J. Aquat. Plant Manage. 60: 16–22

Evaluation of florpyrauxifen-benzyl on invasive hybrid watermilfoil in a central Minnesota lake

KYLIE BLOODSWORTH CATTOOR, APRIL LONDO, JAKE WALSH, AND KEEGAN LUND*

ABSTRACT

Eurasian watermilfoil (*Myriophyllum spicatum* L.) and hybrid watermilfoil (*Myriophyllum spicatum* L. × *Myriophyllum sibiricum* Kom.; HWM hereafter) are invasive submersed aquatic plants that cause recreational and ecological disturbances in many North American waterways. In Minnesota, these problematic invasive species are primarily managed to maintain open water and to prevent spread in and among lakes. The principal management tools utilized in the state are selective herbicide treatments or mechanical cutting of the invasive plant. In spring 2018, a new selective auxin-mimic herbicide, florpyrauxifen-benzyl, was trialed and evaluated for efficacy in controlling HWM. This management effort represented the first time florpyrauxifen-benzyl was utilized in a public waterbody in Minnesota. Changes were examined in invasive and native plant frequency from June to 1 yr after treatment in two 4.9-ha study plots treated at 5.79 $\mu g\ L^{-1}$. Aquatic vegetation surveys were conducted pre- and posttreatment to assess the efficacy of the herbicide treatment in a localized area of dense HWM growth. Changes in native aquatic plant species presence were measured and overall showed few to no declines, whereas HWM decreased from 72 to 1% and 58 to 8% after treatment and remained low 1 yr after treatment. In both instances, florpyrauxifen-benzyl adequately controlled HWM and is an effective partial-lake treatment tool that should be considered for invasive milfoil management.

Key words: aquatic plant management, Eurasian watermilfoil, herbicide treatment, *Myriophyllum spicatum, Myriophyllum spicatum* × *Myriophyllum sibiricum*.

INTRODUCTION

Aquatic plants provide important structure and function to freshwater ecosystems and vary in abundance, composition, and distribution based on the overall environmental qualities and chemistries of lakes (Moyle 1945, Dar et al. 2014). Eurasian watermilfoil (*Myriophyllum spicatum* L.; EWM) is an invasive aquatic plant that has spread throughout North America within the last century (Smith and Barko 1990). EWM can form dense monotypic stands that surface mat and impede recreational use, outcompete and displace native plants, and further reduce the overall native plant diversity and abundance (Madsen et al. 1991). Additionally, EWM can hybridize with native northern watermilfoil (*Myriophyllum sibiricum* Kom.). Hybrid watermilfoil (*Myriophyllum spicatum* L. × *Myriophyllum sibiricum* Kom; HWM) can grow faster in a broader range of ecological conditions than EWM (LaRue et al. 2013, Taylor et al. 2017).

Due to their invasive nature both EWM and HWM are classified as invasive by the Minnesota Department of Natural Resources (MN DNR) and will hereafter be referred to jointly as "invasive milfoil." Invasive milfoils were first discovered in Minnesota in 1987 and are currently confirmed in 395 waterbodies (852,925 total ha). Invasive milfoils are managed at the individual lake scale by stakeholders such as lake associations and local units of government to slow the spread or reduce the nuisance of the invasive plant. Management has included eradication attempts but more commonly these efforts provide annual nuisance control at the partial-lake scale. The goals of these treatments are varied but management must provide selective control and minimize harm to nontarget plants. The MN DNR supports these efforts through providing technical assistance, coordinating cooperative research, funding grants, and regulating management activities through permitting (MINN. S. 84D.02 2020).

Management tools to control populations of invasive milfoil in Minnesota include the use of herbicides, mechanical cutting, hand removal or combinations of the aforementioned. The most common herbicides used are synthetic auxin mimics such as 2,4-D or triclopyr (Green and Westerdahl 1990, Netherland and Getsinger 1992, Glomski and Netherland 2010), contact herbicides such as diquat dibromide (Skogerboe et al. 2006) and endothall (Netherland et al. 1991), and lake-wide fluridone treatments (Netherland et al. 1993). The conventional standard of invasive milfoil control efforts are partial-lake treatments utilizing the auxin mimic 2,4-D due to its efficacy in milfoil management, cost, and selectivity.

Within the last two decades, however, numerous studies have shown that EWM and HWM may respond differently to traditional auxin-mimic treatments with some hybrid milfoils showing reduced sensitivity to 2,4-D and triclopyr (Glomski and Netherland 2010, LaRue et al. 2013). Nault et al. (2018) confirmed that large scale 2,4-D treatments in Wisconsin lakes were less effective at controlling HWM compared to EWM. Recent genetic analysis of invasive milfoils in Minnesota revealed that the majority of HWMs appear to be concentrated in the Twin Cities metropolitan area (Eltawely et al. 2020). In recent years, numerous failed treatments using 2,4-D have been reported to the MN DNR

*First, second, third, and fourth authors: Natural Resource Specialist, Natural Resource Specialist, Aquatic Invasive Species Research and Grants Coordinator, and Invasive Species Specialist, Minnesota Department of Natural Resources, 500 Lafayette Road, St. Paul, MN 55155. Current address of fourth author: Minnesota Department of Natural Resources, 1200 Warner Road, St. Paul, MN 55106. Corresponding author's E-mail: Keegan.Lund@state.mn.us. Received for publication February 17, 2021 and in revised form April 28, 2021.

in this region of the state. For lake managers, the consideration of hybrid genotypes potentially responding differently to traditional milfoil herbicide treatments is becoming an issue of increased concern.

An incipient, naturalized population of HWM was first reported in the lake and confirmed by the MN DNR in 2012. HWM, initially discovered at low abundance and distribution, quickly expanded throughout the lake in subsequent years spreading from 0.04 to 17.9 ha of HWM from 2012 to 2015 (Barr Engineering 2019). In 2015, the Lake Jane Association began partial lake management of nuisance HWM growth with 2,4-D. These treatments provided summer suppression; however distribution of HWM increased from 27.8 ha in 2017 (Barr Engineering 2019). In May of 2018, a lake-wide survey determined HWM nuisance growth was present throughout the littoral zone of the lake (Figure 1). Aquatic invasive plant control in Minnesota is limited to the 15% littoral area for pesticide use as outlined in Minnesota Rule (MINN. R. 6280.0350 2009). Given the state restrictions, the Lake Jane Association was interested in piloting new management tools that would have higher efficacy or provide longer-term control compared to the previous 2,4-D partial-lake treatments.

Florpyrauxifen-benzyl was registered with the U.S. Environmental Protection Agency for aquatic use in 2017. The herbicide is an arylpicolinate synthetic auxin, a new class of synthetic auxins that differs in binding affinity and may have higher activity and improved response compared with 2,4-D and triclopyr (Richardson et al. 2016). Preliminary studies by Netherland and Richardson (2016) demonstrated florpyrauxifen-benzyl had high efficacy for controlling hydrilla, EWM, and crested floating heart (*Nymphoides cristata* Roxb. Kuntze). Florpyrauxifen-benzyl has shown little to no activity on common native submersed and floating-leaf species through small-scale laboratory trials examining concentration exposure times (hereafter CET; Netherland and Richardson 2016, Richardson et al. 2016, Beets and Netherland 2018). Conversely, invasive milfoils are highly sensitive to florpyrauxifen-benzyl and require very low concentrations (as low as 3 $\mu g\ L^{-1}$) and short uptake times (6 h; Beets et al. 2019) compared with 2,4-D (4,000 $\mu g\ L^{-1}$, > 12 h; Green and Westerdahl 1990) and triclopyr (1,500 to 2,500 $\mu g\ L^{-1}$, > 12 h; Netherland and Getsinger 1992).

This study evaluates the efficacy and nontarget effects of the first application of florpyrauxifen-benzyl in a Minnesota lake to control expanding hybrid milfoil populations. The demonstration was repeated in two geographical areas of the lake from 2018 to 2020. This study provides new knowledge in field performance and selectivity of florpyrauxifen-benzyl supported by existing mesocosm studies (Netherland and Richardson 2016, Richardson et al. 2016, Beets and Netherland 2018).

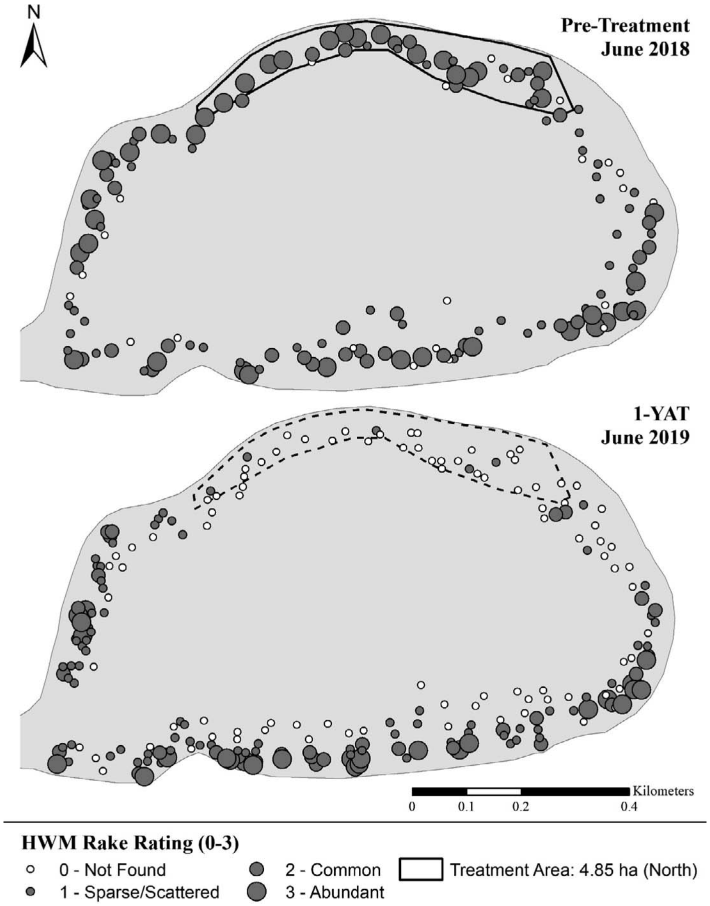

Figure 1. Lakewide qualitative assessment and rake fullness rating (0 to 3) of hybrid watermilfoil prior to treatment (top) and 1 yr after treatment (YAT; bottom) in Lake Jane. Area outlined in solid black was treated on 18 June 2018 in the north part of the lake and is displayed as a black dashed line in 2019 for the untreated year. Surveys occurred on 5 June 2018 and 10 June 2019.

METHODS

Site description

Lake Jane (45°0′56″N, 92°55′23″W) is a small (62 ha), deep (maximum depth of 11.9 m) mesotrophic lake located 14.2 km northeast of Saint Paul, Washington County, MN. Its shoreline extends 3.2 km and the littoral area is approximately 42.1 ha. Lake Jane is a part of the Valley Branch Watershed which consists of 39 major subwatersheds that drain into the St. Croix River. Lake Jane is a heavily utilized recreational lake with one public water access and is primarily surrounded by residential development. Lake Jane supports a diverse native aquatic plant community with up to 28 native and 2 invasive submersed plant species.

Herbicide treatment

In early 2018, ProcellaCOR® EC[1] (florpyrauxifen-benzyl: 2-pyridinecaroxylic acid, 4-amino-3-chloro-6-[4-chloro-2-fluoro-3-methoxy-phenyl]-5-fluoro-, phenyl methyl ester) was approved by the Minnesota Department of Agriculture as a registered pesticide for aquatic use in Minnesota. In June 2018, a 4.9-ha area was treated in Lake Jane to control invasive milfoil. In June 2019 this same method was repeated in another portion of the lake on the opposite shoreline (Figure 2). Each treatment was analyzed independently as the spatial location and timing were different

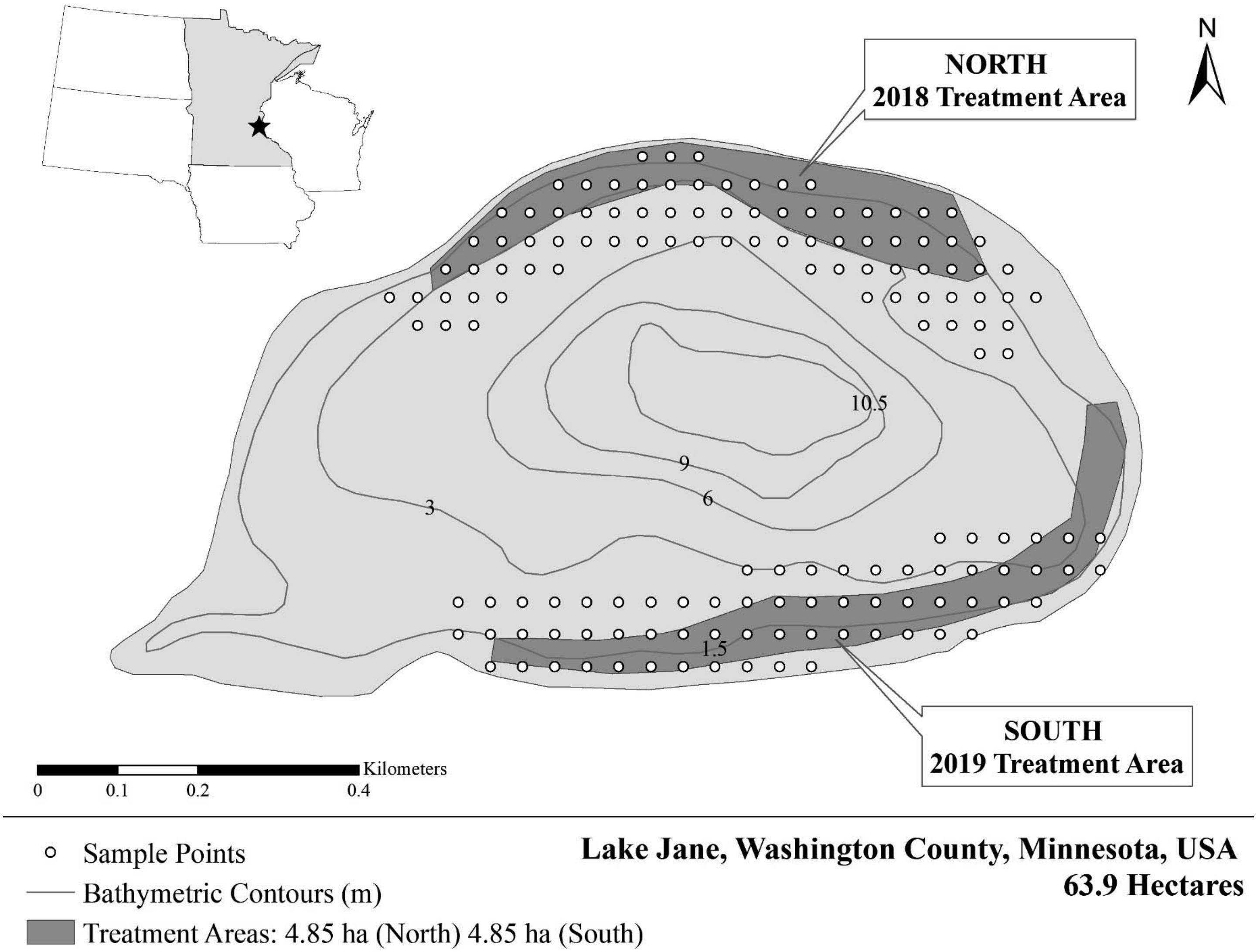

Figure 2. Regional location of Lake Jane, Washington County, Minnesota (inset). Dark shaded areas were treated with florpyrauxifen-benzyl in 2018 (4.85 ha) and 2019 (4.85 ha) denoted as "North" and "South," respectively. White solid dots are the plant sampling locations. Depth contours show lake bathymetry depth in meters.

between treatment areas. The initial treatment area extended 714 m in length and was administered along the northern shoreline with open water on 55% of the treatment edge. The second treatment area was similar and extended 885 m in length following the southern lake contours with open water on 50% of the treatment edge. Average depth of both treatment areas was 2.0 m and water temperatures at the time of treatment ranged from 23 to 25 C measured 0.3 m below the surface. A licensed pesticide applicator applied florpyrauxifen-benzyl at a rate of 5.79 µg L^{-1} totaling 22.14 L for each treatment area. Product was applied in-water with trailing hoses submerged 0.6 m below the surface with a SCS 4400 used to control application rate based on boat speed and a 15.24-m application swath width.

Aquatic vegetation surveys

In order to capture pre- and posttreatment distribution of invasive milfoil growth and also identify potential treatment areas, meandering rake surveys were conducted (spring 2018 and spring 2019). These surveys are used to identify HWM lake-wide presence prior to the study design and to qualitatively assess reductions in HWM within and outside treatment areas. These targeted surveys are completed by regularly throwing a double-sided rake within the littoral zone to precisely delineate the edges of potential dense invasive milfoil beds. While this qualitative assessment does not lend itself to statistical analysis, it provides higher-resolution data for invasive plant treatments and assessments (MN DNR 2020). To quantify treatment effect, the point-intercept method was used and both are standard practices within the MN DNR. The effects of florpyrauxifen-benzyl on aquatic plants were determined by examining the distribution of individual plant species pretreatment (12 and 14 June), posttreatment (6 wk after treatment), and 1 yr after treatment (1 YAT) using a grid-based point-intercept method (Madsen 1999, Hauxwell et al. 2010).

Point-intercept survey points were placed in an evenly spaced grid 35 m apart, which included the treated area and an 80-m buffer. The purpose of the treatment buffer was to analyze effect both within the treated area and beyond due to presumed herbicide dissipation. As florpyrauxifen-benzyl in the literature has been shown to have short uptake time, we evaluated the efficacy of these treatments at the partial-lake scale. This spacing allowed for placement of 83 points in the North study plot and 65 points in the South study plot. The purpose of the point-grid survey was to measure changes in submersed aquatic plant frequency and abundance. Frequencies of occurrence (FOO) is a percentage of how often a plant species is found calculated by the number of points where an individual plant species is present divided by the total number of points sampled in the littoral zone.

Plant samples were collected by throwing and dragging a double-sided rake 3 m along the lake bottom at each sampling point. HWM abundance was estimated on a 0 to 3 scale (scale of 0 [no plants], 1 [sparse, $<$ 25% rake coverage], 2 [common, 25 to 75% rake coverage], and 3 [abundant, $>$ 75% rake coverage]) based on rake-head coverage as a means to depict qualitative change in abundance. Aquatic vegetation was identified to the species or genus level (Crow and Hellquist 2000a,b). For each species, a Pearson's chi-square analysis ($P \leq 0.05$; Madsen 1999) was used to detect significant changes in FOO within the year of treatment (pretreatment vs. posttreatment) and 1 YAT (pretreatment vs. 1 YAT). Additionally, the average number of native species per point was calculated by summing the number of native submersed species observed at each sample point and then dividing by the number of points sampled within the littoral zone. Due to nonnormally distributed species richness data (Shapiro-Wilk normality test: $W = 0.95$, $P << 0.001$), we used pairwise Wilcoxon rank sum tests to compare richness between the pretreatment and 1-YAT surveys within the North and South study plots (all analyses performed in the statistical program R; R Development Core Team 2020).

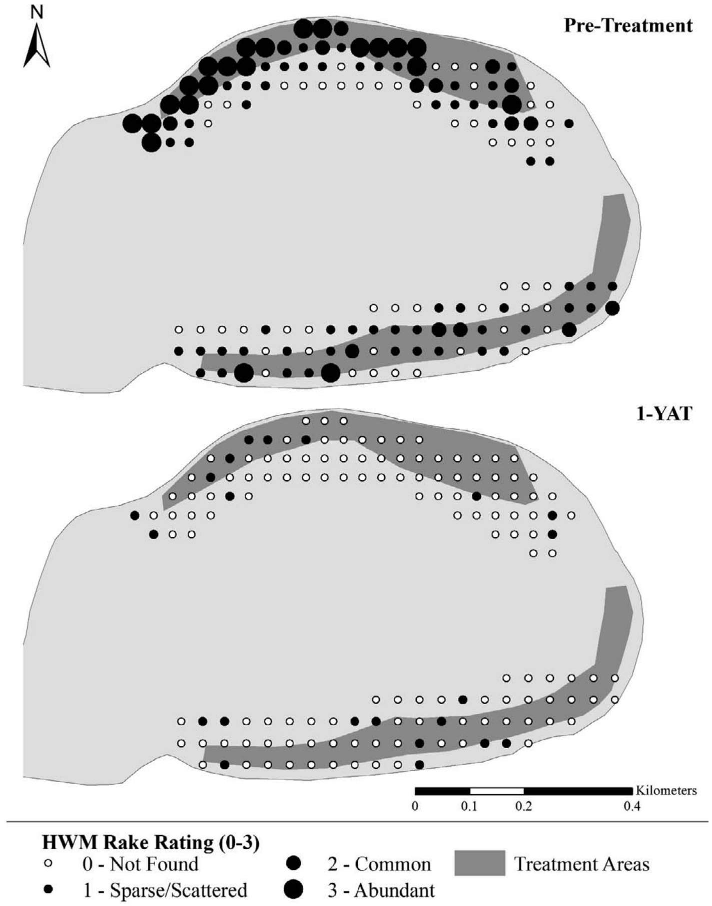

Figure 3. Spatial distribution and rake fullness rating (0 to 3) of hybrid watermilfoil (HWM) prior to treatment (top) and 1 yr after treatment (YAT; bottom) in the North and South study plots. Areas treated are shaded in dark grey. The northern treatment occurred on 18 June 2018 with a pretreatment survey on 14 June 2018 and a 1-YAT survey on 6 August 2019. The southern treatment occurred on 13 June 2019 with a pretreatment survey on 12 June 2019 and a 1-YAT survey on 20 June 2020. Some data are omitted for the South study plot due to inconsistent sampling across surveys.

RESULTS AND DISCUSSION

Efficacy of HWM

The pretreatment surveys within the North (June 2018) and South (June 2019) study plots, showed HWM at 72 and 58% FOO (Figure 3). The FOO of HWM reduced to 1 and 8% at 6 wk posttreatment, indicating the efficacy of florpyrauxifen-benzyl was high. HWM plants were devoid of leaves, possessing dark root crowns and limp stems, showing no signs of possible regrowth, and were presumed nonviable. Surveys occurring 1 YAT showed 14% (North) and 17% (South) FOO of HWM within the study plots but was still significantly lower than pretreatment conditions (Table 1).

One disadvantage of partial-lake treatments is the potential for the reestablishment of HWM via stem fragmentation of untreated HWM in other parts of the lake. Stem fragmentation of invasive milfoils is documented as a common mechanism of intra- and interlake dispersal (Kimbel 1982, Madsen et al. 1988, Smith and Barko 1990). Trace amounts of HWM plants were found and ranked as "sparse" with only one to three stems of new growth present when retrieved from a sampling rake. A follow-up lake-wide HWM assessment conducted June of 2019 showed the majority of these occurrences found outside the study plot indicating there was ample invasive milfoil present to allow for new propagules to enter previously treated areas (Figure 1). Lake Jane has a highly developed shoreline and is a heavily utilized recreational lake, which may also contribute to fragmentation, dispersal, and reestablishment of HWM throughout the lake.

Impacts on native plants

Overall, native species richness improved with the number of native submersed species increasing from 12 to 15 (North) and 11 to 14 (South) with the average number of native submersed species per point increasing from 2.4 to 3.1 (North) and 2.9 to 3.3 (South) 1 YAT. In the North study

Table 1. Frequency of occurrence percentage for all aquatic plants within the North ($N = 83$) and South ($N = 65$) study plots in Lake Jane. For the North plot, surveys occurred pretreatment (Pre) on 14 June 2018 and 1 yr after treatment (1 YAT) on 6 August 2019. For the South plot, surveys occurred Pre on 12 June 2019 and 1 YAT on 30 June 2020. Invasive species are noted in bold and listed first. The plus (+) and minus (–) indicate a significant difference ($P \leq 0.05$) between Pre and 1 YAT using a Pearson's chi-square analysis.

		North		South	
Common Name	Scientific Name	Pre	1 YAT	Pre	1 YAT
Hybrid watermilfoil[1]	***Myriophyllum spicatum* L. × *M. sibiricum* Komarov**	72	14 –	58	17 –
Curlyleaf pondweed[2]	***Potamogeton crispus* L.**	27	1 –	42	2 –
Arrowhead	*Sagittaria spp.* L.	9	2	6	2
Brown fruited rush	*Juncus pelocarpus* Mey.	0	0	2	0
Canadian waterweed	*Elodea canadensis* Michx.	61	78 +	78	85
Claspingleaf pondweed	*Potamogetan richardsonii* (Ar. Benn.)	0	2	0	0
Coontail	*Ceratophyllum demersum* L.	14	22	22	20
Fern pondweed	*Potamogeton robbinsii* Oakes	23	33	46	60
Flatstem pondweed	*Potamogeton zosteriformis* Fern.	0	1	0	2
Illinois pondweed	*Potamogeton illinoensis* Morong	0	0	9	5
Largeleaf pondweed	*Potamogeton amplifolius* Tuckerm.	9	16	0	9
Longleaf pondweed[1]	*Potamogeton nodosus* Poir.	3	14 +	0	6 +
Muskgrass	*Chara spp.* Valliant	29	33	37	29
Naiad	*Najas spp.* L.	42	33	49	23
Needle spikerush	*Eleocharis acicularis* L.	0	4	2	0
Northern watermilfoil	*Myriophyllum sibiricum* Komarov	3	1	0	0
Quillwort	*Isoetes spp.* L.	0	1	2	0
Ribbon leaved pondweed	*Potamogeton epihydrus* Raf.	0	0	5	0
Sago pondweed	*Stuckenia pectinata* (L.) Börner	6	0 –	0	0
Small pondweed	*Potamogeton spp.* L.	5	5	0	2
Stonewort	*Nitella spp.* Agardh	0	0	0	17 +
Variableleaf pondweed	*Potamogeton gramineus* L.	0	0	2	0
Water celery[1]	*Vallisneria americana* Michx.	10	27 +	0	11 +
Water stargrass	*Heteranthera dubia* (Jacqu.) Macm.	0	2	0	0
Watershield	*Brasenia schreberi* J.F. Gmel.	1	0	3	6
White water crowfoot	*Ranunculus aquatilus* L.	0	0	2	6
White waterlily	*Nymphaea odorata* Ait.	0	0	3	0
Whitestem pondweed	*Potamogeton praelongus* Wulf.	34	37	45	57
Total no. of natives submersed species present		12	15	11	14
Average no. of native submersed species per site		2.4	3.1	2.9	3.3

[1]Plant species showed significant changes in both treatments.
[2]Significant declines are attributed to postsenescence.

plot, average species richness at each site was significantly higher in the 1-YAT survey (3.1 ± 1.5 SD) than pretreatment (2.4 ± 1.4 SD; Wilcoxon rank sum test $P = 0.01$; Figure 4). In the South study plot, we found that the average native submersed species richness per site did not differ between pretreatment (3.0 ± 1.0 SD) and 1 YAT (3.3 ± 1.1 SD; Wilcoxon rank sum test $P = 0.22$; Figure 4).

Increases in mean species richness per site in the North study plot may be due to potential release from competition with HWM. In this instance, it appears that the removal of HWM had a positive impact on the presence of native species. A reduction in canopy cover and overall biomass of milfoils allows for more light penetration and increased availability of space for certain native species to thrive (Madsen et al. 1991, Wersal et al. 2010). The selective suppression of florpyrauxifen-benzyl on HWM was observed both 6 wk posttreatment and 1 YAT. Because we did not observe a significant response in the South study plot, changes in overall species richness may also be attributed to natural seasonal or spatial variation in the plant community of Lake Jane. Nonetheless, these results are consistent with native species responses measured through FOO here and reflect similar results from the literature documenting the limited effects of florpyrauxifen-benzyl on native submersed plant species (Netherland and Richardson 2016, Beets et al. 2019).

The pretreatment surveys documented 17 submersed, 3 emergent, and 2 floating-leaf native species found in either the North or South study plot or both (Table 1). An increase in submersed species was observed 1 YAT and these included claspingleaf pondweed [*Potamogetan richardsonii* (Ar. Benn.)], flatstem pondweed (*Potamogeton zosteriformis* Fern.), stonewort (*Nitella spp.* Agardh), and water stargrass [*Heteranthera dubia* (Jacqu.) Macm]. Significant increases in longleaf pondweed (*Potamogeton nodosus* Poir.) and water celery (*Vallisneria americana* Michx.) were observed during and 1 YAT in both study plots. A significant reduction in sago pondweed [*Stuckenia pectinata* (L.) Börner] occurrence was observed in the North study plot 1 YAT and has not been reported in the literature as susceptible to florpyrauxifen-benzyl (Beets and Netherland 2018). Sago pondweed is a low-occurring species in Lake Jane and may require further field investigation to evaluate possible species specific sensitivities to this herbicide. Watershield (*Brasenia schreberi* J.F. Gmel.) is considered highly sensitive to florpyrauxifen-benzyl per the product label and in areas outside of the study plots, watershield showed herbicide-related effects such as epinasty 3 wk after treatment;

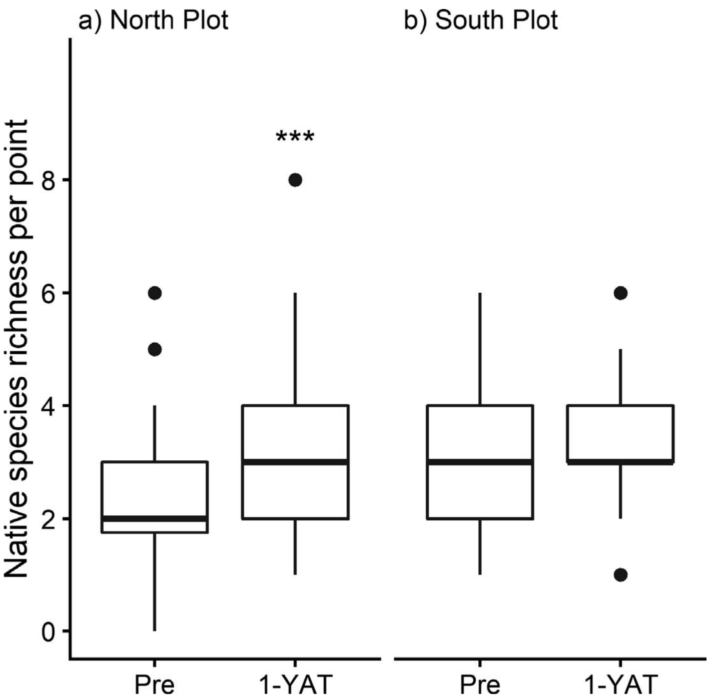

Figure 4. Boxplot comparing submersed native species richness pretreatment (Pre) and 1 yr after treatment (1 YAT) within the (a) North and (b) South study plots in Lake Jane. In each boxplot, the median is surrounded by the first and third quartile (Q1, Q3), and the minimum ($Q1 - 1.5 \times [Q3 - Q1]$) and maximum ($Q3 + 1.5 \times [Q3 - Q1]$) are whiskers with the resulting outliers represented by points. Native richness was significantly higher (***, $P < 0.05$) 1 YAT in the North plot. Native richness did not differ by survey timing in the South plot.

however, no apparent lakewide reductions in watershield frequency or distribution were noted throughout this study.

Management implications

Florpyrauxifen-benzyl is a highly effective tool for partial-lake treatments of HWM based on the results from this study. HWM was effectively controlled and killed during the year of treatment and limited HWM was observed in the study plots 1 YAT. Further, HWM occurrence remained high outside of treatment areas (Figure 1). In addition, the submersed native plant community showed no significant declines, rather the native plant community was maintained or in some cases increased in the North and South study plots after treatment. As a newly registered herbicide for invasive milfoil management, identifying potential nontarget impacts and determining long-term efficacy beyond 1 yr for partial-lake treatments will require further field evaluation of both study plots in Lake Jane.

Historically, effective tools for invasive milfoil management on the partial-lake scale have been limited. CET relationships established in the literature for traditional auxin mimics (Green and Westerdahl, 1990, Netherland and Getsinger 1992) were most effective in whole-lake milfoil management (Nault et al. 2018). Use rates have been refined in whole-lake applications where exposure can be extended for longer periods of time, potentially producing multiyear control of invasive milfoils (as low as 100 $\mu g\ L^{-1}$ at > 14 d exposure, Glomski and Netherland 2010, Nault et al. 2018). Yet whole-lake applications are not without risk to native plant communities as studies have also shown impact to particular native plant species with known auxin sensitivities (Nault et al. 2018).

Due to the regulatory restrictions in Minnesota, the majority of invasive milfoil treatments occur at the partial-lake scale. While herbicide concentrations can be applied at higher use rates to accommodate shorter contact times (e.g., 2,4-D at 2 ppm for at least 24 h, Green and Westerdahl 1990), these are often difficult to maintain in the field due to rapid dissipation of the herbicide immediately following application. In the case of Lake Jane and most lakes managed in Minnesota, partial-lake treatments are subject to open water, wind, and wave action that disperse herbicides away from the intended treatment area within hours. To our knowledge, florpyrauxifen-benzyl is the first selective herbicide to provide multiyear control of HWM in partial-lake treatments in Minnesota. Therefore, future field studies evaluating florpyrauxifen-benzyl that refine use patterns, nontarget impacts, and treatment size limitations would benefit lake managers.

The impact of invasive milfoil genetics on management outcomes is another area of research requiring further scrutiny that may benefit lake managers. Invasive milfoil in Lake Jane was later genetically confirmed as HWM. As previously mentioned, several studies and anecdotal reports show certain hybrid genetic strains have reduced sensitivity to traditional auxin mimic herbicides (e.g., 2,4-D and triclopyr) and show faster, more competitive growth rates compared to pure parental EWM (Glomski and Netherland 2010, LaRue et al. 2013, Nault et al. 2018). Beets et al. (2019) additionally demonstrated that HWM had lower sensitivity to florpyrauxifen-benzyl compared with EWM. Future invasive milfoil treatments may benefit from genetic verification coupled with herbicide sensitivity screenings to determine potential efficacy problems and contribute to alternative management solutions. Having such information, especially for lakes that share common genotypes, may help guide future management decision making.

As is evident here, invasive milfoil management at the partial-lake scale is influenced by numerous compounding factors (e.g., hybridization, CET, and within-lake dispersal) and ultimately lake managers should continually retool control efforts as outcomes are analyzed and new control tools are made available. In this study we demonstrated that florpyrauxifen-benzyl effectively provided up to two seasons of HWM control with limited significant impact to native aquatic plant species. Additional potential benefits of this herbicide as a management tool include reduced herbicide use and limited contact time compared with traditional auxin herbicides. In the future, evaluating florpyrauxifen-benzyl with a larger sample of different EWM and HWM populations in both partial- and whole-lake control scenarios is recommended. Finally, quantitative monitoring (pre- and posttreatment) remains important for evaluating management outcomes and should be incorporated into invasive plant management programs whenever feasible.

SOURCES OF MATERIALS

[1]ProcellaCOR® EC, SePRO Corporation, 11550 N Meridian St., Suite 600, Carmel, IN 46032.

ACKNOWLEDGEMENTS

The authors would like to thank Patrick Selter with PLM Lake & Land Management Corporation for performing the herbicide treatments. We would also like to thank the Lake Jane Association and LeeAnn Leitch for their support of this study. We appreciate the review of this manuscript by W. Crowell, R. Morehouse, M. Heilman, R. Thum, editor and reviewers for their expertise and valuable input. Citation of trade names does not constitute an endorsement or approval of the use of such commercial products.

LITERATURE CITED

Barr Engineering. 2019. Point Intercept Plant Surveys at Long Lake, Long Lake-Katherine Abbott Pond, Lake DeMontreville, Lake Olson, Lake Jane, Lake Elmo, and Silver Lake. https://www.vbwd.org/docs/2019-Nov__Rpt__Point-Intercept%20Plant%20Surveys__Final.pdf. Accessed April 1, 2020.

Beets J, Heilman M, Netherland MD. 2019. Large-scale mesocosm evaluation of florpyrauxifen-benzyl, a novel arylpicolinate herbicide, on Eurasian and hybrid watermilfoil and seven native submersed plants. J. Aquat. Plant Manage. 57:49–55.

Beets J, Netherland M. 2018. Mesocosm response of crested floating heart, hydrilla, and two native emergent plants to florpyrauxifen-benzyl: A new arylpicolinate herbicide. J. Aquat. Plant Manage. 56:57–62.

Crow GE, Hellquist CB. 2000a. Aquatic and wetland plants of northeastern North America. Volume 1. Pteridophytes, gymnosperms, and angiosperms: Dicotyledons. The University of Wisconsin Press, Madison, WI. 480 pp.

Crow GE, Hellquist CB. 2000b. Aquatic and wetland plants of northeastern North America. Volume II. Angiosperms: Monocotyledons. The University of Wisconsin Press, Madison, WI. 400 pp.

Dar N, Pandit A, Ganai B. 2014. Factors affecting the distribution patterns of aquatic macrophytes. Limnol. Rev. 14:75–81.

Eltawely JA, Newman RM, Thum RA. 2020. Factors influencing the distribution of invasive hybrid (*Myriophyllum spicatum* × *M. sibiricum*) watermilfoil and parental taxa in Minnesota. Diversity 12:1–20.

Glomski LM, Netherland MD. 2010. Response of Eurasian and hybrid watermilfoil to low use rates and extended exposures of 2, 4-D and triclopyr. J. Aquat. Plant Manage. 48:12–14.

Green WR, Westerdahl HE. 1990. Response of Eurasian watermilfoil to 2, 4-D concentrations and exposure times. J. Aquat. Plant Manage. 28:27–32.

Hauxwell J, Knight S, Wagner KI, Mikulyuk A, Nault ME, Porzky M, Chase S. 2010. Recommended baseline monitoring of aquatic plants in Wisconsin: Sampling design, field and laboratory procedures, data entry and analysis, and applications. Wisconsin Department of Natural Resources PUB SS-1068 2010, Madison, WI. 46 pp.

Kimbel JC. 1982. Factors influencing potential intralake colonization by *Myriophyllum spicatum* L. Aquat. Bot. 14:295–307.

LaRue EA, Zuellig MP, Netherland MD, Heilman MA, Thum RA. 2013. Hybrid watermilfoil lineages are more invasive and less sensitive to a commonly used herbicide than their exotic parent (Eurasian watermilfoil). Evol. Appl. 6:462–471.

Madsen JD. 1999. Point intercept and line intercept methods for aquatic plant management. US Army Engineer Research and Development Center, Aquatic Plant Control Technical Note M1–02, Vicksburg, MS. 16 pp.

Madsen JD, Eichler LW, Boylen CW. 1988. Vegetative spread of Eurasian watermilfoil in Lake George, New York. J. Aquat. Plant Manage. 26:47–50.

Madsen JD, Sutherland JW, Bloomfield JA, Eichler LW, Boylen CW. 1991. The decline of native vegetation under dense Eurasian watermilfoil canopies. J. Aquat. Plant Manage. 29:94–99.

[MN DNR] Minnesota Department of Natural Resources. 2020. Guidance for Delineating Invasive Aquatic Plants. https://files.dnr.state.mn.us/eco/invasives/guidance-delineating-iap.pdf. Accessed April 10, 2021.

[MINN. R. 6280.0350] Minnesota Rules, part 6280.0350, subpart 4, item A; MINN. R. 6280.0350 (2009). https://www.revisor.mn.gov/rules/6280.0350/. Accessed April 10, 2021.

[MINN. S. 84D.02] Minnesota Statutes, section 84D.02, subd 2; MINN. S. 84D.02 (2020). https://www.revisor.mn.gov/statutes/cite/84D.02. Accessed April 10, 2021.

Moyle J. 1945. Some chemical factors influencing the distribution of aquatic plants in Minnesota. Am. Midl. Nat. 34:402–420.

Nault ME, Barton M, Hauxwell J, Heath E, Hoyman T, Mikulyuk A, Netherland D, Provost S, Skogerboe J, Van Egeren S. 2018. Evaluation of large-scale low-concentration, 2, 4-D treatments for Eurasian and hybrid watermilfoil control across multiple Wisconsin lakes. Lake Reserv. Manage. 342:115–129.

Netherland MD, Getsinger KD. 1992. Efficacy of triclopyr on Eurasian watermilfoil: Concentration and exposure time effects. J. Aquat. Plant Manage 30:1–5.

Netherland MD, Getsinger KD, Turner EG. 1993. Fluridone concentration and exposure time requirements for control of hydrilla and Eurasian watermilfoil. J. Aquat. Plant Manage. 32:189–194.

Netherland MD, Green WR, Getsinger KD. 1991. Endothall concentration and exposure time relationships for the control of Eurasian watermilfoil and hydrilla. J. Aquat. Plant Manage. 29:61–67.

Netherland MD, Richardson RJ. 2016. Evaluating sensitivity of five aquatic plants to a novel arylpicolinate herbicide utilizing an organization for economic cooperation and development protocol. Weed Sci. 64:181–190.

R Development Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Richardson RJ, Haug EJ, Netherland MD. 2016. Response of seven aquatic plants to a new arylpicolinate herbicide. J. Aquat. Plant Manage. 54:26–31.

Skogerboe JG, Getsinger KD, Glomski LA. 2006. Efficacy of diquat on submersed plants treated under simulated flowing water conditions. J. Aquat. Plant Manage. 44:122–125.

Smith CS, Barko JW. 1990. Ecology of Eurasian watermilfoil. J. Aquat. Plant Manage. 28:55–64.

Taylor LL, McNair JN, Guastello P, Pashnick J, Thum R. 2017. Heritable variation for vegetative growth rate in ten distinct genotypes of hybrid watermilfoil. J. Aquat. Plant Manage. 55:51–57.

Wersal RM, Madsen JD, Woolf TE, Eckberg N. 2010. Assessment of herbicide efficacy on Eurasian watermilfoil and impacts to the native submersed plant community in Hayden Lake, Idaho, USA. J. Aquat. Plant Manage. 48:5–11.