Conservation risks and benefits of establishing monarch butterfly (*Danaus plexippus*) breeding habitats close to maize and soybean fields in the north central United States: A landscape-scale analysis of the impact of foliar insecticide on nonmigratory monarch butterfly populations

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Abstract

Establishing habitat in agricultural landscapes of the north central United States is critical to reversing the decline of North America’s eastern monarch butterfly (*Danaus plexippus*) population. Insecticide use could create population sinks and threaten recovery. Discouraging habitat establishment within a 38-m zone around crop fields is a suggested risk mitigation measure. In Story County, Iowa, United States, this mitigation would discourage habitat establishment in 84% of roadsides and 38% of noncrop land. It is unclear if the conservation benefits from establishing habitat close to crop fields outweigh suppression of population growth owing to insecticide exposure. Consequently, monarch conservation plans require spatially and temporally explicit landscape-scale assessments. Using an agent-based model that incorporates female monarch movement and egg laying, the number and location of eggs laid in Story County were simulated for four habitat scenarios: current condition, maximum new establishment, moderate establishment, and moderate establishment only outside a 38-m no-plant zone around crop fields. A demographic model incorporated mortality from natural causes and insecticide exposure to simulate adult monarch production over 10 years. Assuming no insecticide exposure, simulated adult production increased 24.7% and 9.3%, respectively, with maximum and moderate habitat establishment and no planting restrictions. A 3.5% increase was simulated assuming moderate habitat establishment with a 38-m planting restriction. Impacts on adult production were simulated for six representative insecticides registered for soybean aphid (*Aphis glycines*) management. Depending on the frequency of insecticide applications over a 10-year period, simulated production increased 8.2%–9.3%, assuming moderate habitat establishment with no planting restrictions. Results suggest that the benefits of establishing habitat close to crop fields outweigh the adverse effects of insecticide spray drift; that is, metapopulation extirpation is not a concern for monarchs. These findings are only applicable to species that move at spatial scales greater than the scale of potential spray-drift impacts. *Integr Environ Assess Manag* 2021;17:989–1002. © 2021 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Agroecosystems, Insect conservation, Landscape-scale risk assessment, Pesticide toxicology, Population sinks

INTRODUCTION

The monarch butterfly (*Danaus plexippus*) is native to North America, with multivoltine subpopulations that migrate on either side of the Rocky Mountains. Monarchs that do not migrate reside in southern Mexico, Central America, Florida, the Caribbean, Hawaii, Australia, New Zealand, and southern Europe (Brower & Jeansonne, 2004; Lyons et al., 2012; Pfeiler et al., 2017; Pierce et al., 2014; Servín-Garcidueñas & Martínez-Romero, 2014; Zhan et al., 2014). North American migratory monarchs account for approximately 90% of the worldwide population (US Fish and Wildlife Service, 2020). Despite differences in migratory behavior and overwintering sites, the eastern and western migratory North American monarch butterfly population is considered panmictic (Pyle, 2015). Results from studies to date do not reveal significant variation in the nuclear
lands, pastures and grasslands, and grassy areas bordering portions of existing Conservation Reserve Program (CRP) Conservation practices include establishment of milkweed States (Oberhauser et al., 2017; Thogmartin et al., 2017). Conservation of the eastern monarch is currently approached from multiple perspectives based on regional needs in the southern plains and north central states (Flockhart, et al., 2015; Oberhauser et al., 2017). Because stable isotope analyses suggest a large fraction of overwintering monarchs originate in the north central United States (Flockhart et al., 2017; Wassenaar & Hobson, 1998), conservation actions in this region emphasize establishing and maintaining milkweed (primarily Asclepias spp.), the monarch’s obligate host that provide oviposition sites and larval forage (US Fish and Wildlife Service, 2020).

The decline in the eastern monarch butterfly population in North America can be reversed by substantial conservation efforts in agricultural landscapes of the north central United States (Oberhauser et al., 2017; Thogmartin et al., 2017). Conservation practices include establishment of milkweed and nectar resources in rural roadsides, marginal croplands, portions of existing Conservation Reserve Program (CRP) lands, pastures and grasslands, and grassy areas bordering maize and soybean fields (Thogmartin et al., 2017). In the 2020 Species Status Assessment (US Fish and Wildlife Service, 2020), the USFWS concluded monarch exposure to insecticides in agricultural landscapes could be a threat to population recovery because of reduced survival and development. Owing to similar concerns, the Monarch Butterfly Wildlife Habitat Evaluation Guide, released by the US Department of Agriculture Natural Resources Conservation Service (Natural Resources Conservation Service, 2016), discouraged placement of monarch breeding habitat within 38 m of crop fields treated with pesticides, unless integrated pest management (IPM) was employed. Employing a 38-m no-plant zone around crop fields could exclude the establishment of milkweed in large portions of agricultural landscapes. For example, in Story County, Iowa, United States, a 38-m no-plant zone around conventional maize and soybean fields represents approximately 84% of rural roadside rights-of-way (ROWs) and 38% of grassland, CRP land, pastures, railroad ROWs, riparian corridors, and wetlands. In developing habitat restoration plans, resource managers need to assess whether the conservation benefits of establishing new monarch breeding habitat close to maize and soybean fields will outweigh potential suppression of population growth caused by increased insecticide exposure. Put another way: Would nonmigratory monarch population growth rate be higher if

- milkweed was established in all available space in agricultural landscapes, but with a high likelihood of insecticide exposure to monarch larvae close to crop fields; OR
- milkweed was established outside a 38-m “no-plant” zone around crop fields, but with a lower likelihood of insecticide exposure to monarch larvae?

Pollinator resource management decisions of this nature require spatially explicit landscape-scale assessments (Topping et al., 2020; Uhl & Brühl, 2019). A landscape-scale analysis needs to consider the spatial and temporal heterogeneity of monarch breeding habitat patches, agricultural fields, pastures, rural road ROWs, weather conditions, pest pressure, and likely insecticide-use patterns, as well as the susceptibility of different monarch life stages to insecticide exposure at varying distances from treated crop fields (Grant & Bradbury, 2019; Krishnan et al., 2020).

The spatial arrangement and density of new milkweed habitat patches, regardless of insecticide exposure, can influence realized monarch fecundity within a landscape. Adult female monarchs are vagile, that is, they are not habitat patch residents but instead move extensively among milkweed patches in a landscape (Zalucki & Lammers, 2010). Females are estimated to fly up to 15 km/day (Zalucki et al., 2016). Simulation studies suggest higher egg densities are expected in landscapes with uniformly distributed, small habitat patches, as compared with landscape configurations with fewer large habitat patches (Grant et al., 2018; Zalucki & Lammers, 2010; Zalucki et al., 2016). The extent to
which increased realized fecundity will result in increased population size depends on cumulative larval survival rates from egg to adult (Zalucki & Kitching, 1982; Zalucki et al., 2016). Survival rates can now be estimated from count data obtained through monarch monitoring studies in habitat patches within different landscapes (Grant et al., 2020). Impacts of insecticide exposure on monarch larval survival can be modeled with the recent publication of cuticular and dietary toxicity studies that include estimates of mortality in habitat at varying distances from treated maize and soybean fields (Krishnan et al., 2020).

Here we illustrate how spatially explicit, individual-based monarch population models (Grant et al., 2018) and life-stage-specific monarch toxicity data (Krishnan et al., 2020) can be integrated to simulate landscape-scale risks and benefits associated with different habitat-establishment scenarios and insecticide-use patterns. Specifically, we used a demographic model that incorporates mortality from natural causes (e.g., predation) and insecticide exposure to simulate adult monarch production in Story County, with different spatially explicit milkweed-augmentation scenarios under a variety of foliar insecticide applications to manage soybean aphids (Aphis glycines) and true armyworms (Mythimna unipuncta). We demonstrate the power of linking laboratory toxicology data, statistical methods, and simulation modeling at a landscape scale to improve understanding of the risks and benefits of different conservation and agronomic practices.

**METHODS**

Our objective was to assess the potential impact of insecticide spray drift on adult monarch recruitment in north central US agricultural landscapes using Story County (1 486.5 km²), as an area representative of the Des Moines Lobe, a region of intensive agriculture (Griffith et al., 1994). Comprehensive and detailed descriptions of the agent-based simulation modeling, survival estimation, and demographic modeling are described in Supplementary Material A. As depicted in Figure 1, we combined monarch larval toxicity results for six representative insecticides (Krishnan et al., 2020), a landscape-scale, agent-based model that simulates monarch movement and egg laying (Grant et al., 2018), and a Bayesian Markov Chain Monte Carlo (MCMC) statistical model (Grant et al., 2020) to estimate stage-specific survival probabilities under natural conditions with no pesticide exposure. The six insecticides are representative of commercial compounds typically used to manage early- and late-season insect pests in maize and soybean production in Iowa and the north central states (Krishnan et al., 2020; beta-cyfluthrin [pyrethroid], chlorantraniliprole [antranilic diamide], chlorpyrifos [organophosphate], and clothianidin, imidacloprid, and thiamethoxam [neonicotinoids]).

Grant et al. (2020) published a model to estimate overall cumulative survival probability of monarch eggs through adults. We used informative prior distributions to estimate stage-specific survival probabilities from egg to fifth larval instar, with a cumulative survival probability of 0.014 (see the *Natural Larval Survival* section in Supporting Information A). With prior distributions, the MCMC chains converged, and we obtained stage-specific survival estimates (Table S1). There was sufficient information in the data to generate posterior distributions very different from the prior distributions, which provides substantial confidence that the parameter estimates were accurate (Figure S1). When no priors were used, the estimates were the same (Table S2), providing substantial confidence that the stage-survival estimates were robust. These estimates were used in the enhanced population simulation code in Grant et al. (2020) to estimate the number of adults produced from the eggs laid. Stage-specific survival estimates were also used to predict the number of individuals from each stage present at the time of insecticide drift on Day 12 (Table S17).

We generated four milkweed-establishment scenarios outside crop fields: Scenario 1, current baseline condition; Scenario 2, maximum milkweed augmentation in available space; Scenario 3, moderate milkweed augmentation in available space; Scenario 4, moderate milkweed augmentation established only outside a 38-m no-plant zone around crop fields. These scenarios are implemented in the landscape as Geographic Information System (GIS) shapefiles with varying milkweed densities in 41 326 habitat patches (polygons). The scenarios explore the likely range of milkweed augmentation expected based on the Iowa Monarch Conservation Strategy (Iowa Monarch Conservation Consortium, 2018). Density of milkweed augmentation was based on assumptions made by Thogmartin et al. (2017). Milkweed density in the landscape model is the only variable that is different among the four scenarios; the number of egg-laying adult females and the natural and insecticide survival rates are constant. The agent-based model was used to simulate egg laying in spatially explicit land-cover classes. A demographic model was developed to simulate the number of adults produced from the eggs laid on the landscape. The insecticide spray-drift zone was modeled as an area on the north and west sides of soybean fields. The spray-drift zone often overlapped with the no-plant zone (Figure 2). In areas that were not subject to spray drift, we simulated monarch adult production using natural survival rates (Grant et al., 2020). In areas subject to spray drift, monarch production was adjusted by the inclusion of larval insecticide-specific mortality rates (Krishnan et al., 2020). Insecticide exposure from spray drift was estimated for aerial (i.e., airplane) and ground (i.e., a self-propelled applicator with spray nozzles 0.5 m [low boom] or 1.3 m [high boom] above the ground) applications (Krishnan et al., 2020).

Our model simulates one nonmigratory monarch generation in late July through late August, when soybean aphid outbreaks are expected. For true armyworm outbreaks, one generation was simulated in mid-May through early June. Because insecticide applications typically occur once per year per pest (Krishnan et al., 2020 and references cited therein), we modeled one monarch generation in

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spring to determine the annual effects of insecticide exposure owing to management of true armyworm and another monarch generation in summer to determine the annual effects of insecticide used to manage soybean aphids. In late summer, egg laying is not highly synchronized and monarch generations can overlap (Zalucki & Rochester, 2004); consequently, the model is not intended to reflect a specific nonmigratory generation or period within July and August. Rather, the model can be conceptualized as running over 24 days. Eggs are laid over 10 days in the agent-based model. The cumulative eggs laid in the agent-based model are spread over 12 days in the demographic model. By Day 12, a natural distribution of life stages is present. Spray drift and associated mortality occurs
on Day 12. The demographic model then runs for 12 more days until all eggs and larvae have died or surviving larvae have eclosed.

Our modeling simulated the number of adult monarchs produced under the four monarch habitat-establishment scenarios and, in the case of soybean aphid management, varying frequencies of single annual insecticide applications over a 10-year period (i.e., 0, 1, 3, 5, or 10 annual applications over a 10-year period). Adult production over a 10-year period was the sum of annual production for years with no insecticide application combined with the sum of annual production for the years when an insecticide was applied. We assumed that losses in one year have no effect on the population in later years, and the number and distribution of eggs laid are held constant for each year.

To summarize, we used an agent-based model to simulate the number of monarch eggs laid in Story County. We then used natural survival rates to simulate the number of eggs that survived to the adult stage outside the 38.1-m insecticide spray-drift zone. For monarch eggs within the spray-drift zone, we used larval survival estimates derived from Krishnan et al. (2020) to simulate additional mortality owing to insecticide exposure. We summed adults produced inside and outside the drift zone to determine the number of adults produced in Story County, in one monarch generation. We employed this process with four different milkweed-augmentation scenarios, six insecticides applied aerially or by ground equipment, and different annual insecticide application assumptions over a 10-year period to manage an early- and late-season insect pest.

RESULTS

Patterns of eggs laid on the landscape

Assuming baseline habitat (Scenario 1), our simulations reveal 2,176,354 eggs laid by one nonmigratory monarch generation in Story County. Under the milkweed-augmentation Scenarios 2 (maximum augmentation), 3 (moderate augmentation), and 4 (moderate augmentation outside a 38-m no-plant zone), 2,713,414, 2,379,294, and 2,253,138 eggs were laid, respectively (Table S4), which correspond to 24.7%, 9.3%, and 3.5% increases, respectively, as compared with Scenario 1 (Table S5; Figures S2–S5). Increases occurred only in roadways (mainly Scenarios 2 and 3), grassland/pasture (Scenarios 3 and 4), and low-intensity development areas (Scenarios 2–4; see Figure S6). All other land-cover types, for Scenarios 2–4, had minor decreases in eggs laid because female monarchs spent less time in the baseline habitat. The highest percentage of eggs were laid in grassland and pasture (39%–48%; Table S5), followed by non-genetically modified (GM) maize, and soybean fields (25%–41%), low-intensity development areas (17%), and
roadsides (9%–17%). Other habitats combined, such as GM maize and soybean fields, forests, wetlands, and railroad ROWs, had 1%–2% of the eggs laid (Figures S2–S5).

Under Scenario 1, 28% of eggs were laid inside the no-plant zone (Tables 1 and S6), which included 90% and 40% of the total eggs laid in roadsides and grassland/pastures, respectively. In Scenarios 2 and 3, most of the increase in eggs laid occurred within the no-plant zone. The number of eggs laid in roadsides within the no-plant zone increased 139% (Scenario 2) and 63% (Scenario 3). In Scenario 4, eggs laid within the no-plant zone decreased 5% from Scenario 1, because monarch agents spent more time in the improved habitat outside the zone (recall that, under Scenario 4, baseline milkweed is present in the no-plant zone). Most of the gains for Scenario 4 occurred in grasslands and pastures outside the no-plant zone.

**Natural survival and adult monarch production assuming no insecticide exposure from spray drift**

We use Scenario 3 to illustrate the calculations to determine the number of individuals in each stage on Day 12 for each land-cover type (Table S7). By Day 12 of the simulation, 2,379,294 eggs were laid at a rate of 198,274.5/day. We calculated progression and survival through stages over the 12 days and determined that 20% (479,957 eggs) of the original eggs survived and were distributed across six stages (Table S17). Note that these proportions are the same for each habitat enhancement scenario, but for brevity are not shown.

Adult monarch production in Story County for one summer generation was summed over 10 years (Table 2). With only natural survival probability applied to the population, monarch production over 10 years was 347,940, 433,800, 380,380, and 360,220 adults for Scenarios 1, 2, 3, and 4, respectively (an increase of 24.7%, 9.3%, and 3.5% for Scenarios 2, 3, and 4 over the baseline).

**Adult monarch production assuming foliar insecticide applications for soybean aphid management**

**Patterns of eggs laid in the spray-drift zone.** When the spray-drift zones and no-plant zones were mapped onto Story County’s landscape, the total area of the spray-drift zone was much smaller than the total no-plant zone area (Figure 2). The spray-drift zones were not completely contained within the no-plant zones; in some cases, spray

### Table 1

| No-plant zone and land-cover type | Scenario 1 (%)<sup>a</sup> | Scenario 2 (%)<sup>b</sup> | Scenario 3 (%)<sup>c</sup> | Scenario 4 (%)<sup>d</sup> |
|----------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Total eggs in no-plant zone      | 28                        | 39                        | 34                        | 25                        |
| Total eggs outside no-plant zone | 72                        | 61                        | 66                        | 75                        |
| Roadsides eggs in the no-plant zone | 90                    | 91                        | 91                        | 84                        |
| Roadsides eggs outside the no-plant zone | 10                    | 9                         | 9                         | 16                        |
| Grass/pasture eggs in the no-plant zone | 40                    | 40                        | 40                        | 33                        |
| Grass/pasture eggs outside the no-plant zone | 60                    | 60                        | 60                        | 67                        |
| Low-intensity dev. eggs in the no-plant zone | 32                    | 42                        | 36                        | 3                         |
| Low-intensity dev. eggs outside the no-plant zone | 68                    | 58                        | 64                        | 97                        |

*Note:* See Table S6 for the number of eggs laid used to calculate these percentages.

<sup>a</sup>Scenario 1: Baseline habitat condition (Supporting Information A).

<sup>b</sup>Scenario 2: Maximum milkweed augmentation (see Supporting Information A).

<sup>c</sup>Scenario 3: Moderate milkweed augmentation (see Supporting Information A).

<sup>d</sup>Scenario 4: Moderate milkweed augmentation with no augmentation in the no-plant zone.

### Table 2

|                  | Scenario 1<sup>a</sup> | Scenario 2<sup>b</sup> | Scenario 3<sup>c</sup> | Scenario 4<sup>d</sup> |
|------------------|------------------------|------------------------|------------------------|------------------------|
| Maximum total production | 347,940               | 433,800               | 380,380               | 360,219               |
| Production outside drift zone | 318,102               | 386,963               | 343,294               | 332,659               |
| Maximum production inside drift zone | 29,840              | 46,840               | 37,090               | 27,560               |
| Proportion of total inside drift zone | 0.09               | 0.11               | 0.10               | 0.08               |

*Note:* Total production is partitioned between production within and outside the drift zone.

<sup>a</sup>Baseline habitat condition (see Grant et al., 2018 and Supporting Information A).

<sup>b</sup>Maximum milkweed augmentation (see Thogmartin et al., 2017 and Supporting Information A).

<sup>c</sup>Moderate milkweed augmentation (see Thogmartin et al., 2017 and Supporting Information A).

<sup>d</sup>Moderate milkweed augmentation with no augmentation in a 38-m no-plant zone surrounding maize and soybean fields.
drift that originated in soybean fields drifted onto adjacent maize fields. Eggs laid by the monarch agents in the spray-drift zone are the same as those reported above (see the section Adult monarch production assuming no insecticide exposure from spray drift), but now divided into those laid within and outside the spray-drift zone, instead of within and outside the no-plant zone. Of the total eggs laid in the county, 9%, 11%, 10%, and 8% were laid in the spray-drift zone, for Scenarios 1, 2, 3, and 4, respectively (Table 2). Across all four scenarios, 94%–98% of eggs in the spray-drift zone were in grasslands and pasture, roadsides, non-GM maize fields, and low-intensity development areas (Table S8).

Impact of insecticide spray drift on survival through pupation

The realized cumulative natural survival rate from egg to adult was 0.016 (Table S9). We simulated the additional mortality that insecticide spray drift adds to natural mortality in years when insecticide was applied. Chlorantraniliprole (CTR) applied aerially results in a cumulative survival rate of 0.0028 in the spray-drift zone, which is a difference of −0.0132 from the natural rate. In order of greatest mortality to least, the differences in survival for aerial application compared with natural survival were −0.0132, −0.0126, −0.0120, −0.0093, −0.0039, and −0.0028 for CTR, chlorpyrifos (CFS), beta-cyfluthrin (BCF), clothianidin (CDN), imidacloprid (IMI), and thiamethoxam (TMX), respectively (Table S9). For high boom application, the differences in survival were −0.0113, −0.0087, −0.0077, −0.0049, −0.0009, and −0.0002, for CTR, CFS, BCF, CDN, IMI, and TMX, respectively (Table S10).

Adult monarch production in Story County

We summed monarch production in the drift zone and outside the drift zone to calculate total simulated monarch production over 10 years for Story County. Minimum and maximum adult monarch production in the county with aerial applications was 318 102–347 942, 386 963–433 803, 343 294–380 384, and 332 659–360 219 for Scenarios 1, 2, 3, and 4, respectively (Figure 3; Tables 2 and S11). The minimum and maximum productions represent the bounding assumption of 0% and 100% mortality, respectively, in the spray-drift zone. Adult production estimates between these maximum and minimum bounding assumptions (Tables S13 and S14) reflect the larval mortality rates in the spray-drift zone (Figure 4; Table S14). Scenario 2 has the highest monarch production, followed by Scenarios 3, 4, and 1. Consistent with lower mortality rates in the spray-drift zone (Figure 5; Table S14), high boom applications have less impact on adult production (Figure S7).

Spray drift from CTR applications caused the greatest reduction in monarch production for Story County, followed by CFS, BCF, CDN, IMI, and TMX, respectively. Under current habitat conditions (Scenario 1), aerial applications of CTR more than 1, 3, 5, and 10 times over 10 years reduced monarch production by 0.71%, 2.13%, 3.55%, and 7.09%, respectively, compared with the no-insecticide drift case (Table S12). On the other end of the spectrum, aerial applications of TMX caused a reduction of 0.15%, 0.45%, 0.75%, and 1.51% in adult production, respectively, compared with the no-insecticide drift case (Table S12). High boom applications cause less mortality. CTR reduced adult production by 0.61%, 1.82%, 3.04%, and 6.07%, whereas TMX reduced adult production by 0.01%, 0.04%, 0.06%, and 0.12%, when applications occurred 1, 3, 5, and 10 times over 10 years, respectively (Table S12). The same frequencies of application under a bounding assumption of 100% mortality in the spray-drift zone resulted in 0.86%, 2.57%, 4.29%, and 8.58% fewer adults, respectively. Under Scenarios 2–4, the percentage of monarchs lost to insecticides is similar to Scenario 1. Scenario 4 produces the most adults, whereas Scenario 2 produces the fewest. For example, if CTR is applied five times over 10 years, 3.55%, 3.16%, 4.03%, and 4.46% fewer adults are produced than with the no-insecticide drift case in Scenarios 1, 4, 3, and 2, respectively (Table S12).

Comparing across rather than within scenarios, we found that, for CTR applications in 10 of 10 years, simulated adult production in Scenarios 4, 3, and 2 increased 4.38%, 8.17%, and 22.21%, respectively, over Scenario 1. For TMX application in 1 of 10 years, adult production over 10 years increased 3.55%, 9.30%, and 24.63% over Scenario 1 for Scenarios 4, 3, and 2, respectively.

In terms of individual monarchs, aerial applications of CTR 1–10 times over 10 years caused losses of 2 467–2467–24 670 adults in the spray-drift zone; for TMX, this ranged from 524 to 5 240 adults (Figure 4; Table S13). Under the assumption of 100% larval mortality in the spray-drift zone, the losses ranged from 2 984 to 29 840 adults. Similar percentages of monarchs were killed in the spray-drift zone over the four scenarios; the greatest loss in population size was predicted for Scenario 2, followed by Scenarios 3, 1, and 4 (see Figure 4; Table S14).

In summary, Scenarios 3 (medium milkweed augmentation) and 2 (maximum milkweed augmentation) simulations produced more monarchs than Scenario 1 (baseline habitat). Scenario 3 produced more adult monarchs than Scenario 4 in most cases. For example, Scenario 3 produced 0.45%, 2.51%, and 4.57% more monarchs than Scenario 4 even if 100% larval mortality in the spray-drift zone occurs in 1, 3, and 5 years of 10 years. However, if 100% larval mortality occurred every year for 10 years, Scenario 3 produces 4.70% fewer monarchs than Scenario 4.

Adult monarch production assuming foliar insecticide applications for true armyworm management

For the true armyworm insecticide application scenario in maize fields, of the 2 176 354 eggs laid in Scenario 1 (Table S4), 15 799 eggs (0.73%) were laid in the spray-drift zone and 2 160 555 eggs (99.27%) were laid outside the drift zone. Of the larvae that hatch from eggs laid in the drift zone, only 7 899 (50% of 15 799) would be subject to spray drift. When there is no insecticide exposure, we simulated 34 794 adults produced in Story
In the worst-case scenario where 100% larval mortality occurs in the spray-drift zone, monarch production was reduced by 126 (0.36%) to 34,668 adults. A similar percentage reduction occurred for Scenarios 2–4 because the survival rate is constant across scenarios. The minimal impact of insecticide use on annual adult production is the result of the low level of true armyworm pressure (see Supporting Information A); therefore, simulations over a 10-year period were not generated.

**DISCUSSION**

Because 77% of all potential monarch habitat in the north central United States is in agroecosystems (Thogmartin et al., 2017), exposure to foliar insecticides is potentially a major threat to monarch recovery, especially in light of the high mortality rates found in laboratory studies (Krishnan et al., 2020; US Fish and Wildlife Service, 2020). We hypothesized that new milkweed added to an agricultural landscape in the north central United States could create population sinks (areas that have the net effect of reducing the total landscape population; see Pulliam, 1988) or perhaps ecological traps (areas that attract female monarchs with newly planted milkweed and contribute to decreased overall population growth; see Robertson & Hutto, 2006) because of insecticide exposure. Recent guidelines

**FIGURE 3** Adult monarch production in Story County, Iowa, assuming aerial insecticide application to manage soybean aphids. Panels depict adult production with spray drift in 5 of 10 years, 3 of 10 years, 1 of 10 years, and 10 of 10 years. No drift assumes no insecticide spray drift outside insecticide-treated soybean fields. Predicted adult monarch production is based on insecticide-specific cuticular and dietary larval mortality rates. The 100% bars assume an insecticide mortality rate of 100%. BCF, beta-cyfluthrin; CDN, clothianidin; CFS, chlorpyrifos; CTR, chlorantraniliprole; IMI, imidacloprid; TMX, thiamethoxam. Milkweed-establishment scenarios are ordered from least to greatest production.
discouraged establishment of new milkweed bordering maize and soybean fields, unless IPM was practiced (National Resources Conservation Service, 2016). However, the effect of no-plant zones on monarch populations at the landscape scale has not been quantified. Consequently, we conducted simulations that require multiple sources of information and models to quantify the effect of multiple milkweed-establishment scenarios and insecticide application patterns on adult monarch production.

By employing a spatially explicit, agent-based model for adult monarch movement and egg-laying behavior in an agricultural-dominated landscape (Grant & Bradbury, 2019; Grant et al., 2018), a monarch demographic model (Grant et al., 2020), and estimated insecticide-specific, field-scale mortality rates following foliar applications (Krishnan et al., 2020), we determined that employing a no-plant zone around maize and soybean fields likely produces fewer adult monarchs than unconstrained milkweed augmentation. We also demonstrate that implementation of recommended economic thresholds established for soybean aphid IPM practices, which results in one, three or five annual applications in different regions of Iowa over a 10-year period (see Krishnan et al., 2020 and references cited therein), likely supports greater adult monarch...
production than management practices that rely on annual prophylactic applications in each of 10 years. Because of the vagile behavior of egg-laying adult females, our simulations indicate that insecticide exposure to habitat patches close to treated crop fields are not likely to create population sinks that cause a landscape-scale decline in adult production.

**Landscape-scale monarch production assuming different habitat-establishment scenarios**

A spatially explicit, agent-based model (Grant et al., 2018), which was subsequently calibrated with monitored egg densities in Story and Boone counties, Iowa (Grant & Bradbury, 2019), was used to predict movement of nonmigratory, summer-breeding female butterflies and resultant egg densities in 17 land-cover classes. Based on this calibration, our simulations revealed 4%–26% increases in eggs laid for Scenarios 2, 3, and 4, compared with the baseline scenario (Table S5). To estimate larval survival probability, we employed the Bayesian state-space model, described in Grant et al. (2020), to estimate survival probabilities from field counts of stage-structured monarch populations on roadsides in Boone County, Iowa. Grant et al. (2020) constrained their conclusions to the cumulative survival probability from egg to pupation. For our demographic

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**FIGURE 5** Adult monarch production in the spray-drift area of Story County, Iowa, assuming high boom insecticide application to manage soybean aphids. Panels depict adult production with spray drift in 5 of 10 years, 3 of 10 years, 1 of 10 years, and 10 of 10 years. No drift assumes no insecticide spray drift outside insecticide-treated soybean fields. Predicted adult monarch production is based on insecticide-specific cuticular and dietary larval mortality rates. The 100% bars assume an insecticide mortality rate of 100%. BCF, beta-cyfluthrin; CDN, clothianidin; CFS, chlorpyrifos; CTR, chlorantraniliprole; IMI, imidacloprid; TMX, thiamethoxam. Milkweed-establishment scenarios are ordered from least to greatest production.
modeling, we needed to decompose the cumulative survival into stage-survival probabilities. With the monitoring data we used, the stage-survival estimates were very stable, giving us substantial confidence in the estimates. Application of the Grant et al. (2020) model to estimate stage-specific survival for other monarch datasets, and other stage-structured animal populations, would likely be successful, if sufficiently dense field-count datasets are available.

Once the egg density and survival rate inputs to our central demographic model were obtained, we modeled adult production under different habitat-establishment scenarios. We first assumed no insecticide exposure to provide a frame of reference. Assuming no spray drift should not be construed as a situation in which producers are restricted from using insecticides; rather these modeling results could represent situations in which spray-drift buffers are required within a maize or soybean field or future application technologies eliminate spray drift. Increases in adult monarch production paralleled increases in the number of eggs laid because the same survival rate was used for each milkweed-augmentation scenario. Simulated adult monarch production increased 24.7% when maximum augmentation was enacted in Scenario 2. With moderate milkweed augmentation (Scenario 3), adult production was predicted to increase 9.3%. If a 38-m no-plant zone policy was enacted in Story County, we predict the number of adult monarchs produced would drop to 3.5% above the baseline. Clearly, a significant proportion of the potential new monarch production that could result from milkweed augmentation is in the no-plant zone.

**Landscape-scale monarch production assuming foliar insecticide applications**

Our discussion of the landscape-scale effects of foliar insecticide application focuses on the management of soybean aphids, which can be a serious soybean pest (Hodgson et al., 2012). As noted previously, insecticide applications to manage true armyworms are rare (Krishnan et al., 2020; Supporting Information A), and the simulated impact on adult production was minimal.

Our analyses suggest that more monarch conservation benefits (i.e., adult production) will be realized if new habitat is established wherever space permits, including close to soybean fields, as compared with the benefits of only establishing new habitat outside a 38.1-m no-plant zone around the crop fields. When simulations for the same insecticide application rate, and frequency of application over 10 years are compared for scenarios with and without the no-plant zone, more monarchs are likely to be produced without constraints on habitat-establishment sites. Even assuming the worst realistic case in Scenario 3 (moderate habitat establishment and CTR sprayed in 5 of 10 years), more monarchs are produced than the best case for Scenario 4 (moderate habitat establishment outside the no-plant zone and 10 years). Under Scenario 3, the predicted number of adult monarchs produced over 10 years ranges from 365,049 for CTR applications in 5 of 10 years to 379,732 for TMX applications in 1 of 10 years (Table S11). Under Scenario 4, the predicted production ranges from 334,267 for CTR to 345,177 for TMX (Table S11). Further, the lowest adult production simulated for Scenario 3 (365,049) is more than the highest Scenario 4 adult production (345,177).

Our simulations indicate that CTR, CFS, and BCF may have the greatest impact on adult production, consistent with estimated field-scale mortality rates for cuticular and dietary exposures (Krishnan et al., 2020; Table S17). Our field-scale analyses demonstrate that aerial applications of CTR, the most toxic insecticide studied, causes 91–100% mortality of instars caused by cuticular exposure within 38 m downwind of treated fields (Table S17). In all, 65–99% of the surviving larvae are predicted to die from subsequent dietary exposure. Thus, ignoring landscape factors such as wind direction at time of insecticide application, pest type/location, frequency of insecticide application, monarch behavior, and level of milkweed augmentation would suggest that more than 90% of monarch larvae would die in the landscape following foliar CTR applications. However, as our landscape analyses demonstrate, this is likely not the case. In central Iowa, where soybean aphid populations exceed the economic threshold by approximately three times over 10 years, and the wind direction is generally from the southeast, CTR aerial applications are predicted to reduce adult production 1.90%–2.68% compared with a no-insecticide exposure assumption across the four scenarios (Table S12). Thus, using only field-scale mortality results grossly overestimates insecticide risks and grossly underestimates the monarch conservation benefits of establishing milkweed in agricultural landscapes.

To further explore the potential impact of insecticide mortality assumptions and potential spray-drift management options, we included two additional analyses. First, we assumed a 100% larval mortality downwind of treated fields for both Scenarios 3 and 4. Under this assumption, landscape-scale adult productivity still remains greater in Scenario 3 than in Scenario 4. This result is consistent with the greater number of eggs laid in the landscape under Scenario 3. In the second analysis, we compared adult productivity under Scenario 4 assuming no spray drift to Scenario 3 with spray drift. Our simulations revealed that insecticide applications would have to occur at unrealistic frequencies over 10 years to reduce Scenario 3 production levels to Scenario 4 production levels. This comparison demonstrated that, in a year in which an insecticide is applied, Scenario 3 still produces more adults than Scenario 4. In a year with insecticide application, to reach the point where adult production under Scenario 3 equals adult production in Scenario 4, the survival rate following insecticide exposure would have to decrease 26% (Table S18). Of course, in years without any insecticide exposure, Scenario 3 produces significantly more adults than Scenario 4, as discussed previously.

Our simulations of adult production assume exposure to a single insecticide, but in reality, formulated products to manage soybean aphids can contain two active insecticide ingredients. For example, Beseige contains chlorantraniliprole and lambda-cyhalothrin; Swagger
contains imidacloprid and bifenthrin; and Endigo contains thiamethoxam and lambda-cyhalothrin. Because the active ingredients in these formulated products have different modes of action, the mortality of the formulations can be estimated assuming response addition (National Research Council, 2013). Assuming that beta-cyfluthrin's cuticular and dietary toxicity and exposure concentrations are comparable with lambda-cyhalothrin’s, another Type II pyrethroid, the mortality rates for aerial applications of Endigo and Beseige would be approximately 2%–22% greater than those predicted for CTR alone (the most toxic insecticide) for Scenario 3 in central Iowa over 10 years (Table S11). The simultaneous use of fungicides and insecticides to manage fungi and soybean aphids is not uncommon (Hodgson et al., 2012; Johnson et al., 2009); either a concentration (Belden & Brain, 2018) or a response addition model could be used to estimate larval mortality for these tank mixtures. This approach would not capture any synergistic or antagonistic effects of pesticide mixtures; however, nonadditive responses are relatively rare (Belden & Brain, 2018; Cedergreen, 2014; National Research Council, 2013). Olaya-Arenas et al. (2020) also did not detect any synergistic effects when monarch larvae were chronically exposed to milkweed leaves treated with a cocktail of insecticides, fungicides, and herbicides at mean and maximum concentrations reported in Indiana agricultural settings. To further explore insecticide-use patterns on landscape-scale adult production, we could also incorporate the acute toxicity of foliar applications to eggs, pupae, and second-generation adults as well as chronic insecticide effects on larvae that survive exposure to spray-drift residues (Krishnan et al., 2021). However, as noted previously, even when assuming 100% mortality of monarchs downwind of a treated field, landscape-scale adult productivity is greater when habitat is established within and outside the 38.1-m buffer zone (Scenario 3) than when new habitat is planted only outside the no-plant zone (Scenario 4).

Over the next 10 years, it is likely new insecticides will enter the market and replace at least some of the active ingredients modeled in this study. In addition, it is reasonable to assume that future insecticide formulations and spray-nozzle technology could further mitigate spray drift. If maize and/or soybean insect pressure increases, there could be an associated increase in insecticide use and spray drift, which would result in higher monarch mortality rates. There could also be future shifts in maize and soybean production; however, the ratio of soybean to maize hectares has remained relatively stable (Iowa State University Extension, 2017). To the extent future insecticides are less potent to monarchs and/or are applied with reduced spray drift, predicted monarch production would likely be similar to what we estimated in the TMX and no-spray-drift scenarios. If future insecticides are more toxic to monarchs, predicted adult production would be less than what we predicted for CTR. As noted previously, even if future products caused 100% mortality of monarchs downwind of a treated field, predicted landscape-scale adult productivity would be greater with habitat established throughout the landscape than with a scenario in which new habitat is only planted outside a no-plant zone.

**Landscape-scale population dynamics**

In their review of pesticide effects on flower-visiting insects, Uhl and Brühl (2019) noted the need to assess insect movement at the landscape scale to improve pesticide ecological risk assessments. Topping et al. (2020) also called for landscape-scale assessments to better assess the potential for pesticide applications to create population sinks that could drive declines in nontarget populations. Topping et al. (2003) described an agent-based model (ALMaSS) to simulate movement of a variety of vertebrate and invertebrate species, including a ground beetle (Bembidion lampros), a spider (Erigone atra), and the field vole (Microtus agrestis) within agricultural landscapes with varying crop production practices and pesticide applications. When modeling responses of Bembidion lampros and Erigone atra, which can move approximately 0.01 km/day and have much smaller home ranges than monarch butterflies, Topping et al. (2014, 2015) concluded that treated crop fields, and potentially noncrop vegetation bordering treated fields, can become ecological traps within a 100 km² area. Although monarch populations have different source-sink dynamics because of the vagile behavior of adult females, our results and those of Topping et al. (2003, 2014, 2015) underscore the need to integrate species-specific ecotoxicology, movement ecology, and landscape ecology to improve the means to assess ecological risks of pesticides to nontarget species over relevant spatial and temporal scales.

With regard to the question of whether a no-plant zone would produce more or fewer adult monarchs across a landscape, our results indicate that, when insecticide drift occurs, the drift zone area is smaller than the 38-m no-plant zone area. The gains in egg density outweigh subsequent larval losses simply on a by-area basis. We might ask a narrower question: Are there any areas on the landscape that are consistently exposed to insecticides from year to year and function as sinks? If we could predict where pesticide drift would occur, we might avoid planting milkweed in drift zones to maximize production. Wind direction on days of insecticide application is, however, variable over years even if it comes from a predominant direction (Figures S6 and S7). Thus, habitat on different sides of the treated fields could be exposed (or not exposed) to insecticides from year to year.

The results of our landscape analysis are based on an agent-based model (Grant & Bradbury, 2019; Grant et al., 2018) that reflects the highly vagile behavior of nonmigratory female monarch butterflies and their ability to move 5–10 km/day over 10 days (Grant et al., 2018; Zalucki & Lammers, 2010; Zalucki
et al., 2016). If monarchs are extirpated from a location owing to spray drift, the highly vagile behavior of adult females suggests that new eggs would be laid in these locations within days. For monarch butterflies, the nearly complete lack of metapopulation dynamics means that any losses are simply losses from the population at large, without any consequence to spatial population dynamics. The scale over which adult females move is substantially greater than the scale of the spray-drift zone. Consequently, the concept of metapopulation extirpation is not relevant. These findings cannot be assumed for other species with different movement behavior and metapopulation dynamics. Insecticide drift, and the potential for metapopulation extirpation, is a greater concern for less vagile species in a north central landscape (e.g., the rusty patched bumblebee [Bombus affinis]). When metapopulations are eliminated, it may take a long time for a location to be recolonized. In areas with multiple colocated species of conservation concern, natural resource, and agricultural managers will need to consider species-specific movement ecology and insecticide sensitivity in landscape planning.

Population trends for the monarch butterfly population east of the Rocky Mountains are estimated by quantifying the forest canopy occupied at the overwintering grounds in Mexico. As with most insects, monarch populations fluctuate from year to year, primarily through environmental factors such as weather (Grant & Bradbury, 2019). Quantifying effects of insecticide exposure on the annual population growth rate should be a goal of future modeling efforts. Our results and modeling approach could be included within published models designed to predict continental responses of the eastern monarch population based, in part, on changes in vital demographic rates for migratory and nonmigratory generations in different regions of North America under different conservation scenarios, insect pest management practices, and climatic patterns (e.g., see Flockhart, et al., 2015; Oberhauser et al., 2017; Voorhies et al., 2019).

CONCLUSIONS

Estimated field-scale mortality rates from insecticide spray drift raise concerns about adverse effects on monarch populations; however, the monarch is a vagile species not confined to metapopulations. Consequently, a spatially explicit, landscape-scale assessment over several years is required to reasonably assess potential impacts of insecticide use on the nonmigratory generations of monarchs in the summer-breeding range of the north central United States.

In response to our opening question: Would nonmigratory monarch population growth rate be higher if:

- milkweed was established in all available space in agricultural landscapes, but with a high likelihood of insecticide exposure to monarch larvae close to crop fields; OR
- milkweed was established outside a 38-m no-plant zone around crop fields, but with a lower likelihood of insecticide exposure to monarch larvae?

We conclude that the growth rate will likely be higher if milkweed is established in all available space in agriculture landscapes. By using a landscape-scale analysis, we determined that insecticide spray drift can attenuate, but not preclude, landscape-level population growth with increased breeding habitat, although monarchs utilizing habitat within 38 m downwind of a treated field may be nearly eliminated in a generation in years an insecticide is applied. Minimizing impacts on landscape-scale population growth can be achieved by employing IPM. Milkweed augmentation in all areas of the agricultural landscape can contribute to reversing monarch butterfly population declines.

DATA AVAILABILITY STATEMENT

Data and metadata pertaining to this manuscript are publicly available through GitHub at https://github.com/tgrant7.

SUPPORTING INFORMATION

Supporting Information A: Methods.
Supporting Information B: Tables and Figures.

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