Received: 9 August 2021 | Revised: 25 February 2023 | Accepted: 23 July 2023

DOI: 10.1002/jwmg.22484

RESEARCH ARTICLE

THE JOURNAL OF WILDLIFE MANAGEMENT

THE WILDLIFE SOCIETY

Marshbird response to herbicide control of cattail in northwestern Minnesota

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U.S. Fish and Wildlife Service

Abstract

Wetlands provide essential habitat for a wide variety of wildlife species. In the once wetland-rich Prairie Pothole Region and adjacent areas of central North America, many wetlands have been converted to agricultural production. Many remaining wetlands experience ecological change via the invasion and spread of non-native plant species, such as non-native narrowleaf (*Typha angustifolia*) and hybrid cattail (*Typha* x *glauca*), which spread aggressively and displace native vegetation, especially in large, impounded wetlands. Management of wetlands in these landscapes often includes broad-scale herbicide application intended to break up mats of cattail and restore areas to more wildlife-friendly conditions. Although restoration of wildlife habitat is a common goal of such management, marshbird response to invasive cattail control is poorly understood. To evaluate the effects of cattail management on wetland wildlife, we conducted standardized call-broadcast surveys for 5 species of marshbirds at 9 study sites that included survey locations associated with areas treated with herbicide and paired areas not treated with herbicide in wetland impoundments in northwestern Minnesota, USA, using a before-after, control-impact study design. We surveyed American bitterns (*Botaurus lentiginosus*), least bitterns (*Ixobrychus exilis*), pied-billed grebes (*Podilymbus podiceps*), soras (*Porzana carolina*), and Virginia rails (*Rallus *limicola*) during the breeding season prior to herbicide application (late summer and early autumn of 2015) and during the 3 breeding seasons after herbicide application (2016–2018). We modeled species counts using a generalized linear mixed model with year-by-treatment interactions as fixed effects and site as a random effect. Before herbicide application, expected mean counts did not differ between treatment and control survey locations. Three years post-treatment, we detected significant increases in expected mean counts at treatment compared to control survey locations for soras ($t_{193} = -3.373$, $P = 0.020$) and Virginia rails ($t_{193} = -3.167$, $P = 0.037$), and point estimates for all species except least bittern were higher at treatment survey locations. Overall, our results suggest that these marshbird species responded positively to herbicide control of invasive cattail and that breeding marshbirds in these and similar wetland systems may experience positive population response over a period of at least 3 years following treatment.

KEYWORDS

American bittern, *Botaurus lentiginosus*, cattail, herbicide, invasive plants, marshbirds, pied-billed grebe, *Podilymbus podiceps*, *Porzana carolina*, Prairie Pothole Region, *Rallus limicola*, sora, Virginia rail, wetlands

The Prairie Pothole Region (PPR) and adjacent areas of central North America were once a vast complex of prairie grasslands and glaciated wetlands and lakes (Dahl 2014). Beginning in the late nineteenth and early twentieth centuries, conversion of wetlands for agricultural uses and other purposes eliminated extensive areas of wetlands in the PPR. Drainage and other changes to hydrology disrupted and altered patterns of water flow and nutrient cycling, bolstering conditions favorable to invasion by non-native plants (Kantrud and Newton 1996, Zedler and Kercher 2004, Blann et al. 2009, Tuchman et al. 2009, Kloiber and Norris 2013). In PPR wetlands, the dominance of invasive plants has resulted in reduced diversity of the wetland food web, reducing habitat quality for wildlife species that depend on wetlands (Weller 1981, Johnson and Dinsmore 1986, Mulhouse and Galatowitsch 2003). Despite elimination and alteration of extensive areas, wetlands in the PPR remain important to many wildlife species, although it is not well understood how some wildlife respond to altered characteristics of wetlands dominated by invasive vegetation or to efforts to restore native vegetation communities (National Research Council 1992, Ratti et al. 2001, Pulfer et al. 2014).

Land managers often aim to restore wetlands to conditions that existed prior to becoming dominated by invasive vegetation (Vacek and Friske 2012, Minnesota Prairie Plan Working Group 2018), under the assumption that such conditions will support a diversity of wetland-dependent wildlife (Delphey and Dinsmore 1993, VanRees-Siewert and Dinsmore 1996, Glisson et al. 2015). In particular, management of restored and altered wetlands in the PPR and adjacent landscapes often focuses on manipulating cattail (*Typha* spp.; Zedler 2000) via herbicide application or mechanical removal. Vegetation communities in many PPR wetlands have shifted from marshes with heterogeneous native species including broadleaf cattail (*Typha latifolia*) into dense, monotypic stands of more robust and aggressive non-native narrowleaf (*Typha angustifolia*) and hybrid (*Typha* x *glauca*) cattail (hereafter, cattail; Galatowitsch et al. 1999, Bourdaghs et al. 2015). As a result, many remaining wetlands have diminished plant diversity and structural heterogeneity, and altered hydrology from sedimentation and other mechanisms (Tuchman et al. 2009, Spyreas et al. 2010). The most widespread approach to manage extensive areas dominated by cattail is direct application of herbicide (Bansal et al. 2019). On large, impounded wetlands, herbicide application breaks up floating beds of cattail (Linz and Homan 2011), thereby creating a more heterogeneous mixture of open water and emergent vegetation with greater edge density among vegetation cover types, which favors regeneration of native emergent plant species (Linz et al. 1994, Galatowitsch 2006, Linz and Homan 2011). These conditions are believed to be more favorable for breeding marshbirds (Bolenbaugh et al. 2011); however, few studies (Linz et al. 1994, Linz and Blixt 1997, Linz and Homan 2011, Anderson et al. 2019) have investigated effects on wildlife from widespread herbicide application to control invasive wetland vegetation, and the response of breeding marshbird populations to changes that result from reducing large patches of cattail is unknown. In general, there is almost no published information on breeding marshbird response to herbicide application to control invasive cattail in PPR wetlands dominated by invasive cattail.

In general, breeding marshbirds prefer habitat with patches of emergent vegetation interspersed with open water or mudflats (Lor and Malecki 2006), high edge-to-interior ratio (Chabot et al. 2014), and plant communities with a range of canopy height and density (Johnson and Dinsmore 1986) that are generally free of woody vegetation (Bolenbaugh et al. 2011, Harms and Dinsmore 2013). In the PPR, however, marshbird-habitat relations in the context of wetland vegetation are poorly documented (but see Fairbairn and Dinsmore 2001, Orr et al. 2020). Most marshbird species rely on seasonally dynamic water levels, and some species, particularly rails (family Rallidae), are abundant in wetlands that include diverse vegetation structure and patchy interspersion of cover types (Johnson and Dinsmore 1986, Tacha and Braun 1994, Fairbairn and Dinsmore 2001, Zimmerman et al. 2002, Orr et al. 2020). If treating areas dominated by cattail with herbicide restores these conditions, then breeding marshbird use and abundance may increase in wetlands following herbicide application (as reported for black terns [*Chlidonias niger*]; Linz et al. 1994, Linz and Blixt 1997).

To assess how herbicide application to control invasive cattail influences marshbird populations, we assessed an index of marshbird abundance (standardized counts) at large, impounded wetlands in northwestern Minnesota, USA, prior to and for 3 years following operational herbicide application to control invasive cattail. Our specific objectives were to 1) estimate responses of individual marshbird species based on change in counts (an index of abundance) from before to after herbicide application and compared between wetland areas that received herbicide application and nearby similar wetland areas that did not (before-after, control-impact study design; Green 1979) and 2) assess the timing and magnitude of any observed responses. If marshbirds responded to changes in wetland conditions resulting from herbicide application, we expected to see changes in marshbird counts, although we anticipated the direction, magnitude, and timing of those changes may vary among species.

STUDY AREA

We conducted surveys for breeding marshbirds at large (>30 ha), impounded wetlands near the eastern edge of the PPR in northwestern Minnesota (Figure 1). This landscape has low relief and high water-holding capacity, resulting in large pooled basins with slow overland water flow and peat bog conditions (Ecoregion Level 3: 5.2.2 glaciated plains of ancient Lake Agassiz and 9.2.2 northern peatlands; Wiken et al. 2011). Climate in northwestern Minnesota is classified as warm-summer humid continental with mean annual precipitation from 51–56 cm, with a small proportion of the total coming as snow (Minnesota Department of Natural Resources [MNDNR] 2015). Extreme minimum temperatures are −40°C to −43°C and extreme maximum temperatures are near 35°C (MNDNR 2015).

Efforts in the late 1800s and early 1900s to farm this area included ditching, peat removal, and other attempts to drain water more quickly from the landscape (Bourdaghs et al. 2015). Subsequent protection and restoration of wetland areas has resulted in large, sloped basins impounded by earthen embankments with

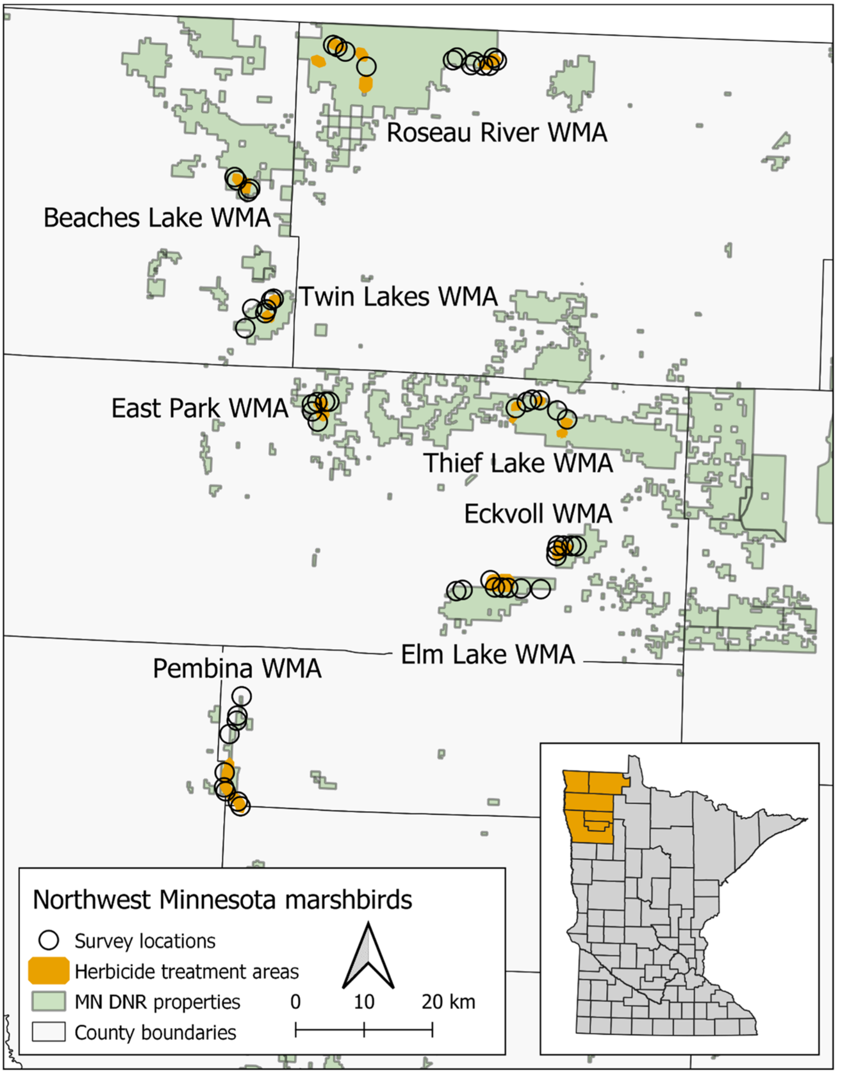

FIGURE 1 Minnesota Department of Natural Resources (MN DNR) Wildlife Management Areas (WMAs) in northwestern Minnesota, USA, with large, impounded wetlands invaded by dense cattail stands where we evaluated the effects of herbicide to control cattail on breeding marshbird counts in 2015–2018.

integrated water-control structures (i.e., gated) and managed water levels. Generally, these wetlands and surrounding areas are managed to control water movement through the landscape and provide habitat for wildlife. These changes, however, alter hydrology of deep wetland basins and provide conditions that favor invasion by cattail (Zedler and Kercher 2004), which quickly becomes the dominant vegetation, resulting in large portions of surface area covered with floating mats (i.e., not rooted in the substrate) of cattail (Wiltermuth and Anteau 2016), with little open water. Land managers employ a variety of techniques to control cattail, including dredging, disking, mowing, burning, grazing, water-level manipulation, and herbicide application (Beule 1979, Sojda and Solberg 1993, Elgersma et al. 2017, Bansal et al. 2019). Long-term control strategies often involve broad-scale application of herbicide at approximately 10-year intervals combined with mechanical control in shallow areas during the period between herbicide treatments (Galatowitsch et al. 1999, Zedler 2000).

TABLE 1 Summary of marshbird surveys on large cattail-dominated wetlands on Minnesota Department of Natural Resources Wildlife Management Areas (WMAs) in northwestern Minnesota, USA, that were targeted for a large-scale glyphosate herbicide application to control cattail during late summer and autumn 2015. We evaluated whether herbicide application affected marshbird abundance by conducting surveys during spring breeding seasons at paired treatment and control sites and evaluated change in number of detections from before to 3 years after herbicide application (2015–2018).

Study site name	Area of WMA (ha)	Treatment area (ha)	Number of survey locations		Years surveyed
			Herbicide	No herbicide	
Beaches Lake	12,393	62.3	2	2	2
East Park	4,220	122.0	2	4	4
Eckvoll	2,626	121.9	4	2	3
Elm Lake	6,370	370.1	4	4	4
Pembina	2,638	186.8	4	4	4
Roseau River east	30,418	58.2	4	4	4
Roseau River west		213.0	2	2	4
Thief Lake	22,241	30.4	3	3	4
Twin Lakes	3,591	45.1	3	3	3
Total			28	28	

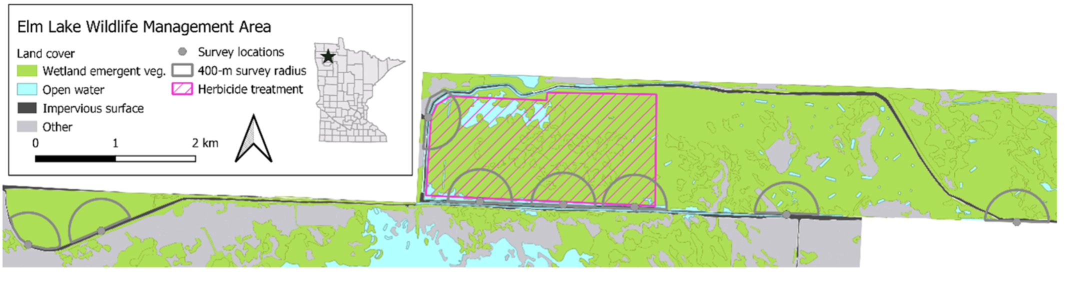

FIGURE 2 Elm Lake Wildlife Management Area in northwestern Minnesota, USA, indicating areas that received aerial glyphosate application to control cattail in late summer and early autumn 2015, and marshbird survey locations conducted in 2015–2018.

We examined wetlands on wildlife management areas (WMAs) in northwestern Minnesota that were managed to control invasive cattail by the MNDNR. Wildlife management areas in this portion of Minnesota often include impounded wetlands, which are primarily managed by manipulating water levels to promote desirable vegetation (often wild rice [*Zizania palustris*]) and wetland conditions that support breeding and migrating waterfowl and other birds. In 2015, the MNDNR implemented a program of herbicide application to control cattail in impounded wetlands in WMAs intended to return wetland conditions to those resembling a hemi-marsh (i.e., a roughly even mix of open water and emergent vegetation). Managers delineated areas with the highest density of cattail at 8 WMAs (Beaches Lake, East Park, Eckvoll, Elm Lake, Pembina, Roseau River, Thief Lake, and Twin Lakes WMAs; Table 1; Figures 1 and 2; elevation = ~285–355 m) as priorities for herbicide application. Third-party vendors applied Rodeo® Herbicide (with glyphosate as active ingredient; Dow Agrosciences, Indianapolis, IN, USA) with surfactant at a target rate of 3.77 L/ha (maximum rate of 7.02 liters/ha) with a minimum volume of 47 L/ha.

They applied the herbicide in late summer and early autumn (5 August–6 September 2015) to 1,179 ha of cattail mats via aerial sprayers (on fixed-wing aircraft), and to another roughly 30 ha via ground application (using backpack sprayers and from amphibious vehicles).

METHODS

We used a before-after, control-impact study design (Green 1979, O'Donnell et al. 2015) to compare counts of marshbirds at WMAs within the herbicide program area during 4 spring breeding seasons, including the spring before herbicide treatment and 3 subsequent springs after treatment. We conducted surveys for marshbirds at portions of wetlands that received herbicide application (treatment) and at paired wetland areas that did not (control), and considered these pairs to be study sites. At each study site, we selected survey locations (locations where we conducted marshbird surveys, see below) on the edges of treatment and control wetland areas that were similar in terms of initial vegetation composition, density, and interspersion (i.e., all survey locations were adjacent to monotypic invasive cattail). Where possible, we chose control survey locations within the same impounded wetland basin as the treatment survey locations. At some wetland basins, most similarly dense cattail-dominated wetlands within the basin may also have been targeted for herbicide application, and in some cases, suitable control survey locations were unavailable; in those cases, we chose alternative control survey locations in wetland basins adjacent to those with treatment survey locations. We conducted marshbird surveys at 9 study sites that included paired treatment and control survey locations (1 study site per WMA, except at Roseau River, which was large enough to encompass 2 study sites; Figure 1; Table 1). At 4 study sites, treatment and control survey locations were within the same basin (Figure 2) and at 5 study sites, nearest treatment and control survey locations were separated by 1.1–5.7 km in different wetland basins.

We established multiple treatment and control survey locations (Table 1) within study sites and conducted call-broadcast surveys based on the Standardized North American Marsh Bird Monitoring Protocol (Conway 2011). We positioned survey locations >400 m apart to minimize repeated detections of the same marshbirds from multiple survey locations. To facilitate effective sampling and minimize potential influence of surveys on marshbird behavior, we placed survey locations where observers could stand to detect marshbirds aurally and visually, and with a broad view of the wetland basin, near the wetland edge, often along an embankment or management access road. We therefore sampled the edges of large, impounded wetlands at all survey locations. We established 28 treatment and 28 control survey locations across our 9 study sites (example in Figure 2; Table 1). Wetland vegetation characteristics were similar among survey locations, with each adjacent wetland being dominated by invasive monotypic cattail (Figure S1, available in Supporting Information).

We conducted surveys for marshbirds during the spring breeding season (late May to mid-June; Table 2) before herbicide application (which occurred in late summer and early autumn 2015 and was coordinated by the MNDNR) and during the 3 springs following herbicide application. We conducted initial surveys in spring 2015 at all 9 WMA study sites (Table 1). We repeated surveys in 2016 at all 9 study sites and surveyed a subset of study sites in 2017 (n = 8) and 2018 (n = 6). We conducted surveys during crepuscular periods around sunrise (~0.5 hour before and up to 3 hours past sunrise) or around sunset (~3 hours before until ~0.5 hour after sunset) to incorporate diurnal variation in marshbird availability. The same observer conducted surveys within paired sites at a WMA, and we conducted surveys at locations in the same order within individual sites. In 2015 and 2016, 2 observers (NMH and a field technician; a different field technician in each of those years) conducted surveys, and in 2017 and 2018, NMH conducted all surveys.

Upon arriving at a survey location, the observer recorded environmental conditions (e.g., ambient temperature, wind speed and direction, and cloud cover; to confirm that conditions were within protocol parameters [Conway 2011]) and initial observations of all bird species; this first 3- to 4-minute period after arrival also served as a settling period intended to minimize the influence of the observer on marshbird behavior. The observer then

TABLE 2 Marshbird detections and summary statistics on large cattail-dominated wetlands in northwestern Minnesota, USA, that were targeted for a large-scale glyphosate herbicide application to control cattail during late summer and early autumn 2015. Detections were either auditory or visual, with visual detections noted in parentheses. Values with an asterisk are significant at a 95% confidence level.

Species	Treatment	2015 8 June to 13 June	2016 26 May to 7 June	2017 30 May to 3 June	2018 28 May to 4 June	Total
American bittern	No herbicide	29	55	22	4 (4)	114
	Herbicide	13	31	28	6 (7)	85
		$t_{193} = 2.241$ $P = 0.332$	$t_{193} = 2.447$ $P = 0.225$	$t_{193} = -0.926$ $P = 0.983$	$t_{193} = -1.183$ $P = 0.936$	
Least bittern	No herbicide	4	4	3	2	13
	Herbicide	11	2	6	0 (1)	20
		$t_{193} = -1.855$ $P = 0.583$	$t_{193} = 0.735$ $P = 0.996$	$t_{193} = -1.065$ $P = 0.963$	$t_{193} = 0.519$ $P = 1.000$	
Pied-billed grebe	No herbicide	11	18	11	2 (1)	43
	Herbicide	6	7	7	10	30
		$t_{193} = 1.013$ $P = 0.972$	$t_{193} = 1.952$ $P = 0.517$	$t_{193} = 0.778$ $P = 0.994$	$t_{193} = -1.936$ $P = 0.528$	
Sora	No herbicide	24	16	15	1 (1)	57
	Herbicide	20 (1)	9	31	16 (7)	84
		$t_{193} = 0.318$ $P = 1.000$	$t_{193} = 1.326$ $P = 0.888$	$t_{193} = -2.385$ $P = 0.255$	$t_{193} = -3.373$ $P = 0.020$*	
Virginia rail	No herbicide	7	8	9	1	25
	Herbicide	12	4	13	17 (7)	53
		$t_{193} = -1.230$ $P = 0.922$	$t_{193} = 1.106$ $P = 0.955$	$t_{193} = -0.884$ $P = 0.987$	$t_{193} = -3.167$ $P = 0.037$*	
Total	No herbicide	75	101	60	16	252
	Herbicide	63	53	85	71	272
		$t_{1,000} = 0.649$ $P = 0.998$	$t_{1,000} = 3.547$ $P = 0.010$*	$t_{1,000} = -2.326$ $P = 0.280$	$t_{1,000} = -5.574$ $P < 0.001$*	

conducted an 11-minute survey. The first 5 minutes involved passive observation without broadcasting marshbird vocalizations. The later 6 minutes were divided into 1-minute intervals (30 seconds of broadcast calls and 30 seconds with no broadcast calls) during which we broadcast calls of 6 marshbird species in order (Conway 2011): least bittern (*Ixobrychus exilis*), yellow rail (*Coturnicops noveboracensis*), sora (*Porzana carolina*), Virginia rail (*Rallus limicola*), American bittern (*Botaurus lentiginosus*), and pied-billed grebe (*Podilymbus podiceps*). We obtained the recommended species, order of broadcast, and standardized recorded calls from the North American Marsh Bird Monitoring Program organizer (http://ag.arizona.edu/research/azfwru/NationalMarshBird/). We broadcast recorded calls from a SanDisk Clip Sport mp3 player (SDMX24; SanDisk Corporation, Milpitas, CA, USA) at 80–90 dB from 1 m away using a portable game speaker (Cass Creek Big Horn Remote Speaker, Cass Creek, Grawn, MI, USA). The observer recorded all aural and visual detections of marshbirds in the target wetlands (i.e., the wetland in front of the observer when the observer was facing the wetland), regardless of distance from the observer, and recorded the estimated location of each detected (either visually or aurally) marshbird using printed aerial photographs that included indications of distances out to 400 m, a laser rangefinder, and compass. Recording estimated locations on printed aerial photographs helped observers track multiple individuals calling during surveys to reduce double-counting and verify that the individual was within the target wetland. Final data for analysis included only birds within 400 m from survey locations to minimize error associated with estimating distance beyond 400 m and to avoid including the same marshbirds in data for >1 survey location.

To evaluate the response of marshbirds to herbicide application, we compared the expected mean marshbird counts at treatment versus control survey locations each year with a generalized linear mixed model (GLMM) with a Poisson distribution (R package glmmTMB; Brooks et al. 2017, R Core Team 2021). We analyzed each marshbird species individually with study sites included as a random effect and with a treatment-by-year interaction (O'Donnell et al. 2015), considering only marshbirds detected during the 11-minute survey period. Because we expected vegetation to respond to herbicide treatment in ways that could affect probability of detecting marshbirds visually (i.e., by decreasing vegetation density and increasing extent of open water) in the years following the year of treatment, we repeated our analyses using only aural detections and compared those results to results using both aural and visual detections to assess whether probability of visual detection changed through time. We evaluated significance with GLMM *t*-ratios and *P*-values with a Tukey-adjustment method based on contrasts on the log-scale and log-transformed expected mean counts and 95% confidence intervals for plotting using the emmeans package (Lenth 2022). We completed all analyses in Program R version 4.2.2 (R Core Team 2021).

Our study design did not involve measuring vegetation or other wetland metrics (e.g., extent of open water). Instead, *post hoc*, we assessed whether there was an evident change in vegetation within treated polygons (i.e., the areas of wetlands treated with herbicide) following herbicide application using remotely derived indices of greenness (normalized difference vegetation index [NVDI]; Kriegler et al. 1969) and water reflectance (normalized difference water index [NDWI]; McFeeters 1996) from 2010–2020 (Figure S2 available in Supporting Information). To assess potential differences in land-cover-type composition between treatment and control survey locations prior to herbicide application, we used the Minnesota Land Cover Classification and Impervious Surface Area by Landsat and Lidar (2013 update - version 2; https://gisdata.mn.gov/dataset/base-landcover-minnesota, accessed 15 Feb 2023) to describe land cover within 400 m of survey locations in 2013 (2 years prior to the first year of our study).

RESULTS

During 2015–2018, we conducted 202 surveys for marshbirds at survey locations on 8 WMAs (9 study sites) and recorded 524 observations of the 5 marshbird species we detected (Table 2). American bittern was the most detected species (199 observations), followed by sora (141), Virginia rail (78), pied-billed grebe (73), and least bittern (33), with no detections of yellow rails. We did not detect any differences in expected mean counts at treatment versus control survey locations during spring 2015 surveys (prior to herbicide application) for any species (Table 2; Figure 3).

After herbicide application, the expected mean counts varied among species and by year (Table 2; Figure 3). In 2016, the first year after herbicide application, we detected no statistically significant difference in expected mean counts between treatment and control survey locations for any marshbird species (Table 2). Similarly, there were no significant differences in expected mean counts for any marshbird species in 2017 (the second spring following herbicide application). In the third spring following herbicide application (2018), we observed higher expected mean counts at treatment versus control survey locations for soras ($t_{193} = -3.373$, $P = 0.020$) and Virginia rails ($t_{193} = -3.167$, $P = 0.037$; Table 2; Figure 3), and point estimates of expected mean counts were higher for all marshbird species at treatment survey locations except least bitterns (Figure 3). Patterns in expected mean counts from models using only aural detections were similar to those from models using both aural and visual detections.

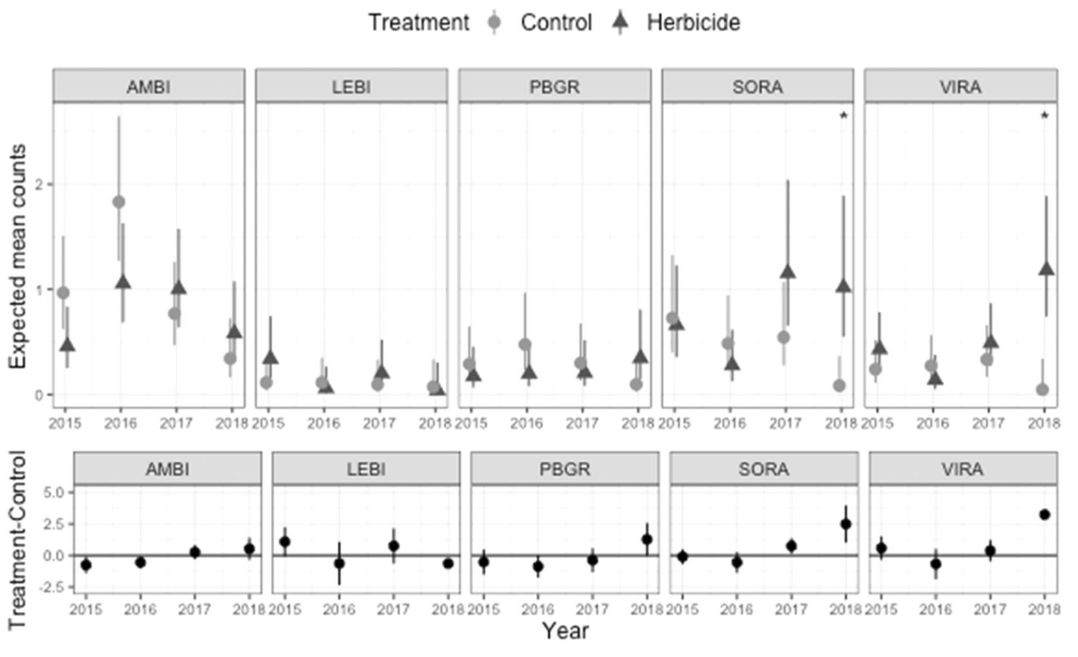

FIGURE 3 Expected mean marshbird counts (upper panel; error bars represent 90% CI) within years 2015 to 2018 in 9 study sites that included both herbicide and control (areas not treated with herbicide) survey locations in northwestern Minnesota, USA, and the difference between expected mean marshbird counts (lower panel) for 5 species of marshbirds: American bittern (AMBI), least bittern (LEBI), pied-billed grebe (PBGR), sora (SORA), and Virginia rail (VIRA). Asterisks represent significant treatment effects at $P < 0.10$.

Although we did not measure vegetation characteristics in our study, our informal observations of vegetation response to herbicide application were consistent with those described in the literature. The first spring after herbicide application, vegetation structure and condition were similar at areas treated with herbicide and areas not treated with herbicide—large swaths of dead residual vegetation from the previous growing season. With the emergence of new growth, however, areas treated with herbicide had far less green vegetation density than did areas without herbicide application (Figure S3, available in Supporting Information). Without renewed growth, residual vegetation in areas treated with herbicide decayed over time and floating mats begin to disintegrate from wave and wind action (Sojda and Solberg 1993, Linz et al. 1994). The second season after treatment, at areas treated with herbicide, vegetation differed both from the first year following treatment and from areas not treated with herbicide; live cattail was less vigorous and decay of residual stems of previous years' growth resulted in vegetation with less structural complexity (Figure S4, available in Supporting Information). Both NVDI and NDWI indicated a strong response following herbicide application (Figure S3), with a decrease in NVDI beginning in 2016 and extending for several years and a similar decrease in NDWI, followed by an increase in NDWI beginning about 2–3 years following herbicide application. Land-cover-type composition surrounding survey locations was similar between treatment and control sites prior to the period during which we conducted our study (Figure S5, available in Supporting Information).

DISCUSSION

Three springs following herbicide application to impounded PPR wetlands dominated by invasive cattail in northwestern Minnesota, soras and Virginia rails exhibited increased expected mean counts, and point estimates of counts of 4 (all except least bittern) of the 5 (American bitterns, soras, Virginia rails, pied-billed grebes, and least bitterns) marshbird species we monitored were higher at areas treated versus not treated with herbicide. Based on expected mean counts at paired treatment and control survey locations, none of the marshbird species that we monitored exhibited a population-level response to herbicide application the spring following application. There was no apparent population-level response for any of the 5 species 2 years following herbicide application, based on comparison of expected mean counts the spring prior to herbicide application, although point estimates for soras were higher in treatment vs. control survey locations, indicating an upward trend that became apparent the following year. We posit that herbicide application increased habitat quality for most of the marshbird species we monitored 3 years following herbicide application to control invasive cattail. Furthermore, there appeared to be no downward trend in marshbird abundance associated with herbicide application for any of the 5 species we monitored (Figure 3). We note that our assessment of least bitterns, the only species that did not appear to respond positively following herbicide application, was likely constrained by small sample sizes resulting from their relatively quiet calls and consequent short detection distances (Benoît et al. 2009, 2011). And, even though they were known to have previously been present in our study area (Sidie-Slettedahl 2013), we detected no yellow rails during our surveys, probably because they are scarce in the area, prefer shallow wetlands and meadows dominated by sedges (unlike the wetlands we studied), and are most active at night (Bart et al. 1984, Martin et al. 2014, Sidie-Slettedahl et al. 2015), outside the periods we conducted surveys.

We observed no difference in expected mean counts of marshbird species we monitored in the breeding season prior to herbicide application between areas targeted for herbicide application and areas not targeted for herbicide application, which indicates our control survey locations served as an appropriate reference to evaluate the treatment. Furthermore, initial land-cover-type composition was similar between treatment and control survey locations prior to 2015 (Figure S5), the first year we conducted surveys and prior to herbicide application. In the last 3 years of our study, changes in vegetation resulting from herbicide application could affect marshbird behavior that could make them more detectable by observers or increase the ability of observers to detect marshbirds (i.e., by increasing visibility resulting from changes in vegetation), or both; however, we found no evidence of an influence of changes in visual detection probability on patterns in expected mean counts of marshbirds based on the similarity of results using only aural detections.

Our study design did not allow us to elucidate the mechanism(s) that resulted in increased counts of marshbirds. Although monitoring vegetation was not a component of our study, we posit that the timing of the marshbird response we observed likely reflected the timing and nature of the response of cattail to herbicide application. Generally, immediately after herbicide application, above-water-level portions of plants that experience direct contact with herbicide begin to die, and herbicide is translocated into roots and rhizomes of floating mats of vegetation and of vegetation rooted in the substrate. The first spring after herbicide application and during the period when marshbirds return to breeding locations in the PPR, vegetation structure and condition appear similar at treated and untreated areas—large swaths of dead residual vegetation (either from plant senescence or the effects of herbicide) from the previous growing season. Later in spring, at the emergence of new growth, areas treated with herbicide have diminished green vegetation density and over time, residual vegetation decays, and floating mats begin to disintegrate through wave and wind action (Sojda and Solberg 1993, Linz et al. 1994). During subsequent winters, the weight of snow and freezing causes cattail mats to disintegrate and sink, creating more edges and interspersion of open water, resulting in higher structural heterogeneity and higher plant species diversity (Lishawa et al. 2015). We suspect that these changes in wetland vegetation in our study increased habitat quality for breeding marshbirds, especially for rails (Conway and Eddleman 1994, Melvin and Gibbs 1994, Fairbairn and Dinsmore 2001, Orr et al. 2020).

Breeding marshbird expected mean counts in our study increased in response to control of cattail in impounded PPR wetlands, similar to increases in black tern abundance following chemical control of cattails reported by Linz et al. (1994) and Linz and Blixt (1997). Black tern abundance increased (Linz et al. 1994) the year following herbicide application to control monotypic cattail in PPR wetlands in North Dakota, in 1 of 2 experiments, and that response persisted for the 2 years they monitored wetlands following treatment. The immediate cause of this response was likely change in vegetation structure that increased habitat quality in both our study and that of Linz and Blixt (1997), such as decaying cattail mats broken apart by wind and wave action, exposing more open water and mud flat areas where marshbirds may forage. Similarly, waterbird abundance increased on Finnish wetlands managed to reduce dense, homogeneous areas of emergent vegetation, although Lehikoinen et al. (2017) did not include herbicide application to control emergent vegetation as a treatment in their study. There was no association between herbicide application on monotypic cattail and marshbird abundance in east-central Minnesota, but Anderson et al. (2019) reported that vegetation biomass (their surrogate for changes in wetland vegetation) in treatment (combinations of herbicide application, grazing, and fire) and control wetlands was not different following treatment.

A common result of management actions to reduce dense vegetation is increasing the amount of irregular patch edges and openings of exposed shallow water or mudflat, which affords foraging areas and conditions where native hydrophytic plant species produce seed and harbor macroinvertebrates that comprise marshbird food. We suspect that herbicide application in the wetlands we studied increased marshbird breeding habitat quality within 3 years of treatment through altering vegetation and other wetland characteristics, including changes in vegetation, effects on food availability, or both. For example, food abundance and availability may be affected either directly or indirectly by herbicide application, although we do not know the extent or direction of these effects in the system we studied. In addition, marshbird-habitat relations in the context of wetland vegetation and the response of breeding marshbirds to large-scale changes in vegetation and wetland characteristics are poorly documented in the PPR (but see Fairbairn and Dinsmore 2001, Orr et al. 2020)—future evaluation of the potential effects of food abundance and availability, factors that influence marshbird detection, and marshbird-habitat relations at the breeding home-range scale may provide further insight into the response of marshbirds to control of invasive vegetation in PPR and other wetlands. For impounded PPR wetlands, our results indicate a positive response of breeding marshbirds to chemical control of invasive, monotypic cattail vegetation, and that the effect of that control on marshbirds is evident 3 years following treatment and may extend further. Furthermore, although the general patterns among populations of marshbird species we monitored were similar, the strength and magnitude of responses varied among species, suggesting that other aspects of marshbird-habitat relations also likely influenced marshbird populations in the systems we studied.

MANAGEMENT IMPLICATIONS

We observed evidence of an increase in marshbird abundance 3 years following application of herbicide in late summer and early autumn to control invasive cattail that dominated impounded PPR wetlands in northwestern Minnesota. We hypothesize that marshbirds responded to the changes in vegetation and wetland characteristics that occur in cattail-dominated, impounded wetlands following herbicide application including increased structural and plant diversity and spatial heterogeneity that increased the amount of open water and edge between open water and emergent vegetation. These changes may have also affected food availability and nesting habitat quality. Our assessment suggests that breeding marshbirds respond positively following application of herbicides to control cattail in impounded PPR wetlands, but increases in abundance lag herbicide application by several years. Furthermore, we did not observe any potential negative population-level effects for the 5 marshbird species we studied. It is not clear how long the effects of herbicide application on marshbird abundance might last in the system we studied, but periodic herbicide treatments may be necessary to maintain vegetative conditions associated with increased breeding marshbird abundance.

ACKNOWLEDGMENTS

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the United States Government or the University of Minnesota. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the United States Fish and Wildlife Service. We thank D. P. Rave, C. M. Herwig, D. G. Pietruszewski, R. E. Prachar, J. D. Huener, K. R. Arola, G. A. Hoch, R. W. Franke, and D. C. Franke for assistance developing the project objectives, pilot data collection, providing access to study sites, and their insights into wetland ecology and management. We thank the staff at Thief Lake and Roseau River Wildlife Management Areas for accommodating field crews during marshbird surveys; M. E. Tuma for assistance with data preparation; H. L. Saloka for assistance with all aspects of project support; and T. M. Harms, 4 anonymous reviewers, and 2 associate editors for reviewing earlier versions of this manuscript. Funding for this project was provided by the United States Fish and Wildlife Service Prairie Pothole Joint Venture through Research Work Order 102 at the Minnesota Cooperative Fish and Wildlife Research Unit (cooperators include the U.S. Geological Survey, the University of Minnesota, the MNDNR, the Wildlife Management Institute, and the U.S. Fish and Wildlife Service).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

The University of Minnesota Institutional Animal Care and Use Committee (IACUC protocol #1503-32456A) approved the protocol for this study.

DATA AVAILABILITY STATEMENT

The data and code used in analyses are archived and publicly available at https://doi.org/10.5281/zenodo.8239361.

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Associate Editor: Courtney Conway.

SUPPORTING INFORMATION

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How to cite this article: Hill, N. M., D. H. Johnson, T. R. Cooper, A. A. Archer, and D. E. Andersen. 2023. Marshbird response to herbicide control of cattail in northwestern Minnesota. Journal of Wildlife Management e22484. https://doi.org/10.1002/jwmg.22484