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Effectiveness of herbicides on *Lysimachia vulgaris*: a 17-year case study

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Case Study

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Abstract

Garden loosestrife (*Lysimachia vulgaris* L.), is an invasive wetland plant that is subject to management in King County, WA, USA. Large-scale management efforts are generally conducted using herbicides. In this case study, we analyzed 17 yr of monitoring and treatment data in four riparian areas in King County to estimate the rate of spread of *L. vulgaris* and the efficacy of herbicidal treatments against *L. vulgaris* populations. In each area, herbicide treatments were applied annually. In three of the areas, the area infested with *L. vulgaris* did not change over time, while in the fourth area populations of *L. vulgaris* were spreading at a rate of 0.79 m^2 yr^{-1}. There were a greater number of sampled locations infested with *L. vulgaris* over the 17-yr period, and because populations were either not spreading or spreading slowly, it is possible that populations were becoming more fragmented. There was no relationship between the percentage of the infested area treated with herbicides and the area infested in the following year. However, there was a negative relationship between the area treated and the percent change in the invaded area; specifically, in years when <80% of the infested area was treated, there was an increase in the percent change of the invaded area between the year of treatment and the following year. The results of this study suggest that at the current level of management effort, the spatial extent of *L. vulgaris* did not retract over the 17-yr study period.

Introduction

The establishment and spread of aquatic invasive plants is a threat to the biodiversity and function of wetland and riparian ecosystems (Zedler and Kercher 2004) that provide vital habitat, breeding sites, and essential resources for many native species of waterfowl, songbirds, amphibians, and mammals (Dahl 1990; Kauffman 1988). Garden loosestrife (*Lysimachia vulgaris* L.) is a herbaceous, creeping rhizomatous, self-seeding perennial wetland plant native to Eurasia that is currently invading King County, WA (Dillon and Reichard 2014; Taylor 2017). It was introduced to North America through the horticulture industry and is now established in wetland habitats in the northeastern, midwestern, and northwestern United States (Klinkenberg 2019). Impacts due to *L. vulgaris* include clogged waterways, degradation of wildlife habitat, and a decrease in species diversity (Messick and Kerr 2007).

Management of *L. vulgaris* in wetland areas is complicated by its ability to rapidly reproduce and spread through seed and vegetative fragmentation (Taylor 2017). Consequently, the manual removal of *L. vulgaris* is largely infeasible, especially over larger areas. Manual removal can also facilitate seed dispersal and leave behind plant fragments that can regenerate and be dispersed throughout waterways (Dillon and Reichard 2014). Manual control techniques are generally only feasible for small or pioneering stands in which entire removal is ensured. Instead, most management tactics against *L. vulgaris* involve applications of herbicides.

Lysimachia vulgaris was first reported in Washington in 1978 (Washington State Noxious Weed Control Board 2019) and is currently classified as a Class B noxious weed in Washington (Washington Administrative Code 16-750-011). The classification requires it to be managed in areas where it is not widespread. In addition, local municipalities can decide to manage *L. vulgaris* in its established range. By 1990, *L. vulgaris* had spread throughout the riparian zones of Lake Washington and Lake Sammamish. Due to the negative effects of *L. vulgaris* (Messick and Kerr 2007), the Washington State Noxious Weed Control Board requires control of *L. vulgaris* in susceptible areas in King County.

Management of *L. vulgaris* populations in Washington generally consists of applying one or multiple of the following herbicides: glyphosate, imazapyr, imazamox, and triclopyr triethylamine salt. However, there has been limited research on the effectiveness of these herbicides for control of *L. vulgaris*. Moreover, one of the recommended control methods, imazapyr, is a nonselective herbicide with considerable soil activity and a long half-life (Gianelli et al. 2013; McDowell et al. 1997), and consequently, some plant species cannot

Table 1. Trade names, active ingredients, and manufacturers of the herbicides used in this study.

Product trade name	Active ingredient	Manufacturer
Aquamaster™	Glyphosate (53.8%), other ingredients (46.2%)	Bayer Crop Science, Leverkusen, Germany
Rodeo™	Glyphosate (53%), other ingredients (46.2%)	Corteva Agriscience, Wilmington, DE, USA
Polaris™	Imazapyr (27.7%), (1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid) (72.3%)	Nufarm, Melbourne, Australia
Clearcast™	Imazamox (12.71%), other ingredients (87.9%)	SePRO Corporation, Carmel, IN, USA
Renovate 3™	Triclopyr:2-[(3,5,6-trichloro-2-pyridinyl)oxy] acetic acid, triethylamine salt (44.4%), other ingredients (55.6%).	SePRO Corporation, Carmel, IN, USA

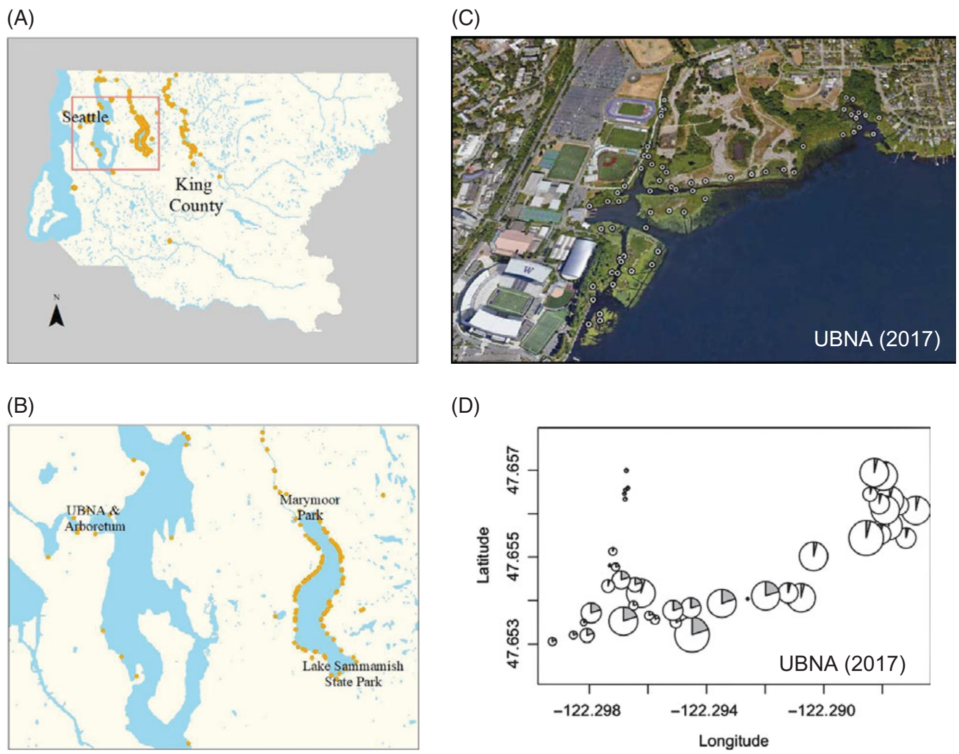

Figure 1. (A) Locations of areas infested with *Lysimachia vulgaris* (orange dots) in King County, WA. (B) Sampling locations used this in study included the Union Bay Natural Area (UBNA), Washington Park Arboretum, Marymoor Park, and Lake Sammamish State Park. (C) As an example of the sampling effort used across all sites and years, patches ($N = 43$) at the UBNA, where *L. vulgaris* was detected in 2017, are shown. (D) Proportional bubble plot of the sampling effort at the UBNA in 2017 ($N = 43$); the size of the circle reflects the total area of patch with some presence of *L. vulgaris*; within each circle, the gray region represents the percent of the patch estimated to be invaded by *L. vulgaris*.

grow in soil treated with imazapyr for up to 6 mo (U.S. Environmental Protection Agency 2006). In a prior study, Messick and Kerr (2007) reported that a 1.5% solution of triclopyr triethylamine salt or a 2% solution of glyphosate reduced garden loosestrife populations in the Rutherford Slough from 2002 to 2006, but they also observed increased germination of the seedbank following plant reduction. In this study, we quantified the area invaded by *L. vulgaris* over a 17-yr period in King County, WA, to estimate its rate of spread and measure the effect of herbicidal treatments.

Materials and Methods

Study Area

We used records of herbicide treatments and estimates of *L. vulgaris* populations from four sites in northwestern King County, WA (Figure 1). Two sites, Lake Sammamish State Park (2004 to 2018) and Marymoor Park (2005 to 2018) are located around Lake Sammamish. The remaining two sites consisted of the Union Bay Natural Area (2007 to 2018) and the Washington Park Arboretum (2010 to 2018), which are both components of the University of Washington Botanic Gardens located along Union Bay and Portage Bay. All study sites contained a mix of nonnative plant species, such as field bindweed (*Convolvulus arvensis* L.), purple loosestrife (*Lythrum salicaria* L.), canary grass (*Phalaris canariensis* L.), and Himalayan blackberry (*Rubus armeniacus* Focke), and native plant species, such as marsh cinquefoil (*Comarum palustre* L.), broadleaf cattail (*Typha latifolia* L.), bulrush (*Scripus* spp.), rose spirea (*Spiraea douglasii* Hook.), rushes (*Juncus* spp.), and sedges (*Carex* spp.). A prior study of the Lake Sammamish shoreline estimated that more than 25% (~12 km) of the shoreline was infested with *L. vulgaris* (Messick and Kerr 2007). To manage *L. vulgaris* at these sites, a combination of a surfactant, glyphosate, imazapyr, imazamox, and/or triclopyr triethylamine salt were used (Table 1). Treatments were applied as a spot spray annually between July and October (Table 2). The percent of herbicide concentrate

Table 2. Summary of the treatments used, area invaded and treated, survey and treatment dates, and the applicators and application methods for study sites.[a]

Year	Product(s) applied	Invaded area	Survey date(s)	Percent invaded area treated	Dates of treatment	Applicator/application method[b]
	L of herbicide concentrate	m^2				
Lake Sammamish State Park						
2004		91.8	Aug. 4	100	Sept. 9	
2005		1016.7	Jul. 5, Aug. 2	100	Aug. 2, 8, 26	KC/BP
2006		168.2	Jul. 25	100	Jul. 25, Aug. 24	
2009		341.1	Aug. 18, 24	99	Aug. 18, Sept. 18	
2010		410.7	Jul. 26, 29	96	Jul. 26, 29, Oct. 19	
2011		108.7	Aug. 9	62	Aug. 31, Sept. 2	
2012		315.5	Aug. 13, 27	100	Sept. 7, 19	C/BP
2013	Imazapyr (1.1)	447.0	Aug. 6, 13, 15, 18	100	Aug. 6, 13, 19	C/BP
2014	Imazapyr (1.3)	168.0	Jul. 28, Aug 8, 14	100	Jul. 28, Aug. 12, 14	C/BP
2015	Imazapyr (0.7); Triclopyr (0.7)	439.2	Aug. 24, Sept. 9	100	Aug. 24, Sept. 9	C/BP
2016	Triclopyr (1.3)	366.0	Aug. 3, 30	100	Aug. 3, 30	KC and C/BP
2017	Imazapyr (1.4); Triclopyr (1.4)	437.6	Jul. 31, Aug. 16	100	Jul. 31, Aug. 16	KC and C/BP
2018	Imazapyr (1.3); Triclopyr (0.6)	384.2	Jul. 31	99	Jul. 31, Sept. 21	C/BP
Marymoor Park						
2001		418.1	Jul. 24		Aug. 8	Manually removed
2005		4,588.5	May 17	100	Sept. 30	C/BP
2010		16,127.6	Aug. 4	75	Sept. 20	C/BP
2012		11,883.5	Sept. 27	80	Sept. 27	C/BP
2013	Imazapyr (11.8)	7,552.4	Jul. 3, Sept. 12, 13	90	Sept. 14	C/BP
2014	Imazapyr (15.4)	7,639.4	Sept. 22	95	Sept. 22	C/BP
2015	Imazapyr (26.9)	2,574.3	Aug. 17	90	Aug.17	C/BP
2016						
2017	Imazapyr (16.8)	2,123.0	Sept. 15	75	Sept. 15	C/BP
2018	Imazapyr (32.7)	1273.2	Sept. 19	85	Sept. 19	C/BP
Union Bay Natural Area and the Washington Park Arboretum						
2007	Triclopyr (10.0) Glyphosate (11.0)	267.6	Aug. 11	100	Aug. 22, 27, 29, 30	UW/S
2008	Triclopyr (20.6)	167.2	Jul. 21 Aug. 11	80	Jul. 21 Aug. 11	UW/S
2009		395.2	Jul. 13	100	Jul. 13	UW/B
2010		2,186.2	Jul. 14, 15 Sept. 22	95	Jul. 14, 15 Sept. 22	UW/B
2011	Triclopyr (85.3)	197.7	Aug. 10-12	85	Aug. 10-12	UW/B
2012	Imazapyr (40.8) Triclopyr (3.6)	165.9	Jul. 11,12 Sept. 12	100	Aug. 1, 7 Sept. 13, 18	UW/B
2013	Imazapyr (78.7) Triclopyr (59.1)	1,874.6	Jul. 3, 9, 10	100	Jul. 26 Aug. 6, 7, 21 Sept. 6, 10 Sept. 19, 26 Oct. 9	UW/B
2014		666.3	Jul. 14, 15 Sept. 4	100	Jul. 14, 15 Sept. 4	UW/B
2015	Triclopyr (10.7)	6,282.1	Jul. 12, 13	10	Aug. 26 Sept. 28	UW/B
2016	None	530.6	Jul. 13	0	None	UW/B
2017	Glyphosate (214.9) Imazamox (56.8)	3,164.0	Jul. 10, 11 Jul. 28	85	Aug. 9, 11 Aug. 18, 23	UW/B
2018	Imazapyr (93.1) Triclopyr (46.6)	4,680.8	Jul. 20 Aug. 22	100	Aug. 8, 9, 13 Sept. 7	UW/B

[a]In cells with missing values, data were not available.
[b]Applicator: C, contractor; KC, King County; UW, University of Washington. Application method: B, boat-mounted tank and handheld spray gun; BP, backpack sprayer; S, Spotlyte sprayer.

used in the final solution ranged from 0.5% to 2%, with the exception of a 3% solution of imazamox that was used in 2017. The King County Noxious Weed Control Program worked with property owners to hire contractors to apply these herbicides.

Data Collection

Treatment records, which included the type of herbicide used and area treated, for each site were obtained through the King County Noxious Weed Control Program. The licensed applicator, type of

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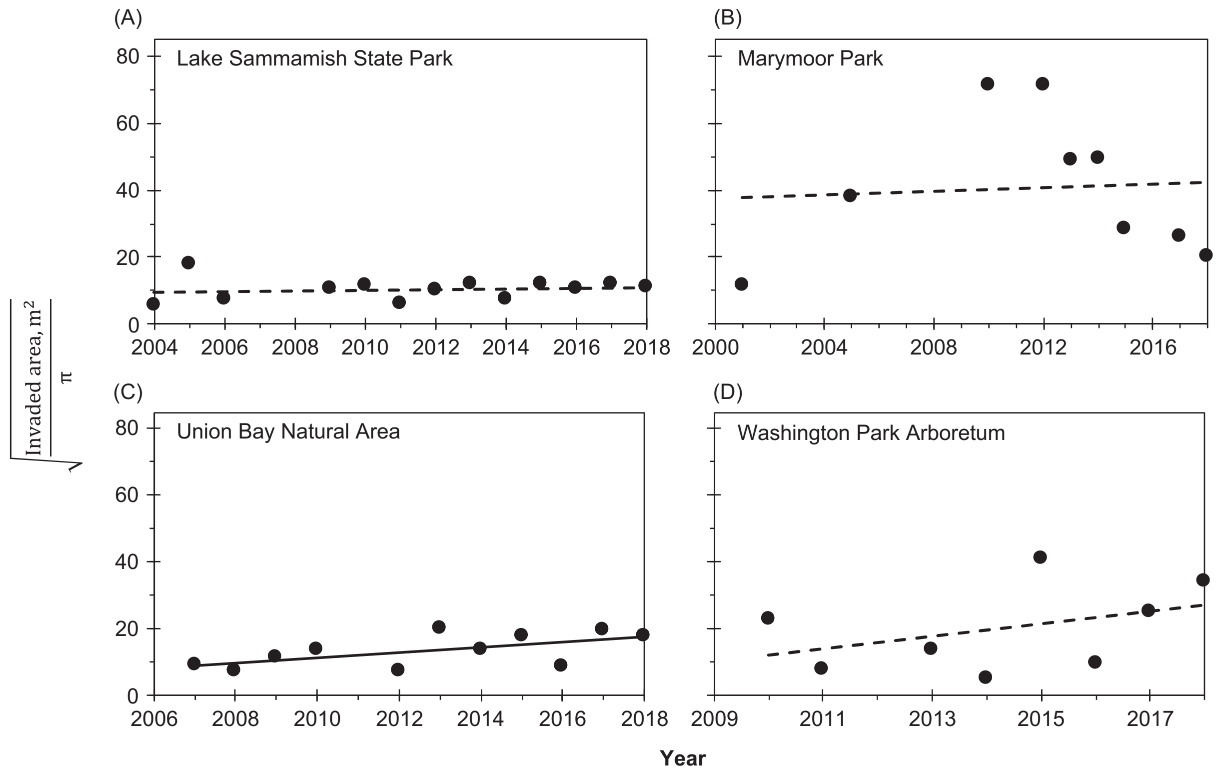

Figure 2. Estimates of *Lysimachia vulgaris* spread rates through regression of the square root of the estimated invaded area over time at each site. Dashed trend lines are shown as a reference and indicate that the estimate of the regression slope was not different than 0, whereas the solid trend line indicates a positive slope with a rate of spread of 0.79 $m^2\ yr^{-1}$.

herbicides and surfactants used, and the timing of applications varied from site to site and from year to year (Table 2). More than 80% of the area infested with *L. vulgaris* was chemically treated each year, with the exception of 2007 (~64.0%), 2011 (49.8%), and 2016 (75.9%). In addition, at each site, the King County Noxious Weed Control Program estimated the area invaded by *L. vulgaris*. Estimates were obtained by naked eye assessment from a canoe using Trimble GPS units (2001 to 2016) or ESRI Collector for ArcGIS (2017 to 2018). When *L. vulgaris* was detected, the total area of the patch invaded by *L. vulgaris* was estimated and the patch was georeferenced. Then, within each invaded patch, the percent of the patch invaded by *L. vulgaris* (percent coverage) was estimated. The final estimated area invaded was calculated by multiplying the area of patch containing *L. vulgaris* by the percent coverage. An example of the sampling effort for the Union Bay Natural Area in 2017 is presented in Figure 1C and D. All estimates of the invaded area were made before the implementation of control measures. A summary of the treatments used, estimated area invaded by *L. vulgaris*, percent of area treated, survey and treatment dates, and applicators and application methods for all study sites is presented in Table 2. Data from the Union Bay Natural Area and the Washington Park Arboretum are combined in Table 2; although estimates of the invaded area at the Union Bay Natural Area and the Washington Park Arboretum were available for each site separately, which allowed us to quantify spread at each site, other details, including the products used and amounts, survey and treatment dates, and applicators and application methods, were only available for both sites combined, because both are administrated by a single entity (the University of Washington Botanic Gardens).

Analyses

Annual spread rates for *L. vulgaris* were estimated for each site using a square-root area regression method (Shigesada and Kawasaki 1997). For each year, the square root of the estimated invaded area, Y, according to

$$Y = \frac{\sqrt{\text{area invaded in m}^2}}{\pi} \qquad [1]$$

was regressed as a function of time, beginning with each site's first year of monitoring. The estimate of the slope was used to determine significance (i.e., H_0: slope estimate = 0) and, if significant, estimate the radial rate of spread (Gilbert and Liebhold 2010; Shigesada and Kawasaki 1997; Tobin et al. 2007).

To measure the effectiveness of herbicidal treatments, we quantified the Pearson's correlation coefficient (r) between the percentage of the area treated with herbicides and the area invaded by *L. vulgaris* in the following year. We also quantified the correlation between the percentage of the area treated with herbicides and the percent change in the invaded area between the year of treatment and the following year. Finally, we combined data from all sites to examine the variation in the number of sampled locations that were positive for *L. vulgaris* over time. All analyses were conducted in R (R Core Team 2018).

Results and Discussion

When the square root of the estimated invaded area was analyzed as a function of time, there were no differences at Lake Sammamish

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State Park ($t = 0.35$; df = 11; P = 0.73), Marymoor Park ($t = 0.19$; df = 7; P = 0.86), Washington Park Arboretum ($t = 1.09$; df = 6; P = 0.32) (Figure 2). The mean area invaded over the duration of the 17-yr study period was 361.1 m^2 at Lake Sammamish State Park, 6,491.6 m^2 at Marymoor Park, and 1,714.9 m^2 at the Washington Park Arboretum. However, there was an increase in invaded area (slope estimate = 0.79, SE = 0.35) at the Union Bay Natural Area ($t = 2.27$; df = 9; P = 0.05; $R^2 = 0.37$), indicating that *L. vulgaris* has spread approximately 0.79 $m^2\ yr^{-1}$ at this site between 2007 and 2018, from 8.9 m^2 in 2007 to 17.6 m^2 in 2018 (Figure 2). Collectively, our data indicate that management efforts using herbicides have not resulted in a decrease in the area invaded by *L. vulgaris* over a 17-year period; however, it also indicates containment, as *L. vulgaris* has not spread at sites, with the exception of the Union Bay Natural Area, over the same time period. A previous report stated that a 1.5% solution of triclopyr triethylamine salt reduced the population of *L. vulgaris* at a specific location in Rutherford Slough, King County, WA, between 2002 and 2006 (Messick and Kerr 2007). In this study, which included more sites and data collected over a longer time period, *L. vulgaris* infestations were stable or spread slowly.

Future experimental studies are needed to quantify the spread rate of *L. vulgaris* in the absence of any management. For example, in a study of the spread of *L. salicaria*, it was reported that the population size increases, or spreads, at a rate of 12% per year if left untreated (Bureau of Land Management 2015). Although *L. salicaria* is in a different genus than *L. vulgaris*, the two species are relatively similar in their vigorous invasive tendencies and habitat preferences; thus, spread rate data from *L. salicaria* could provide some insight into the expected spread of *L. vulgaris* in the absence of herbicidal treatments.

When examining the relationship between the number of sampled locations that were positive for *L. vulgaris* and time (2003 to 2018) across all four sites, there was a positive slope ($t = 10.5$; df = 15; P < 0.01; adjusted $R^2 = 0.88$), indicating that the number of sampled locations where *L. vulgaris* was present has increased over the time period (Figure 3). The slope estimate suggested that there is a mean increase of 7.5 sampled locations that are positive for *L. vulgaris* each year. Given that the area invaded by *L. vulgaris* at most sites did not increase over time, or increased at a rate of 0.79 $m^2\ yr^{-1}$, this analysis could suggest that the population of *L. vulgaris* is becoming fragmented, possibly as a result of consistent applications of herbicides from year to year. Alternatively, the steady increase in the number of sampled locations positive for *L. vulgaris* could be due to advances in spatial data collection and processing tools that have occurred over the last 17 yr. However, if fragmentation is occurring, this can be beneficial to control efforts, particularly if the species is subject to a strong Allee effect (i.e., positive density dependence; Tobin et al. 2011). Another possibility is that fragmentation is hindering overall management success by creating smaller populations that are more difficult to detect and thus subsequently manage. Controlled experiments would be required to ascertain whether chemical treatments can produce fragmentation of *L. vulgaris* populations and whether the fragmentation of *L. vulgaris* populations facilitates subsequent management strategies.

There was no correlation between the area treated with herbicides and the area invaded by *L. vulgaris* in the following year (r = −0.28; df = 13; P = 0.30), indicating no relationship between these two variables (Figure 4A). However, there was a negative correlation between the area treated with herbicides and the percent change in the invaded area in the following year (r = −0.53; df = 13; P = 0.04; Figure 4B). It is important to note that there were only 3 yr when <80% of the invaded area was treated with herbicides across the 17-year period, and in each of those 3 yr, there was an increase in the area invaded in the following year (Figure 4B). For example, in 2007, ~64% of the invaded area was treated, and the invaded area increased from 1,763 m^2 to 6,032 m^2. Similarly, ~50% of the population was treated in 2011, and the invaded area increased from 13,242 m^2 to 20,316 m^2.

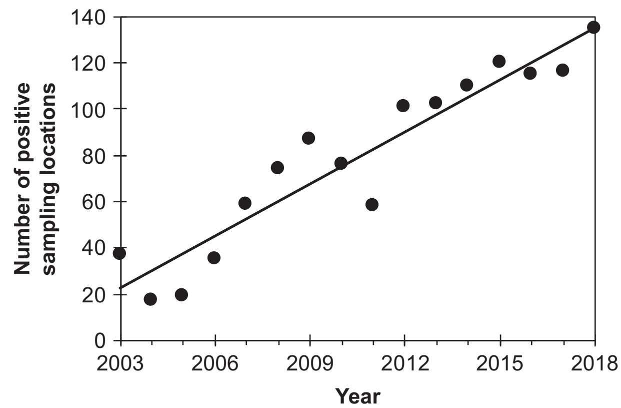

Figure 3. The number of sampled locations across all sites in which *Lysimachia vulgaris* was detected. The solid line is the regression fit.

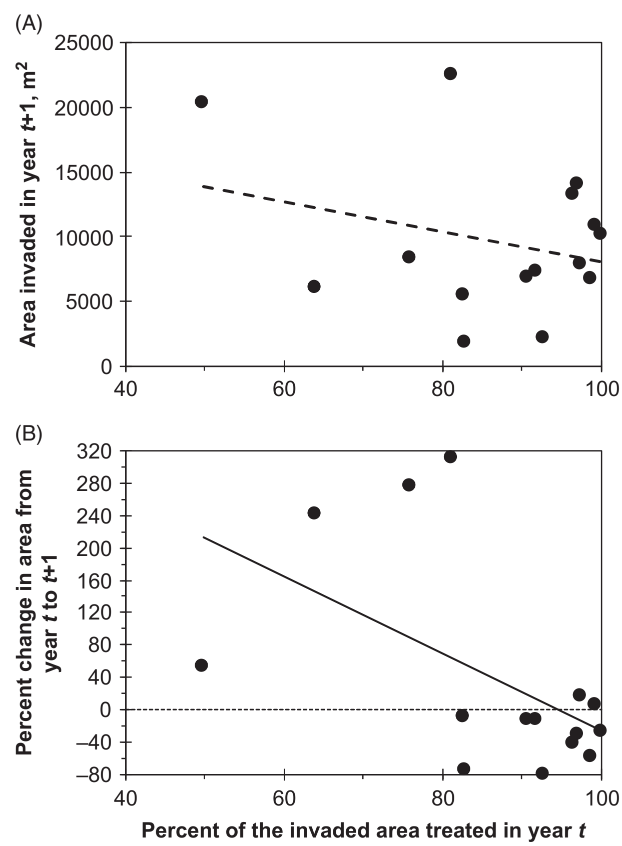

Figure 4. (A) Relationship between the percent of the area infested with *Lysimachia vulgaris* that was treated using herbicides and the area (m^2) infested *L. vulgaris* with in the following year. (B) Relationship between the percent of the area infested with *L. vulgaris* that was treated using herbicides and the percent change in the infested area between the year of treatment and the year following treatment. The dashed line represents no change, whereas the solid line indicates a change.

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The overall results of this case study demonstrate that *L. vulgaris* has been contained and that containment is more likely to be successful when a high percentage of the invaded area (>80%) is chemically treated each year. Further research is still needed to better understand the ecological impacts of the herbicides currently in use and their effect on follow-up restoration plans. An improved understanding of this noxious weed and the long-term implications of herbicide treatments will better inform management plans for landowners and policy makers.

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