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Review

# Use of glyphosate for managing invasive cattail (*Typha* spp.) to disperse blackbird (Icteridae) roosts

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ABSTRACT

Hybrid cattail (*Typha* × *glauca* Godr.) has become the dominant emergent vegetation in many wetlands of central North America's Prairie Pothole Region (PPR). Hybrid cattail, an invasive species, can outcompete native emergents and form a dense canopy that alters the original physiognomy and ecological processes of the wetland. Blackbirds (Icteridae), which number in the millions in late summer in the PPR, use cattails for reproduction, loafing and roosting. Ripening crops, especially sunflower, planted near wetland roost sites can sustain considerable economic damage from blackbirds. Producers of sunflower in North Dakota and South Dakota can obtain assistance from the U.S. Department of Agriculture's Wildlife Services unit to prevent blackbird damage. Beginning in 1991, Wildlife Services began aerially spraying cattails with glyphosate herbicide to reduce roosting substrate and lessen the severity of localized sunflower damage. As the program enters its 20th year, we review published research aimed at assessing the ecological effects and efficacy of glyphosate use in wetlands. Additionally, we incorporate unpublished data gathered to enhance the program's environmental safety and efficacy.

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## 1. Introduction

### 1.1. Sunflower and blackbirds

Sunflower is an important commodity to rural economies of North Dakota and South Dakota (Bangsund and Leistritz, 1995). In 2009, these 2 states produced 76% ($1.1 \times 10^6$ metric tons) of the U.S. crop (NASS, 2010a). Sunflower became a viable rotational crop in the region in the early 1970s; and from the start, blackbirds (Icteridae) targeted it as a major source of food (Guarino and Cummings, 1985; Hothem et al., 1988; Linz et al., 2002). Blackbirds gorge on the calorie-rich sunflower achenes throughout late summer and early fall preparing for the physical and energetic stresses of migration (Linz et al., 1983b, 1984; Homan et al., 1994). The 3 species causing damage, in order of importance, are the red-winged blackbird (*Agelaius phoeniceus* L.), common grackle (*Quiscalus quiscula* L.) and yellow-headed blackbird (*Xanthocephalus xanthocephalus* Bonaparte). In aggregate, about 75 million blackbirds stage in North Dakota and South Dakota over the duration of pre-migratory and migratory periods beginning in late August and ending in October (Peer et al., 2003).

Annually, U.S. Department of Agriculture's Wildlife Services (USDA-WS) receives hundreds of requests for assistance to protect agricultural crops from damage caused by blackbirds. A majority of requests are for protection of sunflower fields planted near cattail-dominated wetlands, where damage can be economically unsustainable, forcing some growers to remove sunflower from planting rotations (Linz and Homan, 1998; Kleingartner, 2002). In fact, Otis and Kilburn (1988) found that the main predictor of severity levels of blackbird damage is presence–absence of nearby wetlands, with fields located near wetlands receiving 2–4× more damage. A cattail-dominated wetland can harbor >70,000 blackbirds, with wetlands containing >20,000 birds being common in North Dakota (Linz et al., 2003). Blackbirds emanating from cattail roosts employ a foraging strategy that limits their activity radii. For example, >80% of sunflower fields visited by radio-tagged red-winged blackbirds occurred ≤10 km from roost sites (Besser et al., 1981). Choosing the closest available high quality food source provides the bird with an optimal energy gain per unit of energy expended and allows for more rapid storage of migratory energy reserves (Pyke, 1984). Additionally, blackbirds are molting in late summer, which hampers flight efficiency and tends to restrict flight distances (Linz et al., 1983a).

Peer et al. (2003) used bioenergetics and population models to determine that annual direct economic cost from blackbird predation was US$5.0 to $10.0 million. This estimate was

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comparable to the US$4.0 to $11.0 million loss calculated from field surveys of damage conducted statewide in North Dakota, South Dakota and Minnesota in 1979 and 1980 (Hothem et al., 1988). During these years, average field loss was 1–2%, with 2% of surveyed fields showing losses >10%. This amount of damage should not cause serious conflicts between blackbirds and sunflower producers; however, the extent and pattern of damage are inadequately portrayed for the growers that plant in areas with high wetland densities. In the 1990s, 345 randomly selected fields in 4 important sunflower producing counties located in the Prairie Pothole Region (PPR) of North Dakota and South Dakota were surveyed for bird damage; of these, 36 (10%) had damage ≥5% and 22 (6%) ≥10% damage (Linz et al., 2002). Damage >5% is considered an economically important threshold. The high incidence of damage found in this survey probably resulted from a direct relationship between blackbird abundance and distribution of cattail-dominated wetlands (Otis and Kilburn, 1988; Forcey et al. 2008).

In 1991, USDA-WS initiated a cattail management program in North Dakota and South Dakota with a goal to disrupt the critical habitat link between blackbird damage to sunflower and nearby cattail-dominated wetlands (USDA, 2006). Through 2009, USDA-WS has annually sprayed about 1500 ha of cattail, using aerial applications of the herbicide, glyphosate. The techniques used by USDA-WS were developed by scientists over 20 years of experimental research that included studies on spray pattern (strips), percent coverage, glyphosate concentrations and volumes and environmental impacts. In this paper, we review the literature used to support scientific needs of the management program. Moreover, we incorporate findings from unpublished research that enhanced environmental safety and efficacy of the program as it developed and progressed.

## 2. Cattails in the Prairie Pothole Region

Narrow-leaved cattail (*Typha angustifolia* L.), an Old World species, was well established in eastern North America by the late 1800s (Hotchkiss and Dozier, 1949; Stuckey and Salamon, 1987; Kantrud, 1992). Narrow-leaved cattail hybridized with the indigenous common cattail (*Typha latifolia* L.) and produced a viable cross that is now considered a separate North American species, hybrid cattail (*T.* × *glauca* Godr.). Wind-borne seeds quickly established new stands. By the 1950s, both narrow-leaved and hybrid cattail were commonly found in the PPR (Stevens, 1963; Kantrud, 1992). Hybrid cattail is a generalist and can be found in shallow-water areas (<30 cm) and mudflats of wetlands, margins of ponds and lakes, roadside ditches, irrigation canals and backwater areas of rivers and streams. Once established at a site, it spreads rapidly through robust rhizomatous growth (Merendino and Smith, 1991; van der Valk and Davis, 1978).

Hybrid cattail is a successful invader and competitor with native emergents because it is tolerant of shade, moderate salinities, high concentrations of ammonium and water depths up to 72 cm (Waters and Shay, 1992). These characteristics give hybrid cattail a competitive edge that can result in exclusion of native emergent species (Weller, 1975; Davis and van der Valk, 1978; Farrer and Goldberg, 2009). By the 1970s, hybrid cattail was the most abundant large hydrophyte in wetlands of the PPR (Kantrud, 1992; Galatowitsch and van der Valk, 1994). Wetlands, formerly consisting of mosaics of open water and sparse stands of hardstem bulrush (*Schoenoplectus acutus*, syn *Scirpus*; Buhl ex Bigelow A. Löve and D. Löve), were closed by dense canopies of hybrid cattail (Kantrud, 1992).

The loss of spatial heterogeneity caused by invasive cattail has resulted in declines in diversity and abundance of numerous wetland species and has provided a refuge for migrating blackbirds (Kantrud, 1986; Solberg and Higgins, 1993; Linz et al., 2003). These concerns led Ralston et al. (2007) to estimate the areal coverage of cattail in North Dakota's PPR (97,042 $km^2$) using 120 3.2 × 3.2 km sample plots. They identified 15,986 wetlands (= 1.1 ha), with 4494 (28%) wetlands (= 2.4 ha) containing cattails. Coverage of cattail averaged 37% of wetland basin areas. Semipermanent wetlands contained over 50% of the total cattail observed in the sample. Semipermanent wetlands harbor the largest numbers of migrating blackbirds (Linz et al., 2003). In Stutsman County, North Dakota, which is a high sunflower production area, an average of 20,500 blackbirds used wetlands averaging 94 ha (Linz et al., 2003).

## 3. Glyphosate herbicide

### 3.1. Glyphosate properties

Mechanical methods for managing cattail (e.g., burning, mowing and disking) are labor-intensive, expensive and often ineffective because the stands quickly reestablish themselves through vigorous growth of rhizomes (Beule, 1979). Moreover, semipermanent wetlands typically contain sufficient standing water to prevent use of mechanical equipment. It is possible to manage cattails by flooding, but wetlands in the PPR seldom have water controls to facilitate this action. To overcome these impediments, state and federal government agencies have opted to use aerially applied glyphosate herbicide for controlling cattails (Sojda and Solberg, 1993; Solberg and Higgins, 1993; Linz et al., 2004). Aerial application is the best method for managing cattail in semipermanent wetlands because basin areas are usually too large for ground-based sprayers (Linz et al., 2003).

Glyphosate ([N-(phosphonomethyl) glycine], Chemical Abstract Number 1071-83-6), is a systemic, broad-spectrum, post-emergence herbicide registered by the U.S. Environmental Protection Agency (USEPA) in 1974 and reregistered in 1993 (USEPA Reg. No. 524-343). The Monsanto Company (St. Louis, Missouri, USA) held the patent on the glyphosate molecule until the year 2000; thereafter, a number of companies began formulating and selling glyphosate under a myriad of trade names. In this paper, we refer only to the aquatic formulations of glyphosate and provide mass in acid equivalents. We caution that glyphosate formulated for terrestrial uses may contain non-herbicidal components and surfactants [e.g., POEA (polyoxyethylene-alkylamine)] that have been found harmful to aquatic life *in vitro* (Folmar et al., 1979; Henry et al., 1994; Mann and Bidwell, 1999; Howe et al., 2004; Relyea, 2005).

Glyphosate is most effective in late summer when cattails are actively metabolizing and transporting carbohydrates to their rhizomes. Glyphosate inhibits protein synthesis by blocking the shikimic acid pathway, a metabolic pathway not present in vertebrates and invertebrates (Cole, 1985; Franz et al., 1997; Alibhai and Stallings, 2001). Plants treated with glyphosate show stunted growth, yellowing, leaf wrinkling and wilting, with tissue death occurring 4–20 days following application (Franz et al., 1997). When treating emergents, the potential exists for glyphosate to reach surface waters. On contact with surface water, glyphosate's herbicidal activity decreases rapidly by 1) adsorption to suspended soil particles and sediment, 2) microbial degradation and 3) photolysis (Bronstad and Friestad, 1985). The major pathway for the compound's destruction is microbial degradation. The half-life of glyphosate in soils and water is 3–140 and 12–70 days, respectively. Linz et al. (1999) monitored glyphosate-treated and reference wetlands for 2 years and found no significant post-treatment effects for abiotic variables, including water temperature, pH, $PO_4$, $NO_3$-N, dissolved $O_2$ and total conductivity.

### 3.2. Glyphosate efficacy on cattails

In the 1970s, Mueller and Lembi (1975) and Lembi (1978) conducted efficacy trials with glyphosate on emergent vegetation, including cattails. Mueller and Lembi (1975) showed that glyphosate applied at 3.3 kg ha$^{-1}$ killed 40% of cattails during flowering, whereas 6.6 kg ha$^{-1}$ killed 60%. In a later trial, Lembi (1978) found that 1.5 kg ha$^{-1}$ glyphosate killed 100%. Lembi (1978) did not report the relationship of efficacy to timing of application or the longevity of control. Both pilot studies provided valuable data for future experimental research that led to registration of glyphosate for use on emergent wetland vegetation.

In 1983–1984, Comes and Kelley (1989) used an all-terrain vehicle to apply 2.2, 3.4 and 4.4 kg ha$^{-1}$ of glyphosate to cattail across 3 dates (early July, mid-August, mid-September) that corresponded developmentally to full bloom, post anthesis and seed maturity, respectively. The solutions contained 0.5% v/v surfactant and 280 l ha$^{-1}$ of water. They reported unsatisfactory results for the 2.2 kg ha$^{-1}$ treatment applied across all dates. However, efficacy of 3.4 kg ha$^{-1}$ and 4.4 kg ha$^{-1}$ was comparable across the August and September application dates. Increasing the water volume to 560 or 1120 l ha$^{-1}$ did not improve efficacy (Comes and Kelley, 1989).

In August 1985 and July 1986, Solberg and Higgins (1993) used a fixed-winged aircraft to spray cattail-dominated wetlands in South Dakota with 7.0 l ha$^{-1}$ (3.4 kg ha$^{-1}$) glyphosate. [Note: we have determined and verified (Ken Higgins, Personnel communication) that the 2.8 l ha$^{-1}$ rate published in Solberg and Higgins (1993) was a metric conversion error]. The 3.4 kg ha$^{-1}$ rate was the maximum rate permitted by the label at the time of the experiment (Monsanto Company, 1988). One year later, the authors reported that nearly 100% of the cattails were dead. Repeated annual visits to the sprayed wetlands showed that treatment effects lasted at least 4 years, if water depths were stable and reseeding thereby thwarted.

In 1987, Messersmith et al. (1992) used a backpack sprayer to apply glyphosate at 2 locations near Fargo, North Dakota, USA, across 3 dates (18 June, 27 July, 3 September), with 2 spray volumes (75 l ha$^{-1}$, 224 l ha$^{-1}$) and 3 application rates (1.7, 2.6, 3.4 kg ha$^{-1}$). The authors found that cattail control was substantially reduced with the 1.7 kg ha$^{-1}$ application rate, whereas cattail control was nearly equal between the 2.6 and 3.4 kg ha$^{-1}$ rates. They found that control tended to be better for the later sprays than the mid-June spray. Spray volume had no effect on level of cattail control. Scientists for the USDA conducted several efficacy field trials between 1989 and 1998 (Homan et al., 1992; Linz et al., 1992, 1995, 1996a). All were conducted in North Dakota using fixed-wing aircraft. Except when testing efficacy related to application volumes, a spray volume of 47 l ha$^{-1}$ was used. All trials focused on maximizing cost–benefits achievable through aerial applications, including use of below-label rates, low-volume solutions and synergistic effects of seasonal timing.

In August and September 1989 and 1990, Linz et al. (1992) conducted efficacy tests using 5 rates of glyphosate, ranging from 2.2 to 3.4 kg ha$^{-1}$. Cattail stems were counted just prior to spraying and during July and August in the following 2 years. The below-label rate of 2.2 kg ha$^{-1}$ controlled cattail as effectively as the minimum-labeled rate (2.5 kg ha$^{-1}$).

In mid to late July 1990 and 1991, Linz et al. (1996a) treated wetlands with 2.5 kg ha$^{-1}$ glyphosate applied in 15-m wide parallel strips. Wetlands received 90%, 70% or 50% spray coverage, with the results compared to a set of reference wetlands. Analysis of false-color infrared, aerial images taken in August of the pre-treatment year showed that cattail coverage averaged 84% across all wetlands. After 2 years post-treatment, cattail coverage declined to 31% of the treated wetland basin areas, whereas cattails covered 65% of the reference wetlands. The areal coverages of living cattail were similar in post-treatment years across the 3 different spray coverages.

In 1992, wetlands were treated with 2.5 kg ha$^{-1}$ glyphosate and compared with reference wetlands. Analyses of aerial images showed that cattail coverage in treated wetlands was reduced from 70% to 26%, with cattail coverage remaining the same for 2 years post-treatment (Homan et al., 1992; Linz et al., 1995). In reference wetlands, cattail coverage 1 year post-treatment remained near the 80% pre-treatment coverage; however, coverage declined to 40% in the second year post-treatment because of inundation of wetlands from above-normal levels of precipitation in 1993 and 1994. Other indicators of efficacy, such as declines in roost sizes and positive differences in sunflower production near treated wetlands compared to reference wetlands, were not statistically significant, perhaps caused by basin flooding and the concomitant loss of cattail coverage in all wetlands used in the sample (Linz et al., 1995). A linear regression analysis, however, yielded a strong positive relationship between sunflower production loss and blackbird roost size. Thus, providing evidence that fragmenting dense roosting habitat could reduce production losses resulting from foraging blackbirds.

Finally in mid- and late July and late August 1998, 5 cattail-dominated wetlands (>70% coverage) in central North Dakota were treated with glyphosate at 47 l ha$^{-1}$ and 28 l ha$^{-1}$ (Homan, Unpublished data). The minimum label-recommended rate of glyphosate (2.5 kg ha$^{-1}$) was used (Monsanto Company, 1988). Application timing was also incorporated into the experiment by using early and late spraying periods. The volume treatments were applied alternately in strips 15 m wide, with each treatment lane separated by an untreated buffer strip of living cattail 6 m wide. One-half of the wetland was sprayed during mid- and late July (early) and the remaining half sprayed in late August (late). Analysis of infrared images showed similar percentages of living cattail across the 4 post-treatment years and among the 4 treatments (Fig. 1). By the fourth year post-treatment, however, all treatments started to show cattail regrowth, with the late period–low-volume treatment recovering at a faster rate than the other treatments. Even so, treated lanes only averaged 10% living cattail over all

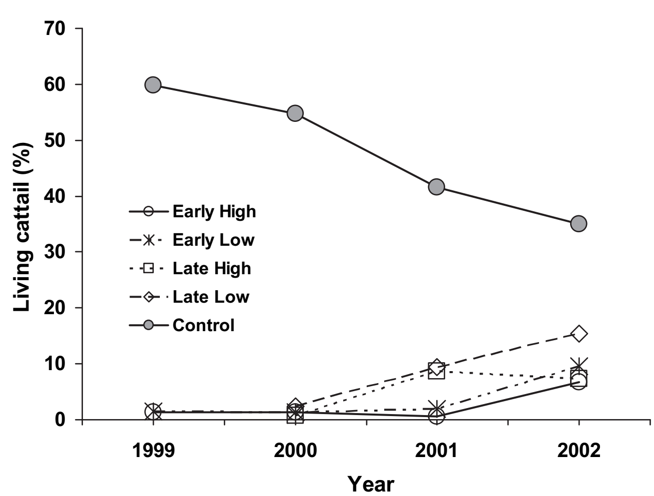


**Fig. 1.** The percentage of living cattail in five wetlands in North Dakota treated with glyphosate herbicide in 1998 and monitored for regrowth of cattail until 2002. There were 4 treatments including the combinations of early- (July) and late-date (August) sprays with high volume (47 l ha$^{-1}$) and low-volume (28 l ha$^{-1}$). The relative standard error (SE/$\bar{x}$ × 100) averaged 48% over treatment years.

treatment types compared to >70% cattail coverage in all 5 wetlands during the pre-treatment period. Cattails sprayed in July collapsed prior to the onset of blackbird migration in late August, showing that early application of glyphosate could effectively eliminate roosting substrate within season. Cattails sprayed in late August, however, retained the necessary rigidity and stem density to accommodate roosting blackbirds until the following year.

### 3.3. Glyphosate effects on aquatic organisms

In the 1980s and 1990s, scientists investigated effects of aquatic formulations of glyphosate on invertebrate populations in laboratory and field settings. Solberg and Higgins (1993) found more aquatic invertebrates in untreated cattails of glyphosate-treated wetlands than in cattails from reference wetlands and found comparatively fewer invertebrates in glyphosate-treated portions of treated basins than in adjacent areas having untreated cattails. They speculated that some of the invertebrates moved from the treated areas to adjacent untreated areas of individual wetlands. These findings led to additional studies on the effects of glyphosate on aquatic invertebrates (Buhl and Faerber, 1989; Henry et al., 1994; Linz et al., 1999).

Buhl and Faerber (1989) conducted laboratory studies on midge larvae (*Chironomus riparius* Meigen) to assess acute toxicities of Rodeo® (Monsanto Company, St. Louis, Missouri, USA) and 2 commonly used adjuvants [Activator N.F.® (Loveland Industries, Inc., Greeley, Colorado) and Ortho X-77® (Chevron Environmental Health, Richmond, California)]. The authors found that the 48-h $EC_{50}$ value (median effective concentration) for Rodeo® was 5600 mg $l^{-1}$, which is defined as "practically non-toxic" in the EPA's toxicological terminology. However, the 48-h $EC_{50}$ values of the 2 surfactants were classified as "moderately toxic" to midge larvae. Similarly, Henry et al. (1994) found that Rodeo (R) was "practically non-toxic" to several species of aquatic invertebrates in laboratory and field studies. In laboratory studies, Henry et al. (1994) found that *Daphnia magna* Straus was the most susceptible of the studied invertebrate species; the $LC_{50}$ (median lethal concentration) for *D. magna* Straus to glyphosate was 117 mg $l^{-1}$ and glyphosate tank-mixed with Ortho X-77 Spreader® and Chem-Trol® drift retardant (Chemorse, LTD., Des Moines, Iowa) was 70 mg $l^{-1}$. These values are rated as practically non-toxic" and "slightly toxic." Of the 2 components mixed with the Rodeo® formulation, Henry et al. (1994) found that Ortho X-77 Spreader® in laboratory tests was about 83–136 times more toxic than glyphosate with a $LC_{50}$ of 2.0 mg $l^{-1}$ ("moderately toxic"), whereas Chem-Trol® drift retardant was rated as "practically nontoxic."

Henry et al. (1994) and Linz et al. (1999) conducted field experiments in North Dakota on effects of glyphosate on wetland invertebrates and water quality. In 1990, Henry et al. (1994) used a predicted USDA-WS operational spray formulation (tank mixture of 2.5 kg $ha^{-1}$ glyphosate, 0.5% v/v Ortho X-77 Spreader®, Chem-Trol® and water). The authors observed no difference in survival of caged invertebrates between treated and reference wetlands after 21 days post-treatment and concluded that operational use of glyphosate would not pose a hazard to aquatic invertebrates. Indeed, the projected wetland concentration of the most toxic of the spray formulation's components (Ortho X-77 Spreader®) was 65 times less than the laboratory $LC_{50}$ of 2.0 mg $l^{-1}$ (Henry et al., 1994).

Linz et al. (1999) found that numbers of Gastropoda (4X greater), Corixidae (5X) and Chironomidae (7X) were all significantly greater in treated wetlands than reference, whereas numbers of Chaoboridae were 3× greater in reference wetlands than treated wetlands. Glyphosate treatments did not reduce or increase numbers of Copepoda, Ostracoda, Cladocera, Crustacea, Hydracarina and Oligochaeta.

The USEPA has classified glyphosate formulations as 'slightly toxic" to "moderately toxic" to amphibians and 'slightly toxic" to "practically non-toxic" to fish (Giesy et al., 2000). Cattail-dominated wetlands are generally marginal habitat for fishes because of high salinity levels and shallow-water depths, the latter making wetlands prone to summer- and winter-kill. Glyphosate does not bioaccumulate in amphibians and fishes, but applications to aquatic vegetation in water bodies having already low levels of dissolved oxygen or high temperatures could become hazardous to these groups because of increased eutrophication caused by mass decay of vegetation (Folmar et al., 1979).

### 3.4. Glyphosate treatment effects on birds using cattail-dominated wetlands

In 1985 and 1986, Solberg and Higgins (1993) found that glyphosate-treated wetlands had greater pair densities of waterfowl (Anatidae) than did reference wetlands. Densities of waterfowl nests, however, were similar between treatment and reference wetlands. In a pilot study, Linz et al. (1992) conducted pre-treatment and post-treatment counts during late summer in 4 treated wetlands in North Dakota and showed that numbers of marsh wrens (*Cistothorus palustris* Wilson) and 2 species of rails [sora (*Porzana carolina* L.) and Virginia rail (*Rallus limicola* Vieillot)] declined significantly. Numbers of adult ducks, ducklings and shorebirds (Scolopacidae) increased in the post-treatment period by multiples that ranged from 2 to 3× their pre-treatment numbers; the increases were not statistically significant due to small sample size and large variability in counts among wetlands (Linz et al., 1992).

From 1990 to 1993, Linz et al. (1996a,b, 1997) investigated impacts of glyphosate-treated wetlands on spring use by numerous wetland-dependent bird species in North Dakota. The authors found that marsh wren, red-winged blackbird and yellow-headed blackbird numbers declined significantly in at least 1 of the study years following application (Linz et al., 1996a). On the other hand, numbers of waterfowl responded positively and significantly to glyphosate treatments in post-treatment years (Linz et al., 1996b). Numbers of diving ducks (Aythyinae) increased each year during 2 years of post-treatment counts, whereas dabbling ducks (Anatinae) increased significantly only in the second year post-treatment. Two members of the Rallidae family [sora and American coot (*Fulica americana* Gmelin)] showed contrasting responses to glyphosate treatments. Numbers of American coots increased in treated wetlands during each of 2 post-treatment years, whereas sora numbers declined in the first year post-treatment but not in the second (Linz et al., 1997). However, even in the second year post-treatment, sora numbers remained much higher in reference wetlands (>2×) than treated wetlands. Linz and Blixt (1997) demonstrated that numbers of black terns (*Chlidonias niger* L.), a species that was in decline in some areas of its range, were positively correlated with wetland proportions of open water and dead cattail resulting from applications of glyphosate.

Although most of the research conducted on effects of cattail reduction from glyphosate was on bird species using wetlands in spring and summer, a winter study was conducted on ringed-necked pheasants (*Phasianus colchicus* L.), which use residual cattail cover winter cover (Homan et al., 2000, 2003). The research compared spring territorial crowing calls between treated and reference 23-$km^2$ quadrats. The data suggested that the proximity of glyphosate-treated wetlands did not affect male pheasants' choice of upland territories. No difference was detected in numbers of territorial crowing calls in the quadrats where all cattail-dominated wetlands >2 ha had been treated with glyphosate compared to similar quadrats with untreated wetlands.

## 4. Discussion

### 4.1. Ecological effects

Aquatic invertebrates makeup 70–99% by volume of waterfowl diets during the reproductive season (Swanson and Duebbert, 1989) and correlations between densities of aquatic invertebrates and waterfowl numbers have been detected (Murkin et al., 1982). Moreover, a decrease in aquatic invertebrate density can slow the rate of duckling growth and ultimately reduce survival rate (Cox et al., 1998; Hunter et al., 1984). Thus, an economically important natural resource is potentially at risk when pesticides are applied to wetlands. With this in mind, it was not surprising that scientists focused on responses of invertebrates to glyphosate treatments.

Henry et al. (1994) found the $LC_{50}$-value of glyphosate tank mix for the most sensitive of the tested invertebrate species was 117× greater than the highest *in vivo* concentration found in glyphosate-treated wetlands. Thus, direct negative effects from glyphosate toxicity were not expected nor detected. Indirect effects, especially from declines in the levels of dissolved $O_2$ (DO), presented a more serious hazard to invertebrate survival. For example, glyphosate treatments on dense cattail stands will generate nearly 4 tonne ha$^{-1}$ of decaying vegetation, which could dramatically reduce DO levels (Neely and Baker, 1989). However, Linz et al. (1999) showed that DO levels were similar between glyphosate-treated and reference wetlands. This observation agrees with Cole's (1985) assessment that wind-driven waves and spray in open areas of wetlands increase the absorptive surface at the air–water interface, moving DO down the water column and offsetting any reduction in DO from decomposition. The plentiful supply of nutrients from mass decomposition of decaying emergent vegetation likely increased algal production from more sunlight on the water surface and adequate levels of DO probably contributed to increased numbers of both grazing and predacious invertebrates and a commensurate increase in waterfowl use. Murkin and Kadlec (1986) and Solberg and Higgins (1993) obtained similar results from glyphosate-induced cattail reduction showing increased use by waterfowl and increased abundance of invertebrate species important to waterfowl (e.g., *C. riparius*). We speculate that black terns, another species dependant on wetlands for reproduction, responded positively to glyphosate treatments not only because of availability of nesting substrate provided by mats of dead cattail stems, but from an increase in food resources provided by flying invertebrates hatching from the opened wetlands (Linz and Blixt, 1997; Linz et al., 1994).

Of course, the fragmentation of dense stands of cattails will cause reductions in use of treated wetlands by some vertebrate species. Reduction of cattail coverage has a negative effect on blackbirds and wrens because they require vertical nest substrate to attach nests (Linz et al., 1996a). Abundance of rails (Rallidae) and bitterns (Ardeidae) and some species of ducks that build overwater nests within living stands of emergents will decline in treated wetlands (Krapu et al., 1979; Linz et al., 1997). Additionally, pheasants, deer and other furbearers that use standing residual cattail for winter cover can be affected; and lastly, cattail reduction affects muskrats, which eat the rhizomes of cattail and build lodges from cattail stems that, in turn, may be used as nest sites by birds. The negative impacts of glyphosate treatment on these species are ameliorated by staggering glyphosate treatments on large wetland complexes, which helps diversify the stages of cattail regeneration and provide heterogeneous nesting and foraging habitat for negatively impacted species. Moreover, USDA-WS annually sprays only about 1% of the total cattail available in North Dakota (USDA, 2006). Cattail recovery is dependent on water levels but our post-treatment observations suggested that most wetlands develop a good interspersion of cattail and open water in 4–6 years. Finally, we believe that the scale of natural processes that affect the demise and regrowth of cattail stands in the PPR landscape dwarfs that of the USDA-WS cattail management program. The inherent dynamics causing natural creation and destruction of cattail are an ongoing phenomenon in the PPR and wetland-dependent species deprived of cattail cover in one wetland will likely move to a nearby wetland that meets their ecological needs (Homan et al., 2003).

### 4.2. Impact on USDA-WS cattail management program

In 2000, the USDA-WS updated their cattail management protocol after 20 years of cumulative research on glyphosate efficacy and application methodology. The changes included lowering the spray volume from 47 l ha$^{-1}$ to 28 l ha$^{-1}$ and application rate from a minimum label-recommended rate of 2.5 kg ha$^{-1}$ to a below-label rate of 2.2 kg ha$^{-1}$. Although applications as low as 1.7 kg ha$^{-1}$ provide moderate control of cattail (Messersmith et al., 1992), the treatment longevity range of 4–6 years, sought by USDA-WS, might not be achieved (Linz et al., 1992).

The research that supported use of a lower spray volume (28 l ha$^{-1}$) was particularly important to the cattail management program, because it allowed rotary-winged aircraft (helicopters) to compete with fixed-wing aircraft in cost effectiveness. The deployment of helicopters in 2000 caused a chain of protocol alterations that led to a reduction in the minimum basin-size requirement (from 6 ha to 4 ha) and elimination of drift retardant. The precision of spray coverage achieved by helicopter led to lower risks of harm to adjacent, glyphosate-sensitive crops, which had been a cause of litigation concerns by fixed-wing applicators.

### 4.3. Economic analysis of cattail management program

In 2009, treatment cost, including glyphosate, surfactant and helicopter application, was about US$95/ha, a decrease of about 30% since 1995 (Leitch et al., 1997; Linz et al., 1995). Assuming daily sunflower consumption by one blackbird is 0.009 kg day$^{-1}$ (Peer et al., 2003), each bird will damage 0.27 kg over a 30-day damage period. With sunflower's 5-year (2004–2009) market price valued at US$0.37 kg$^{-1}$ (NASS, 2010b), a single blackbird (combining sexes and species) damages about US$0.10 of sunflower year$^{-1}$. Thus, growers must anticipate an average of 950 blackbirds ha$^{-1}$ (US $95 ha$^{-1}$/US$0.10 year$^{-1}$) of cattail to justify treatment costs. Regrowth of cattail following treatment is contingent on water levels. If water depths remain stable at >30 cm, there should be few living cattail for at least 4 years and perhaps up to 6 years (Merendino and Smith, 1991). A treatment that is effective for at least 4 years requires only 238 blackbirds day$^{-1}$ ha$^{-1}$ of cattail to justify costs, provided sunflower is planted every year on lands somewhere near the treated wetland. Cattail-dominated wetlands harboring >238 blackbirds ha$^{-1}$ are common in North Dakota and roosts containing >1000 blackbirds ha$^{-1}$ are located each year in sunflower growing areas of the PPR (Linz et al., 1992, 2003).

## 5. Conclusions and recommendations

Presumably, dispersing dense concentrations of blackbirds from their roost sites spreads bird damage over a larger area. This management tactic appears to have helped sunflower producers reduce the severity of damage sustained in fields located near cattail-dominated wetlands. Although statistical evidence to support this concept is indirect (Linz et al., 1995), the continued strong demand for the program suggests empirically that the program is achieving its objective.

Wildlife groups often disagree on the methods used by agriculture to solve wildlife conflicts. The USDA-WS cattail management program, however, appears to meet the requirements of wildlife interests and agriculture (McEnroe, 1992; Stromstad, 1992). Fragmenting dense cattail stands returns wetlands to their original configuration, which promotes avian diversity while preventing the formation of large roosting aggregations of blackbirds. We submit that the current cattail management program has been well documented and has the potential to be the basis for further cooperation between wildlife and agricultural groups.

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