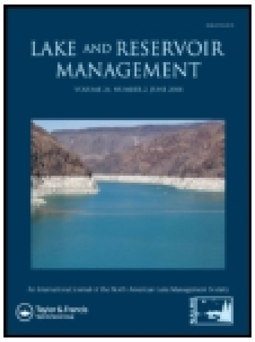

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A three-year evaluation of triclopyr for selective whole-bay management of Eurasian watermilfoil on Lake Minnetonka, Minnesota

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Abstract

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Impact of whole-bay, low-dose triclopyr applications for selective control of Eurasian watermilfoil (*Myriophyllum spicatum*: EWM) was evaluated on Lake Minnetonka, Minnesota, from 2011 to 2013. To assess invasive and native plant frequency and abundance over multiple seasons following management, we collected plant frequency, herbicide concentration, biomass, and hydroacoustic data. Two enclosed bays, St. Albans (64 ha) and Grays (64 ha), were treated at 300 μg/L. St. Albans was treated in late May 2011 and 2013 and Grays was treated in late May 2012. Triclopyr half-lives ranged from 8.6 to 12.1 days. A larger, more open bay, Gideons (133 ha), was treated by targeting 50 ha of EWM beds at 1500 μg/L in early June 2011. Triclopyr half-lives in Gideons treatment blocks averaged 3.7 days with a bay-wide half-life of 9.4 days. Near complete loss of EWM in the 3 bays was observed the year of treatment. Increased EWM frequency was observed the following June and August; however, EWM remained a minor component of bay-wide biomass ($<$2%). Number of points with native plants, mean native species per point, and native species richness in the bays were not reduced following treatment. Native species decreasing in frequency included *Myriophyllum sibiricum*, *Zosterella dubia*, *Elodea canadensis*, and *Potamogeton zosteriformis.* Most native plants showed no significant posttreatment change in frequency. Hydroacoustic data did not indicate bay-wide decreases in percent coverage or biovolume. Treatments provided up to 2 seasons of EWM control without reducing the overall distribution and abundance of native plants.

Key words: aquatic herbicide, aquatic plant management, chemical control, invasive aquatic plant, *Myriophyllum spicatum*, renovate

The herbicide triclopyr (3,5,6-Trichloro-2-pyridinyloxy-acetic acid) has been evaluated for selective control of Eurasian watermilfoil (EWM: *Myriophyllum spicatum*) in northern waters (Getsinger et al. 1997, 2000, Poovey et al. 2004, Wersal et al. 2010). These trials generally targeted discrete beds of EWM in areas with short water retention times. Recent laboratory trials evaluating the response of invasive and native plants to low-dose triclopyr and 2,4-D treatments suggest that a new use pattern could be effective in areas where herbicide concentrations can be maintained (Glomski et al. 2009, Glomski and Netherland 2014, Netherland and Glomski 2014). Nault et al. (2014) reported on the impacts of whole-lake 2,4-D treatments in 2 Wisconsin Lakes following exposure to low concentrations over an extended period. Sustained large-scale, low concentration treatments of herbicide for selective EWM control are typically associated with fluridone (Getsinger et al. 2002, Madsen et al. 2002, Crowell et al. 2006); however, recent data suggest this strategy may also work with auxin herbicides.

Lake Minnetonka is a heavily utilized waterbody located west of Minneapolis/St. Paul and spans 5801 ha, separated into 15 morphologically distinct bays (Smith et al. 1991). EWM was discovered in the lake in 1987, with subsequent spread throughout numerous bays of the lake. While the ability of EWM to maintain nuisance growth over long periods of time has been questioned (Smith and Barko 1990), the 24-year period of EWM growth and management activities in Lake Minnetonka suggest an ongoing problem. Biological and environmental characteristics favoring invasive EWM growth have been studied, and although surface

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canopy formation is a focus of ecologists (Grace and Wetzel 1978, Nichols and Shaw 1986, Madsen 1998), it also drives citizen complaints.

In response to ongoing EWM problems, the Lake Minnetonka Conservation District initiated a multiyear demonstration project in 2007 to determine if targeting EWM at a whole-bay scale could reduce management inputs over time. Reliance on presence/absence point-intercept methodology (Madsen 1999, Mikulyuk et al. 2010) to assess efficacy of treatments led to stakeholder concern because EWM frequency was often not congruent with perceptions of decreased abundance following treatment. Likewise, concern was expressed that point-intercept results were masking herbicide impacts to native plant abundance and density.

Use of point-intercept sampling as a primary assessment technique must be considered in terms of viable alternatives. Extensive labor requirements associated with biomass sampling and the need for costly equipment and data processing capabilities associated with hydroacoustics has discouraged incorporating these efforts into routine plant assessments. Johnson and Newman (2011) describe a biomass sampling technique that reduces efforts associated with sample collection. While hydroacoustic data can show temporal and spatial changes in plant coverage and abundance following management efforts (Valley and Drake 2005, 2007, Valley et al. 2006, Zhu et al. 2007, Sabol et al. 2009), issues with costs and data processing requirements have discouraged adoption by resource managers. Recent availability of low-cost recording sonar units has led to renewed consideration of incorporating hydroacoustic technology into submersed plant assessments (Netherland and Jones 2012).

Our objective was to evaluate invasive and native plant frequency and abundance over multiple seasons following whole-bay management with triclopyr. We assessed (1) bay-wide herbicide concentrations; (2) changes in percent area covered and biovolume of submersed vegetation via hydroacoustic transects; and (3) multiseason changes in frequency and biomass of EWM and native plants following whole-bay herbicide applications.

Methods

Study sites

St. Albans Bay (64 ha; 63% littoral), Grays Bay (64 ha; 84% littoral), and Gideons Bay (133 ha; 54% littoral) are located in Lake Minnetonka, Minnesota (Fig. 1). Both St. Albans and Grays bays have narrow inlets that limit hydraulic exchange with the main body of water, whereas Gideons Bay is more open and thought to be subject to increased water exchange with the main lake. Grays Bay is the outlet for Lake Minnetonka, and despite the narrow inlet, this bay can be subject to increased exchange in years when water flows are high. In 2011, the treatment of Grays Bay was postponed due to high flow rates and concerns of treated water being introduced to Minnehaha creek. In contrast, water flow at the outlet was minimal in May 2012 at the time of the whole-bay herbicide application. All 3 bays support dense beds of EWM that impact various stakeholder uses of the water. Although water quality sampling was not a significant component of this study, data from the Minnehaha Creek Watershed District (MCWD 2013) are available for bays throughout Lake Minnetonka for 2011 through 2013 (www.minnehahacreek.org/data). These data indicate that Secchi disk transparency for the bays ranged from 2.6 to 5.2 m, chlorophyll *a* ranged from 2.0 to 5.5 μg/L, and total phosphorus (P) ranged from 15.3 to 19.7 μg/L during the 3-year study period. The water clarity indicates that macrophytes were not light-limited during the course of this evaluation. All 3 bays were recognized by the MCWD for superior water quality during the course of these trials.

Herbicide treatments and water sampling

Herbicide treatments on the 3 bays were conducted to demonstrate a bay-wide approach to EWM control. These treatments required significant planning, stakeholder approval and funding, and permitting by the Minnesota Department of Natural Resources (MDNR). Our objective was to monitor the treatment outcomes on Grays Bay that had been part of the large-scale demonstration since an original triclopyr/endothall treatment in 2008, and on 2 bays that had not previously been managed at a bay-wide scale (St. Albans and Gideons). Although the label allows triclopyr treatments at concentrations up to 2500 ug/L, bay-wide strategies selectively targeting EWM resulted in the use of much lower treatment concentrations. The treatment rates described below were based on prior mesocosm research, the desire to achieve selective EWM control, and operational budgets.

St. Albans Bay was treated on 26 May 2011 to achieve a bay-wide concentration of 310 μg/L triclopyr via the application of Renovate OTF granular herbicide (Renovate OTF, SePRO Corp., Carmel, IN). The treatment was calculated based on the entire volume of the bay. The treated area (ha), mass of product applied, target concentration in the treatment zone, bay-wide concentration, and water sample intervals are shown in Table 1. On 14 June 2013, St. Albans Bay received an application of Renovate OTF granular herbicide to achieve a bay-wide concentration of 300 μg/L triclopyr above the thermocline (Table 1).

Water samples were collected from 6 sites in the bay at mid-depth (above the thermocline) by personnel from Freshwater Scientific Services LLC and the Three Rivers Park District (Fig. 2). To monitor vertical distribution of the

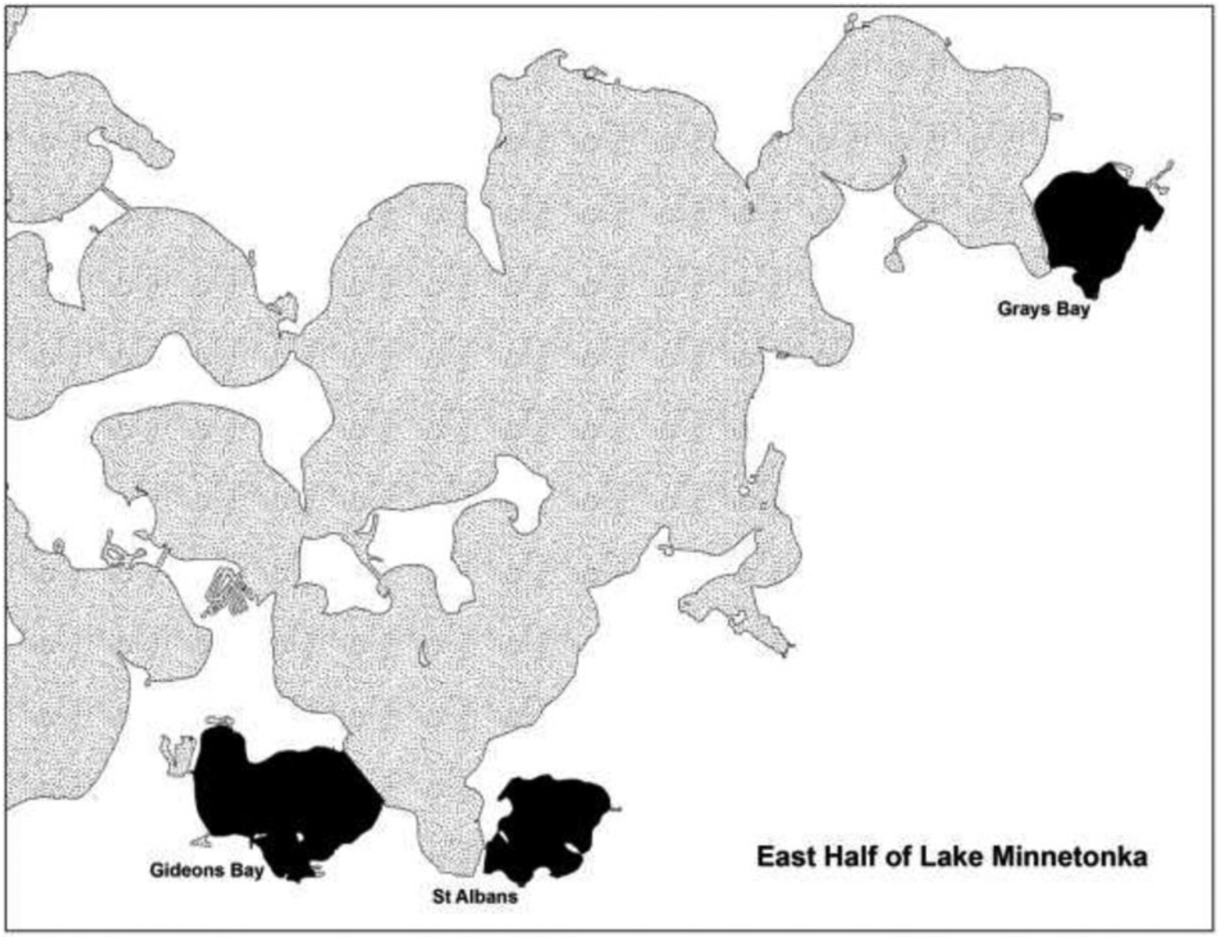

Figure 1. Location of 3 bays on Lake Minnetonka, MN sampled as part of a large-scale demonstration project evaluating bay-wide applications of triclopyr for selective control of Eurasian watermilfoil. Both St. Albans and Grays bays are connected to the main lake by small narrow inlets, whereas Gideons Bay has a much broader connection to the main lake.

herbicide, water was sampled at every meter to a depth of 7 m at the deepest sample site. Following the 2011 treatment, samples were collected in dark HPDE bottles and analyzed for triclopyr using an enzyme-linked immunoassay (ELISA) at the University of Florida Center for Aquatic and Invasive Plants (Fox et al. 2002). Following the 2013 treatment, we collected samples at the same location used in 2011. Samples were collected in dark

Table 1. Summary of treatment dates, treated area, amount of herbicide applied, target concentrations in the treatment area, bay-wide herbicide concentrations, and water sampling intervals for St Albans, Gideons, and Grays Bays following application of triclopyr.

Bay	Trmt. Date	Treated Area (ha)	Mass of Product Applied (lbs)	Target Conc. in Trmt Zone (μg/L)	Bay-wide Conc. (μg/L)	Sample Intervals (days)
St. Albans	26 May 11	40	859	750	300	0,1, 3, 6, 8, 11, 14, 19
	11 Jun 13	16	768	2000	300	0, 2, 5, 7, 14, 17
Gideons[1,2]	9 Jun 11	50	1083	1500	100	0, 1, 2, 3, 4, 6, 10
Grays	25 May 12	54	650	300	300	1, 3, 7, 11, 19

[1]A reduced scale treatment of 22 ha at 0.75 mg/L^{-1} triclopyr (a 79% reduction in herbicide use compared to 2011) was applied on June 22nd 2012, on discrete EWM beds that began to recover in late 2011.

[2]While a bay-wide concentration was not part of the original treatment plan for Gideons Bay, posttreatment water sampling indicated that a bay-wide concentration of approximately 100 μg/L was achieved.

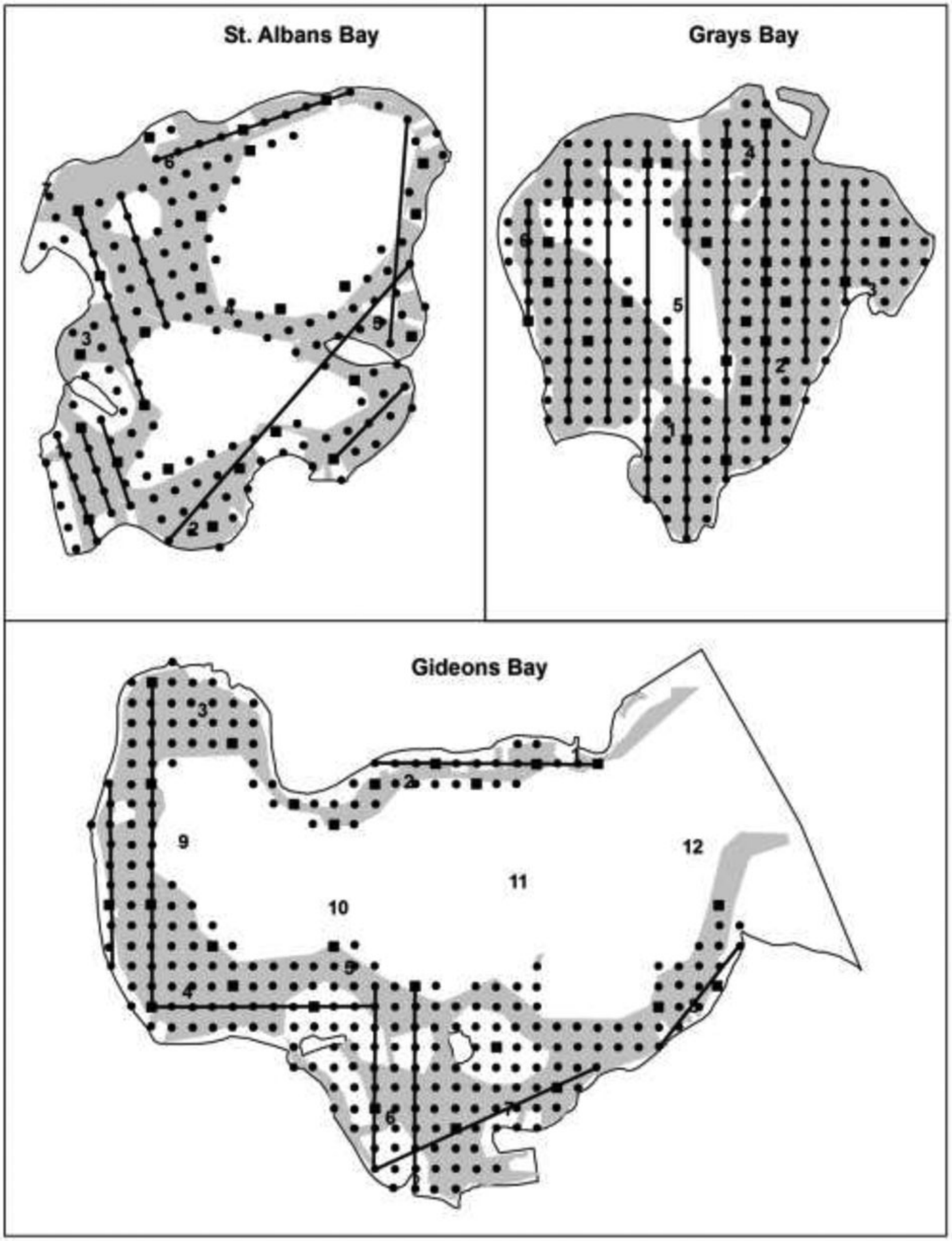

Figure 2. Sampling sites located in the 3 bays included in the demonstration project on Lake Minnetonka, MN. Numbers represent water sampling sites, shaded gray areas represent herbicide application sites, squares represent biomass collection sites, bold lines represent hydroacoustic transects, and small points are part of the point-intercept grid (<5 m) sampled to collect plant frequency data in the littoral zone.

HPDE bottles and shipped to the SePRO Corporation in Whitakers, North Carolina, for analysis with an HPLC-MS method (Fox et al. 2002).

Grays Bay was treated on 25 May 2012 with an application of Renovate OTF granular herbicide. The herbicide was calculated to achieve a bay-wide target concentration of 300 μg/L triclopyr based on the water volume measured above the thermocline (Table 1). Grays Bay has been part of the large-scale demonstration project since 2008, and it received a whole-bay treatment in May 2008 with a combination of endothall and triclopyr (1000 and 250 μg/L, respectively) and a whole-bay treatment in June 2009 with triclopyr (1000 μg/L). There were no large-scale management actions in 2010, 2011, or 2013.

Water samples for triclopyr analysis (Fox et al. 2002) were collected from 7 sites in the bay at mid-depth by personnel from the Three Rivers Park District (Fig. 2). To monitor vertical herbicide distribution, water was sampled at the deepest sample site every meter to a depth of 7 m.

Gideons Bay was treated on 9 June 2011 with an application of Renovate OTF granular herbicide. At total of 50 ha were treated to achieve a target concentration of 1500 μg/L within the treatment block (Table 1). A bay-wide sampling effort was established to determine triclopyr concentrations both within and outside of the treated areas.

Water samples for triclopyr determination (Fox et al. 2002) were collected from 12 sites in Gideons Bay (Fig. 2). Eight sites were located within treatment beds, and samples were collected at mid-depth. Four sites were located in the open water in the middle of the bay, and samples were collected at 2 m depth. Vertical water sampling was not conducted in this bay; however, a thermocline was measured in the open water sites at a depth of 5.5 m.

On 22 June 2012, Gideons Bay received an additional Renovate OTF application of 232 kg to 22 ha at a target concentration of 750 μg/L. Due to the 57% reduction in acreage and 50% reduction in herbicide use rate applied (a 79% reduction in overall herbicide use), bay-wide herbicide concentrations (expected to be <25 μg/L) were not sampled following this application. In late May 2013**,** an 8 ha application of Reward (active ingredient diquat) was applied for control of curlyleaf pondweed (CLP; *Potamogeton crispus*), and there was also no herbicide sampling associated with this application.

Macrophyte monitoring

In each bay we used the 5 m contour as the limit for sampling rooted macrophytes to ensure that the surveys covered the littoral zone as legally defined by the MDNR ($\leq$15 ft [4.6 m]). Bay-wide aquatic plant surveys were initiated during the first week of June using a grid-based point-intercept approach described by numerous investigators interested in comparing pretreatment and posttreatment conditions (Madsen 1999, Madsen et al. 2002, Nault et al. 2014). A sampling grid with 46 m spacing was utilized for all 3 study bays to match prior efforts initiated under the whole-bay demonstration effort. The number of sites visited in St. Albans, Gideons and Grays bays were 334, 559, and 268 sites respectively. Multiple sites were deeper than 5 m and were not included in the littoral analysis. Species presence was recorded at each site at depths up to 5 m in 2011 through 2013 using a rake (40 cm head) attached to an extension pole. In 2012 and 2013 qualitative rankings of EWM were assigned based on plant abundance at each site; 1 (small fragment present), 2 (multiple plants present), or 3 (dense plants growing at or near the surface). Whereas a ranking of 2 could represent a wide range of densities, rankings of 1 and 3 were of greatest interest for this study because they allowed distinguishing between fragments that are likely not visible or problematic from a stakeholder perspective versus a surface mat that is highly visible to the stakeholder. This system was based on use of earlier rake density rankings described by Hauxwell et al. (2010). To reduce subjectivity, we limited our rankings to invasive EWM and CLP. Based on significant reductions of EWM detected in the treated bays during the early August sampling in 2011, we included an additional survey in late September on one-third of the sample points in each bay to determine if EWM had potential to rebound later in the growing season. In lieu of conducting 3 sample events per year, we moved the posttreatment sample events to the third week of August for 2012 and 2013.

Percent frequency of occurrence for each species was calculated based on the total number of points where present divided by the number of points in the littoral zone ($<$5 m). The June 2011 data represented the pretreatment condition for each bay. June and August posttreatment frequency data for 2012 and 2013 were compared to data collected in 2011 using Pearson's chi-square analysis ($P \leq 0.05$; Madsen 1999, Nault et al. 2014). For 2011, analyses were conducted to compare June and August data to determine changes in frequency within the year of treatment. Thereafter, analyses were conducted to compare June data from 2012 and 2013 to the initial June 2011 data, and the August 2012 and 2013 data to the initial August 2011 data. These were 2×2 comparisons. Statistically significant reductions using chi-square were not determined for those species with frequencies that remained $<$5%. Mean submersed species per point was calculated by summing the number of native submersed species observed at each point and then dividing this number by the number of points in the littoral zone.

In addition to the plant data collected from 2011 to 2013 for this study, we reviewed plant frequency data collected in 2009 on St. Albans and Gideons bays by Blue Water Science (St. Paul, MN) using a similar point-intercept methodology, and 2010 frequency data on Grays Bay collected by the U.S. Army Engineer Research and Development Center using the same point-intercept sampling grid. These data were not included in the analysis described above; however, they provided additional information on the pretreatment conditions experienced in late spring (Jun) and summer (Aug or Sep) on these bays during a year when no treatment was conducted.

Plant biomass samples were collected from 30 randomly selected survey points in each bay at depths <5 m using a rake sampling methodology (Johnson and Newman 2011). Samples were sent to the University of Florida Center for Aquatic and Invasive Plants and sorted to species for weighing. Once sorted, plants were dried at 70 C for 72 h or more. In reviewing the variation associated with biomass data for individual species, we ultimately combined data from all species to determine if treatments impacted overall biomass. Biomass data over the 3-year period are presented as mean values for the 30 sample sites ±95% confidence intervals (CI). We also separated total native and EWM biomass to determine the impact of management on EWM contribution to overall bay biomass.

Hydroacoustic transects

At the time this project was initiated, there were ongoing evaluations on the use of low-cost sonar units to determine pretreatmemt and posttreatment conditions of percent area covered (PAC) and percent biovolume (BV) along transects to assess efficacy of large-scale hydrilla management (Netherland and Jones 2012**).** This approach seemed well-suited to address stakeholder concerns regarding impacts of whole-bay treatments on overall abundance of submersed aquatic vegetation (SAV) in Lake Minnetonka. Prior to treatment in 2011, we established 9 transects in each bay (due to technical issues, we were only able to analyze 8 transects on Gideons Bay) and collected data using a Lowrance HDS 5 recording fathometer (Lowrance HDS, Navico Inc., Tulsa, OK). Transects were established to intersect sites along the point-intercept grid map. Transects were not uniform in length and were chosen to reflect a variety of water depths and initial plant densities (Fig. 2). Hydroacoustic transect distances ranged from 207 to 995 m, averaging 376, 673, and 490 m for St. Albans, Grays, and Gideons bays, respectively. The boat running speed was 4–6 mph, and data were collected at ~15 pings/s. Detailed guidelines for collection of SAV data along transects can be found at www.cibiobase.com (cibiobase, Navico, Inc., Minneapolis, MN). We uploaded the recorded sonar files to the cibiobase site to determine presence of SAV and height of vegetation in the water column. These values were used to determine the PAC and BV along each transect. These parameters can also be calculated using a manual process that allows the operator to download the hydroacoustic data into an Excel spreadsheet and choose random points along transects to determine presence or absence of vegetation and height of vegetation in the water column (Hoyer et al. 2008). This manual process proved labor intensive, and following comparison of more than 75 transects analyzed manually versus the cibiobase website (including multiple transects from Lake Minnetonka in 2011), the differences were negligible given the efficiencies of automated analysis. All subsequent transects in 2012 and 2013 were analyzed using the cibiobase method.

The distance between the bottom acoustic signature and top of the plant canopy was recorded as the plant height for each ping. Plant heights were averaged across all pings within a GPS coordinate point. Plant heights from pings within a coordinate point that averaged <5% of depth were considered not vegetated to minimize false detections by bottom detritus. Any points that exceeded this 5% threshold were considered vegetated in percent area vegetation calculations. The minimum depth for vegetation detection was 0.73 m. For presentation of PAC and BV data, we determined the average PAC and BV ±95% CI for the 9 transects collected within each bay in June and August 2011 to 2013 to determine if treatments resulted in an overall change in either submersed plant coverage or BV.

Results

Herbicide concentrations and plant frequency data

St. Albans Bay

Following both the 2011 and 2013 whole-bay treatments in St. Albans Bay, triclopyr half-lives of 11.5 and 12.6 d were measured (Fig. 3A and 3B). Despite use of a granular herbicide, there was rapid dissipation of triclopyr throughout the epilimnion. Initial triclopyr concentrations following the 2011 application were 510 μg/L, ~30% higher than target treatment concentrations. This high concentration was attributed to the presence of a thermocline that prevented triclopyr from moving into waters <5 m in depth (data not shown). Accounting for the presence of a thermocline prior to treatment in 2013 resulted in an 11% reduction in overall herbicide use; however, measured triclopyr concentrations of 230 μg/L remained below the target concentration of 310 μg/L (Fig. 3B).

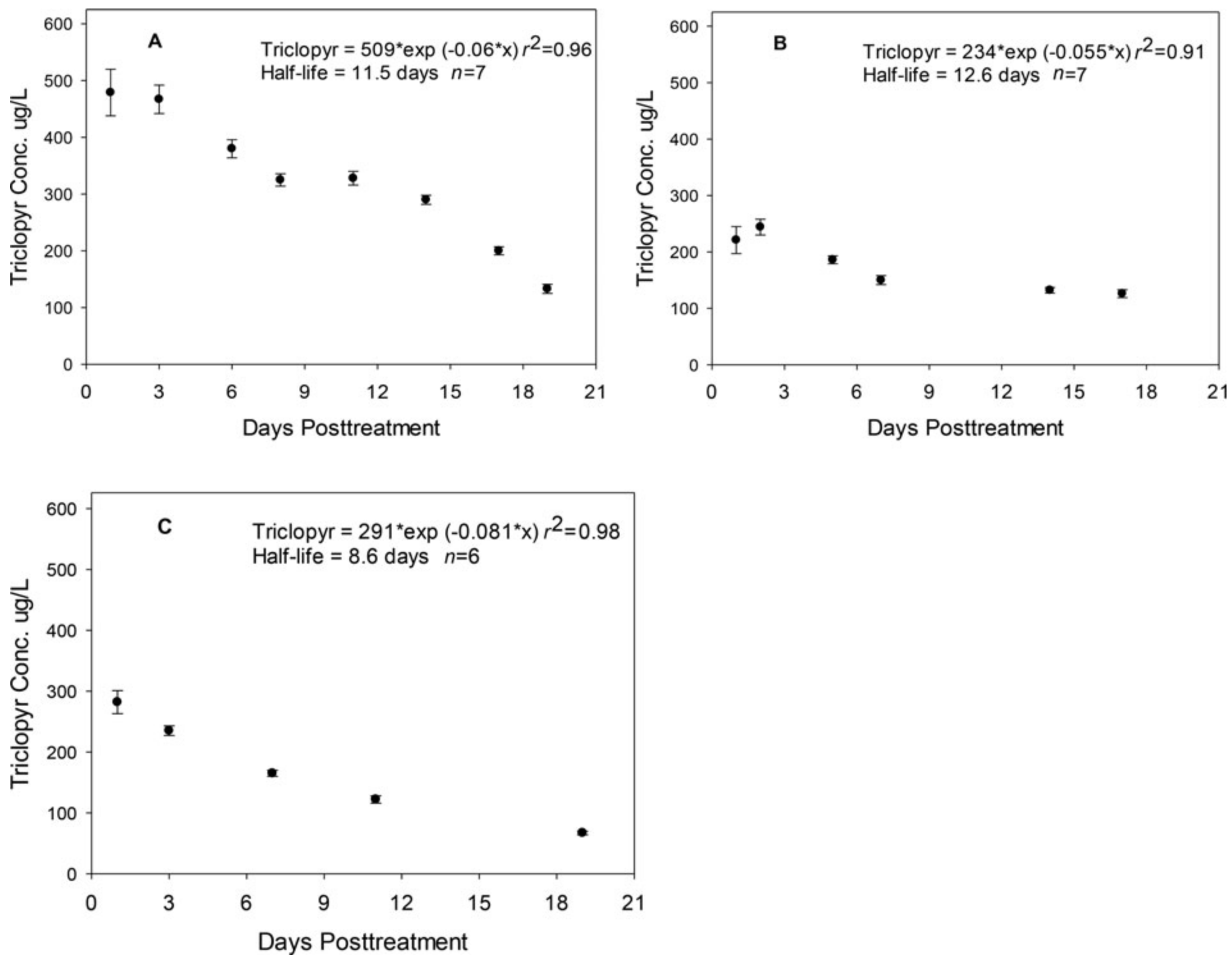

Figure 3. Triclopyr concentrations (μg/L $\pm$ 95% CI) following whole bay treatment on St. Albans Bay in (A) 2011 and (B) 2013, and in Grays Bay in (C) 2012. Each point represents the average of 7 sample sites on St. Albans Bay and 6 sample sites on Grays Bay. Bay-wide triclopyr half-lives were determined via nonlinear regression analysis.

EWM frequency declined from 54% in June to 0% in August 2011 following the whole-bay treatment in St. Albans Bay (Table 2). Additional frequency sampling during late September 2011 resulted in the detection of one small fragment of EWM (data not shown). By 2012, EWM frequency increased to 12% in June and to 38% in August. The rake density ratings for EWM in 2012 indicated that 85% of the sites in June and 65% of the sites in August were small fragments rated as a 1 (Table 3). Nonetheless by August 2012, there were numerous areas where EWM was given a rating of 3. These sites were in the same areas where EWM beds were initially dense in 2011. The subsequent 2013 herbicide treatment resulted in EWM frequency declining from 55% in June to <1% in August.

CLP showed a significant increase in frequency (6 to 53%) from June 2011 to 2012; however, data indicated that 55% of sites were rated as a 1 in June 2012. By June 2013, CLP frequency decreased to 10% despite no management efforts targeting this species. While triclopyr treatments have been associated with increases in CLP density the spring following treatment, declines in CLP density (potentially related to winter snowfall) have also been noted by other investigators (Johnson et al. 2012, Valley and Heiskary 2012).

Frequency of the native species *Elodea canadensis*, *Zosterella dubia*, and *Potamogeton zosteriformis* all significantly decreased following treatment (Table 2). These plants remained present in St. Albans Bay, and *P. zosteriformis* rebounded by June 2012. Limited impacts on native species were noted following the 2013 application. High frequency natives such as *Ceratophyllum demersum* and *Potamogeton robinsii* were not reduced by either the 2011 or 2013 application. Native species that increased following whole-bay treatments in 2011 included *Potamogeton amplifolius*, *Potamogeton richardsonii*, *Vallisneria ameri-*

Table 2. Frequency of occurrence data collected for St. Albans Bay (2011–2013). Asterisks indicate differences in frequency comparing June 2011 data to Aug 2011, June 2012, and June 2013 data, and Aug 2011 data to Aug 2012 and Aug 2013 data in a pair-wise comparison (Chi-square, $P \leq 0.05$). Whole-bay triclopyr was applied at a target concentration of 300 μg/L in late May 2011 and late June 2013. A total of 63% of 334 sample points were located in the littoral zone.

	EWM (*Myriophyllum spicatum*)	CLP (*Potamogeton crispus*)	*Native*[5]	(*Ceratophyllum demersum*)	(*Elodea canadensis*)	(*Najas flexilis*)	(*Potamogeton amplifolius*)	(*Potamogeton richardsonii*)	(*Potamogeton robbinsii*)	(*Potamogeton zosteriformis*)	(*Ranunculus longirostris*)	(*Stuckenia pectinata*)	(*Vallisneria americana*)	(*Zosterella dubia*)	Chara	Species Richness
Jun 2009[1]	62	16		41	14	3	15	25	43	13	—	—	4	16	11	—
Aug 2009[1]	70	0		34	8	4	6	11	36	10	3	—	26	23	4	—
Jun 2011	54	6		39	19	4	16	19	44	22	7	1	0	12	9	14
Aug 2011[2]	0*	0*		46	18	12	21	24	39	2*	0*	10*	35*	2*	18*	14
Jun 2012[3]	12*	53*		43	2*	1	40*	31*	57*	17	16*	16*	18*	4*	24*	15
Aug 2012	38*	2		39	8*	14	18	30	30	15	3	14	29	4	18	17
Jun 2013[3]	55	10		40	13	18*	23	44*	48	21	9	1	3	5	13	17
Aug 2013	<1	0		45	7*	21*	19	29	42	15	4	12	37	3	17	17

[1]June and September 2009 data were compiled from previous frequency surveys (Blue Water Science, St. Paul, MN) and were not included in the comparative analysis
[2]August 2011 data were compared to the June 2011 data to allow comparison of within-season treatment impacts in the first year of application
[3]June 2012 and 2013 data were compared to the June 2011 frequency data
[4]August 2012 and 2013 data were compared to the August 2011 frequency data
[5]Native plants not shown in table remained below 10% frequency included *Bidens beckii* (1–6%), *Myriophyllum sibiricum* (0–2%), *Potamogeton praelongus* (1–7%), *Potamogeton pusillus* (0–2%), *Nymphaea odorata* (4–9%), and *Utricularia* spp. (1–3%), *Potamogeton illinoensis** (1–4%). All plants above 5% frequency of occurrence were included in Chi-square analysis; however, only those above 10% frequency were included in table above.

Table 3. Density ratings of EWM density in 3 bays on Lake Minnetonka, MN, following management with triclopyr herbicide. A rating of 1 represents a small fragment and a rating of 3 represents a dense canopy of Eurasian watermilfoil (EWM) on or just below the water surface. A rating of 2 is a broad category that represents everything in between. Data are presented as the% of EWM rated 1, 2, or 3, and the total number of site rated a 1, 2, or 3.

Year	Month	Trmt. Date	Total Sites in Littoral Zone	% Sites with EWM (# of sites with EWM)	% EWM Rated 1 (# of sites rated 1)	%EWM Rated 2 (# of sites rated 2)	%EWM Rated 3 (# of sites rated 3)
St. Albans Bay							
2012	Jun		170	12 (20)	10 (17)	1 (3)	0 (0)
	Aug		170	35 (60)	23 (39)	7 (12)	5 (9)
2013	Jun	14 Jun	170	55 (95)	12 (20)	35 (60)	9 (15)
	Aug		173	1 (2)	0.5 (1)	0.5 (1)	0 (0)
Gideons Bay							
2012	Jun		293	36 (106)	17 (50)	14 (42)	5 (14)
	Aug		293	43 (125)	20 (58)	21 (61)	2 (6)
2013	Jun		293	10 (30)	7 (20)	3 (9)	0.3 (1)
	Aug		301	17 (50)	4 (12)	12 (37)	0.3 (1)
Grays Bay							
2012	Jun	25 May	235	86 (204)	8 (18)	54 (128)	24 (58)
	Aug		235	18 (42)	16 (38)	1 (3)	0.4 (1)
2013	Jun		235	3 (7)	3 (6)	0.4 (1)	0 (0)
	Aug		240	31 (74)	22 (52)	7 (16)	2 (6)

cana, and *Chara* spp. Water lilies (*Nymphaea odorata* and *Nuphar lutea*) occurred in distinct and highly visual beds on St. Albans Bay and showed strong initial injury symptoms associated with triclopyr exposure following the 2011 treatment. Despite the visual injury associated with herbicide treatment, these beds remained intact, and frequency of occurrence did not change. The number of sample points with native submersed plants, mean number of native species per point, and native species richness in St. Albans Bay were stable from 2011 to 2013 (Tables 2 and 4).

Grays Bay

In 2012, treatment of Grays Bay resulted in a triclopyr half-life of 8.6 d (Fig. 3C). Initial measured triclopyr concentrations were 290 μg/L, very close to the target bay-wide treatment concentration of 300 μg/L. Both Grays and St. Albans bays have narrow inlets and are subject to limited mixing from the larger waterbody. Extended exposure periods to low triclopyr concentrations (as noted in both St. Albans and Grays Bays) have been shown to provide control of EWM in mesocosm trials (Glomski and Netherland 2010, Netherland and Glomski 2014).

Grays Bay received no significant management in 2011, and frequency data indicated a significant expansion of EWM from 56 to 90% between June and August (Table 5). At the time of the triclopyr application in late May 2012, EWM frequency remained at 88%. In August 2012, EWM frequency was reduced to 18%; however, abundance ratings indicated that 38 of the 42 sites with EWM contained small fragments rated as 1 (Table 3). Following an extended cool spring in 2013, EWM frequency was down to 3% in June but increased to 31% by August. Multiple sites had EWM densities that received a rating of 3 during the August survey whereas CLP remained at a low density during all survey periods.

The increases and decreases in native plant frequency between June and August 2011 in this untreated bay demonstrated a challenge associated with attributing an individual species response to herbicide treatment. In both June and August of 2011, numerous areas of the bay were dominated by dense beds of EWM. High frequency native plants such as *C. demersum*, *P. richardsonii*, and *P. robinsii* showed some variation in frequency but no evidence of a response to treatment in 2012. Aside from reductions from June 2012 to August 2012 in *E. canadensis* (23 to 3% frequency) and *Z. dubia* (27 to 8%), there was limited evidence of an in-season treatment effect on native plants. Overall, native plant frequency, mean number of native species per point, and native species richness found in Grays Bay remained stable from 2011 to 2013 (Tables 4 and 5).

Gideons Bay

Behavior of triclopyr in Gideons Bay was more complex because this bay was larger and more connected to the main

Table 4. Following large-scale triclopyr treatments of St. Albans, Gideons, and Grays Bay, the % Eurasian watermilfoil (EWM) frequency, % invasive EWM biomass, % native plants biomass, % native plant frequency, mean number of native taxa per point, % area covered with plants, and % submersed plant biovolume along 9 transects (via hydroacoustics) were recorded during June and August from 2011 to 2013.

Year	Month	Trmt Date	% EWM Frequency	% EWM Biomass	% Native Biomass	% Native Plant Frequency	Mean Native Taxa Per Point	% Area Covered with Plants (±95% CI)	% Plant Biovolume (±95% CI)
St. Albans Bay									
2011	Jun	26 May	54	30	68	80	1.9	81 (9)	25 (5)
	Aug		0	0	100	93	3	85 (7)	40 (6)
2012	Jun		12	4	96	91	2.6	91 (6)	77 (6)
	Aug		38	3	97	90	2.4	84 (8)	61 (5)
2013	Jun	14 Jun	55	10	90	91	3.5	87 (5)	51 (7)
	Aug		1	0	100	93	3.3	86 (8)	53 (5)
Gideons Bay									
2011	Jun	9 Jun	49	24	73	90	2.3	80 (7)	30 (4)
	Aug		5	1	99	89	2.8	85 (9)	42 (4)
2012	Jun	*	31	8	91	89	2.5	91 (9)	72 (8)
	Aug		44	8	92	94	3.3	88 (11)	67 (7)
2013	Jun		11	8	92	91	2.5	85 (6)	38 (5)
	Aug		29	5	95	92	3.4	94 (4)	67 (7)
Grays Bay									
2011	Jun		56	27	73	86	2	70 (7)	37 (4)
	Aug		90	46	54	90	3.2	81 (8)	60 (6)
2012	Jun	25 May	88	64	36	90	2.4	87 (5)	73 (7)
	Aug		16	2	98	89	3.2	76 (8)	41 (6)
2013	Jun		3	15	85	87	3.1	81 (6)	50 (7)
	Aug		31	1	99	90	3.1	87 (7)	64 (4)

*A reduced scale treatment of 22 ha at 750 μg/L triclopyr (a 79% reduction in herbicide use compared to 2011) was applied on 22 June 2012 on discrete EWM beds that began to recover in late 2011.

waterbody. The treatment in 2011 was applied at higher rates to a series of both large and small blocks as well as small narrow shoreline strips (Fig. 2). Triclopyr concentrations in the treatment blocks were ~5–15 times below the target concentration of 1500 μg/L throughout the sampling period (Fig. 4). Although this may be partially attributed to the extended release of product (~12–36 h) from a granular herbicide, rapid dispersion of triclopyr across the large bay was observed within 1 day of application. Triclopyr concentrations in untreated sample sites in the middle of the large bay were similar to many of the targeted treatment sites by 1 day after treatment (DAT) suggesting a bay-wide exposure to low concentrations of triclopyr. As noted for St. Albans Bay, the presence of a thermocline at ~6 m prevented deep-water mixing of the triclopyr in these open water sites. Given the confounding issues with initial triclopyr behavior in this large open bay, triclopyr half-lives were determined based on data collected from day 2 to day 10. We calculated an average half-life of 3.7 d in the areas where the large-blocks were treated (Fig. 4) and an average half-life of 9.4 d in untreated open water areas (Fig. 4). Although the total days of exposure to triclopyr in this large open bay were unexpectedly similar to that calculated for the closed bays, a key difference was that the other bays reached equilibrium around 300 μg/L triclopyr whereas Gideons reached equilibrium closer to 100 μg/L. The presence of a thermocline was important in maintaining an extended exposure to low concentrations of triclopyr in Gideons Bay. Although there was no stated objective for providing extended exposures to lower concentrations of triclopyr in Gideons Bay, the data demonstrated this was essentially the outcome of the application.

A significant decline in EWM frequency occurred from June to August 2011 (49 to 5%) following the whole-bay treatment (Table 6). A subsequent sampling event in September 2011 showed that EWM frequency had increased to 18%, suggesting a late season recovery. This recovery was prominent in areas where the dense beds of EWM had been previously detected in June 2011. EWM frequency increased to 31 and 44% in June and August 2012, respectively, despite an additional June 2012 triclopyr treatment. For both 2012

Table 5. Frequency of occurrence data collected for Grays Bay (2011–2013). Asterisks indicate differences in frequency comparing June 2011 data to Aug 2011, Jun 2012, and Jun 2013 data, and Aug 2011 data to Aug 2012 and Aug 2013 data in a pair-wise comparison (chi-square, $P \leq 0.05$). Whole-bay triclopyr was applied at a target concentration of 300 μg/L in late June 2012. A total of 84% of 268 points were located in the littoral zone.

	EWM (*Myriophyllum spicatum*)	CLP (*Potamogeton crispus*)	Native[5]	(*Ceratophyllum demersum*)	(*Elodea canadensis*)	(*Najas flexilis*)	(*Potamogeton amplifolius*)	(*Potamogeton illinoensis*)	(*Potamogeton richardsonii*)	(*Potamogeton robbinsii*)	(*Potamogeton zosteriformis*)	(*Stukenia pectinata*)	(*Vallisneria americana*)	(*Zosterella dubia*)	Chara	Species Richness
Jun 2010[1]	45	0		49	21	24	12	5	48	6	0	25	11	13	39	—
Aug 2010[1]	57	0		32	20	34	9	8	51	3	0	34	28	20	27	—
Jun 2011	56	0		36	29	32	8	1	30	8	0	2	0	16	29*	13
Aug 2011[2]	90*	0		19*	6*	38	24*	17*	52*	16*	14*	40*	30*	43*	4	14
Jun 2012[3]	88*	22*		39	23	13*	41*	9*	65*	17*	14*	23*	9*	27*	18	16
Aug 2012[4]	16*	0		40	3	13*	30	14	53	15	5*	15*	31	8*	6	13
Jun 2013[3]	3	6		21*	2*	1*	19*	1	61*	7	4	1	1	2*	1	15
Aug 2013[4]	31*	4		34	3	31	26	29*	57	13	4*	33	34	26*	13	16

[1]June and August 2010 data were compiled from previous frequency surveys (Blue Water Science, St. Paul, MN) and were not included in the comparative analysis
[2]August 2011 data were compared to the June 2011 data to allow comparison of within-season treatment impacts in the first year of application
[3]June 2012 and 2013 data were compared to the June 2011 frequency data
[4]August 2012 and 2013 data were compared to the August 2011 frequency data
[5]Native plants not shown in table remained below 10% frequency included *Bidens beckii* (5–9%), *Potamogeton praelongus* (1–5%), *Potamogeton pusillus* (0–4%), *Ranunculus longirostris* (0–1%), *Nuphar advena* (1–5%), and *Nymphaea odorata* (2–6%). All plants above 5% frequency of occurrence were included in Chi-square analysis; however, only those above 10% frequency were included in table above.

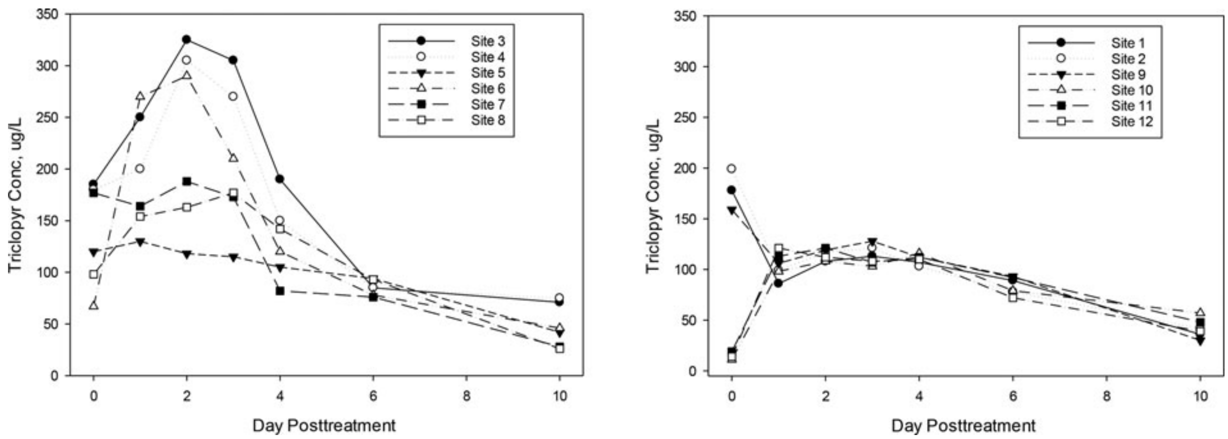

Figure 4. Triclopyr concentrations measured following treatment of 50 ha at 1500 μg/L on Gideons Bay in June 2012. The left panel represents sample sites where triclopyr was applied to larger treatment blocks. The right panel represents sample sites in the middle of bay outside of the treatment blocks (sites 9, 10, 11, and 12) and sites within a narrow treatment strip along an exposed shoreline (sites 1 and 2).

sampling dates, the majority of the EWM detected was still rated as 1 or 2 (Table 3). CLP showed an increase in frequency (8 to 39%) from June 2011 to 2012; however, only 3 sites were rated as 3. Note that the 2012 treatment was scaled back approximately 80% from the 2011 application. This reduced treatment had little impact on EWM frequency, qualitative ratings, or biomass from June to August 2012.

Native species in Gideons Bay that showed a negative response to the bay-wide exposure in 2011 were *Myriophyllum sibiricum*, *E. candensis*, *and Z. dubia* (Table 6). High frequency natives such as *C. demersum*, *P. amplifolius*, *P. zosteriformis*, *P. richardsonii*, *and V. americana* were not impacted by the application. The lack of initial treatment impact on *P. zosteriformis* in Gideons Bay contrasted with observations from Grays and St. Albans bays, suggesting that reduced bay-wide concentrations resulted in less overall injury to this plant. The number of sample points with native submersed plants in Gideons Bay remained stable through the evaluation period. In addition, native plant frequency in the littoral zone and species richness in Gideons Bay either increased or were stable from 2011 to 2013 (Tables 4 and 6). Several sites in the bay near the 10-foot contour supported dense EWM or an EWM–*C. demersum* complex. Much of the EWM recovery in this bay occurred in these deep water off-shore areas (Fig. 5).

Plant biomass

Changes in overall plant biomass within each bay generally trended toward a slight increase in total biomass between the June and August of each year, regardless of whether management was implemented (Fig. 6). In contrast, the percent of the biomass represented by EWM was highly reduced for at least 2 seasons in all 3 bays following triclopyr treatments (Table 4). Although a reduction in Grays Bay total bay biomass was observed in 2012 between the June and August evaluations, note that EWM biomass initially accounted for 64% of the biomass in the bay in June 2012 (Table 4), and loss of EWM accounted for the majority of the reduction in overall biomass. While frequency data suggested recovery of EWM in the season following treatment, the biomass data lagged behind frequency and remained low the season following a whole-bay triclopyr application (Table 4). This finding was also reflected in the rake-toss ratings that suggested values of 1 (small fragments) were often dominant in June of the season following a triclopyr application (Table 3).

From a stakeholder perspective, the low biomass of EWM and high frequency of ratings given a 1 in the season following treatment suggested that 2 years of EWM control was achieved. Plant biomass was lower in June 2013 (native plant frequency data were similar to prior years), suggesting a delayed onset for sprouting and growth following a cool spring in 2013. The biomass data refuted anecdotal claims of decreased native plant abundance in relation to management of EWM with low use rates of triclopyr.

Hydroacoustic transects

Data collected along hydroacoustic transects surveyed in each bay during the June and August suggested a general trend for increased submersed plant coverage and biovolume (height in the water column) between June and August of each year (Table 4). Notable exceptions included Grays Bay in 2012 following the triclopyr treatment and the decreased biovolume in St. Albans between June and August 2012 in a year where no treatment was implemented. As

Table 6. Frequency of occurrence data collected for Gideons Bay (2011–2013). Asterisks indicate differences in frequency comparing June 2011 data to Aug 2011, Jun 2012, and Jun 2013 data, and Aug 2011 data to Aug 2012 and Aug 2013 data in a pair-wise comparison (chi-square, $P \leq 0.05$). Large-scale triclopyr was applied to 50 ha at a concentration of 1500 μg/L in early June 2011. A total of 54% of 559 sample points were located in the littoral zone.

	EWM-I (*Myriophyllum spicatum*)	CLP (*Potamogeton crispus*)	Native[5]	(*Ceratophyllum demersum*)	(*Elodea canadensis*)	(*Najas flexilis*)	(*Potamogeton amplifolius*)	(*Potamogeton illinoensis*)	(*Potamogeton richardsonii*)	(*Potamogeton zosteriformis*)	(*Stukenia pectinata*)	(*Vallisneria americana*)	(*Zosterella dubia*)	(*Utricularia spp.*)	(*Myriophyllum sibiricum*)	(*Nymphaea odorata*)	Chara	Species Richness
Jun 2009[1]	44	1		53	9	2	12	1	15	22	1	4	12	2	5	9	27	—
Sep 2009[1]	58	1		32	4	5	6	—	7	6	1	21	15	6	7	10	22	—
Jun 2011	49	8		47	17	7	15	3	12	24	1	0	16	11	10	8	20	18
Aug 2011[2]	5	8		62*	6*	16*	18	6	16	27	11*	27*	7*	13	< 1	12	24	21
Jun 2012[3]	31*	39*		48	12	0*	27*	3	28*	22	13*	9*	3*	8	3*	8	31*	18
Aug 2012[4]	44*	0*		38*	8	13	17	7	16	23	10	22	10	11	3	7	22	20
Jun 2013[3]	11*	28*		50	13	5	19	5	24*	19	< 1	3	8	4	< 1	4	21	20
Aug 2013[4]	29*	1*		61	19*	12	19	17*	19	31	7	28	19*	9	2	8	11*	21

[1]June and September 2009 data were compiled from previous frequency surveys (Blue Water Science, St. Paul, MN) and were not included in the comparative analysis
[2]August 2011 data were compared to the June 2011 data to allow comparison of within-season treatment impacts in the first year of application
[3]June 2012 and 2013 data were compared to the June 2011 frequency data
[4]August 2012 and 2013 data were compared to the August 2011 frequency data
[5]Native plants not shown in table remained below 10% frequency included *Bidens beckii* (5–8%), *Potamogeton praelongus* (1–5%), *Potamogeton pusillus* (0–2%), *Potamogeton robbinsii* (3–9%), *Potamogeton natans* (3–8%), *Ranunculus longirostris* (0–9%), *Sagittaria* spp. (0–2%), and *Nuphar advena* (4–9%). All plants above 5% frequency of occurrence were included in Chi-square analysis; however, only those above 10% frequency were included in table above.

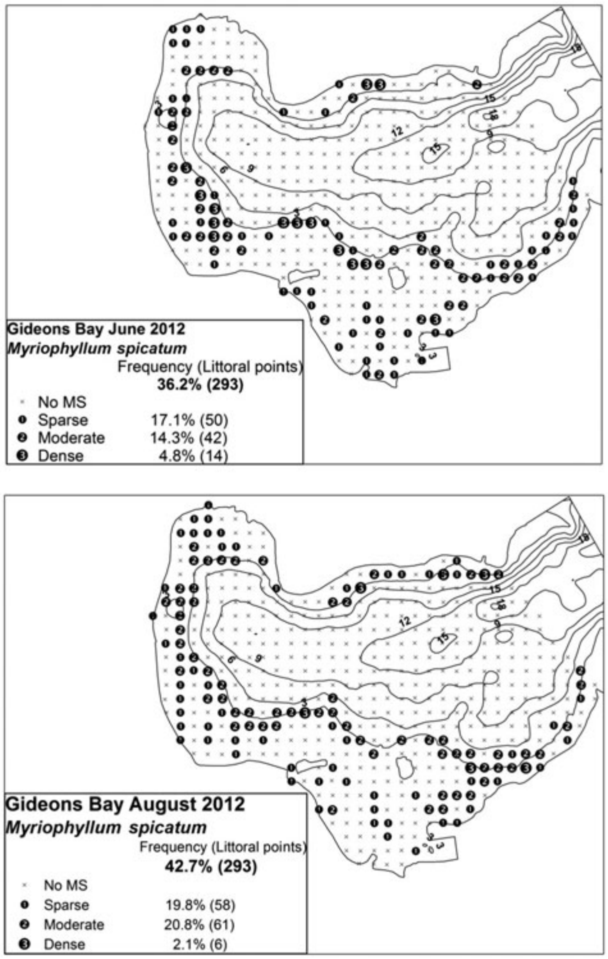

Figure 5. Point-intercept grids on Gideons Bay in Lake Minnetonka, MN, showing frequency of occurrence, spatial distribution, and rake density ratings for *Myriophyllum spicatum* in June (top panel) and August 2012 (bottom panel). Contour lines represent 3 m intervals.

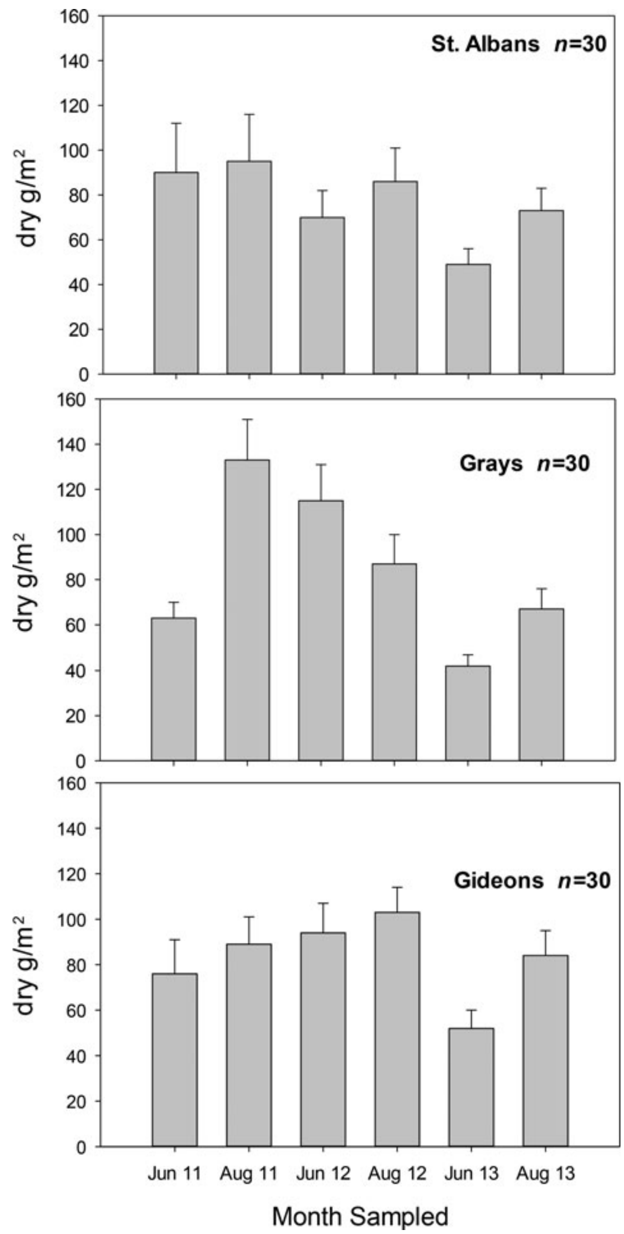

Figure 6. Submersed plant biomass for 3 bays on Lake Minnetonka, MN over a 3-year period. Bars represent the mean biomass (g dry wt.) for 30 samples ±95% CI. St. Albans Bay received whole-bay management in May 2011 and June 2013, Grays in 2012, and Gideons in June 2011.

noted earlier, the reduction in dense EWM coverage following the triclopyr treatment in Grays Bay likely explained the 43% reduction in biovolume. In contrast, the 21% reduction in biovolume observed between June and August 2012 in St. Albans Bay was not readily explained. Overall, these hydroacoustic data were in general agreement with the trends observed in total biomass data. Interestingly, both methods suggested total biomass changes between early June and late August were generally modest in nature. Despite highly favorable conditions for continued growth between June and August, the data suggested the plants in the Minnetonka Bays largely occupied their maximum space and biomass early in the growing season. The hydroacoustic data provided further evidence to refute claims of a large-scale depression in native plant abundance following large-scale management with triclopyr at low use rates. Although the acoustic data do not allow for discriminating species, when used in combination with point-intercept data, the resource manager can obtain an improved assessment for overall impacts on biovolume as well as individual species impacts.

Discussion

The bay-wide treatments were monitored as part of a demonstration program that targeted EWM in selected bays. We did not include untreated reference bays or lakes in our assessments due to various issues with finding comparable untreated bays. We recognize that factors such as year-to-year and within-season variations in temperature and weather conditions may have had confounding effects with our treatments. We included frequency data from 2009 for St. Albans and Gideons bays and 2010 for Grays Bay to provide the reader with some context regarding seasonal changes in plant frequency prior to the onset of this project (Tables 2, 5, and 6). Ice-off dates on Lake Minnetonka were 14 April 2011, 21 March 2012, and 2 May 2013. Water temperature differences likely impacted plant phenology between years. For example, in all 3 bays *V. americana* and *Stuckenia pectinatus* were either not present or present at low frequencies during the June 2011 and 2013 surveys, followed by a marked increase in occurrence by August. Because these plants have been observed to emerge later in the season, it is important to distinguish between treatment impacts and natural events (e.g., ice-off dates) that may impact onset of growth.

Overall, the results of this 3-year monitoring effort confirmed that low use rates of triclopyr for bay-wide applications can provide up to 2 seasons of EWM control. Use rates for these treatments were one-eighth the maximum label use rates. Native plant impacts were somewhat variable between bays, but injury was generally limited to a suite of triclopyr-sensitive species including *E. Canadensis*, *P. zosteriformis*, *M. sibiricum*, and *Z. dubia*. As noted with EWM, these plants showed the capacity for recovery following treatment. In the case of St. Albans and Grays bays, their enclosed nature favored extended exposure to higher concentrations of triclopyr, and these treatments generally provided 2 full seasons of reduced EWM abundance. In the case of Gideons Bay, the treatment applications in 2011 targeted dense EWM beds at a concentration of 1500 μg/L. Subsequent water sampling suggested that actual herbicide concentrations in the treatment plots were quite low and that this treatment strategy essentially resulted in a bay-wide exposure to even lower triclopyr concentrations. The Gideons Bay treatment was enhanced by the presence of a thermocline that allowed lateral spread of the herbicide across the bay versus rapid loss of the product to deeper water sites in the bay. While EWM was controlled the year of treatment, some late season recovery was noted in this bay.

The strategy of targeting bays or larger areas in lakes at reduced use rates may be well-suited to an auxin-mimic herbicide such as triclopyr. While the long-term exposure requirements for fluridone have been well documented (Netherland and Getsinger 1995, Getsinger et al. 2002), the ability to maintain a product such as triclopyr at low concentrations for 1 to 2 weeks may be more practical in many settings. When using this large-scale approach, fluridone, triclopyr, or any other aquatic herbicide is likely to impact a certain suite of sensitive native species. While the term "selective use" is often used when describing these low rate strategies, the reality that some native species are nearly as or more sensitive than the target species should be made clear to various stakeholders. As more information is gathered for the use of low rate auxin mimic herbicides, the ability to choose rates, timing, or products based on native species concerns should improve.

There has been concern expressed that low rate treatment strategies may result in selection of herbicide-resistant strains. In the case of EWM, the need to use low rate strategies for improved plant selectivity is well documented. Documentation that hybrid watermilfoils have shown increased tolerance to auxin-mimic herbicides is problematic for managers because it suggests the potential for treatments to select for these hybrids (Glomski and Netherland 2010, LaRue et al. 2013). Note that despite targeting 1500 μg/L triclopyr on EWM beds in Gideons Bay, the result was a rapid transition to bay-wide concentrations of triclopyr in the 100–200 μg/L range. The recent study by Nault et al. (2014) demonstrates the complexities associated with changing use rates. In these Wisconsin lakes, a slight change in herbicide use rates (500 vs. 300 μg/L 2,4-D) had significant impacts on both the longevity of target plant control and the impact on native species. Simply raising use rates to address concerns with hybrid watermilfoil, resistance development, or treatment longevity will likely create a suite of selectivity issues.

The source of EWM recovery following the treatments in Lake Minnetonka was not documented. Our original concern that high densities of floating fragments observed moving into these bays from other parts of the lake would rapidly recolonize the treated bays was not realized. Recovery patterns of EWM in these bays suggested that areas of the bay that had significant EWM beds prior to treatment were much more likely to support reestablishment. Although this may seem obvious, note that point-intercept methods suggested 0% frequency of EWM was achieved in many of these sites; therefore, EWM was likely either slowly recovering from buried rootcrowns or growing from fragments that became readily established once they landed in these favorable areas. Improved information regarding the source of recovery would have significant value to resource managers.

There has been some stakeholder sentiment that herbicide concentrations should be increased to potentially achieve longer-term control of EWM. Without establishing the source of recovery, it is premature to discuss increasing use rates. In the case of St. Albans Bay, we established that current treatment strategies reduced EWM frequency and biomass to zero during the treatment year, and therefore increasing use rates would seem illogical. As noted earlier, there has also been concern that these low rate treatments may be selecting for hybrid watermilfoil (*M. spicatum* × *M. sibiricum*), and there is value in determining the ratio between EWM and hybrid watermilfoil in managed and unmanaged bays.

The incorporation of biomass and hydroacoustic data into this project provided a more thorough assessment of the status of EWM and native plant responses to the treatment. Incorporating several monitoring techniques to assess treatment results can provide improved context on treatment outcomes to interested stakeholders and regulators. During this evaluation effort, there has been rapid change in the use of hydroacoustic technology to provide SAV maps of entire bays and lakes. This technology will continue to move forward, and although we did not include mapping in our original project objectives, by the end of this project we were collecting data via navigation of the point-intercept grids that allowed rapid and relatively passive whole-bay mapping of SAV in each bay. Although this technology is still being vetted and the strengths and weaknesses discussed (Valley et al. 2015, Radomski and Holbrook 2015), there is significant promise for resource managers to incorporate this technology to generate large-scale, low-cost maps of SAV distribution and abundance through time. Both of these assessment techniques suggest that low rate triclopyr applications can provide good initial control of EWM while minimizing any sustained impacts to the native plant community.

One key observation from the hydroacoustic units related to the abundance of coontail in the deep water sites in these bays. Although we were able to detect strong signatures of vegetation growing 1–2.5 m in height in water depths of 5–7 m, these extensive plant beds were almost exclusively dense monocultures of coontail, as confirmed by multiple rake tosses. This finding was not included in the frequency data; however, any future large-scale management plans need to include these large coontail beds. As a non-rooted macrophyte, coontail is capable of sequestering nutrients from the water column and thus converting them into plant biomass, providing habitat and sediment stabilization in the deeper waters of these bays. Moreover, these results suggest that plant surveys should account for maximum depth of plant colonization versus use of an arbitrary depth for sampling.

Although there has been discussion of the potential merits of early-season herbicide applications in the upper Midwest for improved selectivity (Poovey et al. 2002, Skogerboe et al. 2012), results from this trial suggest some caution should be exercised when using large-scale triclopyr. Recent mesocosm work demonstrated that under some scenarios, early-season treatments were much less effective than later-season applications (Netherland and Glomski 2014). In contrast, the native plants included in this mesocosm trial were not impacted by treatment timing with triclopyr. Early-season strategies may also be compromised by lack of a thermocline and potential rapid loss of herbicide to deeper water.

The integration of frequency, biomass, hydroacoustic data, and herbicide concentration data represented a significant investment of time in assessing a treatment outcome. Although such an extensive approach is not a good fit for every monitoring project, it does yield several complimentary pieces of information that can provide resource managers with a more complete picture of treatment outcomes. This approach is likely a good fit for large-scale, high-profile projects where stakeholders have disparate objectives. The ability to display distinct areas occupied by invasive plants and quantify their density can provide data in place of anecdotal observations.

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