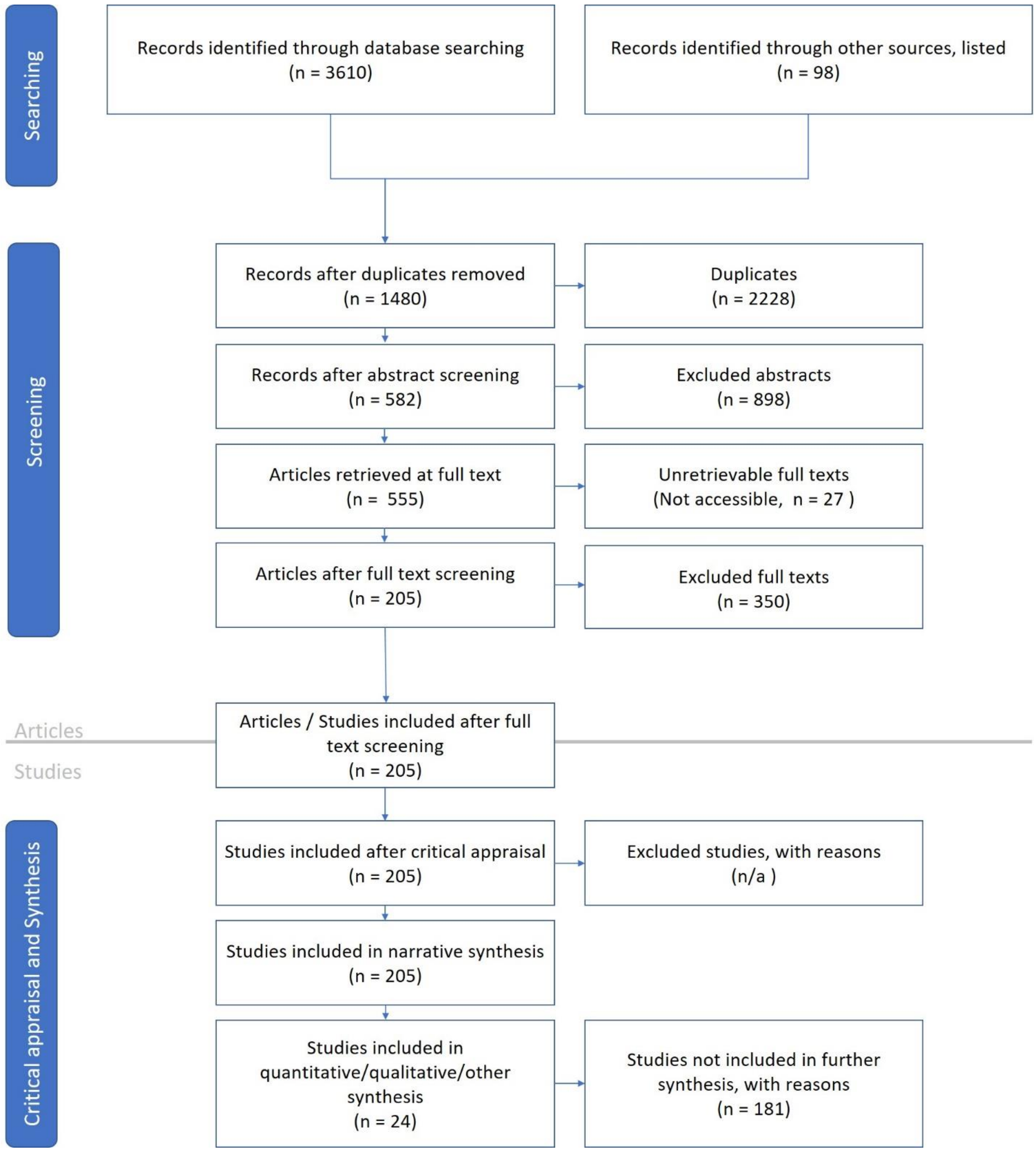

Figure 2. ROSES flow diagram outlining search results and screening (following Haddaway et al 2017).

Pollinating insects (34.6%) were the most common subject of our search results. Most of the gray literature in the narrative synthesis focused on this broad category that includes bees, butterflies, and hoverflies. Results that focused more specifically on bees (11.7%) or butterflies (28.3%) were typically peer-reviewed academic studies. Monarch butterflies were the focus of 7.3% (15) of our search results, while work on both monarchs and their host plant milkweed (*Asclepias* spp.) made up 2.9% (6) of the results. Plants, including milkweed, were the focus of 13.7% of search results, and 10.2% of the results examined both pollinators and plants (Table 2).

Table 2. Summary statistics of literature search results (n = 205)

Category	Number of results	Percent of total
Source		
Peer-reviewed literature	107	52.2
Gray literature	18	8.8
Google Search	80	39.0
Time		
Pre-2000	3	1.5
2000-2009	28	13.7
2010-2015	56	27.3
2016-Present	97	47.3
Undated	21	10.2
Location		
North America	126	64.5
Europe	70	34.1
Global	9	4.4
ROW Type		
Roadside	130	63.4
Railway	15	7.3
Multiple types	56	27.3
Other*	4	2.0
Pollinator taxa		
Bees	24	11.7
Butterflies	58	28.3
Pollinating insects	71	34.6
Plants	28	13.7
Multiple	21	10.2
Other (wildlife or people)	2	1.0
N/A (not taxa specific)	1	0.5

* includes waterway filter strips, prairie remnants, habitat edges, and a public park

We extracted quantitative data suitable for meta-analysis from 24 papers, totaling 256 cases from which we could calculate effect sizes of the influence of ROW vegetation management on plant and pollinator communities. Characteristics of these data, including variables measured, organisms studied, experimental design, and statistics reported varied widely across these papers. For example, we summarized the data collected into two categories of variables measured: amount or diversity. The amount category includes cases measuring abundance, density, survival, or mortality of plants or pollinators. The diversity category is more uniform, consisting primarily of species richness with a small number of other biodiversity measurements. We assigned two categories of organisms studied: plants or pollinators. Plants include native and non-native forbs, grasses, blooming flowers, shrubs, and trees; pollinators include live or dead solitary bees, bumble bees, butterflies, moths, and hoverflies. Some papers did not classify pollinators into groups and instead reported results for "pollinating insects." Data cases were evenly split between plants and pollinators but trended strongly toward measuring amount over diversity (Table 3). Additionally, the cases were split between measures of effect size; most were suitable for calculating Hedge's d, but some were suitable only for our alternative measure, the correlation coefficient. This variation in our data introduces difficulties in performing a reliable meta-analysis. Further, the number of cases extracted from each study varies widely; along with the variation we recorded in experimental design (Appendix F), this may introduce substantial bias to any meta-analysis (Table 4), leading to our conclusion that a meta-analysis is unsupported with the extracted data. All data extracted are presented in Appendix F.

Table 3. Summary of quantitative data collected in literature review.

Measure	Taxa	Number of cases	Number of studies
Amount	Plants	72	11
Diversity	Plants	56	10
Amount	Pollinators	101	18
Diversity	Pollinators	27	9

Table 4. Studies and cases extracted for calculation of effect size (Hedge's d or correlation coefficient) in literature review.

Study	Hedge's d cases	Correlation coef. cases	Total cases
Wigginton and Meyerson 2018	0	21	21
Kaul and Wilsey 2019	5	0	5
Haan and Landis 2019	2	0	2
Skorka et al 2018	0	4	4
Knight et al 2019	24	0	24
Mollet 2019	0	6	6
Kuder 2019	0	5	5
Entsminger et al 2017	26	6	32
Halbritter et al 2015	9	0	9
Hanley and Wilkins 2015	5	0	5
Noordijk et al 2009	12	0	12
Osgathorpe et al 2012	12	0	12
Skorka 2016	1	0	1
Zinnecker et al 2011	20	0	20
Garbuzov et al 2015	6	0	6
Wrzesien et al 2016	11	0	11
Valtonen et al 2007	2	0	2
Valtonen et al 2006b	1	0	1
Berg et al 2011	12	0	12
Moron et al 2014	6	0	6
Saarinen et al 2005	12	0	12
Phillips et al 2019	45	0	45
Seitz et al 2019	2	0	2
Dee and Baum 2019	1	0	1

3.2. Research question 1: Are there specific ROW management practices that successfully enhance pollinator abundance and diversity?

3.2.1. Mowing

There is ample documentation on ROW vegetation mowing methods that benefit pollinating insects and the plants they visit, including guidance on timing, frequency, spatial arrangement, and technique. Primary sources on these strategies include roadside vegetation management guides from the US DOT Federal Highway Administration (FHWA; Hopwood et al. 2015b, c) and the nonprofit Pollinator Partnership (Galea et al. 2016). These guides rely on scientific literature, case studies from state DOTs, and in some cases, interviews with practitioners to describe best practices in mowing of ROW vegetation. Recommendations are generally consistent across these documents.

The literature suggests that mowing be timed to avoid conflict with pollinator reproduction, which generally coincides with flower bloom throughout the growing season. Therefore, mowing late in the growing season after plants have senesced and most pollinators have completed their reproductive cycle is frequently recommended (Noordijk et al. 2009, Hopwood et al. 2015c, Galea et al. 2016). This is particularly crucial for monarch butterflies, who lay eggs on milkweed plants as they migrate north in the late spring and early summer (Hopwood et al. 2015c). If necessary, summer mowing timed to promote plant regrowth and plant diversity may still provide a variety of floral resources for pollinators (Hopwood et al. 2015c). Lastly, mowing during peak daylight hours gives foraging pollinators a chance to escape from vegetation, potentially increasing survivorship.

In addition to timing, mowing frequency throughout the growing season can be adjusted to benefit pollinators. Mowing ROW vegetation less often, with two or fewer visits, reduces maintenance and labor costs while providing improved pollinator habitat (Noordijk et al. 2009, Harrison 2014). Fewer mowing visits allow more wildflowers to flourish and bloom; additionally, allowing plants to mature promotes root development that increases soil integrity and prevents erosion. Pairing reduced mowing with selective herbicide treatment can lead to rich pollinator habitat that is still safe for drivers (O'Sullivan et al. 2017, Entsminger et al. 2019), though frequent mowing can be an effective component in establishing of planted native seed mixes (Hopwood 2013).

Strategic spatial arrangement of mowed patches benefits plants and pollinators in ROW vegetation. Partial mowing, where patches are mowed along roadsides instead of continuous strips, can provide a refuge for pollinators while the mown vegetation regrows (Noordijk et al. 2009, Hopwood et al. 2015c, Galea et al. 2016), ultimately producing a diverse habitat mosaic; this practice is also called mosaic cutting (Valtonen et al. 2006a). However, partial mowing increases maintenance costs as it requires complex planning and multiple site visits (O'Sullivan et al. 2017). One solution is to limit high frequency mowing to the clear zone or the minimum area required for safe driving visibility (Hopwood et al. 2015c).

Adjusting mowing techniques can also aid in pollinator preservation. Using a flushing bar and moving machinery slowly through vegetation allows pollinators to escape (Hopwood et al. 2015c, Galea et al. 2016). Mowing vegetation no shorter than 10 inches allows plants to recover quickly and provides pollinators with more vegetation to use; for example, butterflies can continue to lay eggs (Hopwood et al. 2015c). One frequent recommendation is to remove mowed vegetation, as this promotes pollinator and plant diversity and abundance (Noordijk et al. 2009, Hopwood et al. 2015c, Galea et al. 2016, Phillips et al. 2019).

3.2.2 Herbicides

Although prevalent in practice, few scientific studies provide empirical support for ROW vegetation management strategies involving herbicide use. Iowa's Integrated Roadside Vegetation Management (IRVM) Manual (Brandt et al. 2015) is a leading source on ROW herbicide use that informs other published documents (Hopwood et al. 2015b, c). These guidelines and BMPs suggest deliberate, selective use of herbicides for elimination of undesirable plant species and promotion of planted or native-growing wildflowers. As with mowing, the timing, frequency, and spatial arrangement of herbicide application can be adjusted to benefit surrounding plants and pollinators in ROW vegetation while also reducing maintenance costs.

Applying herbicides at vulnerable points in undesirable plant life cycles can increase effectiveness and lead to fewer applications. Systemic herbicides can be applied late in the growing season as plants begin to store more energy in their roots; this encourages root uptake of the herbicide, rendering it more effective and at the same time minimizes exposure to pollinators. Additionally, spot-treatment with targeted sprayers reduces drift and the total amount of herbicide used (Hopwood et al 2015b, c). Timing applications and adjusting chemical concentration can provide effective treatment on a flexible schedule. For example, Terry (2018) found that spraying half-rate applications in the early and late season led to longer-term effectiveness, while application late in the season allowed for a delay in timing the next season's application. For large patches of undesirable plants, calibrating equipment for accuracy and spraying in low-wind conditions can limit drift associated with broadcast spraying (Hopwood et al. 2015b, c). Pairing herbicide use with other weed management strategies can reduce potential negative effects on pollinator communities (Brandt et al. 2015), though herbicide use can be critical for establishment of planted native seed mixes (Ohio DOT 2016).

The primary risk to pollinators from herbicides is indirect, occurring through the loss of nectar, pollen, and nesting habitat from flowering plants eliminated by broadcast herbicide use. Further, while it is an emerging area of research, most studies of direct effects of herbicides on bees have been conducted on honey bees, not the unmanaged wild bees targeted by ROW habitat enhancement (Cullen et al. 2019). Similarly, few studies exist on the effects of herbicide application on butterflies. Results are mixed and suggest that effects vary by chemicals used, butterfly species, and butterfly life stage. Larvae appear to be the most vulnerable to survival where herbicides are used (Russell and Schultz 2010, Schultz et al. 2016), though not for all species (LaBar and Schultz 2012, Schultz and Ferguson 2020). Some adult butterflies are less common in areas where herbicides have been applied (LaBar and Schultz 2012), but others remain in place and reproduce at similar rates to control sites (Schultz and Ferguson 2020). Broadly, pairing herbicide use with monitoring of at-risk pollinator species can reveal any negative effects, allowing modification of management strategies to maintain pollinator populations while reducing the presence of invasive plants.

3.2.3. Restoration

There is a substantial amount of scientific literature on habitat restoration from grassy habitat to wildflower-rich natural habitat to benefit pollinators, some of which is specific to rights-of-way. Therefore, guidance and BMPs on planting wildflowers and establishing natural habitat along ROW is extensive. There are also many real-world examples of DOTs restoring ROW habitat to benefit native plants and pollinators. Restoration is a complex process that requires deliberate action at each step from site selection to establishment and planting to long-term maintenance. Clear communication is vital to successful roadside restoration; often multiple teams or agencies with varying areas of expertise are involved, and many restoration projects are highly visible to the public, which may lead to citizen engagement. As with mowing and herbicide use, strategic and deliberate habitat restoration can ultimately benefit pollinators while adhering to safety requirements and reducing maintenance costs. Conventional ROW vegetation management involves frequent mowing and herbicide application to maintain a uniform, grassy right-of-way. These conditions provide disturbed habitat prone to the introduction and establishment of invasive species, leading to a cycle of intensive maintenance (Brandt et al. 2015).

Restoring ROW vegetation to natural pollinator habitat begins with site selection. Restoration sites can be established immediately after completing construction to ensure long-term persistence (Hopwood et al. 2015c). Site characteristics such as topography and width may influence the effectiveness of restored habitat. Variation in topography can lead to greater habitat diversity at restoration sites; this may lead to greater pollinator diversity (Munguira and Thomas 1992, Hopwood et al. 2015a). Wider ROW have more area for floral resources, leading to greater pollinator abundance (Munguira and Thomas 1992, Saarinen et al. 2005, Phillips et al. 2019). Sites that require less preparation for restoration will save time and money and may be a boon to initial efforts in restoring pollinator habitat (Hopwood et al. 2015c, Galea et al. 2016). A site selection rubric is available that details other criteria for successful restoration, including soil characteristics, sun and water availability, and buy-in from the public (Galea et al. 2016). Lastly, the landscape surrounding restoration sites may influence the effectiveness of restored habitat. Invasive plants in nearby areas may encroach newly restored ROW; similarly, little available habitat surrounding the restoration site may lead to limited pollinator population establishment (Hopwood et al. 2015a, Phillips et al. 2020.)

Once selected, restoration sites often require preparation before planting can occur. Preparations include removal of invasive or other undesirable plant species and soil modifications such as grading or amendments such as lime or fertilizer. Wildflowers can then be planted from seed or by transplanting seedlings; the planting method is dependent on site characteristics including shape, size, and accessibility. The most frequent recommendation associated with restoring ROW vegetation to pollinator habitat is to use native plant species (seeds or seedlings), ideally those that are adapted to local climatic conditions (Hopwood et al. 2015a, b, c; Galea et al. 2016, McCargo 2018). Planting a variety of native plant species will provide food to support an abundant and diverse pollinator community; additionally, selecting host plants for specific pollinators (i.e., milkweeds for monarch butterflies) will increase restoration effectiveness (Hopwood 2010, 2013). Lastly, consider the arrangement of planted species. Clumping single species together allows for easier access and efficient foraging by pollinators, and leaving patches of bare ground provides nesting opportunities for ground-nesting bees (Hopwood et al. 2015c, Galea et al. 2016). Vegetation planted close to roads should be short for safety and visibility, and ideally will be tolerant of road salt application for long-term persistence (Hopwood et al. 2015c).

Long-term maintenance, monitoring, and management of restoration sites is critical for persistence in supporting pollinator populations. Management of newly established restoration sites can be intensive, involving watering, mowing, and removal of undesirable plants. Plantings may take up to five years to fully establish; maintaining an annual inventory of plant communities for the first three years can document progress and identify areas needing improvement (Hopwood et al. 2015c, Galea et al. 2016, Kuder 2019).

3.3 Research question 2: Which insect pollinator taxa respond most significantly to common ROW management practices?

3.3.1 Butterflies

Butterflies are the most studied group of pollinating insects in ROW vegetation, with multiple studies observing diverse and abundant butterfly communities in these areas (Munguira and Thomas 1992, Valtonen et al. 2006a, Moron et al. 2014, Drummond 2018). Right-of-way width and site variation provide plant diversity for feeding and resting butterflies, with habitat quality comparable to prairies or wild meadows (Munguira and Thomas 1992, Ouin et al. 2004, Saarinen et al. 2005, Kalarus and Bakowski 2015, Drummond 2018). Further, unmanaged areas associated with roadways such as on-ramps and other highway intersections support more diverse butterfly communities than those found in managed roadside habitat (Valtonen and Saarinen 2005).

Adjusting mowing timing and frequency to coincide with critical points in butterfly life cycles has been repeatedly demonstrated to benefit butterfly populations. Mid-season mowing, while beneficial for plant diversity, decreases butterfly abundance and species richness, though that effect can be mitigated by partial mowing (Munguira and Thomas 1992, Valtonen and Saarinen 2005, Valtonen et al. 2006a, Skorka et al. 2013). Late-season mowing does not reduce butterfly abundance, though mowing at any point in the butterfly life cycle is likely to have some negative effect on populations by eliminating plants used for feeding or egg-laying (Valtonen et al. 2006a). Reducing mowing frequency likely increases butterfly abundance, though that effect is difficult to isolate from correlated increases in floral abundance or late-season population size

(Garbuzov et al. 2015, Halbritter et al. 2015). When paired with frequent mowing, broad herbicide application in ROW vegetation does not further reduce butterfly populations; mowing is assumed to have a greater negative impact than herbicide application (Zinnecker and Larsen 2011). Restored ROW habitat is most beneficial to butterflies when native plant species are dominant; this influence grows with time and is enhanced by a diverse surrounding landscape (Valtonen et al. 2007). Overall, vegetation management techniques that promote native flower abundance and species richness improve butterfly abundance and species richness (Ries et al. 2001).

3.3.1.1 Monarch butterflies

Monarch butterflies in ROW have been extensively studied in recent years, owing to drastic declines in their population over the last two decades. These declines have been primarily attributed to loss of breeding habitat and their host plant, milkweeds (Thogmartin et al. 2017, Daniels et al. 2018, Knight et al. 2019); in response, establishing milkweeds along ROW is now a leading mitigation effort in saving monarch populations (Kasten et al. 2016, Daniels et al. 2018, Knight et al. 2019). Milkweeds were historically regarded as a ubiquitous, weedy plant species, with a survey conducted in roadsides and nearby crop fields in Iowa in 1999 referring to "infestations" at the numerous sites where the plant was observed (Hartzler and Buhler 2000). Nationally, the greatest loss of milkweed stems occurred within crop fields after the introduction of herbicide tolerant crops. This allowed farmers to broadcast spray crop fields with herbicides, essentially eliminating milkweed from growing among crops. Milkweed is frequently found in ROW; nearly 60% of sites assessed in recent surveys have contained milkweed stems (Kasten et al. 2016, Thogmartin et al. 2017). Milkweed establishes readily in frequently disturbed habitats; therefore, ROW are thought to have very high potential for gains in milkweed stem density

(Thogmartin et al. 2017, Kaul and Wilsey 2019). Further, mowing ROW with milkweed promotes plant regeneration and reduces monarch predator abundance, providing egg-laying substrate and food for emerging larvae (Daniels et al. 2018, Thorne 2018, Knight et al. 2019, Haan and Landis 2019). Mowing milkweed early in the season before most monarchs arrive (prior to late June in Maine) has the strongest effect on increasing stem density and butterfly abundance (Thorne 2018, Dee and Baum 2019, Knight et al. 2019).

3.3.2 Bees

In comparison to butterflies, there is little information on the effects of ROW vegetation management on bees, though it is an emerging area of research. One single-season study found that mid-summer mowing without cutting removal decreases bee abundance and diversity for the remainder of the growing season (Phillips et al. 2019). A second study that assessed bee populations over three growing seasons concluded that late season mowing promoted bee abundance, though this finding was subject to substantial variation by study site and sample year. Further, selective herbicide application had a similar outcome (Kuder 2019). Restoring ROW habitat by seeding with native grasses and blooming plants also benefits bee populations, leading to greater bee abundance and species richness in restored sites than in conventionally managed ROW (Hopwood 2008, Mollet 2019). Additionally, providing patches of bare ground in restoration sites increases ground-nesting bee abundance; this can be done by planting clumps of native grasses that grow densely and expose soil at their base (Hopwood 2008, Moron et al. 2014). Bumble bees readily adapt to prairie-like ROW restorations, particularly when flower species are chosen to complement feeding preferences of short- and long-tongued bumble bee species (Clinebell 2003). The effects of restoration on bee communities can be highly variable in the first two years after establishing habitat; longer term observations are suggested for greater certainty of outcomes (Mollet 2019, Kuder 2019).

3.3.3. Plants for pollinators

Studies of ROW plant communities generally conclude that reduced mowing frequency is beneficial, though results vary. Plant diversity can increase with less frequent mowing (Entsminger et al. 2017, Jakobsson et al. 2018, Kuder 2019), though one study found only greater plant diversity in control sites with no mowing, and mowing may allow non-native species to establish (Wigginton and Meyerson 2018, Kuder 2019). Other studies have found that mowing promotes native species (Wrzesien et al. 2016, Entsminger et al. 2017). Less frequent mowing can maintain safe visibility conditions and keep soil in place by retaining plant density (Entsminger et al. 2019). Strategic timing of selective herbicide application can increase effectiveness at reducing undesirable plant abundance. For example, conducting two half-rate herbicide applications at different times in the growing season increased the total length of time that treatments were effective (Terry 2018). An integrated vegetation management scheme consisting of infrequent mowing with cutting removal paired with selective herbicide application may lead to greater native plant diversity, benefitting pollinator communities (Jakobsson et al. 2018, Entsminger et al. 2019, Kuder 2019). Unmanaged ROW also have diverse plant communities and can grow into high-quality pollinator habitat over time (Heneberg et al. 2017).

Establishing robust plant communities through ROW habitat restoration may be sensitive to heavy equipment use in the first two years of growth, either through soil compaction or vegetation loss from mowing (Jorgensen et al. 2018, Wigginton and Meyerson 2018). Passive restoration methods such as eliminating mowing early in site establishment may be beneficial over the long term (Wigginton and Meyerson 2018), though more active management may be required in areas with lower plant diversity in the surrounding landscape (Soper et al. 2019). One long term monitoring study of restored ROW habitat indicates that seeded grasses have the greatest establishment rate, while seeded forb and shrub species are much less likely to successfully establish after five years (Ament et al. 2017). However, establishment appears to be context-dependent, with lower rates of seeded vegetation establishment in less diverse landscapes owing to reduced availability of native plants in surrounding land cover (Soper et al. 2019 and sources within).

3.4. Research question 3: Are there elements of landscape context that affect the success of ROW management for pollinator conservation?

3.4.1 Landscape composition

Plant and pollinator communities in ROW vegetation vary with the land use and natural community composition of the surrounding landscape. Natural or semi-natural grassland habitat generally enhances plant and pollinator communities in nearby ROW vegetation (Davis et al. 2007, 2008, Jakobsson and Agren 2014, Skorka et al. 2013, 2018), although the opposite has also been observed (Berg et al. 2011). In intensively farmed landscapes, ROW may be one of few sources of reliable habitat for pollinators (van Swaay 2003), and restoring ROW habitat may be especially beneficial in these landscapes (Munguira and Thomas 1992). In landscapes containing insect-pollinated crops, bee abundance in ROW habitat can be maintained by blooming crops providing ample pollen and nectar, though bee diversity decreases owing to low blooming plant diversity (Benedek 1997). Rights-of-way near organic farms have more diverse plant communities than those near conventional farms; further, plants in ROW near organic farms are of greater value to wild bees (Henriksen and Langer 2013). As such, ROW restoration efforts in conventional agriculture-dominant landscapes may require more intensive management and a seed mix containing more native and desirable plant species (Soper et al. 2019). Indeed, ROW hedgerow habitat in agriculturally intense landscapes can mitigate negative effects of crop management on bee communities (Hanley and Wilkins 2015). Crop plants have greater seed set in fields near ROW; conversely, native plants in ROW set fewer seeds when surrounded by more cropland (Jakobsson and Agren 2014, Hevia et al. 2016). The type of road in agricultural landscapes may influence bee communities; unpaved livestock roads support greater surrounding bee populations, while paved roads reduce bee density, perhaps owing to mortality associated with vehicle traffic (Hevia et al. 2016, Kallioniemi et al. 2017).

Forest land cover in the surrounding landscape can benefit butterfly abundance in roadsides and bee species richness along railway embankments (Skorka et al. 2013, Moron et al. 2014). Actively managed forests have networks of logging roads that also provide beneficial pollinator habitat; indeed, in heavily forested landscapes, these roads may serve as one of few sources of forage for pollinators (Coulson et al. 2005, Oleksa et al. 2013). Forest canopy openings created by logging roads can provide floral resources and facilitate wild bee access into 100 m of surrounding forest, where standing dead wood provides nesting habitat (Jackson et al. 2014, Westerfelt et al. 2018). Power line ROW through forests may serve as a source habitat for pollinators found foraging along forest roads within 500 m (Berg et al. 2016); similarly, a network of forest roads with wide verges through managed forests promotes some forest-specialist butterflies (Bubova et al. 2015). Research on other land cover types, including wetlands and developed areas, is scarce. Developed land can promote butterfly species richness in ROW, though it can also reduce grassland-associated plant species, potentially leading to a negative outcome for butterflies (Skorka et al. 2013, Cochard et al. 2017). Diverse wetland habitat near ROW supports specialist butterfly species that are not found in the nearby ROW habitat (Swengel and Swengel 2010).

Complexity in the composition or configuration of landscape patches is generally beneficial to pollinators. A mosaic of agricultural and grassland cover types provides diversity in floral resources and habitat substrate, leading to more diverse ROW pollinator communities (Ouin and Burel 2002, van Halder et al. 2017). Composition of the surrounding landscape may even eliminate the negative effects of mowing or selective herbicide application on bee or butterfly diversity in ROW (Valtonen et al. 2006a, Kuder 2019). Restored linear roadside habitat may contain different pollinator communities than larger block-shaped restorations owing to relationships with surrounding land cover (Davis et al. 2007, 2008). Additionally, linear habitat may facilitate butterfly movement (Valtonen and Saarinen 2005, Soderstrom and Heblom 2007). Lastly, the scale at which these relationships are assessed informs the outcomes, as bee body size determines their foraging range and effectively their landscape size (Greenleaf et al. 2007). One study found that the amount of ROW habitat at small scales (400 m) negatively affected small-sized wild bees that cannot fly longer distances to find suitable habitat, whereas large-sized species that can fly greater distances to find suitable habitat were positively affected (Schwantes 2015).

3.4.2 Threats associated with roadside habitat

3.4.2.1 Traffic volume and mortality

One recurring concern of managing ROW habitat for pollinators is incidental mortality associated with vehicle traffic. Early studies did not find substantial butterfly mortality owing to vehicle collisions when butterflies fly over multiple types of roads (Munguira and Thomas 1992, Ries et al. 2001); however, mortality has been assessed in recent studies with varied results.

Insect mortality is generally greater along roads with greater traffic volumes owing to collision or turbulence, though this does not consistently lead to lower abundance or diversity in nearby ROW habitat (Skorka et al. 2013, Baxter-Gilbert et al. 2015, Zielin et al. 2016, Martin et al. 2018, Phillips et al. 2019). One study found greater insect visitation to flowers along railway embankments with intermediate traffic volumes (Wrzesien et al. 2016). Road structure may influence mortality: four lane roads have lower mortality rates than two lane roads, perhaps owing to wider, inhospitable shoulders separating vegetation from traffic (Hopwood 2010). Vegetative medians lead to greater bee and butterfly mortality (Keilsohn et al. 2018). Further, intensive vegetation management and surrounding topography create high-mortality zones along roadways called “blackspots” (Skorka et al. 2015, Kantola et al. 2019, Mora Alvarez et al. 2019). One study conducted in Poland labeled 4% of surveyed ROW as blackspots; these sites consisted of low-quality habitat and contained 49% of the road-killed butterflies collected while surveying (Skorka et al. 2015). In North America, these mortality hotspots have detrimental effects on monarch butterflies; as they migrate from south Texas into northern Mexico, blackspots occur as topography funnels butterflies into flying along or across high-traffic roads (Kantola et al. 2019, Mora Alvarez et al. 2019).

Broad estimates of total insect mortality associated with vehicle traffic are limited and face methodological limitations. One highly publicized study estimated hundreds of billions of dead insects along North American highways every year (Baxter-Gilbert et al. 2015). The extrapolation was based on data collected from just 2 km (1.25 mi) of road, and bees and butterflies made up a small portion of the estimated mortality. Another study assessed dead butterfly persistence along roadsides and found only 5% of observed butterfly carcasses remained after 48 hours, indicating surveys of large insects likely lead to underestimated mortality rates (Skorka 2016). Mortality can be mitigated by surrounding land cover type; studies have found that ROW bordered by forests or grassland have less insect mortality, though grassland has also been linked to greater mortality (Skorka et al. 2013, 2015, Keilsohn et al. 2018). Additionally, pollinators can be prevented from crossing the road by improving habitat quality. Multiple studies demonstrate that butterflies are more likely to cross a roadway when observed in low-quality ROW habitat (Ries et al. 2001, Valtonen and Saarinen 2005, Skorka et al. 2013, Polic et al. 2014).

3.4.2.2. Pollution and pathogens

Air, soil, light, and noise pollution have all been cited as potential threats to pollinator populations in ROW vegetation. Exhaust fumes from diesel engines can degrade floral odors, confusing honey bees and potentially preventing pollination (Girling et al. 2013). Road dust on unpaved roads inhibits wildflower reproduction; seed set is reduced as pollen is replaced with dust particles (Lewis et al. 2017, Waser et al. 2017). Roberts and Phillips (2019) found a number of studies on roadside soil pollution in a similar literature search, concluding that heavy metals are highly concentrated in roadside soil and vegetation and may negatively affect pollinating insects and plant growth (Roberts and Phillips 2019 and sources within). Honey bee hives placed close to high-traffic roadways produce honey with greater concentrations of heavy metals (Bilandzic et al. 2011). Sodium exposure from road salt can alter the physiology of monarch butterflies, affecting how they fly and find food (Snell-Rood et al. 2014). In a recent review of pollinator habitat in ROW, Phillips et al. (2020) conclude that light pollution from streetlights negatively affects nocturnal pollinator populations and suggest strategies to reduce pollinator mortality from light pollution while maintaining safe visibility. Further, streetlights and bursts of ground-level light from headlights have both been found to alter plant physiology (Bennie et al.

2016). Lastly, Davis et al. (2018) found that short term exposure to simulated highway noise increased monarch larval heart rate, but long-term exposure did not; they conclude that adult monarchs can handle chronic noise stress.

Right-of-way habitat may provide a corridor for spread of invasive species, parasites, or pathogens. Non-native plant species reduce native plant diversity and butterfly abundance in ROW (Valtonen et al. 2006b, Brisson et al. 2010); their control is a crucial component of vegetation management with mowing and selective herbicides. Rights-of-way may harbor predatory species, such as fire ants that consume eggs, pupae, and larvae of the federally endangered Schaus swallowtail butterfly (*Papilio aristodemus*) (Forys et al. 2001). Research on parasites and pathogens in ROW habitat is scarce. We found one study that assessed infection rates of both a parasite and a pathogen of monarch butterflies,which did not differ in communities within ROW and managed prairies (Mueller and Baum 2014).

3.4.2.3 Habitat fragmentation

Habitat fragmentation associated with roadway presence may negatively affect pollinator populations through loss of natural prairie-like habitat or by creating a barrier to movement. Adjusting mowing regimes or restoring habitat can mitigate habitat loss and promote pollinator populations (Benedek 1997). Multiple studies have found that high or low-traffic roads are not a barrier to movement by bees (Munguira and Thomas 1992, Bhattacharya et al. 2003, Hopwood et al. 2010). Bumble bees can cross roads to and from nests, but are likely to stay on the same side of a road if they find suitable forage (Bhattacharya et al. 2003; Hopwood et al. 2010). Studies on butterfly movement across roads are less conclusive. High-speed railways do not pose a barrier for homing behavior of a displaced butterfly; butterflies returned home regardless of being displaced along or across the railway (Vandevelde et al. 2012). However, butterflies with low mobility are not abundant along roadsides (Berg et al. 2011), and other studies have observed "trapped" populations of butterflies owing to roads (Jansen et al. 2012, Polic et al. 2014). There may be behavioral differences contributing to likelihood of butterflies crossing roads, i.e., migratory butterflies cross roads easier than non-migratory species, which may turn away from roads (Halbritter et al. 2015).

3.5. Research synthesis and applications: How do answers to the questions above inform best management practices for ROW habitat enhancement for pollinators?

3.5.1 Maine ROW as pollinator habitat

The Maine DOT currently follows many of the suggested management practices for enhancing pollinator habitat in ROW vegetation. A survey of Maine and other New England DOT employees conducted by Campanelli et al. (2019) summarizes these efforts; we describe them here and relate them to the context of our review findings. Maine DOT has reduced mowing along much of its interstate ROW land, with most land outside of safety zones nearest to paved roads mowed only once yearly. Adjusting the timing of annual mowing from June-August to late August or September may provide more blooming plants for pollinators throughout the growing season. Mowing after September may be preferable for plant propagation and late-season pollinators (including monarch butterflies), though the threat of frost may make such timing unfeasible. Maine DOT practices targeted herbicide application along all of their roads, focusing on woody stems only. Owing to the lack of documentation of herbicide practices in the general literature, formal documentation and dissemination of these practices to other DOTs may lead to improved herbicide BMPs for pollinator habitat beyond Maine's borders.

Seeding practices along ROW managed by Maine DOT currently includes three standard seed mixes sourced from out of state, with a focus on reliable establishment and soil stabilization. The agency has explored native seed mixes through a collaboration with the Maine Natural Areas Program and Maine-based NGO Wild Seed Project (McCargo 2018, Campanelli et al. 2019). Maine DOT also collaborates with the Maine Natural Areas Program on plant identification training for road crew personnel, which is recommended by the FHWA (Hopwood et al. 2015c). Habitat restoration practices with native seeds and plants is not yet common along ROW in Maine; implementing this practice following guidance from the Wild Seed Project (McCargo 2018), even on a limited spatial scale, may improve existing pollinator habitat.

Maine DOT has conducted two single-year surveys of ROW vegetation. One project involved photo surveys and vegetation ranking at 40 sites (Campanelli et al. 2019). Another project focused on pollinator habitat, pairing vegetation surveys with butterfly and bumble bee surveys (Drummond 2018). These pollinator habitat surveys found high blooming plant diversity and evenness within ROW across much of the state. This suggests that high quality pollinator habitat already exists in many ROW; however, undesirable plant species were frequently observed, in some cases comprising nearly two thirds of all blooming plant species. Both butterflies and bumble bees were diverse and abundant; bumble bee species composition varied across the state, while butterfly communities were dominated three species, including one exotic (European Skipper [*Thymelicus lineola*]) Overall, blooming plant species richness promoted pollinator abundance (Drummond 2018), suggesting that managing for high quality pollinator habitat within ROW in Maine can support diverse and abundant pollinator populations. Longer term survey work on plants and pollinators in Maine ROW can provide insight on the establishment, effectiveness, and long-term maintenance of native plant-dominant pollinator habitat.

Our assessment of landscape composition found that the type of land cover surrounding Maine ROW influences pollinator communities. Butterflies were more sensitive to surrounding land cover type than bumble bees, and abundance was more sensitive than species richness. Influential land cover types were agriculture/grassland, wetlands/water, and urban/developed; generally, agriculture/grassland and wetlands/water reduced pollinator abundance, whereas the influence of urban/developed land varied by sampling period. In the early season, butterfly abundance was less in ROW surrounded by wetlands/water and urban/developed land, while it was greater in ROW surrounded by deciduous forest. Bumble bee species richness was greater in ROW surrounded by agriculture/grassland in the early season. In the mid-season, butterfly species richness was less in ROW surrounded by deciduous forest and deciduous forest edge. In the late season, total pollinator abundance was greater in ROW surrounded by urban/developed and less in ROW surrounded by agriculture/grassland; these overall relationships were driven mostly by the butterfly community (Figure 3). Over the entire growing season, we found less butterfly abundance in ROW surrounded by agriculture/grassland and greater butterfly species richness in ROW surrounded by coniferous forest. Full results of these analyses are found in Appendix G.

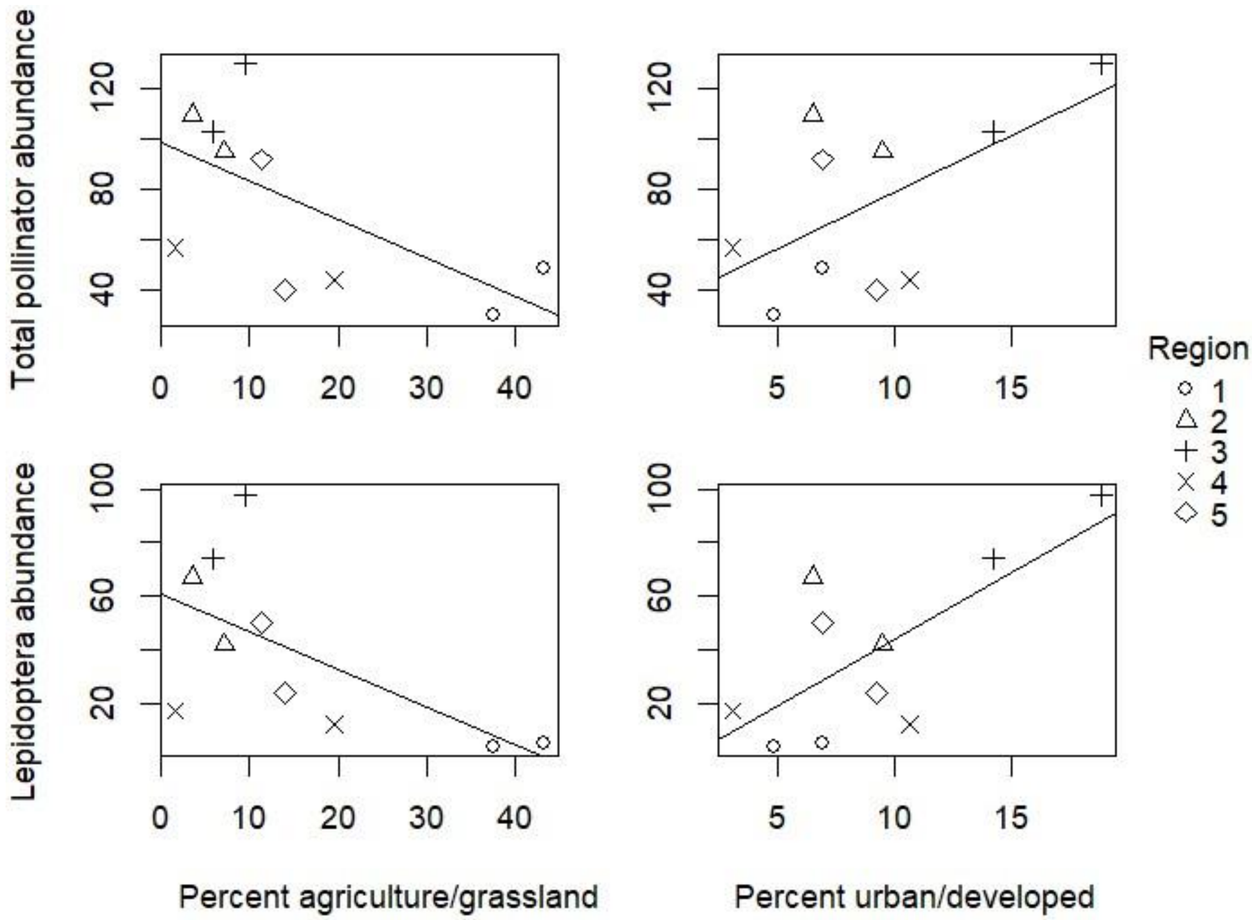

Figure 3. Late season effects of surrounding landscape composition (within 1 km of survey sites, Fig. 1) on pollinator communities in Maine ROW. Data from Drummond (2018).

3.5.2 Case study review

Many state Departments of Transportation have implemented ROW vegetation management practices that benefit pollinators, including reduced mowing regimes, more targeted herbicide use, and habitat restoration. Indeed, many states (IA, ID, MN, NY, OH, OR) were practicing reduced mowing along most rural roads before the FHWA issued any pollinator-focused management recommendations; this was generally owing to constraints on time and money, with pollinator conservation as an unintended benefit (Hopwood et al. 2016). In these states, the entire ROW along these roads is mowed 0-2 times per year at various points throughout the growing season. Research indicates that altering the timing of mowing to the late fall benefits pollinator populations (Hopwood et al. 2015c). Other states have trialed or transitioned to reduced mowing regimes in response to FHWA documentation, including Tennessee (TDOT), Colorado (O'Meara 2017, CDOT 2018), and Delaware (DelDOT 2018).

Although targeted herbicide use is a frequent management recommendation, there are few published case studies demonstrating this practice. Iowa developed their IRVM program in the 1980s owing to their dependence on herbicides for roadside vegetation management; at the time, they were exclusively using herbicides to control roadside weeds and had found the practice cost-intensive and largely ineffective. They transitioned to spot-spray application, and paired with planting native vegetation, have been able to effectively control weeds with less intensive management (Brandt et al. 2015). The Oregon DOT reduced herbicide use by up to 50% alongside roadways over five years by updating spraying equipment, diluting rates of application, and transitioning to spot sprays as opposed to routine blanket sprays (Hopwood et al. 2015c). Wider adoption of these practices may be difficult, as many DOTs cite time and funding constraints to implement changes to existing herbicide use practices in their states (Hopwood et al. 2016).

Right-of-way habitat restoration projects substantially increased in response to the FHWA documentation, either through planting native plant habitat or developing native species seed mixes. The Virginia DOT was an early adopter of this practice and planted four "Pollinator Waystation" plots in 2014, three at Park & Ride lots and one at an interstate rest area (VDOT 2016). Michigan, North Carolina, and Georgia have all planted pollinator habitat since 2015 (MDOT 2017, NCDOT via Hopwood 2017, Solomon 2018). Michigan and North Carolina have planted sunflowers; the NCDOT plants other wildflower species, while the MDOT is considering the addition of custom perennial seed mixes to their management plan. Establishing native plant habitat through seeding is a longer process. Seeds can be spread over larger areas more quickly than plants; however, sourcing native seeds can be difficult (but see McCargo 2018). The Arizona DOT has used native seeds exclusively in revegetation projects since 1992; through collaborations with native seed providers, they are able to obtain the seeds they need for multiple custom seed mixes (Hopwood et al. 2015c, 2016). North Dakota is incorporating pollinator species into seed mixes being planted at a number of roadside sites, including rest areas (North Dakota State Agencies 2018). Many states cite the cost or limited availability of native seed as the major impediment to increasing the use of native plants (Hopwood et al. 2016, Campanelli et al. 2019).

3.5.2.1. Monarch CCAA for ROW

On December 17, 2020, the US Fish and Wildlife Service (USFWS) announced that the monarch butterfly is warranted for listing as an endangered species but is precluded from listing by higher priority actions (USFWS 2020). While the USFWS conducted its review of available information on monarch populations, habitats, and threats, numerous public and private agencies collaborated to develop the Nationwide Candidate Conservation Agreement for Monarch Butterfly on Energy and Transportation Lands, which was published in March 2020 (hereafter referred to as the Monarch CCAA; Monarch CCAA 2020). The Monarch CCAA asks managers of non-Federal ROW to voluntarily adhere to management strategies that improve or establish monarch butterfly habitat by promoting native milkweed species, as suggested by Thogmartin et al. (2017). It includes a Candidate Conservation Agreement with Assurances that permits enrollees to conduct pre-approved management practices on non-Federal ROW that, should the monarch butterfly be listed as an endangered species, would permit take of monarch individuals owing to management activities. This allows ROW managers to continue existing practices while simultaneously encouraging additional conservation measures within ROW, particularly by planting native milkweed species. In Maine, this includes common milkweed (*Asclepias syriaca*) and swamp milkweed (*Asclepias incarnata*), which bloom in the mid-summer and set seed in the fall (McCargo 2018). Enrollment in the Monarch CCAA is open until the USFWS makes a final decision on listing the monarch as an endangered species, which is not expected until 2024 (UIC ERC 2021).

3.5.3 Strategies for successful implementation

Gathering public support when changing ROW vegetation management strategies is critical for project success; many projects cite stakeholder conflict as a major obstacle in implementation (Lucey and Barton 2011, Garbuzov et al. 2015, Kuder 2019, Campanelli et al. 2019). These stakeholders include adjacent landowners, vegetation management subcontractors, and the general public, who may object to less frequent mowing, the introduction of new plant species, and the appearance of "weedy" native vegetation. Stakeholder apprehension can be mitigated through various outreach channels, including mailings, brochures, public meetings, press releases, websites, videos, demonstration gardens, and signage (Lucey and Barton 2011, Garbuzov et al. 2015, Hopwood et al. 2015b, c, Galea et al. 2016, Kuder 2019).

Although many policies and legislative acts have been passed regarding roadside vegetation management for pollinators, funding for these projects remains scarce and is the primary obstacle cited by Departments of Transportation (Hopwood et al. 2016, Campanelli et al. 2019). Innovative partnerships between DOTs and non-profit organizations provide funding opportunities for high-impact environmental stewardship. The Ray C. Anderson Memorial Highway in Georgia is a partnership between the Ray C. Anderson Foundation and the Georgia

DOT; “The Ray” features a pollinator garden along the entirety of its 29 km (18 mi) vegetative median (The Ray 2018 via Solomon 2018). In Florida, the DOT has partnered with the Florida Wildflower Foundation to establish pollinator habitat along roadsides by reducing mowing and planting native wildflowers (Hopwood et al. 2016). Additionally, several states raise funds for pollinator habitat through specialty wildflower license plates (FL, OK, TX, VA; Hopwood et al. 2015b).

4. Discussion

4.1 Synthesis of current knowledge

Our review synthesized several sources of information that reach similar conclusions regarding ROW vegetation management to promote pollinator populations. Adjusting mowing regimes to reduce frequency and postponing mowing until the growing season ends provides more habitat for actively foraging and nesting pollinators. Targeting herbicide applications to spot treatments of undesirable species or waiting until the active pollinator flying season ends to make applications reduces negative outcomes for native plants and pollinators. Lastly, restoring ROW habitat to prairie-like conditions, even over small spatial scales, and featuring diverse native blooming plants and grasses enhances pollinator populations.

There are threats to pollinator populations in ROW associated with vehicle traffic, pollution, and habitat change; however, in most cases, vegetation management to benefit pollinators outweighs these threats. The landscape context surrounding ROW influences plant and pollinator populations, with flowering ROW providing a consistent source of habitat in agricultural, forested, and urban landscapes. Our analysis of ROW along Priority 1 roads in Maine supports these trends. Further, a recent meta-analysis of plant and pollinator communities in ROW and the surrounding landscape found quantitative evidence that ROW plant and pollinator communities are similar to those in prairie-like habitat and are more abundant and diverse than those in agricultural and forested areas, suggesting ROW management and restoration in agricultural and forested areas can provide suitable pollinator habitat (Phillips et al. 2020).

4.2 Knowledge gaps

Research on roadside vegetation management has substantially increased for mowing and restoration, while studies on the effects of herbicide management strategies on both plants and pollinators remain scarce. This is particularly concerning as herbicide use is ubiquitous among state DOTs; more information on how this affects pollinator populations would improve existing management strategies. Results from research on mowing and restoration would be more robust if studies a) conducted inventories of habitat before implementing habitat changes and for multiple subsequent years after implementation and b) directly compared outcomes of various management strategies through robust experimental design. Studies on wild bees are also lacking. There was only one single study in the body of literature that assessed outcomes of both mowing and herbicide use on plant and wild bee populations (Kuder 2019). Assessing wild bee populations in roadside vegetation more broadly would also be beneficial, as much of the existing literature examines butterflies and honey bees.

There is a large body of research that finds restoration of roadside habitat to native species beneficial to plant and pollinator communities, though few of these assess long-term outcomes of restoration projects. Studies that periodically monitor previously restored sites could provide insight on long-term outcomes, though yearly monitoring of plants and pollinators may be a more proactive and effective management approach. If Maine pursues ROW restoration to native-species dominant pollinator habitat, incorporating long-term monitoring could provide important insights on the efficacy of ROW restoration for pollinators.

While many studies exist that connect landscape context to pollinator populations in roadside vegetation, few connect context and vegetation management to pollinator populations. Understanding how the surrounding landscape may promote or prevent pollinator habitat establishment through mowing, herbicide use, and restoration would allow for more effective site location and targeted conservation efforts. Additionally, more assessment is needed on the influence of landscape context on wild bee populations in roadside vegetation; again, much of the existing information focuses on butterflies. In Maine, we observed an influence of landscape composition on pollinator populations, with butterflies more sensitive to surrounding land cover than bumble bees. This initial assessment would benefit from additional survey work in ROW surrounded by influential cover types including agriculture/grassland, urban/developed, and wetlands/water. Expanding survey methods to assess solitary wild bees would provide a more complete assessment of ROW pollinator communities in Maine.

Addressing these knowledge gaps in a rapidly expanding area of research presents an opportunity for meta-analysis with a large, uniform data set. Our assessment of the existing literature did not identify sufficient data for a robust meta-analysis. Future studies that employ a sampling design that incorporates landscape context and temporal and spatial replicates to evaluate effects of management strategies on ROW plant and pollinator communities will provide valuable knowledge for pollinator conservation.

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REFERENCES

Note: * indicates the reference is a literature search result

*Ament, R., Pokorny, M., Mangold, J., and N. Orloff. 2017. Native plants for roadside revegetation in Idaho. Native Plants Journal 18(1): 4-18. 10.3368/npj.18.1.4

Asare, E., Hoshide, A.K., Drummond, F.A., Criner, G.K., and X. Chen. 2017. Economic risk of bee pollination in Maine lowbush blueberry, *Vaccinium angustifolium*. Journal of Economic Entomology 110(5): 1980-1992. 10.1093/jee/tox191

*Baxter-Gilbert, J.H., Riley, J.L., Neufeld, C.J.H., Litzgus, J.D., and D. Lesbarrères. 2015. Road mortality potentially responsible for billions of pollinating insect deaths annually. Journal of Insect Conservation 19(5): 1029-1035. 10.1007/s10841-015-9808-z.

*Benedek, P., 1997. Structure and density of lucerne pollinating wild bee populations as affected by changing agriculture. Proceedings of the 7th International Symposium on Pollination, Ed. K.W. Richards. Acta Horticulturae 437. 10.17660/ActaHortic.1997.437.44

*Bennie, J., Davies, T.W., Cruse, D., and K.J. Gaston. 2016. Ecological effects of artificial light at night on wild plants. Journal of Ecology 104: 611-620 10.1111/1365-2745.12551

*Berg, A., Ahrne, K., Ockinger, E., Svenson, R., and B. Soderstrom. 2011. Butterfly distribution and abundance is affected by variation in the Swedish forest-farmland landscape. Biological Conservation 144: 2819-2831. 10.1016/j.biocon.2011.07.035

Berg, A., Bergman, K.-O., Wissman, J., Zmihorski, M., and E. Ockinger. 2016. Power-line corridors as source habitat for butterflies in forest landscapes. Biological Conservation 201: 320-326. 10.1016/j.biocon.2016.07.034

*Bhattacharya, M., Primack, R.B., and J. Gerwein. 2003. Are roads and railroads barriers to bumblebee movement in a temperature suburban conservation area? Biological Conservation 109:37-45. 10.1016/S0006-3207(02)00130-1.

Bickerman-Martens, K., Swartz, B., Butler, R., and F.A. Drummond. 2017. Documenting the diversity, distribution, and status of Maine bumble bees: The Maine Bumble Bee Atlas and citizen scientists. Maine Policy Review 26(2): 43-49. https://digitalcommons.library.umaine.edu/mpr/vol26/iss2/8

*Bilandzic, N., Dokic, M., Sedak, M., Kolanovic, B.S., Varenina, I., Koncurat, A., and N. Rudan. 2011. Determination of trace elements in Croatian floral honey originating from different regions. Food Chemistry 128: 1160-1164. 10.1016/j.foodchem.2011.04.023

*Brandt, J., Henderson, K., and J. Uthe. 2015. Integrated roadside vegetation management technical manual. USDA NRCS, Iowa DOT. 83 pp.

*Brisson, J., de Blois, S., and C. Lavoie. 2010. Roadside as invasion pathway for common reed (*Phragmites australis*). Invasive Plant Science and Management 3: 506-514. 10.1614/IPSM-09-050.1

*Bubova, T., Vrabec, V., Kulma, M., and P. Nowicki. 2015. Land management impacts on European butterflies of conservation concern: a review. Journal of Insect Conservation 19: 805-821. 10.1007/s10841-015-9819-9

*Campanelli, J., Kuzovkina, Y.A., Ricard, R.M., and C.P. Schulthess. 2019. Attitudes toward and adoption of roadside revegetation using native plants by departments of transportation in New England states. Native Plants Journal 20(1): 31-46.

*Clinebell, R.R., 2003. Foraging ecology of selected prairie wildflowers (Echinacea, Liatris, Monarda, and Veronicastrum) in Missouri prairie remnants and restorations. Proceedings of the 18th North American Prairie Conference. 19 pp.

*Cochard, A., Pithon, J., Jagaille, M., Beaujouan, V., Pain, G., and H. Daniel. 2017. Grassland plant species occurring in extensively managed road verges are filtered by urban environments. Plant Ecology and Diversity 10(2-3): 217-229. 10.1080/17550874.2017.1350764

*Cole, L.J., Brocklehurst, S., Robertson, D., Harrison, W., and D.I. McCracken. 2017. Exploring the interactions between resource availability and the utilization of semi-natural habitats by insect pollinators in an intensive agricultural landscape. Agriculture, Ecosystems and Environment 246: 157-167. 10.1016/j.agee.2017.05.007

*Colorado Department of Transporation (CDOT), "I-76 is Buzzing about new Pollinator Highway Designation." 11 July 2018. https://www.codot.gov/news/2018/july/i-76-is-buzzing-about-new-pollinator-highway-designation-1/. Accessed 31 August 2018.

*Coulson, R.N., Pinto, M.A., Tchakerian, M.D., Baum, K.A., Rubink, W.L., and J.S. Johnston. 2005. Feral honey bees in pine forest landscapes of east Texas. Forest Ecology and Management 215: 91-102

Cullen, M.G., Thompson, L.J., Carolan, J.C., Stout, J.C., and D.A. Stanley. 2019. Fungicides, herbicides, and bees: a systematic review of existing research and methods. PLoS One 14(12): e0225743. 10.1371/journal.pone.0225743

*Daniels, J., Kimmel, C., McClung, S., Epstein, S., Bremer, J., and K. Rossetti. 2018. Better understanding the potential importance of Florida roadside breeding habitat for the monarch. Insects 9, 137: 10.3390/insects9040137

*Davis, J.D., Debinski, D.M., and B.J Danielson. 2007. Local and landscape effects on the butterfly community in fragmented Midwest USA prairie habitats. Landscape Ecology 22:1341-1354. 10.1007/s10980-007-9111-9

*Davis, J.D., Hendrix, S.D., Debinski, D.M., and D.M. Hemsley. 2008. Butterfly, bee and forb community composition and cross-taxon incongruence in tallgrass prairie fragments. Journal of Insect Conservation 12: 69-79. 10.1007/s10841-006-9063-4

*Davis, A.K., Schroeder, H., Yeager, I., and J. Pearce. 2018. Effects of simulated highway noise on heart rates of larval monarch butterflies, *Danaus plexippus*: implications for roadside habitat suitability. Biology Letters 14: 20180018. 10.1098/rsbl.2018.0018

*Dee, J.R., and K.A. Baum. 2019. Mowing frequency influences number of flowering stems but not population age structure of *Asclepias viridis,* an important Monarch host plant. The American Midland Naturalist 182: 27-35. 10.1674/0003-0031-182.1.27

*Delaware Department of Transportation (DelDOT), "National Pollinator Week: Pollinator Practices Take Root at DelDOT." 18 June 2018. https://news.delaware.gov/2018/06/18/national-pollinator-week-pollinator-practices-take-root-deldot/. Accessed 31 August 2018.

Dibble, A.C., Drummond, F.A., Stubbs, C., Veit, M., and J.S. Ascher. 2017. Bees of Maine, with a state species checklist. Northeastern Naturalist 24(15): 1-48. 10.1656/045.024.m1503

Dinno, A., 2017. dunn.test: Dunn's Test of Multiple Comparisons Using Rank Sums. R package version 1.3.5. https://CRAN.R-project.org/package=dunn.test. Accessed 1 February 2017.

Dray, S., and A.B. Dufour. 2007 The ade4 package: implementing the duality diagram for ecologists. Journal of Statistical Software 22(4): 1-20. 10.18637/jss.v022.i04

Dray, S., Pelissier, R., Couteron, P., Fortin, M.-J., Legendre, P., Peres-Neto, P.R., Bellier, E. Bivand, R., Blanchet, F.G., De Caceres, M., Dufour, A.-B., Heegaard, E., Jombart, T., Munoz, F., Oksanen, J., Thioulouse, J., and H.H. Wagner. 2012. Community ecology in the age of multivariate statistical analysis. Ecological Monographs 82(3): 257-275. 10.1890/11-1183.1

Drummond, F.A., 2018. Roadside bumblebee and butterfly survey final report to the Maine Department of Transportation. 15 pp.

Du Clos, B., Drummond, F.A., and C.S. Loftin. 2020. Noncrop habitat use by wild bees (Hymenoptera: Apoidea) in a mixed-use agricultural landscape. Environmental Entomology 49(2): 502-515. 10.1093/ee/nvaa001

*Entsminger, E.D., Jones, J.C., Guyton, J.W., Strickland, B.K., and B.D. Leopold. 2017. Evaluation of mowing frequency on right-of-way plant communities in Mississippi. Journal of Fish and Wildlife Management 8(1):125-139. 10.3996/062016-JWFM-051.

*Entsminger, E.D., Jones, J.C., Guyton, J.W., Leopold, B.D., and B.K. Strickland. 2019. Mowing effects on woody stem density and woody and herbaceous vegetation heights along Mississippi highway right-of-ways. Journal of Fish and Wildlife Management 10(1): 19-37. 10.3996/052018-JFWM-043

Feber, R.E., Smith, H., and D.W. MacDonald. 1996. The effects on butterfly abundance of the management of uncropped edges of arable fields. Journal of Applied Ecology 33(5): 1191-1205.

Forman, R.T.T., Sperling, D., Bissonette, J.A., Clevenger, A.P., Cutshall, C.D., Dale, V.H., Fahrig, L., France, R.L., Goldman, C.R., Heanue, K., Jones, J., Swanson, F., Turrentine, T., and T.C. Winter. 2003. Road ecology: science and solutions. Island Press, Washington, D.C. USA.

*Forys, E.A., Quistorff, A., and C.R. Allen. 2001. Potential fire ant (Hymenoptera: Formicidae) impact on the endangered Schaus Swallowtail (Lepidoptera: Papilionidae). The Florida Entomologist 84(2): 254-258. 10.2307/3496176

*Galea, M., Wojcik, V., Davies Adams, L., and E. Cole. 2016. Technical manual for maintaining roadsides for pollinators: establishment, restoration, management, and maintenance - a guide for state DOT managers and staff. Pollinator Partnership. 36 pp.

*Garbuzov, M., Fensome, K.A., and F.L.W. Ratnieks. 2015. Public approval plus more wildlife: twin benefits of reduced mowing of amenity grass in a suburban public park in Saltdean, UK. Insect Conservation and Diversity 8: 107-119. 10.1111/icad.12085

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, .F, Boreux, V., Cariveau, D., Chacoff, N.P., Dudenhöffer, J.H., Freita,, B.M., Greenleaf, S., Hipólito, J., Holzschuh, A., Howlett, B., Javorek, S.K., Kennedy, C.M., Krewenka, K., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlöf, M., Seymour, C.L., Schüepp, C., Szentgyörgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B., Wanger, T.C., Westphal, C., Williams, N., and A.M. Klein. 2013 Wild pollinators enhance fruit set crops regardless of honey bee abundance. Science 274(1608), 303–13. 10.1126/science.1230200

*Girling, R.D., Lusebrink, I., Farthing, E., Newman, T.A., and G.M. Poppy. 2013. Diesel exhaust rapidly degrades floral odours used by honeybees. Scientific Reports 3: 2779. 10.1038/srep0277

Goulson, D., Nicholls, E., Botias, C., and E.L. Rotheray. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347(6229): 1255957. 10.1126/science.1255957

Greenleaf, S.S., Williams, N.M., Winfree, R., and C. Kremen. 2007. Bee foraging ranges and their relationship to body size. Oecologia 153: 589-596. 10.1078/1433-8319-00070

Groff, S.C., Loftin, C.S., Drummond, F., Bushmann, S., and B. McGill. 2016. Parameterization of the InVEST crop pollination model to spatially predict abundance of lowbush blueberry (*Vaccinium angustifolium* Aiton) native bee pollinators in Maine, USA. Environmental Modelling and Software 79: 1-9. 10.1016/j.envsoft.2016.01.003

*Haan, N.L., and D.A. Landis. 2019. Grassland disturbance increases monarch butterfly oviposition and decreases arthropod predator abundance. Biological Conservation 233: 185-192. 10.1016/j.biocon.2019.03.007

*Halbritter, D.A., Daniels, J.C., Whitaker, D.C., and L. Huang. 2015. Reducing mowing frequency increases floral resource and butterfly (Lepidoptera: Hesperioidea and Papilionidea) abundance in managed roadside margins. Florida Entomologist 98(4): 1081-1092. 10.1653/024.098.0412

*Hanley, M.E., and J.P. Wilkins. 2015. On the verge? Preferential use of road-facing hedgerow margins by bumblebees in agro-ecosystems. Journal of Insect Conservation 19:67-74. 10.1007/s10841-014-9744-3

*Harrison. G.L., 2014. Economic impact of ecosystem services provided by ecologically sustainable roadside right of way vegetation management practices. University of Florida/IFAS Final Report. 35 pp.

*Hartzler, R.G., and D.D. Buhler. 2000. Occurrence of common milkweed (*Asclepias syriaca*) in cropland and adjacent areas. Crop Protection 19:363-366. 10.1016/S0261-2194(00)00024-7

*Heneberg, P. Bogusch, P., and M. Řezáč. 2017. Roadside verges can support spontaneous establishment of steppe-like habitats hosting diverse assemblages of bees and wasps (Hymenoptera: Aculeata) in an intensively cultivated central European landscape. Biodiversity and Conservation 26(4): 843-864. 10.1007/s10531-016-1275-7

*Henriksen, C.I., and V. Langer. 2013. Road verges and winter wheat fields as resources for wild bees in agricultural landscapes. Agriculture, Ecosystems and Environment 173:66-71. 10.1016/j.agee.2013.04.008.

*Hevia, V., Bosch, J., Azcarate, F.M., Fernandez, E., Rodrigo, A., Barril-Graells, H., and J.A. Gonzalez. 2016. Bee diversity and abundance in a livestock drove road and its impact on pollination and seed set in adjacent sunflower fields. Agriculture, Ecosystems and Environment 232: 336-344. /10.1016/j.agee.2016.08.021

*Hopwood, J., 2008. The contribution of roadside grassland restorations to native bee conservation. Biological Conservation 141: 2632-2640. 10.1016/j.biocon.2008.07.026

*Hopwood, J., 2010. Pollinators and roadsides: managing roadsides for bees and butterflies. The Xerces Society for Invertebrate Conservation. 8 pp.

*Hopwood, J., Winkler, L., Deal, B., and M. Chivvis. 2010. Use of roadside prairie plantings by native bees. Iowa State University, 14 pp.

*Hopwood, J., 2013. Roadsides as habitat for pollinators: management to support bees and butterflies. Proceedings of the 2013 International Conference on Ecology and Transportation. 18 pp.

*Hopwood, J., Black, S., Lee-Mader, E., Charlap, A., Preston, R., Mozumder, K., and S. Fleury. 2015a. Literature review: pollinator habitat management and best management practices in highway rights-of-way. U.S. Department of Transportation Federal Highway Administration. 68 pp.

*Hopwood, J., Fleury, S., and S. Black. 2015b. Pollinators and roadsides: best management practices for managers and decision makers. U.S. Department of Transportation Federal Highway Administration. 96 pp.

*Hopwood, J., Black, S., and S. Fleury. 2015c. Roadside best management practices that benefit pollinators: handbook for supporting pollinators through roadside maintenance and landscape design. U.S. Department of Transportation Federal Highway Administration Technical Report FHWA-HEP-16-059. 88 pp.

Hopwood, J., Black, S., and S. Fleury. 2016. Identifying the current state of practice for vegetation management associated with pollinator health and habitat: an interview report. U.S. Department of Transportation Federal Highway Administration Technical Report FHWA-HEP-17-098. 38 pp.

*Hopwood, J., "Pollinator Conservation at 60 MPH." The Xerces Society, 12 March 2017. https://xerces.org/2017/03/12/pollinator-conservation-at-60-mph/ Accessed 31 August 2018.

*Jackson, M.M., Turner, M.G., and S.M. Pearson. 2014. Logging legacies affect insect pollinator communities in southern Appalachian forests. Southeastern Naturalist 13(2): 317-336. 10.1656/058.013.0213

*Jakobsson, A., and J. Ågren. 2014. Distance to semi-natural grassland influences seed production of insect-pollinated herbs. Oecologia 175: 199-208. 10.1007/s00442-014-2904-z

*Jakobsson, S., Bernes, C., Bullock, J.M., Verheyen, K., and R. Lindborg. 2018. How does roadside vegetation management affect the diversity of vascular plants and invertebrates? A systematic review. Environmental Evidence 7: 17. 10.1186/s13750-018-0129-z*Jansen, S.H.D.R., Holmgren, M., van Langevelde, F., and I. Wynhoff. 2012. Resource use of specialist butterflies in agricultural landscapes: conservation lessons from the butterfly *Phengaris* (Maculinea) *nausithous*. Journal of Insect Conservation 16: 921-930. 10.1007/s10841-012-9479-y

Jordan, A., Patch, H.M., Grozinger, C.M., and V. Khanna. 2021. Economic dependence and vulnerability of United States agricultural sector on insect-mediated pollination service. Environmental Science and Technology. 55(4): 2243-2253. 10.1021/acs.est.0c04786

*Jorgensen, N., Mink, J., Soldat, D., Stier, J., and M. Renz. 2018. Effect of soil compaction on the germination and survival of common prairie forbs and grasses in Wisconsin prairie revegetation. Native Plants Journal 19(1): 4-13. https://muse.jhu.edu/article/691955

*Kalarus, K., and M. Bakowski. 2015. Railway tracks can have great value for butterflies as a new alternative habitat. Italian Journal of Zoology 82(4): 565-572. 10.1080/11250003.2015.1078417

*Kallioniemi, E., Astrom, J., Rusch, G.M., Dahle, S., Astrom, S., and J.O. Gjershaug. 2017. Local resources, linear elements and mass-flowering crops determine bumblebee occurrences in moderately intensified farmlands. Agriculture, Ecosystems and Environment 239: 90-100. 10.1016/j.agee.2016.12.039

*Kantola, T., Tracy, J.L., Baum, K.A., Quinn, M.A., and R.N. Coulson. 2019. Spatial risk assessement of eastern monarch butterfly road mortality during autumn migration within the southern corridor. Biological Conservation 231: 150-160. 10.1016/j.biocon.2019.01.008

*Kasten, K. Stenoien, C., Caldwell, W., and K.S. Oberhauser. 2016. Can roadside habitat lead monarchs on a route to recovery? Journal of Insect Conservation 20(6): 1047-1057. 10.1007/s10841-016-9938-y

*Kaul, A.D., and B.J. Wilsey. 2019. Monarch butterfly host plant (milkweed Asclepias spp.) abundance varies by habitat type across 98 prairies. Restoration Ecology 27(6): 1274-1281. 10.1111/rec.12993

*Keilsohn, W., Narango, D.L., and D.W. Tallamy. 2018. Roadside habitat impacts insect traffic mortality. Journal of Insect Conservation 22(2): 183-188. 10.1007/s10841-018-0051-2

Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., and T. Tscharntke. 2007. Importance of pollinators in changing landscapes for world crops. Proc Roy Soc B 274(1608): 303–13. 10.1098/rspb.2006.3721

*Knight, S.M., Norris, D.R., Derbyshire, R., and D.T.T. Flockhart. 2019. Strategic mowing of roadside milkweeds increases monarch butterfly oviposition. Global Ecology and Conservation 19: e00678. 10.1016/j.gecco.2019.e00678

Koricheva, J., Gurevitch, J., and K. Mengersen, Eds. 2013. Handbook of meta-analysis in ecology and evolution. Princeton University Press, Princeton, NJ, USA.

*Kuder, L., 2019. Evaluating integrated roadside vegetation management (IRVM) techniques to improve pollinator habitat. Maryland DOT State Highway Administration Research Report. No. MD-19-SHA/UM/4-38. 52 pp.

LaBar, C.C., and C.B. Schultz. 2012. Investigating the role of herbicides in controlling invasive grasses in prairie habitats: effects on non-target butterflies. Natural Areas Journal 32(2): 177-189. 10.3375/043.032.0207

*Lewis, M.B., Schupp, E.W., and T.A. Monaco. 2017. Road dust correlated with decreased reproduction of the endangered Utah shrub *Hesperidanthus suffrutescens*. Western North American Naturalist 77(4): 430-439. 10.3398/064.077.0404

*Lucey, A., and S. Barton. 2011. Influencing public perception of sustainable roadside vegetation management strategies. Journal of Environmental Horticulture 29(3):119–124.

Maine Department of Inland Fisheries and Wildlife (MDIFW), Maine Department of Marine Resources (DMR), and Maine Natural Areas Program (MNAP). 2015. Maine’s Wildlife Action Plan, Element 1: Maine’s Fish and Wildlife. 66 pp.

*Martin, A.E., Graham, S.L., Henry, M., Pervin, E., and L. Fahrig. 2018. Flying insect abundance declines with increasing road traffic. Insect Conservation and Diversity 11(6): 608-613. 10.1111/icad.12300

McCargo, H., 2018. Maine native plants for roadside restoration: a design and propagation manual. Maine Department of Transportation in collaboration with Wild Seed Project. 176 pp.

McGarigal. K., Cushman, S.A., and E. Ene. 2012. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical and Continuous Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. http://www.umass.edu/landeco/research/fragstats/fragstats.html. Accessed 3 February 2021.

*Michigan Department of Transportation (MDOT), "MDOT expands sunflower planting, increases late season food source for pollinators." 13 Oct 2017. https://www.michigan.gov/mdot/0,4616,7-151-9620-449779--,00.html. Accessed 4 September 2018.

Monarch CCAA/CCA Development Advisory Team, 2020. Nationwide CCAA/CCA for monarch butterfly on energy and transportation lands. Energy Resources Center at The University of Illinois at Chicago. 139 pp.

*Mollet, K.A., 2019. Promoting bee communities through habitat enhancements on public and private lands in Nebraska. MS Thesis, University of Nebraska. 123 pp.

*Mora Alvarez, B.X., Carrera-Treviño, and K.A. Hobson. 2019. Mortality of monarch butterflies (*Danaus plexippus*) at two highway crossing "hotspots" during autumn migration in northeast Mexico. Frontiers in Ecology and Evolution 7: 273. 10.3389/fevo.2019.00273

*Moron, D., Skorka, P. Lenda, M., Rozej-Pabijan, E., Wantuch, M., Kajzer-Bonk, J., Celary, W., Mielczarek, L.E., and P. Tryjanowski. 2014. Railway embankments as new habitat for pollinators in an agricultural landscape. PLoS One 9(7): e101297. 10.1371/journal.pone.0101297

*Mueller, E.K., and K.A. Baum. 2014. Monarch-parasite interactions in managed and roadside prairies. Journal of Insect Conservation 18: 847-853. 10.1007/s10841-014-9691-z

*Munguira, M.L., and J.A. Thomas. 1992. Use of road verges by butterfly and burnet populations, and the effect of roads on adult dispersal and mortality. Journal of Applied Ecology 29(2): 316-329. 10.2307/2404501

*Noordijk, J., Delille, K., Schaffers, A.P., and K.V. Sýkora. 2009. Optimizing grassland management for flower-visiting insects in roadside verges. Biological Conservation 142: 2097-2103. 10.1016/j.biocon.2009.04.009

*North Dakota State Agencies, 2018. North Dakota monarch butterfly and native pollinator strategy. Technical Report, 51 pp. https://gf.nd.gov/gnf/conservation/docs/nd-monarch-butterfly-native-pollinator-strategy.pdf

Oberhauser, K.S., and M.J. Solensky, Eds. 2004. The monarch butterfly -- Biology and Conservation. Cornell University Press, Ithaca, NY, USA.

*Ohio Department of Transportation (ODOT), 2016. Statewide roadside pollinator habitat program restoration guidelines and best management practices. 81 pp.

*Oleksa, A., Gawronski, R., and A. Tofilski. 2013. Rural avenues as a refuge for feral honey bee population. Journal of Insect Conservation 17: 465-472. 10.1007/s10841-012-9528-6

Ollerton, J., Winfree, R., and S. Tarrant. 2011 How many flowering plants are pollinated by animals? Oikos 120: 321-326. 10.1111/j.1600-0706.2010.18644.x

*O'Meara, C., "Buzz about the Colorado Pollinator Highway." *The Daily Camera*, 21 June 2017. https://www.dailycamera.com/2017/06/21/omeara-buzz-about-the-colorado-pollinator-highway/. Accessed 31 August 2018.

*Osgathorpe, L.M., Park, K. and D. Goulson. 2012. The use of off-farm habitats by foraging bumblebees in agricultural landscapes: implications for conservation management. Apidologie 43: 113-127. 10.1007/s13592-011-0083-z

*O'Sullivan, O.S., Holt, A.R., Warren, P.H., and K.L. Evans. 2017. Optimizing UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management. Journal of Environmental Management 191:162-171. 10.1016/j.jenvman.2016.12.062

*Ouin, A., and F. Burel. 2002. Influence of herbaceous elements on butterfly diversity in hedgerow agricultural landscapes. Agriculture, Ecosystems and Environment 93: 45-43. 10.1016/S0167-8809(02)00004-X

*Ouin, A., Aviron, S., Dover, J., and F. Burel. 2004. Complementation/ supplementation of resources for butterflies in agricultural landscapes. Agriculture, Ecosystems and Environment 103: 473-479. 10.1016/j.agee.2003.11.003

*Phillips, B.B., Gaston, K.J., Bullock, J.M., and J.L. Osborne. 2019. Road verges support pollinators in agricultural landscapes, but are diminished by heavy traffic and summer cutting. Journal of Applied Ecology 56(10): 2316-2327. 10.1111/1365-2664.13470

Phillips, B.B., Wallace, C., Roberts, B.R., Whitehouse, A.T., Gaston, K.J., Bullock, J.M., Dicks, L.V., and J.L. Osborne. 2020. Enhancing road verges to aid pollinator conservation: a review. Biological Conservation 250: 108687. 10.1016/j.biocon.2020.108687

*Polic, D., Fiedler, K., Nell, C., and A. Grill. 2014. Mobility of ringlet butterflies in high-elevation alpine grassland: effects of habitat barriers, resources, and age. Journal of Insect Conservation 18: 1153-1161. 10.1007/s10841-014-9726-5

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., and W.E. Kunin. 2010. Global pollinator declines: trends, impacts, and drivers. Trends in Ecology and Evolution 25(6): 345-353. 10.1016/j.tree.2010.01.007

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. Accessed 3 February 2021.

Rader, R., Cunningham, S.A, Howlett, B.G., and D.W. Inouye. 2020. Non-bee insects as visitors and pollinators of crops: biology, ecology, and management. Annual Review of Entomology 65: 391-407. 10.1146/annurev-ento-011019-025055

*Ries, L., Debinski, D.M., and M.L. Wieland. 2001. Conservation value of roadside prairie restoration to butterfly communities. Conservation Biology 15(2): 401-411. 10.1046/j.1523-1739.2001.015002401.x

*Roberts, B., and B. Phillips. 2019. Road verges and their potential for pollinators: a review of the costs, benefits, and management options. Buglife UK: 32 pp.

Russell, C., and C.B. Schultz. 2010. Effects of grass-specific herbicides on butterflies: an experimental investigation to advance conservation efforts. Journal of Insect Conservation 14: 53-63. 10.1007/s10841-009-9224-3

*Saarinen, K., Valtonen, A., Jantunen, J., and S. Saarnio. 2005. Butterflies and diurnal moths along road verges: does road type affect diversity and abundance? Biological Conservation 123: 403-412. 10.1016/j.biocon.2004.12.012

Schultz, C.B., Zemaitis, J.L., Thomas, C.C., Bowers, M.D., and E.E. Crone. 2016. Non-target effects of grass-specific herbicides differ among species, chemicals, and host plants in *Euphydryas* butterflies. Journal of Insect Conservation 20: 867-877. 10.1007/s10841-016-9920-8

Schultz, C.B., and J.A. Ferguson. Demographic costs and benefits of herbicide-based restoration to enhance habitat for an endangered butterfly and a threatened plant. Restoration Ecology 28(3): 564-572. 10.1111/rec.13102

*Schwantes, C.J., 2015. Investigating the impacts of deterministic forces on bees in human modified environments. MS Thesis. University of Colorado. 67 pp.

*Skorka, P. Lenda, M., Moron, D., Kalarus, K., and P. Tryanjowski. 2013. Factors affecting road mortality and the suitability of road verges for butterflies. Biological Conservation 159: 148-157. 10.1016/j.biocon.2012.12.028

*Skorka, P. Lenda, M., Moron, D., Martyka, R., Tryanjowski, P., and W.J. Sutherland. 2015. Biodiversity collision blackspots in Poland: separation causality from stochasticity in roadkills of butterflies. Biological Conservation 187: 154-163. 10.1016/j.biocon.2015.04.017

*Skorka, P., 2016. The detectability and persistence of road-killed butterflies: an experimental study. Biological Conservation 200: 36-43. 10.1016/j.biocon.2016.05.026

*Skorka, P., Lenda, M., and D. Moron. 2018. Roads affect the spatial structure of butterfly communities in grassland patches. PeerJ. 10.7717/peerj.5413

*Snell-Rood, E.C., Espeset, A., Boser, C.J., White, W.A., and R. Smykalski. 2014. Anthropogenic changes in sodium affect neural and muscle development in butterflies. Proceedings of the National Academy of Sciences 111(28): 10221-10226.

*Söderstrom, B., and M. Hedblom. 2007. Comparing movement of four butterfly species in experimental grassland strips. Journal of Insect Conservation 11:333-342. 10.1007/s10841-006-9046-5

*Solomon, A., "Meet Georgia's Solar Road." US News and World Report, 17 July 2018. https://www.usnews.com/news/best-states/articles/2018-07-17/dont-miss-this-highways-solar-road-and-pollinator-garden. Accessed 4 September 2018.

*Soper, J.M., Raynor, E.J., Wienhold, C., and W.H. Schacht. 2019. Evaluating composition and conservation value of roadside plant communities in a grassland biome. Environmental Management 63(6): 789-803. 10.1007/s00267-019-01154-x

Steffan-Dewenter, I., Münzenberg, U., and C. Bürger. 2002. Scale-dependent effects of landscape context on three pollinator guilds. Ecology 83(5): 1421–1432. 10.1890/0012-9658(2002)083[1421:SDEOLC]2.0.CO;2

*Swengel, A.B., and S.R. Swengel. 2010. The butterfly fauna of Wisconsin bogs: lessons for conservation. Biodiversity and Conservation 19: 3565-3581. 10.1007/s10531-010-9916-8

*Tennessee Department of Transportation (TDOT). "Pollinator Habitat Program." https://www.tn.gov/tdot/environmental-home/environmental-highway-beautification-office/beautification-pollinator-habitat-program.html. Accessed 31 August 2018.

*Terry. M.R., 2018. Vegetation management along roadside and railroad right-of-ways. MS Thesis, University of Missouri. 102 pp.

*Thogmartin, W.E., Lopez-Hoffman, L., Rohweder, J., Diffendorfer, J., Drum, R., Semmens, D., Black, S., Caldwell, I., Cotter, D., Drobney, P., Jackson, L.L., Gale, M., Helmers, D., Hilburger, S., Howard, E., Oberhauser, K., Pleasants, J., Semmens, B., Taylor, O., Ward, P., Weltzin, J.F., and R. Wiederholt. 2017. Restoring monarch butterfly habitat in the midwestern US: "all hands on deck." Environmental Research Letters 12: 074005. 10.1088/1748-9326/aa7637

*Thorne, N.H., 2018. Impact of integrated vegetation management practices on green antelopehorn milkweed (*Asclepias viridis* Walter) in right-of-ways and forages. MS Thesis, Mississippi State University. 83 pp.

University of Illinois at Chicago Energy Resources Center, 2021. Monarch CCAA enrollment. http://rightofway.erc.uic.edu/national-monarch-ccaa/ccaa-enrollment/. Accessed 21 April 2021.

US Fish and Wildlife Service, 2020. Endangered and threatened wildlife and plants; 12-month finding for the monarch butterfly. Federal Register 85(243): 81813-81822. 50 CFR Part 17, Docket No. FWS-R3-ES-2020-0103; FF09E21000 FXES11110900000 212.

*Valtonen, A., and K. Saarinen. 2005. A highway intersection as an alternative habitat for a meadow butterfly: effect of mowing, habitat geometry and roads on the ringlet (*Aphantopus hyperantus*). Annales Zoologici Fennici 42(5): 545-556.

*Valtonen, A., Saarinen, K., and J. Jantunen. 2006a. Effect of different mowing regimes on butterflies and diurnal moths on road verges. Animal Biodiversity and Conservation 29(2): 133-148.

*Valtonen, A., Jantunen, J., and K. Saarinen. 2006b. Flora and lepidoptera fauna adversely affected by Lupinus polyphyllus along road verges. Biological Conservation 133: 389-396. 10.1016/j.biocon.2006.06.015

*Valtonen, A., Saarinen, K., and J. Jantunen. 2007. Intersection reservations as habitats for meadow butterflies and diurnal moths: guidelines for planning and management. Landscape and Urban Planning 79: 201-209. 10.1016/j.landurbplan.2005.09.003

*Vandevelde, J-C., Penone, C., and R. Julliard. 2012. High-speed railways are not barriers to Pyronia tithonus butterfly movements. Journal of Insect Conservation 16: 801-803. 10.1007/s10841-012-9513-0

vanEngelsdorp, D., and M. D. Meixner. 2010. Historical review of managed honey bee populations in Europe and the United States and the factors that may affect them. Journal of Invertebrate Pathology 103: S80-S95. 10.1016/j.jip.2009.06.011

*van Halder, I., Thierry, M., Villemey, A., Ouin, A., Archaux, F., Barbaro, L., Balent, G., and M.-L. Benot. 2017. Trait-driven responses of grassland butterflies to habitat quality and matrix composition in mosaic agricultural landscapes. Insect Conservation and Diversity 10: 64-77. 10.1111/icad.12200

*van Swaay, C.A.M., 2003. Butterfly densities on line transects in The Netherlands from 1990-2001. Entomologische Berichten 63(4): 82-87.

Venables, W.N., and B.D. Ripley. 2002 Modern Applied Statistics with S. Fourth Edition. Springer, New York, NY, USA.

Villemey, A., Jeusset, A., Vargac, M., Bertheau, Y., Coulon, A., Touroult, J., Vanpeene, S., Castagneyrol, B., Jactel, H., Witte, I., Deniaud, N., De Lachapelle, F.F., Jaslier, E., Roy, V., Guinard, E., Le Mitouard, E., Rauel, V., and R. Sordello. 2018. Can linear transportation infrastructure verges constitute a habitat and/or a corridor for insects in temperate landscapes? A systematic review. Environmental Evidence 7(5). 10.1186/s13750-018-0117-3

*Virginia Department of Transportation (VDOT), 2016. Pollinator Habitat Program. 5 pp. http://www.virginiadot.org/business/resources/maintenance/php_dec_2015.pdf

*Waser, N.M., Price, M.V., Casco, G., Diaz, M., Morales, A.L., and J. Solverson. 2017. Effects of road dust on the pollination and reproduction of wildflowers. International Journal of Plant Science 178(2): 85-93. 10.1086/689282

Webster, R. and P.G. deMaynadier. 2005. A baseline atlas and conservation assessment of the butterflies of Maine. 127 pp.

*Westerfelt, P., Weslien, J., and O. Widenfalk. 2018. Population patterns in relation to food and nesting resource for two cavity-nesting bee species in young boreal forest stands. Forest Ecology and Management 430: 629-638. 10.1016/j.foreco.2018.08.053

*White House Office of the Press Secretary, "2014 Pollinator Presidential Memo." 20 June 2014. https://www.nps.gov/subjects/pollinators/presidential-memo.htm. Accessed 31 August 2018.

*Wigginton, S.K., and L.A. Meyerson. 2018. Passive roadside restoration reduces management costs and fosters native habitat. Ecological Restoration 36(1): 41-51. 10.3368/er.36.1.41

*Wojcik, V.A., and S. Buchmann. 2012. Pollinator conservation and management on electrical transmission and roadside rights-of-way: a review. Journal of Pollination Ecology 7(3): 16-26.

*Wrzesien, M., Jachula, J., and B. Denisow. 2016. Railway embankments-refuge areas for food, flora, and pollinators in agricultural landscape. Journal of Apicultural Science 60(1):97-110. 10.1515/JAS-2016-0004.

*Zielin, S.B., Littlejohn, J., de Rivera, C.E., Smith, W.P., and S.L. Jacobson. 2016. Ecological investigations to select mitigation options to reduce vehicle-caused mortality of a threatened butterfly. Journal of Insect Conservation 20: 845-854. 10.1007/s10841-016-9916-4

*Zinnecker, T., and K.J. Larsen. 2011. A preliminary study on the impact of roadside prairie plantings on plant and insect communities. Luther College, Decorah, IA, USA. 15 pp.

Appendix A: Maine state pollinator species of concern

In 2015, the Maine Department of Inland Fisheries and Wildlife (MDIFW), Maine Department of Marine Resources (DMR), and Maine Natural Areas Program (MNAP) published Maine's Wildlife Action Plan, which remains effective until 2025. The plan lists 10 bumble bee species and 47 butterfly or moth species as pollinator species of concern, which we provide below (Table A.1). The Maine Species of Greatest Conservation Need (SGCN) Tiers are defined as: 1 – highest priority, 2 – High priority, 3 – moderate priority. Priority is assigned according to criteria covering risk of extirpation, population trend, endemicity, regional conservation responsibility, climate change vulnerability, and survey knowledge. A full description of SCGN tiers and their criteria are found in Maine's Wildlife Action Plan (https://www.maine.gov/ifw/fish-wildlife/wildlife/wildlife-action-plan/index.html). The State Conservation Concern codes follow the Endangered Species Act codes and are defined as: E -- Endangered Species, T -- Threatened Species, and SC-- Special Concern Species.

Table A.1. Pollinator species of conservation concern in Maine, 2015.

Scientific Name	**Common Name**	**SGCN**	**State Conservation Concern**
Bombus affinis	Rusty-patched bumble bee	1	SC
Bombus ashtoni	Ashton's Cuckoo bumble bee	2	SC
Bombus citrinus	Lemon Cuckoo bumble bee	3	SC
Bombus fernaldae	Fernald's Cuckoo bumble bee	3	SC
Bombus fervidus	Yellow bumble bee	3	SC
Bombus griseocollis	Brown-belted bumble bee	3	SC
Bombus insularis	Indiscriminate cuckoo bumble bee	2	SC
Bombus pensylvanicus	American bumble bee	2	SC
Bombus sandersoni	Sanderson's bumble bee	3	SC
Bombus terricola	Yellow-banded bumble bee	3	SC
Atrytonopsis hianna	Dusted skipper	3	SC
Boloria chariclea grandis	Purple lesser fritillary	2	T
Boloria frigga saga	Frigga fritillary	1	E
Callophrys gryneus	Juniper hairstreak	2	E
Callophrys hesseli	Hessel's hairstreak	1	E
Callophrys lanoraieensis	Bog elfin	3	
Catocala similis	Similar underwing	3	SC
Chaetaglaea cerata	A noctuid moth	2	SC
Chaetaglaea tremula	Barrens chaetaglaea	3	SC
Citheronia sepulcralis	Pine devil	2	SC
Cucullia speyeri	A moth	3	
Cupido amyntula maritima	Western tailed blue	3	
Danaus plexippus	Monarch	3	
Erora laeta	Early hairstreak	2	SC
Erynnis brizo	Sleepy duskywing	2	T
Hemaris gracilis	Graceful clearwing	3	SC

Hemileuca lucina	New England buckmoth	3	
Hemileuca maia maia	Eastern buckmoth	2	SC
Hesperia leonardus	Leonard’s skipper	3	SC
Hesperia metea	Cobweb skipper	3	SC
Lapara coniferarum	Southern pine sphinx	3	SC
Lepipolys perscripta	A moth	3	SC
Lithophane lepida lepida	Pine pinion	2	SC
Lycaena dorcas claytoni	Clayton’s copper	2	T
Lycia rachelae	Twilight moth	2	T
Metarranthis apiciaria	Barrens metarranthis moth	2	SC
Nepytia pellucidaria	A moth	3	SC
Oeneis polixenes katahdin	Katahdin arctic	1	E
Paonias astylus	Huckleberry sphinx	3	SC
Papilio brevicauda gaspeensis	Short-tailed swallowtail	3	SC
Papilio Troilus	Spicebush swallowtail	3	SC
Plebejus idas	Northern blue	2	SC
Plebejus idas empetri	Crowberry blue	2	SC
Polygonia satyrus	Satyr comma	3	SC
Psectraglaea carnosa	Pink sallow	2	SC
Satyrium edwardsii	Edwards’ hairstreak	2	E
Satyrium titus	Coral hairstreak	3	SC
Satyrodes Appalachia	Appalachian brown	3	SC
Spartiniphaga inops	Spartina borer moth	3	
Speranza exonerata	Barrens itame	2	SC
Thorybes bathyllus	Southern cloudywing	3	SC
Xylena thoracica	Acadian swordgrass moth	3	SC
Xylotype capax	Broad sallow	3	SC
Xystopeplus rufago	Red-winged sallow	3	SC
Zale lunifera	Bold-based zale moth	3	SC
Zale obliqua	Oblique zale	3	SC
Zanclognatha martha	Pine barrens Zanclognatha	1	T

Appendix B: Search keyword list

Population keywords:
Study organisms

Plants:
- vegetation
- flower
- flowering
- bloom
- blooming
- floral/flora
- forage
- resources
- nesting
- shrubs
- forbs
- herbs
- plant(s)
- invasive
- non-native/naturalized
- native

Animals:
- pollinating insects
- bees
- wild/solitary bees
- bumblebees
- Apoidea/vespoidea/papilionoidea
- Hymenoptera
- butterflies/moths
- Lepidoptera
- Hoverflies/Syrphidae
- wasp(s)/sphecidae
- Pollinators

Listed species:
Bees: Hymenoptera: Apoidea
State listed: (* = also federally listed)
- *Bombus affinis*
  - Rusty-patched Bumble Bee*
- *Bombus ashtoni*
  - Ashton's Cuckoo Bumble Bee
- *Bombus citrinus*
  - Lemon Cuckoo Bumble Bee
- *Bombus fernaldae*
  - Fernald's Cuckoo Bumble Bee
- *Bombus fervidus*
  - Yellow Bumble Bee
- *Bombus griseocollis*
  - Brown-belted Bumble Bee
- *Bombus insularis*
  - Indiscriminate Cuckoo Bumble Bee
- *Bombus pensylvanicus*
  - American Bumble Bee
- *Bombus sandersoni*
  - Sanderson's Bumble Bee
- *Bombus terricola*
  - Yellow-banded Bumble Bee*

Butterflies & moths: Lepidoptera
State listed: (* = also federally listed)
- *Danaus plexippus*
  - Monarch*
- *Lycaena dorcas claytoni*
  - Clayton's Copper
- *Papilio brevicauda gaspeensis*
  - Short-tailed Swallowtail

Federally listed, but not state listed
- *Speyeria Idalia*
  - Regal fritillary
- *Callophrys irus*
  - Frosted elfin
- *Lycaeides melissa samuelis*
  - Karner blue butterfly

Intervention keywords:

ROW

- roads
- roadsides
- road shoulder
- rails
- railways
- railroad
- power
- powerlines
- pipeline
- utility
- rights-of-way
- highway
- freeway
- interstate
- turnpike
- electric
- transmission line
- transportation
- infrastructure
- verge
- linear
- edge
- side
- margin
- hedgerow
- embankment
- ditch
- buffer
- strip
- corridor

Habitat

Type:

- landscape
- habitat
- semi-natural
- refuge
- meadow
- prairie
- grassland
- pasture
- agriculture
- barren
- shrubland
- wetland
- heath/bog
- scrub
- forest
- woodland
- coniferous
- deciduous
- Early succession
- Urban
- impervious

Context:

- pattern
- patch size
- shape
- complexity
- distance
- dominance
- cover/cover type

Management:

- conservation
- management
- restoration
- disturbance
- burning
- grazing
- mowing
- cutting
- plowing
- mulching
- clearing
- seeding
- planting

- fertilizer
- eradication
- logging
- harvesting
- herbicide/insecticide/ pesticide

Comparator and Outcome keywords:

- community
- population
- species
- composition
- abundance
- richness
- diversity
- assemblage
- reproduction
- persistence
- establishment
- enhancement
- success
- increase
- threat
- mortality
- decrease
- movement
- dispersal
- connectivity

Appendix C: Search keyword combination list

Web of Science:

1. rights-of-way AND management AND pollinators
2. right*-of-way AND management AND pollinators
3. roadside AND management AND pollinators
4. road* AND management AND pollinators
5. road* AND pollinators
6. right*-of-way AND pollinators
7. right*-of-way AND habitat AND management
8. highway AND management AND pollinators
9. highway AND pollinators
10. freeway AND management AND pollinators
11. freeway AND pollinators
12. interstate AND management AND pollinators
13. interstate AND pollinators
14. rail* AND management AND pollinators
15. rail* AND pollinators
16. turnpike AND pollinators
17. transportation AND management AND pollinators
18. transportation AND pollinators
19. transportation infrastructure AND pollinators
20. linear infrastructure AND pollinators
21. utility infrastructure AND pollinators
22. electric infrastructure AND pollinators
23. (Road* OR rail* OR power* OR "right* of way*") AND pollinators AND (management OR conservation OR enhancement OR restoration)
24. powerl* AND management AND pollinators
25. powerl* AND pollinators
26. "power l*" AND management AND pollinators
27. "power l*" AND pollinators
28. "power li*" AND pollinators
29. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND pollinators AND (manag* OR conserv* OR enhanc* OR restor*)
30. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND pollinators AND (burn* OR mow* OR cut* OR plow* OR clear* OR graz* OR disturb* OR eradicat*)
31. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND pollinators AND (seeding OR planting OR mulch* OR fertiliz* OR restor*)
32. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND pollinators AND (herbicid* OR insecticid* OR pesticid*)

33. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinators AND (logg* OR harvest*)
34. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinators AND conserv*
35. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinators AND habitat
36. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinators AND habitat AND (manag* OR conserv* OR enhanc* OR restor*)
37. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND population* AND (establish* OR reproduc* OR persist* OR success* OR increas*)
38. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND population* AND (threat* OR mortal* OR decreas*)
39. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND population* AND (movement* OR dispers* OR connect*)
40. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (population* OR communit* OR diversity OR species OR composition OR assemblage OR abundance OR richness)
41. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND landscape AND (pattern OR complex* OR context)
42. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (“patch size” OR “patch shape” OR distance)
43. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND “semi-natural” AND (habitat OR refug*)
44. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND bee(s)
45. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND bee AND (manag* OR conserv* OR enhanc* OR restor*)
46. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND bumblebee AND (manag* OR conserv* OR enhanc* OR restor*)
47. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (butterfl* OR moth OR moths) AND (manag* OR conserv* OR enhanc* OR restor*)
48. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (hoverfl* OR “hover fl*” OR syrphid*) AND (manag* OR conserv* OR enhanc* OR restor*)
49. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (wasp OR wasps OR sphecid*) AND (manag* OR conserv* OR enhanc* OR restor*)
50. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (Hymenoptera OR Lepidoptera) AND (manag* OR conserv* OR enhanc* OR restor*)
51. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (Apoidea OR Vespoidea OR Papilioidea) AND (manag* OR conserv* OR enhanc* OR restor*)
52. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND “pollinating insects” AND (manag* OR conserv* OR enhanc* OR restor*)
53. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND “insect pollinators” AND (manag* OR conserv* OR enhanc* OR restor*)

54. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (linear OR verge OR *edge* OR margin OR side OR ditch OR embankment OR buffer OR strip OR corridor)
55. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (flower* OR flora* OR bloom* OR forag*) AND (vegetation OR resources OR plants OR shrubs OR forbs OR herbs) AND pollinator*
56. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (nest*) AND (vegetation OR resources OR plants OR shrubs OR forbs OR herbs)AND pollinator*
57. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (invasive OR non-native OR native OR naturalized) AND (vegetation OR resources OR plants OR shrubs OR forbs OR herbs) AND pollinator*
58. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (meadow OR prairie OR grassland OR pasture OR agriculture OR barren OR shrubland OR scrub)
59. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (forest OR woodland OR coniferous OR deciduous OR “early succession*”)
60. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (wetland OR heath OR bog)
61. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND pollinator* AND (urban* OR impervious)
62. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND bumble* bee AND (manag* OR conserv* OR enhanc* OR restor*)
63. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (“Bombus affinis” OR Rusty* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
64. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (“Bombus ashtoni” OR Ashton* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
65. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (“Bombus citrinus” OR Lemon* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
66. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (“Bombus fernaldae” OR Fernald* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
67. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND “Bombus fervidus” AND (manag* OR conserv* OR enhanc* OR restor*)
68. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND (“Bombus griseocollis” OR Brown* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
69. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND “Bombus insularis” AND (manag* OR conserv* OR enhanc* OR restor*)
70. (Road* OR rail* OR powerli* OR “power li*” OR “right* of way*”) AND “Bombus pensylvanicus” AND (manag* OR conserv* OR enhanc* OR restor*)

71. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Bombus sandersoni" OR Sanderson* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
72. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Bombus terricola" OR Yellow* AND bumble*) AND (manag* OR conserv* OR enhanc* OR restor*)
73. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND Bombus AND (manag* OR conserv* OR enhanc* OR restor*)
74. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Danaus plexippus" OR monarch AND butterfl*) AND (manag* OR conserv* OR enhanc* OR restor*)
75. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Lycaena dorcas claytoni" OR "Clayton* copper" AND butterfl* AND (manag* OR conserv* OR enhanc* OR restor*)
76. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Speyeria idalia" OR "Regal fritillary" AND butterfl*) AND (manag* OR conserv* OR enhanc* OR restor*)
77. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Callophrys irus" OR "frosted elfin" AND butterfl*) AND (manag* OR conserv* OR enhanc* OR restor*)
78. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Lycaeides melissa samuelis" OR "Karner blue" AND butterfl*) AND (manag* OR conserv* OR enhanc* OR restor*)
79. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND ("Papilio brevicauda" OR "Short-tailed swallowtail" AND butterfl*) AND (manag* OR conserv* OR enhanc* OR restor*)

Google Scholar:

80. (Road* OR rail* OR powerli* OR "power li*" OR "right* of way*") AND pollinators AND (manag* OR conserv* OR enhanc* OR restor*)
81. Road pollinators
82. (road OR roadside OR "road shoulder" OR highway) (pollinators OR bee OR bumblebee OR bumblebees OR butterfly OR butterflies OR moth OR Hymenoptera OR Lepidoptera) (management OR conservation OR enhancement OR restoration)
83. (rail OR railway OR railways OR railroad OR railroads) (pollinators OR bee OR bees OR bumblebee OR bumblebees OR butterfly OR butterflies OR moth OR moths OR Hymenoptera OR Lepidoptera) (management OR conservation OR enhancement OR restoration)
84. (powerline OR powerlines OR "power line" OR "power lines") (pollinators OR bee OR bees OR bumblebee OR bumblebees OR butterfly OR butterflies OR moth OR moths OR Hymenoptera OR Lepidoptera) (management OR conservation OR enhancement OR restoration)

85. (“transmission line” OR “transmission lines”) (pollinators OR bee OR bees OR bumblebee OR bumblebees OR butterfly OR butterflies OR moth OR moths OR Hymenoptera OR Lepidoptera) (management OR conservation OR enhancement OR restoration)
86. (“right of way” OR “rights of way” OR “right of ways”) (pollinators OR bee OR bees OR bumblebee OR bumblebees OR butterfly OR butterflies OR moth OR moths OR Hymenoptera OR Lepidoptera) (management OR conservation OR enhancement OR restoration)

General Google Search:

87. road management pollinator
88. road conservation pollinator
89. "road" conservation pollinator
90. road restoration pollinator
91. road enhancement pollinator
92. road management bee
93. road management bumblebee
94. road management butterflies
95. road management butterfly
96. road management moths
97. road management hymenoptera
98. road management lepidoptera
99. road management butterflies lepidoptera
100. rail management pollinator
101. rail “conservation” pollinator
102. rail restoration pollinator
103. rail enhancement pollinator
104. rail management butterflies
105. rail management lepidoptera

Appendix D: Inclusion criteria for full-text screening

- Populations: Pollinators, plants; in USA, Canada, or Europe (looking for latitudinal similarity)
    - Included:
        - pollinating insects: bees, butterflies, hoverflies, wasps
            - species of concern (endangered/threatened)
        - flowering plants: trees, shrubs, prairie plants, native plants, invasive plants, early-successional forest plants, pollen and nectar sources
        - nesting resources—bare ground, woody debris
        - People’s perceptions, opinions, and experiences re: ROW management for pollinators
    - Excluded:
        - Anything outside of target geographic range
        - non-pollinating insects, arachnids: beetles, ants, dragonflies, spiders
        - Mammals, amphibians, reptiles, birds
        - Grasses
        - Pollen

- Interventions: Management practices along rights-of-way
    - Included:
        - Management practices: mowing, seeding, planting, burning, restoration, conservation
        - Rights-of-way: roads, rails
            - Regardless of width/length (forest rides and paths can be included)
        - Risks to pollinators associated with ROW: traffic, chemical exposure, habitat loss, electromagnetic fields
    - Excluded
        - powerlines, canals, gas lines
        - Other fallow or non-linear land Mines, solar farms, old fields, urban remnants
            - Field edges
        - Forest harvesting/forest edges
        - Hedgerows

- Comparators: Management or landscape context
    - Included:
        - Management: managed land vs unmanaged land
        - Landscape context: surrounding habitat type, pattern and composition
            - Role in movement across the landscape
        - Types of studies:
            - Observational or experimental field studies

            - Case studies, surveys, and interviews included if they describe management
    - Excluded:
        - Restoration/site design proposals
        - Economic effects or ecosystem services

- Outcomes: effect on diversity and/or abundance of pollinator and/or plant communities
    - Included: abundance, species richness, evenness, assemblage, diversity, presence, absence, occurrence
    - Excluded: unexecuted habitat design proposals, long term observations without intervention
        - Gray literature exempt—generally provides guidelines with no outcomes attached.

Papers are ineligible for narrative review if they meet fewer than 3 (so 0, 1, or 2) criteria or don't meet population criteria. All excluded papers will be recorded in excluded studies database with the reason(s) for exclusion.

Grey literature: Hold to population criteria, allow exemption for outcomes criteria

Appendix E: Critical appraisal, bias assessment, and data extraction protocols

Critical appraisal and bias assessment:

- Fill in the questions addressed column in the reference database:
  1) management strategy: Are there specific ROW (e.g., roadsides and powerlines) management practices that successfully enhance pollinator abundance and diversity?
  2) pollinator taxa: Which insect pollinator taxa respond most significantly to common ROW management enhancement practices?
  3) other influential variables: landscape context, threats: Are there elements of landscape context that serve to enhance (e.g., adjacent fields or wetlands) or threaten (e.g., traffic volume, road class) the success of ROW management for pollinator conservation?

- Bias assessment: ranking papers susceptibility to bias is part of critical appraisal. Following criteria of Villemey et al. 2018:
  - High: no replicates, poor methods, insufficient method description, confounding factors
  - Medium: no info on site selection, CI or BA designs instead of BACI, no spatial replication, difference in the loss of samples between control and treatment, slightly inefficient methods description
  - Low: everything that didn't have any of the previous issues

  Papers have high bias if they meet any of the high bias criteria. Papers with medium bias can have systematic site selection (random is better but is often difficult to achieve in ecological field studies). Papers with medium bias can have multiple treatments per site; this is another limitation affecting many ecological field studies. If each treatment is replicated in a block at each site, this is fine. Papers that do not meet one or both of these criteria have medium bias, while papers that do meet both will have LOW bias, even if they have a CI design. Finally, papers with sites less than 1 km apart will have medium bias, regardless of site selection strategy or treatments per site. Number of years sampled does not influence bias category.

- Quantitative eligibility criteria:
  - Papers must report means and variances for abundance and species richness to be eligible for extraction (or meet reporting requirement of other statistical tests; see effect size section).
  - Papers with extractable data that have high bias in their experimental design will be excluded from meta-analysis.
  - If studies meet all qualitative eligibility requirements but do not meet quantitative eligibility requirements:

- In the excluded studies database, papers will be separated by exclusion from narrative synthesis and meta-analysis OR exclusion from meta-analysis only. Note reason for exclusion when adding papers to database.

Data extraction:

Effect size measure: Hedge's d.

- Requirements to calculate: mean, sample size, and variance for two groups (typically a control and a treatment)
    - Can also calculate from t-test results: record t statistic, result (whether treatment was greater than control or vice versa), and p value
- Alternate effect size measure: correlation coefficient
    - From f tests: record degrees of freedom (df), F value, and p value.
    - Can extract information from other tests; will modify protocol on a case-by-case basis
    - For studies with more than one df, additional calculations will be required

Extract data to Data Extraction database:

- Each entry gets a unique accession number
- Will likely be multiple entries per paper (e.g., for abundance, species richness, or individual species counts)
- Include information on the part of the paper the data came from for easier review/retrieval later on
- Data codes fall into four categories; categories and codes are detailed below.

Data codes and categories:

1) Basic information

- Acc#: Accession number: a unique identifying number for each entry in data extraction database.
- Ref#: reference number as assigned in the reference database. Will likely be multiple accession numbers for each reference number
- Authors: paper authors
- Year: year published
- Page/source: page number, section number, or description of where in the paper to find the extracted data
- Article type: journal article, thesis, or gray literature (listed in reference database)
- Country : country where study was conducted

2) Sources of bias/effect modifiers

- Study design: one of the following
    - Observational (Obs): a study with no control; sites are surveyed for observational purposes with no comparisons made (cannot be included in meta-analysis)

- Comparator-intervention (CI): compares separate sites in current conditions; no site modifications made (most managed vs. unmanaged site studies are CI designs)
    - Before-after-intervention (BA): same sample sites are surveyed before and after management; before management serves as the control
    - Before-after-comparator-intervention (BACI): sample sites surveyed and compared to separate control before and after management
    - Movement mark-recapture: studies of insect movement from one site to another measured with mark-recapture techniques (these studies typically have no control site for comparison unless movement is studied in multiple scenarios)
- ROW type: roadways, railways, powerlines, hedgerows
    - Modifier: type of habitat if both site types are in ROW
- Control habitat: roadways, railways, powerlines, hedgerows, or grasslands/non-ROW habitat
    - Modifier: type of habitat if both site types are in ROW
- Management type: none, mowing, planting, burning, restoration, grazing, cutting, plowing, mulching, clearing, seeding, fertilizer, eradication, logging, harvesting, herbicide, insecticide, pesticide
- Site selection: randomly selected (YES) or systematically selected (NO) (n/a if not specified)
- Site distance: should be at least 1 km (YES) to collect distinct communities. If not, mark NO. If not mentioned, mark n/a.
- Spatial replication: one plot per site = true spatial replication. Mark YES. Multiple plots per site could be pseudoreplication if they are not counted right in analyses.
- Landscape: mark YES if study compares ROW habitat in different landscape contexts, otherwise mark NO.
- Threat: list: traffic volume, barrier to movement, roadkill/mortality, chemicals, etc. (n/a if none)
- Study length: number of years surveying occurred
- Sample year: if there are multiple years of data being recorded, specify sample year (numbered 1, 2,…) here
- # of sample occasions: number of sampling occasions each year

3) Organismal information

- Type of organism: pollinator or plant
- Order
- Family
- Genus
- Species
- Status: conservation status: endangered, threatened, etc.; state, federal, or both

4) Raw data

- Variable: abundance, species richness, etc.
- Nt: number of treatment sites
- Meant: mean number of individuals/species in treatment sites
- Vart: standard deviation of individuals/species in treatment sites
- Nc: number of control sites
- meanc: mean number of individuals/species in control sites
- varc: standard deviation of individuals/species in control sites
- Ncorrected: total number of unique sites. If one control is compared to multiple treatment sites, that will be reflected in this number (so it may not equal Nt+Nc)
- Hedge's d: effect size calculated from N, mean, and var (see Koricheva et al. 2013, pg 62 and Villemey et al 2018, pg 11)
- var of d: calculated variance of Hedge's d (see Koricheva et al. 2013, pg 63 and Villemey et al. 2018, pg 11)
- From f tests:
    - degrees of freedom (df), F value, and p value.

Appendix F: Electronic files of search results

E.1: All search keyword combinations with the number of results from each search

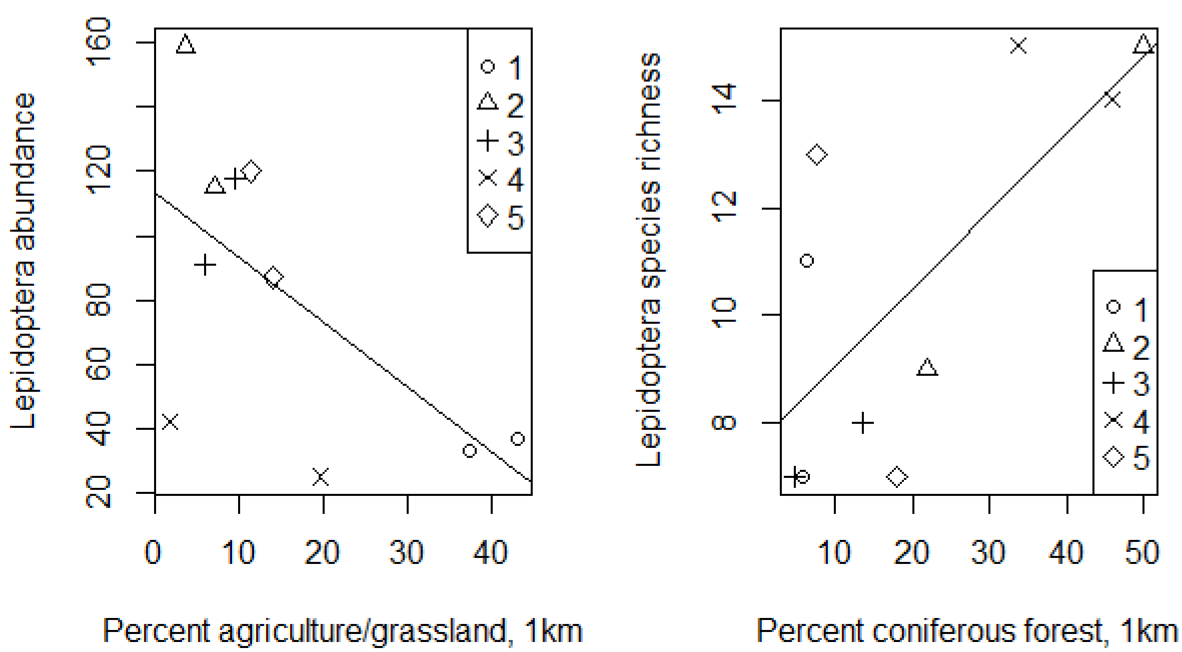
E.2: All collected references with summary information on each and details on their inclusion in or exclusion from narrative review and meta-analysis

E.3: All quantitative data extracted from references

Appendix G: Full results of spatial analysis in landscape surrounding ten Priority 1 ROW sites in Maine.

Table F.1: Land cover types influencing Bombus or Lepidopteran abundance or species richness over the entire 2017 growing season.

	Ag	Con	Dec	Edge	Emg	Urb	Wet
Total abund.	--	--	--	--	--	--	--
Bombus abund.	--	--	--	--	--	--	--
Bombus richness	--	--	--	--	--	--	--
Lepidopt. abund.	d = 8.356 p = 0.004	--	--	--	--	--	--
Lepidopt. richness	--	d = 4.853 p = 0.028	--	--	--	--	--

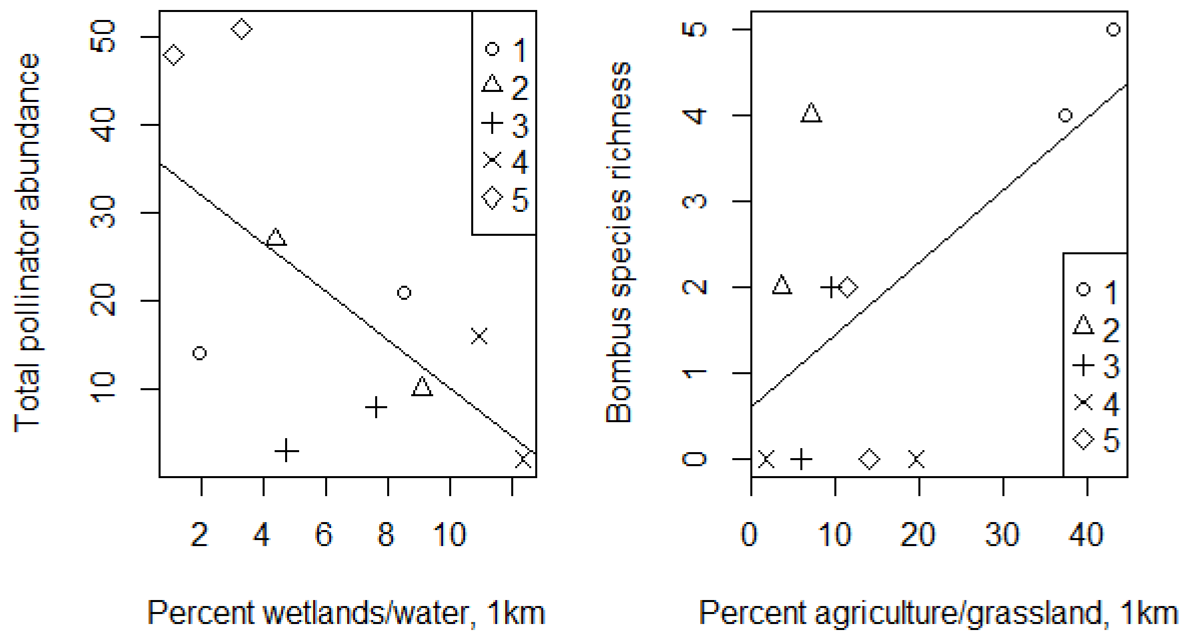


a) b)

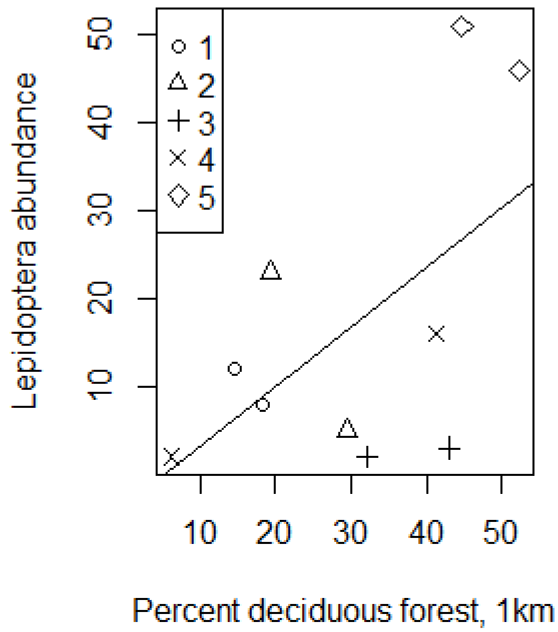
Figure F.1. Significant relationships between a) Lepidopteran abundance and percent of agriculture/grassland and b) Lepidopteran species richness and percent of coniferous forest over the entire growing season in the 1 km surrounding ten Priority 1 ROW sites in Maine. Symbols represent the five geographic regions of the state where survey sites were located.

Table F.2: Land cover types influencing Bombus or Lepidopteran abundance or species richness over the 2017 early growing season.

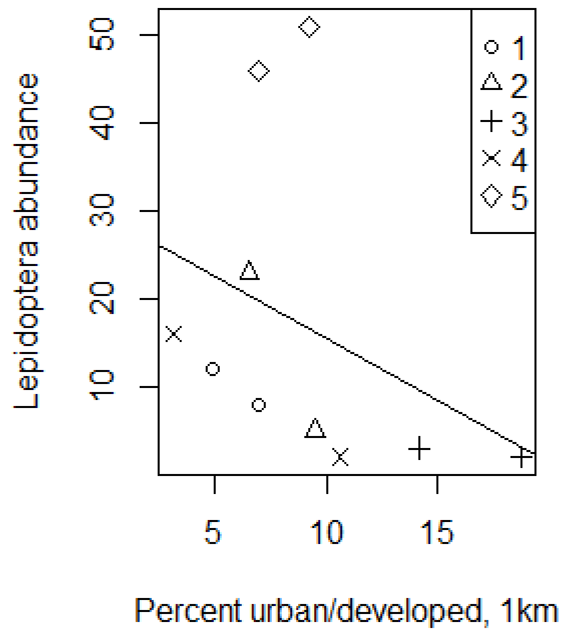
	Ag	**Con**	**Dec**	**Edge**	**Emg**	**Urb**	**Wet**
Total abund.	--	--	--	--	--	--	d = 5.950 p = 0.015
Bombus abund.	--	--	--	--	--	--	--
Bombus richness	d = 5.767 p = 0.016	--	--	--	--	--	--
Lepidopt. abund.	--	--	d = 4.505 p = 0.034	--	--	d = 0.384 p = 0.050	d = 5.409 p = 0.020
Lepidopt. richness	--	--	--	--	--	--	--



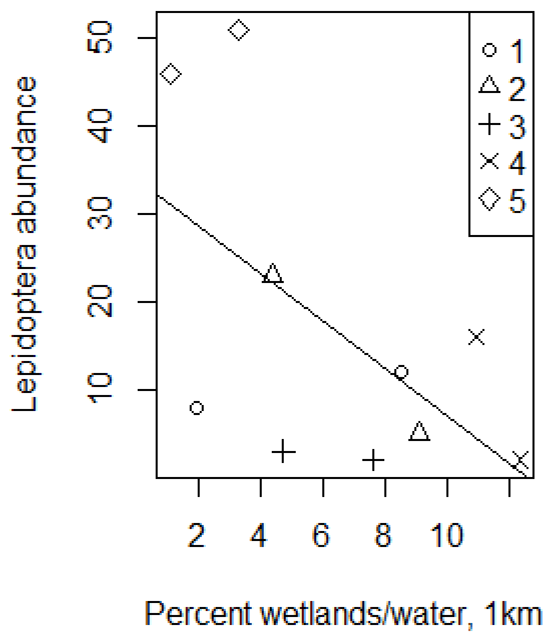
a) b)



c)



d)

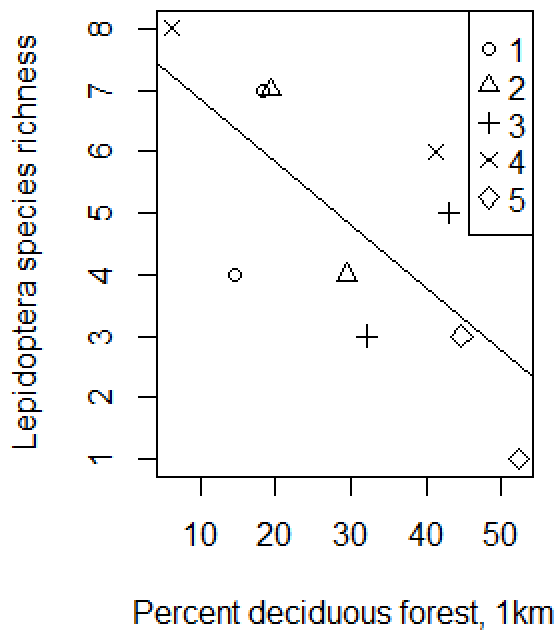


e)

Figure F.2. Significant relationships between a) Total pollinator abundance and percent of wetlands/water, b) Bombus species richness and percent of agriculture/grassland, c) Lepidopteran abundance and percent of deciduous forest, d) Lepidopteran abundance and percent of urban/developed, and e) Lepidopteran abundance and percent of wetlands/water in the early growing season in the 1 km surrounding ten Priority 1 ROW sites in Maine. Symbols represent the five geographic regions of the state where survey sites were located.

Table F.3: Land cover types influencing Bombus or Lepidopteran abundance or species richness over the 2017 mid-growing season.

	Ag	**Con**	**Dec**	**Edge**	**Emg**	**Urb**	**Wet**
Total abund.	--	--	--	--	--	--	--
Bombus abund.	--	--	--	--	--	--	--
Bombus richness	--	--	--	--	--	--	--
Lepidopt. abund.	--	--	--	--	--	--	--
Lepidopt. richness	--	--	d = 4.500 p = 0.034	d = 4.009 p = 0.045	--	--	--



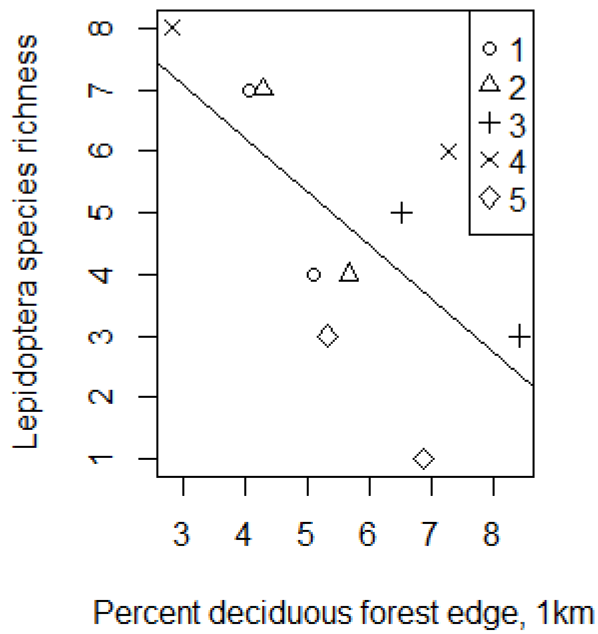


Figure F.3. Significant relationships between a) Lepidopteran species richness and percent of deciduous forest and b) Lepidopteran species richness and percent of deciduous forest edge in the mid-growing season in the 1 km surrounding ten Priority 1 ROW sites in Maine. Symbols represent the five geographic regions of the state where survey sites were located.

Table F.4: Land cover types influencing Bombus or Lepidopteran abundance or species richness over the 2017 late growing season. These results are depicted in Figure 3 of the report.

	Ag	**Con**	**Dec**	**Edge**	**Emg**	**Urb**	**Wet**
Total abund.	d = 7.981 p = 0.005	--	--	--	--	d = 3.833 p = 0.050	--
Bombus abund.	--	--	--	--	--	--	--
Bombus richness	--	--	--	--	--	--	--
Lepidopt. abund.	d = 17.21 p <0.001	--	--	--	--	d = 4.484 p = 0.034	--
Lepidopt. richness	--	--	--	--	--	--	--