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Issues

Optimizing Pest Management Practices to Conserve Pollinators in Turf Landscapes: Current Practices and Future Research Needs

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Abstract

Turfgrass is an important cropping system covering >16 million hectares in the United States. Synthetic insecticides, which are important tools in managing several key insect pests in these landscapes, have been implicated in the decline of managed and wild pollinators. The public perception linking the use of chemical insecticides to pollinator population declines threatens their future use and our ability to maintain functional and aesthetically acceptable landscapes. Extension and research entomologists from across the United States met in 2016 for the "Summit for Protecting Pollinators in Turf" to review the scientific literature on nontarget impacts of pest management practices on pollinators in turfgrass landscapes, to develop best management practices for protecting these organisms, and to identify knowledge gaps and prioritize future research needs. The group identified that there is a scarcity of detailed research on pollinator health in turf landscapes and has prioritized areas where research was most needed to conserve pollinator populations while balancing the needs for maintaining healthy turfgrass.

Key words: pollinator, turfgrass, turfgrass management, insecticide

The ecological services that managed and native bees and other pollinating insects (e.g., butterflies, flies) provide to society are invaluable. An estimated three quarters of the world's flowering plants, and 90% of the world's food crops depend on pollinators to reproduce (Klein et al. 2007). Pollinator populations have experienced significant decline in the past several decades, which ultimately threatens global food supply. Numerous factors have been implicated in the decline of pollinator populations including pathogens, parasites, habitat loss, colony stressors, and pesticide exposure (Potts et al. 2010, Goulson et al. 2015). However, much of the popular press and public perceive insecticides, in particular the neonicotinoids, as the primary factor driving the decline in pollinator populations. This has led to several municipalities across the United States imposing legislative bans on the use of neonicotinoids for aesthetic purposes such as turfgrass management. There is a clear need to develop rational, scientifically based recommendations for best management practices (BMPs) that promote healthy landscapes, while conserving and enhancing pollinator health.

Turfgrasses are a group of perennial grasses capable of surviving low mowing while making a contiguous ground cover. Their uses are diverse, ranging from low-maintenance roadside utility turf to intensely managed areas, such as golf courses, athletic fields, and other recreational areas (Beard and Green 1994). Collectively, turfgrass is the single largest crop in the United States covering over 16.4 million hectares (>40 million acres; Milesi et al. 2005). Environmental benefits of healthy turfgrasses include improved soil and water protection, pollutant filtration, cooling of the environment, reduction of glare and noise, and carbon sequestration (Beard and Green 1994, Bandaranayake et al. 2003, Raciti et al. 2011). Recreationally, turfgrasses beautify parks and landscapes, provide safe playing surfaces for sporting activities, and increase property values (Beard and Green 1994). The economic impact that turfgrasses provide include employment and goods and services provided to sod producers, recreational areas, and landscape management. The estimated impact that the ~16,000 golf courses in the United States alone is estimated at US$69 billion dollars (www.golf2020.com).

Pests, including caterpillars (e.g., armyworms [such as *Mythimna unipuncta*], black cutworm [*Agrotis ipsilon*], sod webworms [*Crambus* spp.]), chinch bugs (*Blissus* spp.), crane flies (such as *Tipula paludosa*), mole crickets (Gryllotalpidae), fire ants (*Solenopsis invicta*), white grubs (Scarabaeidae), and weevils (e.g., billbugs [*Sphenophorus* spp.], annual bluegrass weevil [*Listronotus maculicollis*]), can reduce the aesthetic and functional qualities of turf. To suppress pest populations below damaging levels, most turfgrass managers rely on the use of conventional synthetic insecticides given that these control agents are often inexpensive relative to other tactics, highly effective, fast acting, and, in certain instances, may be applied preventively in advance of pest outbreaks. Synthetic insecticides, when used judiciously, selectively, and responsibly, are powerful tools for pest management. Neonicotinoids, a class of insecticides with a similar chemical structure to that of nicotine, are the most widely used group of insecticides in turfgrass management. Products sold for use in turfgrass include one of four active ingredients: clothianidin, dinotefuran, imidacloprid, or thiamethoxam. Their widespread adoption in turfgrass, though only accounting for 4% of the overall current use in the United States, is largely due to several favorable characteristics, including efficacy against root-infesting white grubs, low mammalian toxicity, and a favorable ease of use compared to older chemistries such as organophosphates and carbamates, which pose greater risks to nontarget animals (Cockfield and Potter 1984, Terry et al. 1993, Zenger and Gibbs 2001).

However, there have been recent concerns about the solubility characteristics of neonicotinoids and their risk of run-off into bodies of water or leaching into groundwater sources along with the negative lethal and sublethal effects these products can have on pollinating insects. A series of extensively publicized events, including an illegal application of a neonicotinoid to flowering linden trees (*Tilia americana*; Mohney 2013), has caused concern for the health of pollinators in managed landscapes. Several municipalities have moved to eliminate the use of neonicotinoids for aesthetic purposes, including turfgrass management (Sandburg and Foster 2007). Given the importance of insecticides, including the neonicotinoids, in turfgrass integrated pest management (IPM), it is critical to develop science-based practices that both achieve pest management goals and minimize negative side effects to beneficial or nontarget organisms. These practices include not only the judicial use of carefully selected insecticides but also the employment of alternative, nonchemical and cultural control strategies.

A working group of turfgrass entomologists, research and extension personnel, and IPM practitioners was formed during the 2016 National Turfgrass Entomology Workshop in Sheboygan, WI. The focus of the group was to 1) review existing scientific literature surrounding potential adverse effects of neonicotinoids in the turfgrass system, 2) develop best management practices for mitigating risk and enhancing pollinating insect habitat and health, and 3) prioritize future research needs. Here, we outline the results from the workshop as a means to represent what is currently known regarding the best approaches for minimizing the potential adverse effects on pollinators. Additionally, we identify knowledge gaps to direct future research efforts and help guide public policy.

Best Management Practices for Integrating Chemical Controls in Turfgrass

Turfgrass managers have been implementing IPM practices for decades to maximize pest management efficacy and efficiency, while reducing nontarget effects on natural enemies (Held & Potter 2012). These managers can avoid negative effects to pollinators by following very similar principles, for example, following label precautions and taking preventive steps to ensure that direct exposure to insecticide residues does not occur. These best management practices are often simple and cheap, and include actions taken before, during, and after insecticide applications.

Preapplication Considerations

Mowing Treatment Area

Misapplication by directly contaminating flowers has resulted in pollinator die-offs, most notably when blooming linden trees were mistreated in Oregon in 2013 (Mohney 2013). Flowering weeds are common and attractive to pollinating insects in turf areas (Larson et al. 2014). To avoid issues with direct floral contamination in turf, it is recommended to mow off the flower heads of weeds like white clover (*Trifolium repens*), dandelion (*Taraxacum officinale*), bird's foot trefoil (*Lotus corniculatus*), and others before treatment. If the insecticide label dictates not to mow before treatment occurs, managers can follow an application with mowing to remove contaminated flowers. Examination of nectar in turf weed flowers treated with neonicotinoids suggests that if new flowers grow in treated areas, the residues transported from the roots of the weeds to the flowering portion are below levels thought to be hazardous to pollinators (Larson et al. 2015). Thus, in the case of turfgrass weeds that are regularly mowed, insecticide applications (even of neonicotinoids) do not pose a prolonged systemic hazard to bees.

Timing of Insecticide Applications

Managers should consider several factors before applying neonicotinoids or any other turfgrass insecticide. Timing of an application can determine whether pollinating insects are exposed to an insecticide or not. Most insecticide applications in turf are made as a preventive sprays (Blaine et al. 2012, Held and Potter 2012), meaning that they are applied between the months of March and June in an effort to prevent any pest damage from occurring to lawns, golf courses, or sports fields. Unfortunately, preventive timing also coincides with the blooming of flowering weeds, the blooms of which can attract multiple species of pollinating insects. If turf managers can wait until May or June to make applications, they can avoid exposing early season species, small and vulnerable colonies of bumble bees (*Bombus* spp.), and honey bee (*Apis melifera*) colonies recovering from winter stress to toxic insecticides. Curative applications made late in the growing season may also accomplish this. Managers can also minimize pollinator exposure to insecticides by restricting foliar insecticide applications to early morning or late evening, when pollinators are not actively foraging. This practice also reduces the risk of insecticide drift to areas adjacent to turfgrass that may support high densities of foraging pollinators. Wind-aided drift can also be minimized by not applying insecticides when winds are blowing above 8–10 kilometers per hour (Bayer Environmental Science 2012).

Insecticide Formulation

The extent to which an insecticide is hazardous to pollinators is not only determined by its inherent toxicity but also by the manufacturer's formulation of the product (Stark et al. 1995). Turfgrass insecticides can be applied in various formulations, including as a liquid spray, as granules, or as a seed dressing. As these formulations vary in their potential to contact and affect pollinating insects, managers who wish to implement more pollinator friendly measures should carefully consider which formulation they choose before application. In a study comparing neonicotinoid liquid sprays to their granular counterparts when both were applied to flowering weeds in a turf setting, it was found that granular applications pose a reduced risk to pollinating insects (Gels et al. 2002). While both liquid and granular products are systemic, granular products are unlikely to directly contaminate the flowering portions of blooming plants. After insecticide granules have been applied, they are irrigated into the soil where insecticide residues are absorbed by the plant's root system. These residues are transported throughout the turfgrass plant to prevent pest damage but have not been found in high enough concentrations in the nectar and pollen of flowering weeds to pose a hazard to foraging insect pollinators (Larson et al. 2014). Translocation of insecticides is driven by plant growth processes that are more likely to move insecticides into plant foliage rather than the floral tissues and nectar of blooming weeds (Buchholz and Nauen 2001, Bonmatin et al. 2005, Blacquière et al. 2012). If a manager is trying to control below-ground pests with a neonicotinoid, granules will accomplish this without the hazard to pollinators (Gels et al. 2002). While liquid formulations could pose more of a hazard by contaminating floral resources present at the time of application, this negative interaction can be avoided through irrigation or removal of flowering weeds with mowing or herbicides (Gels et al. 2002, Larson et al. 2013).

Choice of Insecticide Class

Certain insecticide classes better target certain pests, e.g., neonicotinoids being used for soil-dwelling white grubs (Potter and Held 2002) or pyrethroids for leaf-zone pests such as chinch bugs (Cherry and Nagata 2007) and caterpillars (Williamson and Potter 1997a). Many of these classes, such as the neonicotinoids and older classes of chemistry like the pyrethroids and carbamates, have known negative effects on pollinating insects (Desneux 2007). Chlorantraniliprole, part of the newer anthranilic diamide class of chemistry, can control many of the same pests that are targeted with neonicotinoids and pyrethroids including white grubs, caterpillars, and bill bugs. A study at the University of Kentucky compared the effects of clothianidin (a neonicotinoid) and chlorantraniliprole on foraging bumble bees by applying both products to lawn-type turf with flowering white clover. Colonies were confined to forage for 6 d on treated or untreated clover bloom plots. The bee colonies were then relocated to forage on nontreated clover and other untreated flowering plants for six more weeks. The clothianidin-exposed colonies gained less weight than their nonexposed counterparts, and they subsequently produced no new queens, whereas the chlorantraniliprole exposed colonies gained weight and produced similar numbers of queens in comparison to the nontreated controls (Larson et al. 2013). Chlorantraniliprole appears to be a good fit for industry initiatives to reduce the impacts of turf and landscape management on hymenopteran pollinators, with the caveat that its effects on adult lepidopterans needs further research.

Postapplication Care

Posttreatment irrigation is specified on the label of products like imidacloprid to increase its below ground efficacy. Irrigation can also remove residues from pollinator foraging zones of treated plants and dilute active ingredient concentrations, thereby reducing hazards to pollinating insects (Kunkel et al. 2001, Gels et al. 2002). It is also suggested that irrigation, particularly in the morning, may dilute residues of insecticides present in dew or guttation droplets that accumulate on grasses (Larson et al. 2015, McCurdy et al. in press).

Alternative Methods to Chemical Control

Turfgrass managers may also wish to consider other options outside of traditional preventive insecticide treatments. When done properly, strategies such as cultural and biological control can provide effective alternatives that reduce pest pressure and the need for pesticide inputs (Raupp et al. 1992, Held and Potter 2012). Landscape IPM research over recent decades has demonstrated that incorporating pest control tactics with appropriately timed and applied insecticides can minimize pests by maximizing biotic regulation of pests (Raupp et al. 2010, Held and Potter 2012). As previously mentioned, IPM strategies should be a part of every turfgrass management program as a means for reducing nontarget effects on natural enemies, maximizing plant health, and minimizing pests. These practices translate directly to reducing risks to pollinators. However, to be effective, one must understand the target pest and the products being used to control them, which takes time and effort.

Mechanical control strategies are often the simplest and most easily implemented methods for managing insect pests. These approaches include the physical removal of pests or their damage from the turfgrass system without the use of insecticides. For example, black cutworms deposit their eggs on the tips of grass blades. Mowing and collecting clippings 48 h after oviposition removed over 75% of eggs, reducing next generation caterpillar abundance (Williamson and Potter 1997b). These approaches can be effective in some situations, but often take more time and physical effort than others.

Several cultural management practices have been developed and implemented to control turfgrass insect pests and reduce the need for insecticides (Held and Potter 2012). Selecting and planting turfgrasses resistant to known pests is a great strategy for managing pests with minimal inputs (Reinert et al. 2004, 2009, 2011). This can be achieved through the selection of resistant grass cultivars or seeds containing *Epichloe* endophytes (Braman et al. 2002, Reinert et al. 2004). Some commercially available grasses, such as tall fescue (*Lolium arundinaceum* [Schreb.] S.J. Darbyshire), perennial ryegrass (*Lolium perenne* L.), and red fescue (*Festuca rubra* L.), contain fungal endophytes that produce secondary metabolites that deter insect feeding, and past studies have demonstrated that they can be used to reduce damage by some insect pests. For example, overseeding Kentucky bluegrass (*Poa pratensis*) with endophytic perennial ryegrass (*Lolium perenne*) reduces bluegrass billbug (*Sphenophorus parvulus*) abundance and damage (Richmond et al. 2000). Because endophytes provide additional tolerance to environmental stresses such as drought (Elmi and West 1995), heat (Ravel et al. 1995), and mineral deficiencies (Malinowski et al. 1999), endophyte-enhanced grasses may also provide important agronomic benefits outside of their resistance to surface-feeding insects.

Unfortunately, insect pest resistance is rarely a deciding factor in turfgrass breeding programs or homeowner plant selection, and there are currently a limited number of commercially available pest resistant turfgrasses (Potter 2005). Other, more readily available cultural practices like proper irrigation, fertilization, mowing, and soil physical management can have a drastic effect on insect pest populations (Potter et al. 1996, Held and Potter 2012). For instance, careful irrigation timing may be a key factor in minimizing damage by soil-dwelling pests that prefer wet soil conditions such as European crane flies (Pesho et al. 1981). Fertility management can also play an indirect, but important role in limiting insect pest damage. For example, overfertilization of turfgrasses increases nitrogen content in plant tissue, which increases southern chinch bug (*Blissus insularis*) and fall armyworm (*Spodoptera frugiperda*) fitness and abundance (Busey and Snyder 1993, Davidson & Potter 1995). Maintaining the highest practical mowing height promotes deep, fibrous root systems that enhance tolerance to stress and injury from insect pests (Potter et al. 1996, Wherley et al. 2011). Recent studies have also shown that soil aerification with hollow-tine cultivators, typically performed to reduce soil compaction, enhance porosity, and encourage root growth, can also reduce densities of root-feeding white grubs (McGraw 2012).

Other IPM strategies include multiple approaches to biological control of pests. The easiest and perhaps most effective approach is conserving natural enemies in the landscape by using reduced-risk, selective insecticides and making applications only when needed (Raupp et al.1992, 2001, Held and Potter 2012). This practice falls in direct alignment with efforts to preserve pollinators in the turf landscape. Intentional incorporation of biological control, either through augmentative or conservation biological control, can also help manage pests like white grubs and caterpillars (Held and Potter 2012). Many biological control agents are commercially available for use in turfgrass including parasitic nematodes of the genera *Steinernema* and *Heterorhabditis*, and the entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae*. These products are generally safe for nontarget organisms, compatible with other IPM tactics, and have proven efficacious against a number of turf pests including crane flies, mole crickets, and white grubs (Peck et al. 2008, Held and Potter 2012). For example, the entomopathogenic nematode, *Steinernema scapterisci*, infects mole cricket pests and has been partially attributed with US$13.6 million in annual savings to Florida's cattle forage industry since its introduction (Mhina et al. 2016). Although such products can be used effectively in many situations, they represent only a small portion of the pest management market, and are rarely adopted by turf managers due to high cost compared to conventional insecticides, variable efficacy, and limited shelf life, among others factors (Georgis et al. 2006, Held and Potter 2012). Ongoing research is improving the efficacy and affordability of these nonsynthetic options, which may provide additional alternatives to synthetic insecticides in the future.

Promoting Pollinator Welfare in and Around Managed Turfgrass Sites

Besides adapting the methods by which insecticides are applied, turfgrass managers can actively contribute to pollinator conservation by creating pollinator conservation habitats. One of the leading causes of pollinator decline is habitat loss, leading to shortages of nesting sites and floral resources that pollinators depend on for food (Potts et al. 2010). In the United States, about 1 million acres of farmland or natural habitat are converted to urbanized areas each year (McFrederick and LeBuhn 2006). In highly urbanized areas, managed turfgrass such as lawns, sports fields, and golf courses may be some of the only nonhardscape spaces remaining and there is an increasing interest in utilizing at least portions of these areas for pollinator conservation (Rosenzweig 2003, Dobbs and Potter 2015).

Planting for Pollinators on Golf Courses

Golf course managers and golf organizations such as the United States Golf Association (USGA) have placed special emphasis on increasing the acreage of natural habitat on golf courses. Initiatives like The Audubon Cooperative Sanctuary Program, Wildlife Links program, and the Golf and the Environment Initiative have all demonstrated that golf courses can provide a quality golfing experience while also playing an active role in urban wildlife conservation (Snow and Erusha 2006, Gross and Eckenrode 2012). Not only do such programs benefit wildlife but they can also help to decrease golf course expenditures by reducing the acreage of managed turf and lowering the amount spent on irrigation, mowing, and chemical inputs (Limehouse et al. 2010, Brame 2012). These past successes, paired with rising interest in pollinator welfare led the USGA to begin programs like Making Room for Native Pollinators and to seek collaborations with groups such as the Pollinator Partnership. Golf course superintendents are now utilizing these programs and are seeking other opportunities to ensure their courses are part of pollinator conservation. Another pollinator program, Operation Pollinator, is an international biodiversity project started by Syngenta in 2010. Developed in Great Britain and Ireland, Operation Pollinator was first brought to the U.S. by Emily Dobbs and Daniel Potter of the University of Kentucky. Using bee bowls and other pollinator sampling methods Dobbs and Potter (2015) found that plots managed under Operation Pollinator guidelines attracted 51 unique bee species, and they identified seven wildflower species that were the most successful at attracting pollinators in the Kentucky climatic area—New England aster (*Symphyotrichum novae-angliae*), bergamot (*Monarda fistulosa*), black-eyed Susan (*Rudbeckia hirta*), purple coneflower (*Echinacea purpurea*), plains coreopsis (*Coreopsis tinctoria*), prairie coneflower (*Ratibida columnifera*), and lanceleaf coreopsis (*Coreopsis lanceolata*). Superintendents and others who are interested in establishing pollinator conservation plots should consult their local extension service to learn more about what flowers would work best in their area and should consult sources such as the Xerces Society or Pollinator Partnership for establishment advice.

Monarch Butterfly Conservation

Bees are not the only pollinators that may benefit from increasing naturalized areas on golf courses. Native butterflies, in particular the monarch butterfly (*Danaus plexippus*), are charismatic pollinators that are also threatened by habitat fragmentation (Oberhauser et al. 2008). Monarchs are famous for their continental migration patterns that rely on overwintering sites in Mexico and milkweed plants in the United States and Canada. Unfortunately, both of those resources are in decline (North American Monarch Conservation Plan). Golf courses can help create necessary patches of milkweed to sustain monarch migration by dedicating space to milkweed plantings (such as the Monarch Waystations with Monarch Watch) or by incorporating milkweed into pollinator seed mixtures for naturalized areas. Milkweed blooms also attract other pollinators such as honey bees, bumble bees, and many wild native bees (Dobbs & Potter 2015).

Lawns and Pollinator Conservation

Golf courses are not the only managed turf areas that can contribute to pollinator conservation. Homeowners who have an interest in pollination conservation can plant their own Operation Pollinator conservation plots or take steps to make their yard more hospitable to these important invertebrates. While highly managed turf lawns offer few foraging resources for pollinators (Tonietto et al. 2011), many lawns do contain some flowering weeds such as white clover, *Trifolium repens* (Fabaceae), or common dandelion, *Taraxacum officinale* (Asteraceae). Deemed undesirable by some, these weeds represent an under recognized food source for pollinating insects. A 2014 study found that >50 different species of pollinators visited these weeds and that urban pollinators rely on white clover as an important food source (Larson et al. 2014). Lawns that include rather than exclude clover are already being promoted due to the natural fertilization provided by clover and their ability to withstand drought (Sincik and Acikgoz 2007; McCurdy et al. 2013). It must also be considered that an increase in food plants and visiting pollinators may also lead to higher stinging incidences in lawns. Improved awareness of the importance of white clover for pollinators may increase the acceptance of these plants in turf settings and help the general public to understand the importance of careful and selective insecticide use.

Research Needs

Further development and refinement of pollinator BMP for turfgrass is primarily constrained by the lack of research in a few key areas. Our working group identified questions regarding the impact of turfgrass systems on pollinators that can be broadly characterized as “who, what and how.” *Who* are the pollinators associated with turfgrass ecosystems, *what* characteristics of turfgrass systems have the greatest impact on pollinator communities, and *how* does exposure to the multiple, and often systemic, stressors associated with turfgrass systems impact pollinator health?

Pollinator Diversity in Turfgrass Ecosystems

Approximately 200,000 animal species play a role in pollinating the 250,000 species of flowering plants worldwide (Natural Resource Conservation Service [NRCS] 2005). Of these, >99% are invertebrates including bees, wasps, butterflies, moths, flies, and beetles (NRCS 2005). More than 4,000 species of bees alone are native to North America, with the majority being solitary nesting species. Being mowed and maintained in a permanently immature state, turfgrass plants do not typically provide pollen or nectar, and thus, provide little in the way of resources for pollinators. However, many species of flowering weeds are common in turfgrass, and managed turfgrass systems often include landscape elements that contain flowering ornamental plants. These flowering weeds and ornamental plants can attract and support a variety of pollinators by providing food and nesting sites (Tommasi et al. 2004, Matteson et al. 2008, Larson et al. 2014).

The most recent study documenting pollinator diversity in turfgrass environments (Larson et al. 2014) found roughly 50 species of insects, primarily associated with 2 common flowering weeds. Twenty-five of these were bees representing 4 of the 6 bee families and 11 genera. Studies more broadly focused on urban or suburban habitats vary in the number of bee species (17–111) and genera (7–21) reported (Tommasi et al. 2004, Matteson et al. 2008, Neil et al. 2014, Lerman and Milam 2016). In all of the above studies, native bees comprised the majority of species and often represented the majority of total bee abundance.

Our knowledge of native bee biology is modest next to what we know about honey bees. Most native bees nest underground, although some nest above-ground in wood, pithy stems, or holes excavated by other insects (Cane et al. 2006). Some species make use of man-made structures and thrive in urban settings (Jacob-Remacle 1984). The dietary preference of native bees varies from generalist (polylectic) to specialist (oligolectic; Linsley 1958, Cane and Sipes 2006), and foraging ranges can vary widely with body size (Greenleaf et al. 2007). Although the biology of relatively few species has been studied in detail, their representation within the pollinator community in turfgrass provides a compelling reason for understanding their ecological needs and sensitivities. Research to improve our understanding of native bee biology will help refine pollinator BMP for turfgrass, and could help guide urban pollinator conservation efforts more generally.

Turfgrass Ecosystems as Pollinator Habitat

Because turfgrass plants provide few resources for pollinators, variation in nonturf resource availability, including factors such as the diversity and amount of flowering plants (Jha and Kremen 2013, Blaauw and Isaacs 2014), amount of hardscape (Gayubo and Torres 1991), and the extent of habitat fragmentation (Neame et al. 2013), are likely the major drivers of pollinator abundance and diversity in these systems. Efforts to integrate gardens, pollinator conservation strips, ornamental plantings, and natural habitat into systems that are otherwise dominated by managed turfgrass could provide support for pollinators (Dobbs and Potter 2014, Larson et al. 2014), but understanding how best to plan, design, install, and manage these landscapes to promote pollinator communities will require significant research.

Turfgrass weeds such as white clover and dandelion are readily utilized by a variety of pollinators, providing important resources for these insects over an extended period of time (Matteson et al. 2008, Larson et al. 2014). These same plant species are often considered undesirable in managed turf, but efforts to promote their inclusion in home lawns are gaining some traction. Ground nesting bees in particular tend to be positively associated with grassy, herbaceous ground covers due to the nesting and floral resources provided (Lowenstein et al. 2014). In contrast, turfgrass management practices typically minimize floral resources, discourage bare patches, and may result in compacted soils that are not conducive to nesting (Tonietto et al. 2011). The suitability of turfgrass systems for pollinators could be bolstered by agronomic research clarifying the maintenance needs, environmental stress tolerance, and functional utility of mixed plantings (Sincik and Acikgoz 2007, McCurdy et al. 2013), including evaluation of a much wider range of flowering weedy species. Continuing research into the economic and sociocultural barriers to adoption of lower maintenance turf will help shape outreach and education efforts for pollinator conservation (Hugie et al. 2012, Yue et al. 2012).

Quantifying Risk in Turfgrass Ecosystems

Basic research to understand the risk posed to pollinators from pesticide applications in turfgrass are beginning to provide the baseline of knowledge necessary to encourage the development and implementation of more pollinator-friendly management practices. Risk is a function of dose and exposure, but meaningful estimates of risk are complicated by a number of biological, chemical, and temporal factors that are not well understood. These knowledge gaps are compounded by the lack of acceptable approaches for measuring pollinator health and the paucity of research aimed at understanding the interactive effects of multiple biocides, formulation components, and pathogens on pollinators. For these reasons, studies targeting the movement, uptake, and persistence of systemic insecticides and fungicides in turfgrass systems should be a priority. In addition, the majority of studies have focused on cool season turf grasses in the north central region of the United States. Warm season turfgrasses are treated with the same insecticides, but often with greater frequency due to longer growing seasons in the southern states (McCurdy et al. 2013). There could be possible differences in pollinator visitations to these types of turf or in the expression of insecticides in exudates like guttation or nectar and more needs to be known about the interactions between warm season grasses, pollinators, and pesticides.

Measuring Pollinator Health

The challenge of establishing scientifically and economically acceptable measures of pollinator health stands as an impediment to the long-term studies necessary for understanding the risks associated with chronic exposure to pesticides in turfgrass. Most work in the field of pollinator health has focused on honey bees and bumble bees. In honey bees, methods for assessing colony health in response to pesticide exposure range widely and may include honey production (Floris et al. 2016), brood production and pollen stores (Wu-Smart and Spivak 2016), and the development, mating success and supersedure of queens (Sandrock et al. 2014, Dively et al. 2015, Williams et al. 2015). Similar studies with bumblebees have assessed queen production and survival, nectar storage, colony growth, and brood production (Laycock et al. 2012, Whitehorn et al. 2012, Scholer and Krischik 2014). Recent studies have expanded on this population- and resource-based template by including pollinator nutritional (Mogren and Lundgren 2016), behavioral (Wu-Smart and Spivak 2016), and physiological (Du Rand et al. 2015, Brandt et al. 2016, Sanchez-Bayo et al. 2016) parameters associated with mating, foraging, and immunity. Although honey bees and bumble bees are relatively easy to work with because they have been more or less domesticated for commercial purposes, these eusocial species are not the most representative models for assessing the ecotoxicological effects of pesticides on pollinators (Rundlof et al. 2015).

Exposure to pesticides, including several that are widely used in turfgrass, has been documented in native bee species (Hladik et al. 2016) and although the effects of such exposure have been examined in relatively few cases (Ahmad and Johansen 1973, Scott-Dupree et al. 2009), native species display a much greater range in sensitivity to these compounds compared to honey bees (Arena and Sgolastra 2014). The soil nesting habits of many native pollinator species are also noteworthy given the frequent application of long-residual soil insecticides like neonicotinoids in turfgrass (Lerman and Milam 2016). Not surprisingly, differences in the routes of exposure and sensitivity between bee species have been put forward as justification for including more species in standard ecotoxicity testing required for pesticide registration (Arena and Sgolastra 2014). The development of standardized guidelines for such testing will require a greater understanding of wild bee biology and acceptable methodologies for measuring bee health while minimizing additional economic burden on registrants. Such a framework could also provide an avenue for studies evaluating the effects of chronic pesticide exposure that are currently lacking.

Interactions Between Pesticides and Pathogens

The nutritional, behavioral, and physiological effects of pesticide exposure on pollinators have emerged as an area of importance because of the direct linkage with pathogen resistance. Honey bees in particular are subjected to a host of pathogens and parasites that are largely associated with recent population declines (van Engelsdorp et al. 2009). The causes of colony collapse disorder (CCD) are thought to be a combination of varroa mite and one or more of several viral pathogens, since colony failures are only observed when both the mite and virus are present (Hung et al. 1996, de Miranda et al. 2010, Dainat et al. 2012). Insecticide-mediated suppression of the honeybee immune response could play a pivotal role in the development of this syndrome (Pettis et al. 2012, Mason et al. 2014, Aufauvre et al. 2014).

Di Prisco et al. (2013) reported that sublethal doses of clothianidin negatively influenced NF-κB (nuclear factor kappa-light-chain-enhancer of activated B cells) immune signaling in insects, and that both clothianidin and imidacloprid suppressed honey bee antiviral defenses that are mediated by this transcription factor. NF-κB is a complex of proteins that mediate transcription of DNA, cytokine production, and cell survival. NF-κB plays a key role in cellular responses to a wide range of stresses, including bacterial and viral antigens (Tian and Brasier 2003, Gilmore 2006,). It has also been linked to synaptic plasticity and memory (Albensi and Mattson 2000, Merlo et al. 2002), which could be especially important in eusocial insects such as honeybees. Although mechanistic studies linking pollinator exposure to turfgrass pesticides with immune suppression and subsequent pathogen infection are lacking, they merit attention if turfgrass habitats are to be promoted for pollinator conservation.

Long-Term and Interactive Effects of Pesticides

Understanding the risk to pollinators posed by exposure to turfgrass pesticides is further complicated by the potential for detrimental synergistic effects resulting from exposure to multiple toxins over time. Risk assessments typically focus on acute toxicity measured 1 or 2 d following topical or oral exposure. The potential effects of long-term exposure, and synergism between insecticides, fungicides, herbicides, are rarely considered. Past research, in other growing systems, has also demonstrated potential negative side effects of additives to pesticides, like adjuvants and surfactants (Artz and Pitts-Singer 2015, Fine et. al. 2017), which are also used in turf management. To better understand what is happening in the field researchers should include all of these various combinations of pesticides and other ingredients rather than individual active ingredients. Pollinator responses to residual levels of pesticides that are likely to be encountered in the field has been suggested as a more realistic basis for assessing risk (Sanchez-Bayo and Goka 2014). The distinction between exposure through contact, or ingestion, is pivotal in this regard because the route of exposure can have a significant influence on toxicity. For example, the oral toxicity of clothianidin is 11 times higher than its contact toxicity. Exposure to multiple toxins is also an important consideration since synergistic interactions between ergosterol-inhibiting fungicides (EIFs), pyrethroids, and some neonicotinoids has been observed. Laboratory studies indicate that EIFs may inhibit the cytochrome P450 monooxygenase detoxification system in bees, resulting in several hundred-fold increases in the acute toxicity of cyano-substituted neonicotinoids (Iwasa et al. 2004), and several-fold increases in the toxicity of other insecticides, including some that are used to treat *Varroa* mite infestations in bee hives (Johnson et al. 2013). These findings may have particular relevance in turfgrass systems where the use of pyrethroids, neonicotinoids, and EIFs frequently overlap in space and time.

A study by Sanchez-Bayo and Goka (2014) addresses many key aspects of risk, advocating a modern regulatory framework that incorporates time-cumulative effects of chronic, but variable exposure, route of exposure, and synergism between multiple compounds. The authors argue that the large number and high frequency of pesticide residues found in pollen and nectar collected by bees pose a clear risk that warrants a rethinking of current environmental toxicity testing. Based on environmental toxicology data from a number of sources, their proposed risk scheme points to thiamethoxam, imidacloprid, chlorpyrifos, and clothianidin as posing the highest risk to worker bees and brood feeding on contaminated honey or nectar, while only thiamethoxam posed a high risk to these bees when feeding on contaminated pollen, honey, or nectar. However, the risks posed by systemic neonicotinoids may be underestimated due to their time-cumulative toxicity, synergistic interactions with EIFs, and additive interactions with several pyrethroids. Research on the combined effects of pesticide mixtures and their inert ingredients that are likely to be encountered in turfgrass systems may help guide the development of pest management programs that minimize impacts on pollinators. An important aspect of such research will be to understand and mitigate exposure in turfgrass environments.

Movement, Uptake, and Persistence of Systemic Insecticides and Fungicides

Detailed knowledge of the environmental fate and persistence of pesticides in urban landscapes is essential for understanding potential routes of pollinator exposure. Not surprisingly, the neonicotinoids and EIFs have received intense scrutiny from environmental toxicologists because of their relatively long-residual activity, systemicity, and biological activity (Kim et al. 2003, Held and Potter 2012). The soil half-life of neonicotinoids and EIFs can be quite long, with the half-life of clothianidin and propiconazole being reported at >270 and 315 d, respectively (U.S. Environmental Protection Agency [USEPA] 2003, Kim et al. 2003). Half-life values however, do not necessarily translate into residual activity against pest or nontarget organisms, with much shorter periods of protection typically being reported (Latin 2006, Held and Potter 2012). Pollinators are most likely to be exposed to pesticides through ingestion of contaminated pollen or nectar, but exposure through ingestion of contaminated guttation water, or through contact with contaminated soil (ground nesting species) have not been investigated.

Uptake and translocation of neonicotinoids is determined by a number of factors. Once applied, sorption to soil organic matter may reduce the amount of material available for translocation (Buchholz and Nauen 2001). Remaining bioavailable material may be translocated to plant tissue as a function of transpiration and plant growth, which likely occur at a higher rate in vegetative tissues than in floral tissues and nectar. Larson et al. (2013) reported that the nectar of white clover flowers collected from turfgrass lawns contained 89–319 ppb clothianidin 1 wk after application of Arena 50 WDG at the high label rate. Contamination was serious enough to impair the development of bumble bee colonies that were confined to forage on the treated areas for only 6 d. Importantly however, subsequent confinement of bumble bee colonies, following mowing and re-bloom, did not produce the same negative effects. The exact mechanism through which the nectar was contaminated is not clear and could have been due to a combination of direct application to the flowers and translocation. Further research is needed to characterize the degree to which neonicotinoids and other systemic pesticides are translocated to nectar and pollen of flowering turfgrass weeds, the period of time over which translocation occurs, and if translocated materials pose any risk to pollinators.

Unlike turfgrass weeds, which are likely to be subjected to direct applications of turfgrass pesticides, flowering plants in nearby ornamental beds could be contaminated through drift or lateral movement of active ingredients. Likewise, lawn applications could potentially be taken up and translocated into the blooms of flowering trees situated in turfgrass lawns. Vertical movement of water soluble neonicotinoid insecticides through the soil profile has been well documented (Gupta et al. 2002), raising concerns about leaching of these compounds into groundwater (Huseth and Groves 2013) and subsequent contamination of nontarget organisms through irrigation water. Horizontal movement has received less attention although soil-injected imidacloprid may move several meters laterally from the point of injection (Knoepp et al. 2012). Preliminary data also indicate that contamination of flowering ornamental plants could be significant as a result of drift when liquid formulations are applied (Richmond unpublished). However, because of the perennial cover provided by turfgrasses and the propensity for thatch to accumulate at the soil surface, studies examining the movement of neonicotinoids in turfgrass environments are needed to provide a clearer picture of the risk such off-target movement may pose to pollinators.

In conclusion, neonicotinoids and other insecticides are valuable tools for the green industry to provide the types of turfgrass and ornamental plants that the public demands. In order to continue to benefit from these tools, the industry must use them correctly, in accordance with EPA guidelines and university recommendations. University researchers have identified a variety of nonchemical and cultural control practices that can reduce pesticide exposure to pollinators in turfgrass, and studies have demonstrated that there are simple methods such as mowing that can help to minimize pollinator contact with pesticides in turfgrass where their use is warranted. With careful attention to EPA guidelines and proper and prudent use of these products, it may be possible for the turfgrass industry to avoid losing these valuable chemistries as happened in Europe. Public perception that insecticides are the sole driver of pollinator decline has driven some decision makers to already begin phasing out insecticides for turfgrass use. The green industry must be sure its methods are effective against pests but also defensible with university-generated data.

There are questions about how the overall layout, upkeep, and choice of plants in urban landscapes affects pollinator communities. Further research on the urban foraging habits of pollinators may help to ascertain ways to integrate managed turf, home gardens, pollinator conservation strips, ornamental plantings, and fragments of natural habitat to better support urban pollinator species (Larson et al. 2014, Dobbs and Potter 2015). Finally, more field-realistic evaluations of risk management solutions for turfgrass managers are needed. Ultimately, selective chemistries such as chlorantraniliprole are the future of insecticides in turf but until more of these products are discovered and reach the market the current tools must be used in the least disruptive fashions according to label recommendations.

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