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Assessing risk of *Lymantria dispar* L. invasion management to monarch butterflies (*Danaus plexippus*)

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Abstract
Conflicting conservation goals that lead to management tradeoffs are not uncommon in conservation practice. In this study, we explore a potential conflict between the management of a destructive invasive insect pest, *Lymantria dispar*, and conservation of a widely declining iconic species, the monarch butterfly (*Danaus plexippus*). Specifically, we assess the risk of exposure of susceptible monarch larvae to aerial applications of *Btk*, a Lepidoptera-specific larvicide used in *L. dispar* suppression and eradication. Our findings indicate minimal conflict between *L. dispar* management and monarch conservation, as spatial overlap between *Btk* aerial applications and monarch larvae was found to be marginal. Furthermore, the results of our study indicated specific actions management can take to further minimize potential conflict between these conservation goals. Our study could serve as a guide to other efforts to evaluate potential tradeoffs between the management of invasive species and the conservation of vulnerable species.

KEYWORDS
Bacillus thuringiensis var. *kurstaki*, biopesticides, Btk, conservation conflict, endangered species, invasive species, management tradeoff, pesticides

1 | INTRODUCTION

Conservation and natural resource management goals have the potential to conflict when activities supporting one goal harm another, either directly or indirectly due to opportunity costs associated with investment of time and resources (Negro, La Rocca, Ronzani, Rolando, & Palestrini, 2013; Severns & Moldenke, 2010). For example, in Florida, USA, invasion management goals (e.g., reducing the abundance of an invasive snail, *Pomacea maculata*, and its invasive forage plant, *Hydrilla verticillata*) could negatively impact a conservation biology goal (e.g., sustaining the population of the endangered native snail kite, *Rostrhamus sociabilis*, feeding on these snails) (Cattau, Fletcher Jr, Reichert, & Kitchens, 2016). This study examines a similar potential conflict between management of the invasive insect pest *Lymantria dispar* L. and conservation of declining monarch butterfly (*Danaus plexippus*) populations. A Lepidoptera-specific biological insecticide used in *L. dispar* management, *Bacillus thuringiensis var. kurstaki* (commonly referred to as *Btk*) may be toxic to monarch butterfly larvae, but for monarch losses to result from *L. dispar* management, *Btk* applications must overlap in space and time with monarch larvae presence. The extent to which these occurrences overlap, however, is not yet well-resolved.

Monarch butterflies are an iconic species, whose migration between overwintering grounds in Mexico and breeding and feeding grounds across the United States and southern Canada makes it a celebrated species across North America. Unfortunately, the migratory population of monarch butterflies has declined by ≈80% over the last decade (Semmens et al., 2016). Many current monarch conservation initiatives focus on restoring and enhancing monarch breeding habitat, which consists exclusively of milkweed plants (*Asclepias* spp.) (Oberhauser, 2004). The North Central region of the breeding grounds (comprised primarily by Midwestern U.S. states) has been prioritized for increased action, as it contains the most productive summer breeding grounds (Caldwell, 2016; Flockhart et al., 2013). Concerns regarding the use of *Btk*, a soil bacterium able to produce an insecticidal compound that is toxic to larvae of numerous species of Lepidoptera, in this area and its role in the decline of monarch butterflies are bolstered by findings indicating that larvae of other butterfly species, such as swallowtail butterflies (*Papilio* spp.) and the endangered Karner blue butterfly (*Lycaeides melissa samuelis*), are physiologically susceptible to *Btk* (Herms et al., 2018; James, Miller, & Lighthart, 1993; Johnson, Scriber, Nitao, & Smitley, 1995). Although the risk of impact from *Bt* toxin-expressing pollen from transgenic corn appears to be negligible (Sears et al., 2001), we do not yet have an understanding of the risk of aerial *Btk* applications to monarch butterflies in the United States.

Applications of *Btk* are a key management tool in the suppression and eradication of *L. dispar*, a highly destructive invasive pest. *L. dispar* is an exotic insect introduced into the United States in 1869 that has caused the defoliation of over 81 million acres of forest across 20 U.S. states and five Canadian provinces (Sharov, Leonard, Liebhold, Roberts, & Dickerson, 2002; Tobin, Cremers, Hunt, & Parry, 2016). Repeated defoliation from *L. dispar* outbreaks can lead to wide-reaching ecological effects, including altered species compositions, microclimates and nutrient cycles (Gandhi & Herms, 2010; Lovett, Canham, Arthur, Weathers, & Fitzhugh, 2006). Furthermore, *L. dispar* outbreaks have been estimated to cause approximately $410 million of damage per year to property owners and municipalities (Aukema et al., 2011). *Btk* aerial applications are part of an integrated pest management system to control *L. dispar* spread in the United States (Solter & Hajek, 2009; Tobin & Blackburn, 2007).

Part of *Btk*'s popularity stems from its pathogenic specificity, as it is mostly toxic to Lepidopteran species. However, concerns over non-target effects on native Lepidopterans remain, particularly for threatened and endangered species. Non-target effects of *Btk* have been a matter of public and scientific concern over the last 20 years, prompting numerous studies focused on assessing the effects of aerial applications of *Btk* on non-target organisms (Addison, Otvos, Battigelli, & Conder, 2006; Johnson et al., 1995; Losey, Rayor, & Carter, 1999; Sears et al., 2001). *Btk* has been found to decrease richness and abundance of some non-target Lepidoptera taxa after multiple applications of the pesticide; although in many cases, full recovery was observed in subsequent years (Boulton, Otvos, Halwas, & Rohlfs, 2007; Hall, 1999; Wagner, Peacock, Carter, & Talley, 1996). Potential non-target effects pose a conservation catch-22, in which scientists and managers are compelled to weigh the benefits and detriments of invasive pest management and prioritizing the protection of vulnerable fauna.

Previous studies that have recognized and explored this dilemma show that non-target impacts of aerial applications of *Btk* are greatly superseded by the detrimental effects of widespread defoliation caused by *L. dispar* outbreaks (Manderino, Crist, & Haynes, 2014; Wayland, Manderino, Crist, & Haynes, 2015). In fact, the use of *Btk* was found to decrease the negative effects of defoliation on species richness of beetles (Wayland et al., 2015). However, there are still concerns regarding potential impacts of *Btk* aerial applications on highly vulnerable species, particularly on monarch butterflies.

In this study, we seek to determine whether the needs for *L. dispar* management and for the conservation of monarch butterflies pose conflicting interests. To answer this question, we evaluate the risk of exposure of susceptible monarch larvae to *Btk* by evaluating the spatiotemporal overlap between monarch larvae and *L. dispar Btk* treatments. To assess temporal overlap, we used information on the arrival of monarch butterflies to areas being treated for *L. dispar* with *Btk* aerial application. Spatial overlap was estimated using data on the abundance of monarch habitat in treated areas. Our study represents the first formal assessment of exposure risk in the United States of monarch butterflies, a non-target native species already facing widespread population declines, to aerial applications of *Btk*. Consequently, our study may serve a broader purpose, by providing a blueprint to resolve concerns in conservation management regarding potential tradeoffs between the management of invasive species and the conservation of vulnerable species.

2 | METHODS

Using data provided by the National Gypsy Moth Slow the Spread program on the *Btk* treatments they have coordinated in previous years, we compared the location and timing of 283 *Btk* treatments for *L. dispar* spread management conducted from 2015 to 2018 (Figure 1; see Supporting Information for more details) to the time

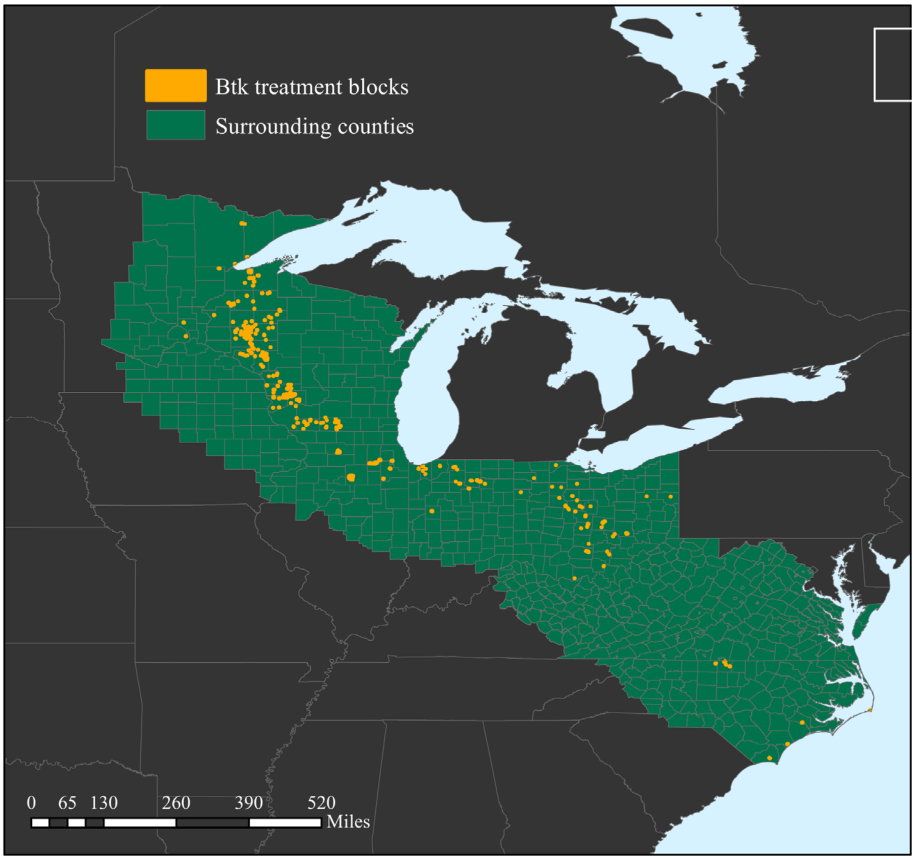

FIGURE 1 Blocks delineated for Btk treatments for gypsy moth suppression under the Slow the Spread program from 2015 to 2018 (n = 283). Surrounding counties that are encapsulated in the active treatment area for the Slow the Spread program have been filled in green

period monarch larvae were present in treatment blocks, as well as the abundance of milkweed in treatment blocks, which we used as a proxy for potential local monarch larval abundance.

We determined the time period during which vulnerable monarch larvae are present based on the arrival of monarch adults. Once adult butterflies arrive to their breeding grounds, they mate and lay eggs almost immediately; eggs hatch within approximately 4 days (Prysby & Oberhauser, 2004). Journey North, a citizen science program housed by the University of Wisconsin-Madison's Arboretum, maps volunteer-reported sightings of monarch butterflies during their northward spring migration in real-time for over 60,000 sites in the United States, Canada and Mexico (Howard & Davis, 2004; Journey North, 2019). We obtained from Journey North the georeferenced dates of first sighting for monarch adults from 1996 to 2020, for 14 states comprising the *L. dispar* transition zone. The transition zone surrounds the leading edge of *L. dispar* invasion and *Btk* treatment blocks, and overlaps the North Central region of the U.S. monarch breeding range. We modeled these data as ordinal dates (i.e., number of days from January 1) to produce yearly estimates with high spatiotemporal resolution of the timing in which monarchs arrive across the *L. dispar* transition zone. We created geostatistically interpolated surfaces of the ordinal date of first sighting for each year from 1996 to 2020 using a simple kriging model (Olea, 1999) in ArcMap (ArcGIS, version 10.7). To estimate uncertainty in the predicted values, we performed Gaussian geostatistical simulations (n = 1,000) for each year's surface (see Supporting Information for more details).

We addressed yearly fluctuations in monarch migration times due to seasonal weather by averaging all 25 years of kriged and geostatistically simulated surfaces. The estimated date of first sighting for each treatment block (t_m) was then extracted from the averaged kriged surface by taking the value at the treatment block centroid. The standard deviation of the simulated estimate was extracted from the averaged geostatistically simulated surface. Monarch larvae were considered present at a given location from time of egg hatch ($t_m + 4$) to time of pupation (generally 14 days after hatching, that is, $t_m + 18$) (Oberhauser, 2004). Confidence intervals for these dates were calculated using the standard deviation value extracted for said location.

To assess the likelihood of monarch larvae presence in treatment blocks, we obtained high-resolution data (30-by-30 m pixels) on the projected abundance of monarch habitat in *Btk* treatment blocks and in 1,000 m buffers around each treatment block that account for aerosolized pesticide drifting outside the spray zone (Teschke, Chow, Bartlett, Ross, & van Netten, 2001). We obtained these data using a Milkweed Calculator developed by the U.S. Geological Survey's Monarch Conservation Science Partnership (Rohweder & Thogmartin, 2016; Thogmartin et al., 2017; see Supporting Information for more details).

3 | RESULTS

3.1 | Temporal overlap between monarch larvae and Btk aerial applications

On average, in the last 25 years, monarch butterflies arrived to the *L. dispar* transition zone between April 15 (ordinal date, hereafter referred to as OD, 105) and June 15 (OD 166) (Figure 2). The average date of arrival of monarchs to treatment blocks was May 25 (OD 145). Initial *Btk* applications (i.e., first application) occurred from April 12 (OD 102) to June 19 (OD 170) (mean date: May 17 [OD 137]). Follow-up applications (i.e., second application) occurred, on average, 5 days after initial applications (OD 142). Ninety-eight percent of initial treatments occurred before monarch larvae hatch in the respective treatment block (albeit only 2.8% with 95% confidence), while 84% of follow-up applications occurred before monarch larvae hatch (only 0.5% with 95% confidence) (Figure 3). The highest levels of overlap were observed in treatment blocks located in the northernmost latitudes, specifically between 41 and 43°, and above 44 ° N latitude) (Figure 3). These overlaps occurred primarily in the state of Wisconsin (Figure 4).

3.2 | Spatial overlap between monarch larvae and Btk aerial applications

In total, treatment blocks contained 26.24 projected hectares of milkweed (123.51 when including a 1,000-m buffer surrounding each block), representing 0.05% (0.05% when including buffer) of the total area contained in treatment blocks from 2015 and 2018 (50,811 ha, 250,879 ha when including buffer) (Table 1). Placed in a larger context, milkweed habitat within treatment blocks represented 0.05% (0.2% when including buffer) of the total amount of projected milkweed in surrounding counties, where treatments are most likely to occur in the near future, and 0.04% (0.18%) of the total amount of milkweed in the Midwestern United States (Thogmartin et al., 2017).

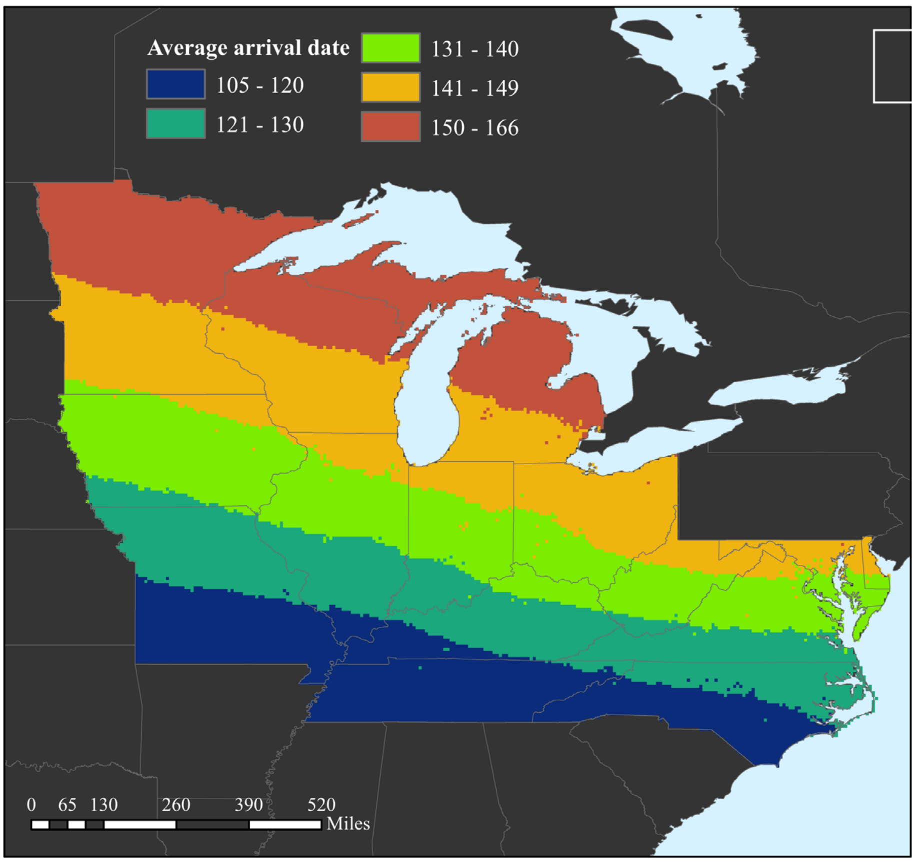

FIGURE 2 Map of estimated ordinal dates of first sighting of monarch adults during their northward spring migration across the gypsy moth transition zone (ordinal day 105 = April 15, ordinal date 166 = June 15)

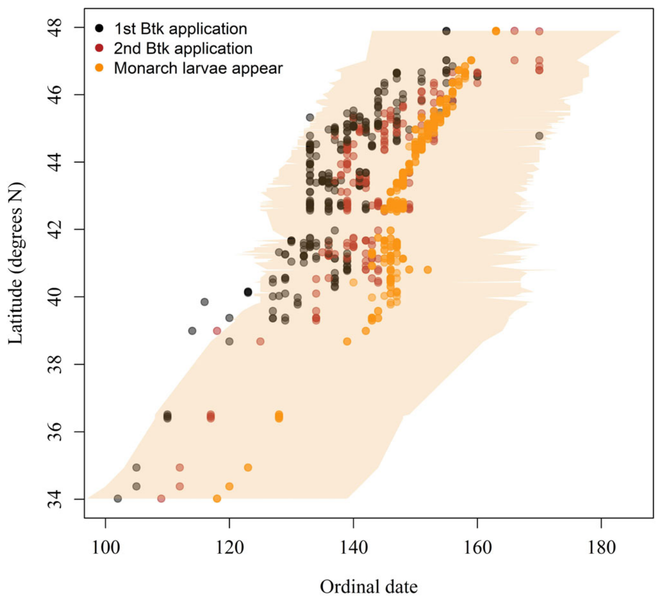

FIGURE 3 Temporal overlap between Btk treatments and monarch larvae presence. Black circles represent individual initial applications (first applications) occurring between 2015 and 2018, while red circles represent individual follow-up applications (second applications). Orange circles represent the appearance of monarch larvae (i.e., 4 days after monarch arrival) to the treatment block. Orange lines represent 95% confidence intervals on monarch larvae appearance. Placement of circles along the *x*-axis indicates the date in which these events occurred or are estimated to have occurred, while placement along the *y*-axis indicates the latitudinal coordinate of each treatment block's centroid

The land cover types that contributed the overwhelming majority of the milkweed found in treatment blocks were exurban roads and rails (19 ha, Figure 5). These land types were trailed by herbaceous wetlands and grasslands/pastures (3 and 2 ha, respectively). As expected, forests (deciduous, coniferous and mixed) were the land cover types most commonly found in *Btk* treatment blocks (51% of the total area covered by treatment blocks), followed by agricultural land types (12%). The third most common land cover types, grasslands and pastures (10%) were also the third most important source of milkweed, indicating a potential area of overlap to be avoided in future treatments. The same patterns were observed in the analyses of treatment blocks including a 1,000 m buffer (Figure 5b).

4 | DISCUSSION

L. dispar management and monarch conservation are not likely to pose conflicting interests due to direct losses of monarch butterflies from *L. dispar* management activities; however, there are specific areas where actions could be taken to further minimize risk posed by Btk treatments. Although there is potential for temporal overlap between monarch larvae and *Btk* treatments, the projected abundance of monarch habitat (i.e., milkweeds) in *Btk* treatment blocks was minimal from 2015 to 2018, and therefore we expect risk to monarch larvae from aerial applications of *Btk* for *L. dispar* spread management to be low. Treatment blocks are delineated to encompass forested problem areas with locally high densities of *L. dispar*, and therefore forested land types are the most prevalent across treatment blocks (51% of the land covered by all treatment blocks). Milkweeds are disturbance-adept perennial forbs that usually occur in open spaces along the banks of waterbodies and waterways, in prairies, forest margins and roadsides (Ulev, 2005). Because forests are not suitable habitats for milkweed, it is understandable that milkweed habitat is rare in treatment blocks (estimated at 0.05% of all area in treatment blocks).

Nonetheless, land cover types that do support milkweed were found in treatment blocks as they occur in proximity to forested areas. The third most common land cover type found in treatment blocks (10% of all treatment blocks), grasslands and pastures, also contributed the third highest amount of milkweed (2 ha). The inclusion (or vicinity) of grasslands and pastures in *Btk* treatment blocks increases the spatial overlap between monarch larvae and *Btk* aerial treatments, furthering the potential for exposure of susceptible monarch larvae to the pesticide. However, the two most important sources of milkweed, exurban roads/rails (19 ha) and herbaceous wetlands (3 ha) were relatively rare in *Btk* treatment blocks (5% and 0.8% of all treatment blocks respectively). Our results indicate that while spatial overlap between monarch larvae and *Btk* treatments appears to be low, certain land cover types, namely grasslands/pastures and exurban roads/rails, require close attention as they represent potential sources of overlap between *L. dispar* treatments and monarch larvae.

The degree to which *Btk* treatments and monarch larvae overlap temporally is much less clear. We estimated that 98% of treatment blocks were sprayed with *Btk* before monarch larvae started appearing. The expected residence time in the environment of toxic *Btk* endotoxins in the environment is only 2–5 days (Scriber, 2001; Sundaram, Sundaram, & Hammock, 1994). Assuming this length of persistence, 81% to 92% of treatments did not temporally overlap with monarch larvae. However, some field studies have demonstrated longer persistence of toxic *Btk*, showing larvicidal activity on nontarget Lepidoptera from 30 days to several months after application (Johnson et al., 1995; Vettori, Paffetti, Saxena, Stotzky, & Giannini, 2003). Since we lack proper understanding of

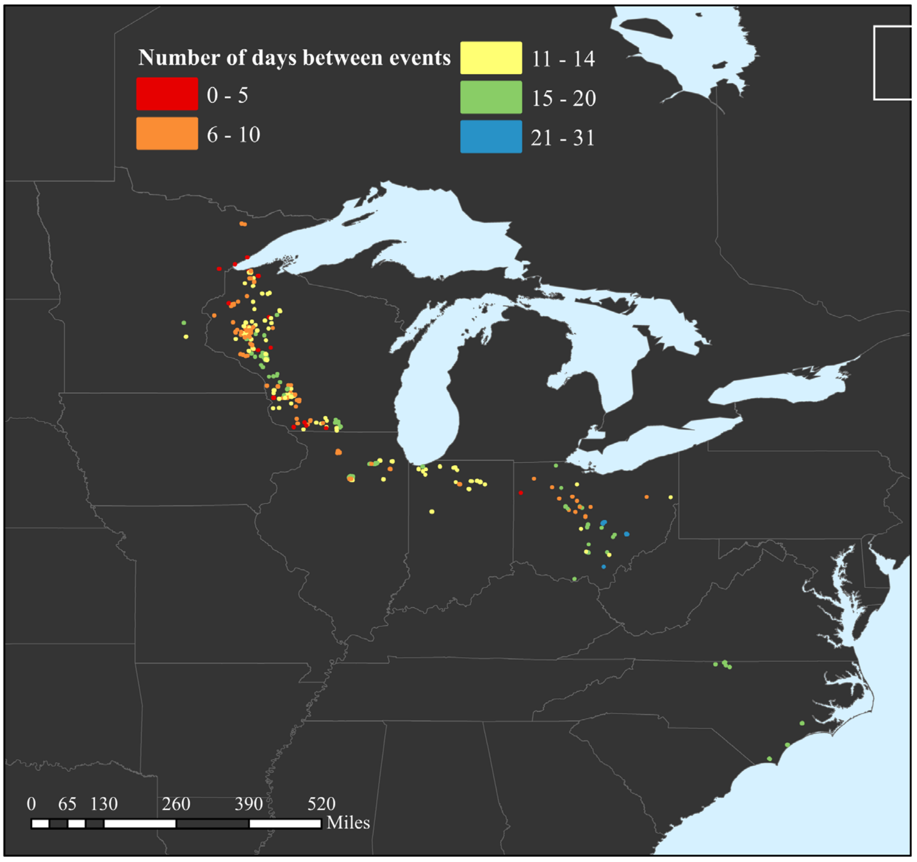

FIGURE 4 Map demonstrating temporal overlap between Btk aerial applications and monarch larvae presence in 283 treatments block delineated for Btk pesticide applications

TABLE 1 Amount of milkweed in *Btk* treatment blocks utilized from 2015 to 2018, the counties surrounding these blocks that fall within the active Slow the Spread treatment area (Figure 1) and in the Midwestern United States

	Treatment blocks	Treatment blocks + buffer	Surrounding counties	Midwestern United States
Projected hectares of milkweed	26	123	55,272[a]	68,718[b]
Proportion of total milkweed within treatment blocks	—	2%	0.05%	0.04%

[a]Calculated projected total number of stems of milkweed at the county level using the USGS Milkweed Calculator tool. The USGS Milkweed Calculator tool assumes a milkweed density of 1.95 stems per meter squared to convert stem counts to milkweed meters. We used this constant to convert number of stems to meters to hectares.

[b]Per Thogmartin et al. (2017) and Pleasants (2017), the current amount of milkweed in the Midwestern United States as of 2014 was 1.34 billion stems. Number of stems in the Midwestern U.S. was converted to hectares as described above.

the dosage at which *Btk* is lethal to monarch butterflies, we are unable to ascertain definitively the degree of exposure of monarch larvae to *Btk* in the environment.

Further complicating the interpretation of our temporal overlap results, our estimates of monarch arrival dates had wide confidence intervals (an average of 20 days across treatment blocks). The lack of precision of our models may be attributed to the nature of the monarch butterfly arrival data utilized in our temporal analyses. Because these data depend on volunteer reports of butterfly sightings, the date of these reported first sightings may not correspond with the actual date of arrival of monarch butterflies to the area. Nonetheless, the estimated dates of monarch arrival to *Btk* treatment blocks correspond with the expected date range for monarch arrivals to the latitudinal regions based on historical observations (Howard & Davis, 2004).

Our findings highlight areas where *L. dispar* pest management can minimize further the risk of exposure of monarch larvae to *Btk*. Land types representing milkweed habitat should be avoided during aerial applications. Currently, applicators attempt to limit spray to tree-covered areas, excluding large open gaps. Although grasslands and pastures are thus excluded from treatment

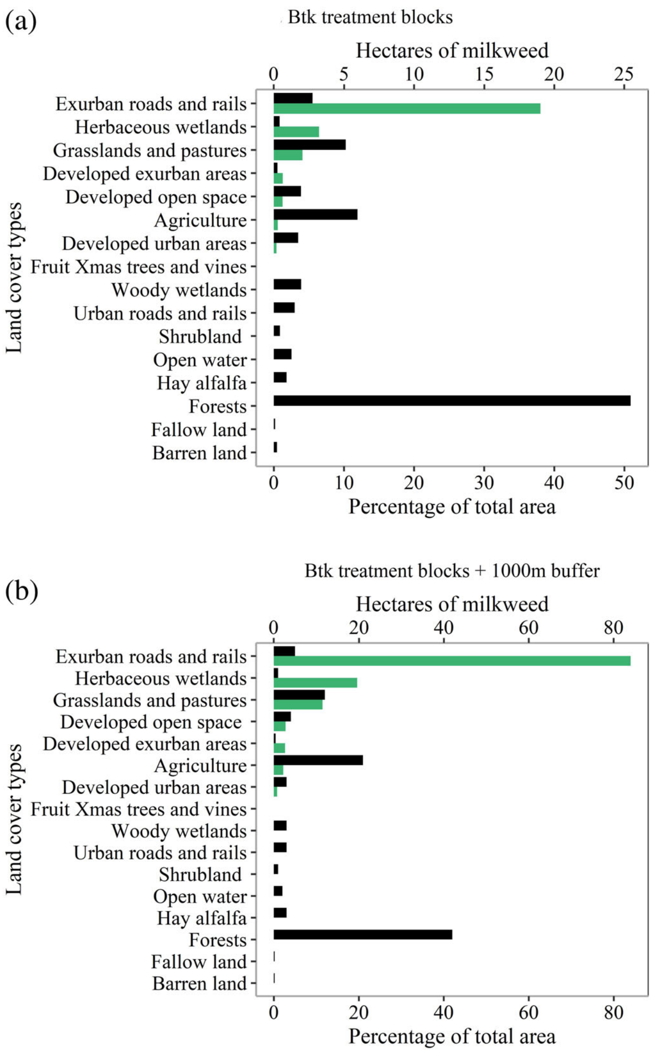

FIGURE 5 Land cover type composition of (a) Btk treatment blocks and (b) Btk treatment blocks plus a 1,000 m buffer. Green bars represent the number of projected hectares of milkweed occurring in these land cover types; black bars represent the percentage of the total area covered by these land cover types. Similar land cover types were grouped to facilitate interpretation. For detailed results, see Tables S1 and S2

blocks, further consideration should be given to roads and rails crossing through and adjacent to forested areas. Ground-based application, for which overspray and drift are typically much reduced, is an option for isolated trees and small forest patches. One widely-used alternative to *Btk* is mating disruption via a synthesized, species-specific mating pheromone. Mating disruption has high efficacy in low-density populations and is the predominant management strategy for where the season-long trap catch is <30 moths trap^{-1} (Onufrieva, Hickman, Leonard, & Tobin, 2019; Tcheslavskaia et al., 2005; Thorpe, 2006). Although *Btk* application is preferred at higher population densities, there is evidence that mating disruption is effective at suppressing higher-density populations (Onufrieva et al., 2019).

Our results demonstrate a geographic trend in the extent to which *Btk* treatments and monarch larvae presence overlap temporally. We found that the vast majority of cases where temporal overlap was observed occurred in areas in the northernmost latitudes of our study area, above 41° north latitude (Figures 3 and 4). Furthermore, 27 of the 30 treatments that occurred after the projected appearance of monarch larvae were follow-up treatments. It is unclear whether this overlap reflects management decisions or increasing coincidence of *L. dispar* and monarch butterfly phenology as latitude increases. Future research should explore this question, especially as *L. dispar* phenology is currently difficult to predict in this region, creating management challenges (K. Thielen Cremers, personal communication).

Conflicts among competing conservation goals are not uncommon. Comprehensive investigation is necessary to better understand the extent of these conflicts and how management tradeoffs occurring as a result of these conflicts may be minimized. Our study on the potential conflict between management of the invasive *L. dispar* and monarch conservation demonstrates that the exposure of susceptible monarch larvae to *Btk* aerial treatments has likely been minimal. Although we expect this trend to continue in the near future, subsequent research efforts should explore how climate change and associated expansions and contractions in the ranges of *L. dispar* and monarch butterflies, as well as climate-induced alterations in these species' phenologies, may result in changes in the current degree of overlap between *L. dispar* suppression treatments and monarch larvae. Nonetheless, our assessment of the spatiotemporal overlap between these events allowed us to identify management actions that could decrease the possibility of future conflict between these conservation goals. We believe other conservation conflicts could follow similar methodologies to decrease potential management tradeoffs.

ACKNOWLEDGMENTS

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CONFLICT OF INTEREST

The authors declare no potential conflicts of interest.

AUTHOR CONTRIBUTIONS

Jonathan A. Walter and Derek M. Johnson secured funding for the study. Jonathan A. Walter conceived and conceptualized the foundation of the study. All authors contributed to the design of the methodology and collection of the data. Gabriela C. Nunez-Mir performed the analyses. Gabriela C. Nunez-Mir led the writing of the manuscript. All authors contributed to the preparation and revision of the manuscript at all stages.

DATA AVAILABILITY STATEMENT

The monarch first sighting data utilized here is publicly available at Journey North (https://journeynorth.org/sightings/). Milkweed abundance data was derived utilizing Milkweed Conservation Planning Tools made available for download at https://www.umesc.usgs.gov/management/dss/monarch/desktop_monarch_conservation_planning_tools.html by the USGS Monarch Conservation Science Partnership. Records on the timing and location of Btk aerial treatments can be found at https://www.gmsts.org.

ETHICS STATEMENT

The authors are not aware of any ethical issues regarding this work.

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SUPPORTING INFORMATION

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

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