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Lythrum salicaria (Purple Loosestrife) Control with Herbicides: Multiyear Applications

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Research Article

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Abstract

This study evaluated the effectiveness of 14 herbicide treatments for purple loosestrife (*Lythrum salicaria* L.) control over a period of 10 yr. The study commenced in 2000/2001 at four wetland locations in Nebraska. The evaluated herbicides included: glyphosate at 2.2 and 3.4 kg ha^{-1}; 2,4-D dimethylamine at 1.4 and 2.8 kg ae ha^{-1}; triclopyr at 1.3 and 2.1 kg ae ha^{-1}; imazapyr at 1.1 and 1.7 kg ae ha^{-1}; metsulfuron at 0.042 and 0.084 ai kg ha^{-1}; fosamine at 13.5 and 22.4 kg ai ha^{-1}; triclopyr at 1.3 kg ae ha^{-1} plus 2,4-D amine at 1.4 ae kg ha^{-1}; and metsulfuron at 0.042 kg ai ha^{-1} plus 2,4-D amine at 1.4 kg ae ha^{-1}. Some treatments provided excellent control (90%) that lasted only one season, while others suppressed *L. salicaria* growth for multiple seasons, depending on the location and the age of *L. salicaria* stand. Application of higher rates of glyphosate, imazapyr, and metsulfuron consistently provided excellent control (≥90%) of *L. salicaria* that lasted 360 d after treatment at most locations. Application of fosamine and the lower rate of 2,4-D amine provided the least *L. salicaria* control at most locations. The older the *L. salicaria* stand, the more multiple applications of herbicides were needed to completely control *L. salicaria*. Generally, there were higher percentages of grasses in the 2,4-D-, triclopyr-, and metsulfuron-treated plots compared with higher percentages of broadleaf species in the glyphosate- and imazapyr-treated plots at each location.

Introduction

Purple loosestrife (*Lythrum salicaria* L.) is an invasive plant species introduced from Eurasia to North America in the early 1880s that has become widespread in the United States (Munger 2002). *Lythrum salicaria* invades wetlands and waterways, threatening biodiversity by displacing native species (Mitich 1999; Mullin 1998). Several studies have demonstrated the impacts of *L. salicaria* on reduction in bird and wildlife habitat and plant biodiversity and alteration of wetland function and sediment chemistry (Emery and Perry 1996; Templer et al. 1998; Thompson et al. 1987; Weiher et al. 1996). It is estimated that more than 40 million ha of U.S. land area are already infested with invasive plants with an estimated economic impact of US$123 billion (Knezevic et al. 2004; Mullin 2000).

The growing awareness of *L. salicaria* threatening the biodiversity in wetlands resulted in a series of studies attempting to manage this invasive species. Several strategies to manage *L. salicaria* have been proposed, including hand pulling, disking, mowing, flooding, and biological and chemical management (Kleppel and LaBarge 2011; Mullin 1998; Wilcox 1989). Cultural and mechanical control methods have been demonstrated to be highly unsuccessful strategies to manage *L. salicaria* (Haworth-Brockman et al. 1993). Moreover, *L. salicaria* does not have natural enemies in the United States, and biological agents are long term and do not provide effective control of *L. salicaria* over large areas (Kleppel and LaBarge 2011; Malecki et al. 1993; McAvoy et al. 2016). Herbicide control of *L. salicaria* has shown the potential for managing this invasive species; however, effective control of *L. salicaria* has only been reported for a short-term period of 1 to 2 yr (Champion et al. 2011; Gabor et al. 1995; Knezevic et al. 2004).

The major reason single-herbicide applications are ineffective for controlling *L. salicaria* is its biology. *Lythrum salicaria* is a perennial species that grows up to 3.5-m tall, with up to 50 herbaceous stems ascending from a resilient rhizomatous root system with a diameter of 0.5 m (Mal et al. 2005; Mitich 1999). In addition, one *L. salicaria* plant can produce an estimated 2.7 million seeds yr^{-1} (Lindgren and Walker 2013; Thompson et al. 1987); therefore, large seedbanks are formed in areas where *L. salicaria* is well established. Herbicide control can be effective in the short term, but the species can germinate from seeds or regrow from rootstock

Management Implications

Our survey suggested that about 5,000 ha of Nebraska's wetlands were infested with purple loosestrife (*Lythrum salicaria* L.) at about the time of the initiation this study in 2001. The presence of *L. salicaria* can reduce biodiversity and alter wetland function. Using herbicides integrated with other control methods can be a very effective strategy for site-specific management of *L. salicaria*. However, use of herbicides to control this perennial weed has been criticized for having potential detrimental effects on non-target plants. Our study showed that sequential application of herbicides could provide effective control of *L. salicaria* over time. The most effective herbicides were glyphosate, imazapyr, and metsulfuron, as they provided control of *L. salicaria* in the shortest time, across all locations and stand ages. Metsulfuron appears to be the most desirable choice, as it had no detrimental effects on the grassy vegetation. Presence of grasses along waterways is promoted by land managers in Nebraska, because grasses provide habitat and food for various bird species (including migratory birds) and feed for grazing animals (deer, livestock). In addition, early detection of *L. salicaria* stands followed by immediate control is critical, as it will increase the chance of managing satellite populations of this weed and reduce the time and costs required for desirable control of *L. salicaria*.

or buds on crowns, which makes it hard to control. Regrowth from secondary buds that were initially dormant during stress is a mechanism through which some perennial species survive (Anderson et al. 2005; Chao et al. 2007; Klimes 2007).

Poor control was reported in dense stands of *L. salicaria*, as an inadequate amount of an herbicide such as triclopyr did not reach the basal portion of the plant (e.g., translocate into the vegetative propagules) (Katovich et al. 1996). Furthermore, while single-season control of *L. salicaria* was achieved with POST-applied triclopyr, inadequate control was reported in subsequent seasons due to reestablishment (Gabor et al. 1995; Knezevic et al. 2004). The authors hypothesized that poor control was likely due to low translocation of the herbicide into the plant rhizomes and that sequential herbicide applications were needed. Therefore, there is a need for a long-term study to evaluate *L. salicaria* control with herbicides.

The spread of *L. salicaria* is reducing the biodiversity of riparian areas across Nebraska and elsewhere in United States. Because *L. salicaria* poses a serious threat to the economic, social, and/or aesthetic well-being of Nebraska's landscape, it was listed in 2001 as a noxious invasive species in our state. Therefore, tactics to minimize the impact of *L. salicaria* must be implemented. The objective of this study was to evaluate the efficacy of 14 herbicides and the degree to which sequential applications are needed to control *L. salicaria* in four wetlands in Nebraska over a 6- to 10-yr period.

Materials and Methods

Site Description

Field trials were conducted at four sites across Nebraska's riparian land (42.37°N, 96.68°W), named according to the respective counties: Buffalo, Brown, Dixon, and Holt. Each site was part of a larger wetland habitat that was under standing water for 1 to 3 mo of the season, mostly March to May. In addition, the water table at all sites was within 50 cm of the soil surface for the rest of the year.

Studies were initiated in 2000 and 2001 with varying lengths of duration. To be specific, the Buffalo site, established along Plate River near Kearney, was initiated in 2001 and ended in 2006. The Brown site, established along the Niobrara River north of Johnstown, was used from 2001 to 2007. The study at the Holt site, along the local private lake north of Atkinson, was conducted from 2000 to 2007. Finally, the fourth study was conducted at the Dixon site, along the Missouri River just north of Newcastle in northeast Nebraska, from 2000 to 2008. In addition, each study site was monitored for 3 yr after completion to make sure that there was no regrowth of *L. salicaria*.

It is important to note that at initiation of this project, each site had *L. salicaria* stands that varied in age. In particular, the Buffalo and Holt sites had 3-yr-old *L. salicaria* stands, Brown had a 5-yr-old stand, and Dixon had a stand that was at least 10-yr old, based on discussion with the landowners.

Monthly rainfall from April to October varied in total amount among years. Total rainfall was less than the 30-yr average in 2000, 2002, 2003, and 2007 but greater in 2001, 2004, 2005, 2006, 2008, and 2009. For example, in 2000, rainfall was 271, 263, 309, and 373 mm compared with 30-yr averages of 414, 472, 488, and 443 mm for the Buffalo, Holt, Brown, and Dixon sites, respectively. Average daily temperatures for the 10 yr of the study were similar to the 30-yr averages. For example, in 2000, the daily average temperatures at Buffalo for June, July, and August were 20, 23, and 25 C compared with 30-yr averages of 21, 25, and 23 C, respectively. Similar temperatures were observed at other locations. Weather conditions were favorable for herbicide application and uptake; temperatures ranged from 20 to 25 C, wind speed from 5 to 8 km h^{-1}, and relative humidity from 50% to 70% (individual site-year data not shown).

In addition to the presence of *L. salicaria*, other species were found within the sites. These species were divided into broadleaf and monocot species. The broadleaf species included: American germander (*Teucrium canadense* L.), partridge pea (*Cassia fasciculata* Michx.), yellow sweetclover (*Melilotus officinalis* L.), hoary vervain (*Verbena stricta* Vent.), common waterhemp (*Amaranthus tuberculatus* var. *rudis*), and curly dock (*Rumex crispus* L.). The monocot species were: common cattail (*Typha latifolia* L.), river bulrush [*Scirpus fluviatilis* (Torr.) A. Gray], reed canarygrass (*Phalaris arundinacea* L.), green foxtail [*Setaria viridis* (L.) P. Beauv.], and smooth brome (*Bromus inermis* Leyss.). These species represented local vegetation present at the sites in the beginning of the experiments or resulting from secondary succession attributed to the selective nature of the herbicides tested. All four sites had soils containing an average of 70% sand. The soil type at the Brown and Dixon site is Uly silt loam consisting of deep, moderately drained soils formed in loess. The Buffalo site has soil types consisting of Uly-Holdrege-Coly silt loams. The Holt site is characterized by the Els fine sand with a transitional layer of grayish-brown (NRCS-USDA 2016). The average aboveground water level ranged from 30 cm of water depth during the March to May period to none over the years of the study. None of the sites had standing water at the time of herbicide application.

Experimental Design and Data Collection

The experiments were established as a randomized complete block design with 14 treatments (Table 1), including a

Table 1. List of herbicides used for control of *Lythrum salicaria* in the study.

Herbicide	Formulation	Trade name	Rate	Manufacturer
			kg ae (ai) ha^{-1}	
Glyphosate[a]	Isopropylamine salt, 480 g ae l^{-1}	Rodeo®	2.2 ae	Dow Agrosciences, Indianapolis, IN 46268
Glyphosate	Isopropylamine salt, 480 g ae l^{-1}	Rodeo®	3.4 ae	Dow Agrosciences
2,4-D dimethylamine	Dimethylamine salt, 455 g ae l^{-1}	2,4-D® amine	1.4 ae	WinField Solutions, Shoreview, MN 55126
2,4-D dimethylamine	Dimethylamine salt, 455 g ae l^{-1}	2,4-D® amine	2.8 ae	WinField Solutions
Triclopyr	Triethylamine salt, 360 g ae l^{-1}	Garlon® 3A	1.3 ae	Dow Agrosciences
Triclopyr	Triethylamine salt, 360 g ae l^{-1}	Garlon® 3A	2.1 ae	Dow Agrosciences
Imazapyr[b]	Isopropylamine salt, 240 g ae l^{-1}	Arsenal®	1.1 ae	BASF Corporation, Research Triangle Park, NC 27709
Imazapyr	Isopropylamine salt, 240 g ae l^{-1}	Arsenal®	1.7 ae	BASF Corporation
Metsulfuron-methyl	Benzoic acid,	Escort® XP	0.042 ai	Bayer Crop Science
Metsulfuron-methyl	Benzoic acid,	Escort® XP	0.084 ai	Bayer Crop Science
Fosamine[c]	Ammonium salt, 480 g ai l^{-1}	Krenite® S	13.5 ai	DuPont Crop Protection, Wilmington, DE 19880
Fosamine	Ammonium salt, 480 g ai l^{-1}	Krenite® S	22.4 ai	DuPont Crop Protection
Triclopyr + 2,4-D	—	Garlon® + 2,4-D® amine	1.3 ae + 1.4 ae	—
Metsulfuron-methyl + 2,4-D	—	Escort® + 2,4-D® amine	0.042 ai + 1.4 ae	—

[a]Added AMS, ammonium sulfate (20.5 g L^{-1}; DSM Chemicals North America, Augusta, GA 30901).
[b]Added ESO, esterified seed oil (0.25 % v/v; Sun-it II®, American Cyanamid, Wayne, NJ 07470), and UAN, urea ammonium nitrate (24 g l^{-1}; DSM Chemicals North America).
[c]Added COC, crop oil concentrate (0.5% v/v; Agridex®, Helena Chemical, Collierville, TN 38017).

nontreated control, with four replications. Each site had identical list of treatments, while randomization differed among sites for each replication. Each plot was 10-m long and 3-m wide. Herbicides were applied when at least 50% of *L. salicaria* plants were at early bloom stage, which was approximately the third week of June. Application at this time facilitates easy identification of plants (purple flowers) by landowners or herbicide applicators. Visual herbicide efficacy ratings were taken at approximately 60 and 360 d after treatment (DAT) using a scale of 0 to 100% (where 0 = no control and 100% = plant death). The number of *L. salicaria* stems per square meter were counted twice, before each herbicide application and at 360 DAT. Composition (%) of broadleaf and monocot species in each experimental plot was also visually documented over time. It is important to note that not all treatments were applied every year at each site. For example, during initial stages of the experiments, all herbicide treatments were applied every year at each site. However, the decision whether to respray a particular treatment was determined at the 360 DAT rating, and all treatments with ratings lower than 100% were resprayed. This resulted in the possibility that some treatments were sprayed almost every year (i.e., multiple years) at some sites while other treatments were applied only in a few years (only when control was <100%). This was especially evident at Dixon site, where some treatments were applied yearly up to 9 yr. Herbicide applications were made using a CO_2-pressurized backpack boom sprayer calibrated to deliver 200 L ha^{-1} at 276 kPa through four 110015-VP flat spray-nozzle tips (Turbo TeeJet®, Spraying Systems, P.O. Box 7900, Wheaton, IL 60187).

Data Analysis

An initial test of normality of data using the PROC UNIVARIATE procedure in SAS v. 9.4 software (SAS Institute, Cary, NC) suggested that the collected data did not follow a normal distribution. Hence, data were arcsine transformed to reduce the heterogeneity of treatment variances. Tests of significance of treatments on *L. salicaria* and broadleaf and grass species were conducted with ANOVA using the PROC MIXED procedure in SAS, with replicates considered random variables. The untreated plot data were excluded from the analyses of visual rating of *L. salicaria* control. Fisher's protected LSD test at $P \leq 0.05$ was used to separate the treatment means of transformed data; however, back-transformed data are presented in tables.

Results and Discussion

Lythrum salicaria Control

Lythrum salicaria was significantly ($P \leq 0.02$) suppressed by herbicide treatments across all locations. Some treatments provided excellent (90%) control that lasted only one season, while others suppressed growth for multiple seasons, depending on the location (Tables 2–9).

At the Buffalo County site, excellent (≥90%) season-long control of the 3-yr-old *L. salicaria* was achieved with higher rates of glyphosate, 2,4-D dimethylamine, triclopyr, or metsulfuron or both rates of imazapyr, with the initial application (Table 2). For example, ≥95% *L. salicaria* control was achieved with

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Table 2. Control of a 3-yr-old *Lythrum salicaria* over time with selected herbicide treatments at Buffalo County, NE, in 2001 to 2003.[a]

Treatment	Rate kg ae (ai) ha^{-1}	Year 1		Year 2		Year 3	
		60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT
		——% control——					
Glyphosate	2.2	70	92	95	97	100	100
Glyphosate	3.4	96	100	100	100	100	100
2,4-D dimethylamine	1.4	80	97	100	100	100	100
2,4-D dimethylamine	2.8	90	100	100	100	100	100
Triclopyr	1.3	75	92	92	97	100	100
Triclopyr	2.1	95	97	100	98	100	100
Imazapyr	1.1	95	100	100	100	100	100
Imazapyr	1.7	98	100	100	100	100	100
Metsulfuron	0.042	80	97	100	95	100	100
Metsulfuron	0.084	92	100	100	100	100	100
Fosamine	13.5	70	100	100	100	100	100
Fosamine	22.4	83	100	100	100	100	100
Triclopyr + 2,4-D	1.3 + 1.4	92	90	100	100	100	100
Metsulfuron + 2,4-D	0.042 + 1.4	94	92	92	95	100	100
LSD (0.05)		31.2	9.6	10.1	15.2	0.00	0.00

[a]DAT, days after treatment.

Table 3. Mean number of *Lythrum salicaria* stems (m^{-2}) in experimental plots, 360 d after treatment (DAT) at Buffalo County, NE, in 2001 to 2003.

Treatment	Rate kg ae (ai) ha^{-1}	Year 0[a]	Year 1	Year 2	Year 3
		——Stem count m^{-2}——			
Glyphosate	2.2	22	7	2	0
Glyphosate	3.4	15	0	0	0
2,4-D dimethylamine	1.4	12	2	0	0
2,4-D dimethylamine	2.8	7	0	0	0
Triclopyr	1.3	12	2	2	0
Triclopyr	2.1	22	7	0	0
Imazapyr	1.1	15	0	0	0
Imazapyr	1.7	10	0	0	0
Metsulfuron	0.042	27	2	0	0
Metsulfuron	0.084	15	0	0	0
Fosamine	13.5	22	0	0	0
Fosamine	22.4	15	0	0	0
Triclopyr + 2,4-D	1.3 + 1.4	22	10	2	0
Metsulfuron + 2,4-D	0.042 + 1.4	7	7	5	0
Nontreated		17	21	22	25
LSD (0.05)		13.2	9.3	11.2	—

[a]Number of stems at the initiation of the study.

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Table 4. Control of a 3-yr-old *Lythrum salicaria* over time with selected herbicide treatments at Holt County, NE, in 2000 to 2002.[a]

Treatment	Rate kg ae (ai) ha^{-1}	Year 1		Year 2		Year 3	
		60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT
		———% control———					
Glyphosate	2.2	97	87	91	100	100	100
Glyphosate	3.4	99	89	96	100	100	100
2,4-D dimethylamine	1.4	77	75	84	86	100	100
2,4-D dimethylamine	2.8	97	49	97	91	100	100
Triclopyr	1.3	75	76	93	91	100	100
Triclopyr	2.1	86	71	94	91	100	100
Imazapyr	1.1	71	96	100	100	100	100
Imazapyr	1.7	75	100	100	100	100	100
Metsulfuron	0.042	65	76	100	100	100	100
Metsulfuron	0.084	72	94	100	100	100	100
Fosamine	13.5	64	89	88	91	100	100
Fosamine	22.4	67	88	85	90	100	100
Triclopyr + 2,4-D	1.3 + 1.4	97	75	100	100	100	100
Metsulfuron + 2,4-D	0.042 + 1.4	90	72	88	100	100	100
LSD (0.05)		10.4	19.9	7.8	3.1	0.0	0.0

[a]DAT, days after treatment.

Table 5. Mean number of *Lythrum salicaria* stems (m^{-2}) in experimental plots, 360 d after treatment (DAT) at Holt County, NE, in 2000 to 2003.

Treatment	Rate kg ae (ai) ha^{-1}	Year 0[a]	Year 1	Year 2	Year 3
		———Stem counts (m^{-2})———			
Glyphosate	2.2	16	5	0	0
Glyphosate	3.4	15	2	0	0
2,4-D dimethylamine	1.4	22	20	10	0
2,4-D dimethylamine	2.8	23	16	9	0
Triclopyr	1.3	26	12	11	0
Triclopyr	2.1	20	7	7	0
Imazapyr	1.1	19	2	0	0
Imazapyr	1.7	13	0	0	0
Metsulfuron	0.042	8	2	0	0
Metsulfuron	0.084	8	4	0	0
Fosamine	13.5	5	3	2	0
Fosamine	22.4	12	5	2	0
Triclopyr + 2,4-D	1.3 + 1.4	12	10	0	0
Metsulfuron + 2,4-D	0.042 + 1.4	8	5	0	0
Nontreated		20	85	77	55
LSD (0.05)		5.3	12.1	19.1	-

[a]Number of stems at the initiation of the study.

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Table 6. Control of a 5-yr-old *Lythrum salicaria* over time with selected herbicide treatments at Brown County, NE, in 2001 to 2005.[a]

Treatment	Rate kg ae (ai) ha^{-1}	Year 1		Year 2		Year 3		Year 4		Year 5	
		60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT
		——% control——									
Glyphosate	2.2	90	92	92	90	100	100	—	—	—	—
Glyphosate	3.4	96	94	97	98	97	100	—	—	—	—
2,4-D dimethylamine	1.4	90	92	89	92	80	84	82	75	100	100
2,4-D dimethylamine	2.8	99	95	97	95	92	81	90	80	100	100
Triclopyr	1.3	95	97	95	87	87	84	70	70	100	100
Triclopyr	2.1	99	92	97	97	92	91	84	82	100	100
Imazapyr	1.1	95	95	97	94	100	100	—	—	—	—
Imazapyr	1.7	96	91	92	97	100	100	—	—	—	—
Metsulfuron	0.042	94	92	95	100	—	—	—	—	—	—
Metsulfuron	0.084	96	96	100	100	—	—	—	—	—	—
Fosamine	13.5	81	85	85	78	77	89	70	94	100	100
Fosamine	22.4	86	87	89	92	77	81	87	97	100	100
Triclopyr + 2,4-D	1.3 + 1.4	90	82	92	92	100	100	—	—	—	—
Metsulfuron + 2,4-D	0.042 + 1.4	90	97	95	75	95	100	—	—	—	—
LSD (0.05)		8.9	13.2	9.9	24.0	20.2	12.9	13.0	13.2	0.0	0.0

[a]DAT, days after treatment. Dashes (—) indicate no spraying because there was no regrowth.

glyphosate (3.4 kg ha^{-1}), triclopyr (2.1 kg ha^{-1}), or imazapyr (1.1 and 1.7 kg ha^{-1}) at 60 DAT for the first year. At 360 DAT, most herbicides provided approximately 90% *L. salicaria* control. However, because no treatment provided 100% control, all treatments were resprayed in the second year. All herbicides provided excellent (>92%) control of *L. salicaria* in the second year, and 100% *L. salicaria* control at both 60 and 360 DAT. Similar control of *L. salicaria* with triclopyr was also reported by Gabor et al. (1995) and Champion et al. (2011). *Lythrum salicaria* stem density at the Buffalo site was also significantly reduced by all treatments in the first year (Table 3). Application of higher rates of glyphosate, 2,4-D dimethylamine, or metsulfuron or both rates of imazapyr and fosamine reduced *L. salicaria* stems to 0 plant m^{-2} in the first year after application. An additional application of lower rates of glyphosate and triclopyr was needed the second year to provide the same level of reduction of *L. salicaria* stems. No new *L. salicaria* stems were found in any treated plots in the third year.

At the Holt County site, excellent season-long control (≥90%) of the 3-yr-old *L. salicaria* stand was achieved by both rates of glyphosate, the higher rate of 2,4-D dimethylamine, and the tank mixture of the lower rate of 2,4-D dimethylamine plus either triclopyr or metsulfuron, but this control did not last up to 360 DAT in the first year (Table 4). For example, a tank mixture of 2,4-D dimethylamine plus triclopyr provided 97% control in 60 DAT, but had declined to 75% control in 360 DAT. Meanwhile, both rates of imazapyr and the higher rate of metsulfuron still provided excellent control in 360 DAT in the first year. With additional application of herbicides in the second year, excellent control that lasted up to 360 DAT was provided by all herbicides except the lower rate of 2,4-D dimethylamine. A similar trend was observed for *L. salicaria* stem density at the Holt site, with stem density reduced by all herbicide treatments the first year (Table 5). After the second year of application, glyphosate, imazapyr, metsulfuron, or the tank mixture of 2,4-D with triclopyr or metsulfuron completely controlled *L. salicaria* with no live stems present. It required an additional spraying of 2,4-D dimethylamine, triclopyr, or fosamine in the second and third years (i.e., total of three applications) to completely prevent regrowth of *L. salicaria* stems.

At the Brown County site, excellent season-long control of the 5-yr-old *L. salicaria* was achieved with all herbicides except fosamine (Table 6). For example, >95% control was achieved with higher rates of glyphosate, triclopyr, imazapyr, or metsulfuron at 60 DAT of the initial application. Similarly, all herbicides (except both rates of fosamine and the tank mixture of 2,4-D dimethylamine plus triclopyr) provided excellent (≥90%) control of *L. salicaria* at 360 DAT of the first year. A similar result was recorded at 60 and 360 DAT in the second and third years. In addition to herbicides that provided excellent control in previous years, both rates of fosamine also provided excellent control that lasted up to 360 DAT by the fourth year. At the fifth year, all herbicides provided excellent (100%) control. All herbicides consistently reduced stem density at each time of observation at the Brown site (Table 7). Three sequential years of applications of metsulfuron, glyphosate, imazapyr, or a tank mixture of 2,4-D dimethylamine plus triclopyr were needed to completely prevent reemergence of *L. salicaria* stems, while five sequential years of

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Table 7. Mean number of *Lythrum salicaria* stems (m^{-2}) in experimental plots, 360 d after treatment (DAT) at Brown County, NE, in 2001 to 2006.

Treatment	Rate kg ae (ai) ha^{-1}	Year 0[a]	Year 1	Year 2	Year 3	Year 4	Year 5
		——————————————————Stem counts (m^{-2})——————————————————					
Glyphosate	2.2	35	7	6	0	0	0
Glyphosate	3.4	32	7	9	0	0	0
2,4-D dimethylamine	1.4	30	21	17	10	9	0
2,4-D dimethylamine	2.8	37	19	17	10	7	0
Triclopyr	1.3	27	13	12	12	11	0
Triclopyr	2.1	37	12	7	7	2	0
Imazapyr	1.1	31	5	0	0	0	0
Imazapyr	1.7	35	10	7	0	0	0
Metsulfuron	0.042	42	17	0	0	0	0
Metsulfuron	0.084	37	14	0	0	0	0
Fosamine	13.5	32	19	11	11	5	0
Fosamine	22.4	31	11	22	35	0	0
Triclopyr + 2,4-D	1.3 + 1.4	37	17	10	0	0	0
Metsulfuron + 2,4-D	0.042 + 1.4	52	12	5	0	0	0
Nontreated		40	65	80	80	70	68
LSD (0.05)		14.4	14.9	20.7	19.2	13.2	—

[a]Number of stems at the initiation of the study.

treatment were needed to achieve same level of control with 2,4-D dimethylamine, triclopyr, or fosamine.

Only four herbicide treatments provided excellent (≥90%) control of the 10-yr-old stands of *L. salicaria* by 60 DAT in the first year at the Dixon County site, including both rates of glyphosate, the higher rate of 2,4-D dimethylamine, or the tank mixture of 2,4-D dimethylamine plus metsulfuron (Table 8). Excellent *L. salicaria* control that lasted for 360 DAT was only achieved with higher rate of glyphosate in the first year. With a second application (i.e., at the second year), virtually all herbicides except the lower rate of triclopyr and the tank mixture of 2,4-D plus triclopyr or metsulfuron provided excellent *L. salicaria* control at 60 DAT, but this control did not last up to 360 DAT in most cases. The few herbicides that provided excellent control at 360 DAT in the second year were glyphosate, imazapyr, or the higher rate of metsulfuron. By the third year, excellent control that lasted for 360 DAT was provided by glyphosate, imazapyr, metsulfuron, or a tank mixture of 2,4-D plus triclopyr or metsulfuron. By the fourth year, imazapyr, metsulfuron, or the tank mixture of 2,4-D plus either triclopyr or metsulfuron did not need to be sprayed as there was no regrowth of *L. salicaria*. Similar to previous years, glyphosate consistently provided excellent control by the fourth year. By the fifth year, only metsulfuron and the tank mixture of metsulfuron plus 2,4-D provided excellent control. By the sixth year, glyphosate and the tank mixture of 2,4-D plus triclopyr or metsulfuron provided excellent control up to 360 DAT. By the seventh year, the tank mixture of 2,4-D plus triclopyr or metsulfuron provided excellent control at both 60 and 360 DAT. By the eighth year, 2,4-D at both rates provided excellent control up to 360 DAT. All herbicides provided excellent control by the ninth year.

Compared with the nontreated check, all herbicide treatments reduced stem population density of *L. salicaria* at the Dixon site at each rating (Table 9). The greatest reduction was achieved with the higher rate of glyphosate at 360 DAT after the first application. By the fourth year of application, plots sprayed with both rates of glyphosate and imazapyr prevented all *L. salicaria* stem regrowth. All herbicides provided complete stem control (0 stems m^{-2}) by the ninth year of application.

Control of Lythrum salicaria over Time

The level of *L. salicaria* control was influenced by the age of the stand at the corresponding site (Table 10). For example, the 3-yr-old stands in Buffalo and Holt counties required 2 to 3 yr of sequential spraying to provide complete control of *L. salicaria* (Table 10). At the Holt site, the 3-yr-old stands were completely controlled by glyphosate, imazapyr, or metsulfuron after 2 yr of sequential spraying, while 2,4-D dimethylamine, triclopyr, or fosamine required 3 yr of spraying. All treatments at Buffalo and Holt counties were rated and monitored for an extra 3 yr after the last spraying, and all ratings showed 100% control (unpublished data).

The 5-yr-old *L. salicaria* stands at Brown, required 2 to 5 yr of sequential spraying to achieve complete (100%) control of stands, depending on the herbicide (Tables 6 and 10). For example, the earliest complete control was achieved with metsulfuron sprayed yearly for 2 yr. The same stands required 3 yr of sequential spraying of glyphosate, imazapyr, or the tank mixture of 2,4-D dimethylamine plus triclopyr to provide complete control. Five years of sequential spraying of 2,4-D

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Table 8. Control of a 10-yr-old *Lythrum salicaria* over time with selected herbicide treatments at Dixon, NE, in 2000 to 2008.

		Year 1		Year 2		Year 3		Year 4		Year 5		Year 6		Year 7		Year 8		Year 9	
Treatment	Rate kg ae (ai) ha^{-1}	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT	60 DAT	360 DAT
		——% control——																	
Glyphosate	2.2	90	84	97	94	95	93	100	100	—	—	100	100	—	—	—	—	—	—
Glyphosate	3.4	98	97	97	96	97	95	100	100	—	—	100	100	—	—	—	—	—	—
2,4-D dimethylamine	1.4	61	32	94	50	76	32	57	54	57	62	65	78	81	76	91	97	100	100
2,4-D dimethylamine	2.8	96	28	97	79	95	72	82	78	71	72	81	80	78	82	90	94	100	100
Triclopyr	1.3	64	25	86	41	79	32	64	63	47	72	72	74	55	76	83	77	100	100
Triclopyr	2.1	85	29	97	50	92	70	90	87	54	90	—	—	78	76	84	83	100	100
Imazapyr	1.1	84	83	97	98	100	100	—	—	—	—	—	—	—	—	—	—	—	—
Imazapyr	1.7	87	89	95	98	100	100	—	—	—	—	—	—	—	—	—	—	—	—
Metsulfuron	0.042	79	30	94	89	100	100	—	—	94	97	—	—	—	—	—	—	—	—
Metsulfuron	0.084	85	30	90	92	100	100	—	—	96	95	—	—	—	—	—	—	—	—
Fosamine	13.5	50	43	94	67	80	89	76	71	66	73	77	85	87	85	87	88	100	100
Fosamine	22.4	76	66	99	75	83	87	69	76	59	90	90	82	83	83	87	87	100	100
Triclopyr + 2,4-D	1.3 + 1.4	85	30	88	52	78	100	—	—	70	85	77	98	100	100	—	—	—	—
Metsulfuron + 2,4-D	0.042 + 1.4	91	30	86	74	95	97	—	—	86	97	99	97	100	100	—	—	—	—
LSD (0.05)		5.3	10.4	6.5	17.9	10.0	15.2	13.4		17.0	15.1	14.9	13.5	10.2	21.1	12.8	16.7	0.0	0.0

[a]DAT, days after treatment. Dashes (—) indicate no spraying because there was no regrowth.

Table 9. Mean number of *Lythrum salicaria* stems (m^{-2}) in experimental plots, 360 d after treatment (DAT) at Dixon, NE, in 2000 to 2008.

Treatment	Rate kg ae (ai) ha^{-1}	Year 0[a]	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 9
		———Stem counts (m^{-2})———							
Glyphosate	2.2	30	7	6	6	0	0	0	0
Glyphosate	3.4	35	8	5	4	0	0	0	0
2,4-D dimethylamine	1.4	55	25	18	15	9	9	7	0
2,4-D dimethylamine	2.8	52	21	18	13	9	6	6	0
Triclopyr	1.3	50	31	20	17	14	10	8	0
Triclopyr	2.1	45	27	19	16	9	9	0	0
Imazapyr	1.1	10	5	5	0	0	0	0	0
Imazapyr	1.7	16	8	2	0	0	0	0	0
Metsulfuron	0.042	10	8	2	0	4	0	0	0
Metsulfuron	0.084	10	6	2	0	2	0	0	0
Fosamine	13.5	20	15	12	8	7	5	5	0
Fosamine	22.4	12	8	8	8	6	4	4	0
Triclopyr + 2,4-D	1.3 + 1.4	15	14	8	8	0	5	5	0
Metsulfuron + 2,4-D	0.042 + 1.4	15	10	7	7	0	6	2	0
Nontreated		37	57	87	82	84	60	54	61
LSD (0.05)		17.2	18.3	23.5	16.1	15.2	15.2	6.1	–

[a]Number of stems at the initiation of the study.

Table 10. Number of sequential herbicide applications (or years) until complete control was achieved for each age group and location in Nebraska of *Lythrum salicaria.*

		3 yr[a]	3 yr[a]	5 yr[a]	10 yr[a]
Treatment	Rate kg ae (ai) ha^{-1}	Buffalo County	Holt County	Brown County	Dixon County
Glyphosate	2.2	2 (2)	2 (2)	3 (3)	4 (6)
Glyphosate	3.4	2 (2)	2 (2)	3 (3)	4 (6)
2,4-D dimethylamine	1.4	2 (2)	3 (3)	5 (5)	7 (8)
2,4-D dimethylamine	2.8	2 (2)	3 (3)	5 (5)	7 (8)
Triclopyr	1.3	2 (2)	3 (3)	5 (5)	7 (8)
Triclopyr	2.1	2 (2)	3 (3)	5 (5)	7 (8)
Imazapyr	1.1	2 (2)	2 (2)	3 (3)	3 (3)
Imazapyr	1.7	2 (2)	2 (2)	3 (3)	3 (3)
Metsulfuron	0.042	2 (2)	2 (2)	2 (2)	4 (5)
Metsulfuron	0.084	2 (2)	2 (2)	2 (2)	4 (5)
Fosamine	13.5	2 (2)	3 (3)	5 (5)	7 (8)
Fosamine	22.4	2 (2)	3 (3)	5 (5)	7 (8)
Triclopyr + 2,4-D	1.3 + 1.4	2 (2)	3 (3)	3 (4)	6 (7)
Metsulfuron + 2,4-D	0.042 + 1.4	2 (2)	2 (2)	3 (4)	6 (7)
Mean		2 (2)	3 (2)	4 (4)	6 (6)

[a]Number of applications (years of application).

dimethylamine, triclopyr, or fosamine were required to completely control the 5-yr-old stands.

The 10-yr-old stand at the Dixon site required 3 to 9 yr of spraying to achieve complete control, which varied across herbicides (Tables 8 and 10). For example, imazapyr required just 3 yr of sequential spraying to achieve complete control, whereas yearly applications of 2,4-D dimethylamine, triclopyr, or fosamine for a period of 9 yr were required to provide complete control of the 10-yr-old stands.

It is important to note that regrowth was observed after complete (100%) control was initially recorded for some treatments (Table 8). Gabor et al. (1995) suggested that multiple application of herbicides and continuous monitoring were required to provide excellent control of older stands of *L. salicaria* due to larger rootstock or dormant bud the stands possessed. For example, metsulfuron, and the tank mixture of 2,4-D dimethylamine plus triclopyr were not applied in the fourth year, as complete control was seen (Table 8). However, regrowth was observed in the fifth year in stands sprayed with metsulfuron, requiring one additional application of the herbicide during the fifth year, after which no regrowth was observed (Table 8). Similarly, regrowth was observed in stands sprayed with the tank mixture of 2,4-D dimethylamine plus triclopyr, necessitating yearly spray of this treatment at the fifth, sixth, and seventh years, after which no regrowth was observed. In addition, after initial complete control was recorded in the fourth year, regrowth of secondary buds was observed in plots sprayed with glyphosate; this regrowth required one additional application of the herbicide in the sixth year, after which no regrowth was observed. The observed regrowth from the crowns, rhizomes, and rootstock buds was not surprising, because some perennial species are known to survive through this mechanism after an initial damage by stress (Chao et al. 2007; Klimes 2007; Rice et al. 1997).

Impact of Herbicides on Local Broadleaf and Grass Species

Composition of broadleaf and grassy species was affected during the period of *L. salicaria* control with herbicides at each location. In general, there were higher percentages of grasses in the 2,4-D-, triclopyr-, or metsulfuron-treated plots compared with higher percentages of non-target broadleaf species in the glyphosate- and imazapyr-treated plots at each location. Differences in proportion of species were expected considering the modes of action and selectivity of these herbicides. For example, use of herbicides that control broadleaf species (e.g., 2,4-D or triclopyr) would be expected to produce an increase in grass cover, and vice versa.

For example, a higher percentage of grasses compared with broadleaf species occurred at Dixon in plots sprayed with 2,4-D dimethylamine, triclopyr, or metsulfuron at 1 yr after the initial application (Table 11). The higher percentage of grass species was maintained throughout the 9-yr period of spraying of these herbicides. In contrast, plots treated with imazapyr had almost no grassy species present due to the generally nonselective nature and longer soil residual activity of imazapyr. Similar impacts of these herbicides were found in other locations (unpublished data). Champion et al. (2011) reported a similar increase in grasses in plots sprayed with triclopyr. The presence of grasses along waterways is promoted by land managers, because grasses provide habitat and food for various bird species (including migratory birds) and feed for grazing animals (e.g., deer, livestock). Thus,

Table 11. Impact of herbicide treatments on local broadleaf and grass species at Dixon, NE, over time (2000 to 2008).[a]

		Year 0[b]		Year 1		Year 2		Year 3		Year 4		Year 5		Year 9	
Treatment	Rate kg ae ha^{-1}	Broad	Grass	Broad	Grass	Broad	Grass	Broad	Grass	Broad	Grass	Broad	Grass	Broad	Grass
		—% composition—													
Glyphosate	2.2	30	60	50	40	40	30	2	2	47	52	60	40	58	40
Glyphosate	3.4	45	40	55	15	32	30	12	2	65	30	70	25	67	25
2,4-D	1.4	16	12	12	17	15	27	30	62	27	35	21	37	37	61
2,4-D	2.8	21	15	15	57	27	40	21	62	25	47	22	67	19	57
Triclopyr	1.3	37	12	15	32	20	37	30	61	27	32	27	40	10	27
Triclopyr	2.1	17	21	12	55	27	40	15	70	20	52	22	50	21	29
Imazapyr	1.1	26	13	54	5	52	0	0	0	60	0	80	10	71	4
Imazapyr	1.7	29	33	80	14	52	4	0	0	72	0	77	0	65	0
Metsulfuron	0.042	12	15	25	64	27	67	20	66	30	67	40	52	37	52
Metsulfuron	0.084	22	21	27	50	36	62	24	76	42	52	21	55	20	75
Fosamine	13.5	32	27	40	25	45	25	20	69	27	65	12	70	50	12
Fosamine	22.4	27	30	40	42	40	17	25	66	45	45	21	62	43	22
Triclopyr + 2,4-D	1.3 + 1.4	15	30	25	53	40	37	20	75	27	57	75	20	35	54
Metsulfuron + 2,4-D	0.042 + 1.4	25	21	27	50	37	47	12	80	15	82	65	30	30	65
Nontreated		5	17	23	31	6	6	9	9	14	9	25	15	35	16
LSD (0.05)		23.3	26.2	23.3	26.2	27.1	26.9	23.1	19.1	17.2	17.6	19.4	21.3	24.7	12.1

[a]Broad, broadleaf plant species; Grass, grassy plant species.
[b]Number of stems at the initiation of the study.

any herbicide that provides satisfactory control of *L. salicaria* without negative impact on grass species is desirable.

The results suggest that herbicides could provide excellent control of *L. salicaria*, and this control is site specific. Excellent (≥90%) control was mostly provided by higher rates of glyphosate, imazapyr, and metsulfuron at most locations. The use of fosamine and a lower rate of 2,4-D dimethylamine provided the poorest *L. salicaria* control at most locations. Thus, from a practical standpoint, the use of glyphosate, imazapyr, and metsulfuron would provide longer-term control with fewer applications (e.g., every 3 to 4 yr), while fosamine, 2,4-D, or triclopyr may require yearly applications, especially for sites with older infestations.

Most importantly, the results from this study suggest that the older the *L. salicaria* stand, the more multiple applications of herbicide are required. Therefore, early control of stands is highly recommended, as it would allow more herbicide options, increase the chance of better control, and reduce the time and cost required for desirable control of *L. salicaria*.

Considering the nature of perennial species, in particular the dormancy of secondary buds on perennial structures (Anderson et al. 2005; Klimes 2007), it would not be surprising to see regrowth occurring 5 to 10 yr later (SZK, personal observation). Long-term studies (likely over a 20-yr period) need to be conducted to confirm this hypothesis. Therefore, frequent visits and long-term monitoring of sites is critical for success.

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