State of Michigan's

Status and Strategy for European Frog-bit (*Hydrocharis morsus-ranae* L.) Management

Scope

Hydrocharis morsus-ranae L. (European frog-bit, hereafter EFB) is a free-floating aquatic plant native to Europe and Asia and invasive in the United States, Canada, and India (Cook and Lüönd 1982; Catling et al. 2003; Ganie et al. 2016). It was first detected outside of cultivation in Canada in 1939, was documented in the United States in 1974, and by 1996 was found in southeast Michigan (Minshall 1940; Roberts et al. 1981; Reznicek et al. 2011). European frog-bit has the potential to negatively impact the quality and use of wetlands and is considered a high-risk invasive species by the Michigan Department of Agriculture and Rural Development (Weibert 2015). This document was initially a product of an Environmental Protection Agency – Clean Water Act Section 205(j) grant between the Michigan Department of Environmental Quality (DEQ) and Central Michigan University (CMU) in 2014 (Hackett et al. 2014). It was significantly revised in 2018 as part of Great Lakes Restoration Initiative (GLRI) Grant Agreement F16AP01019 between the United States Fish and Wildlife Service (USFWS) and DEQ (Cahill et al. 2018). In 2021, it was updated for the purposes of:

- Consolidating current science-based knowledge relative to the biology and ecology of EFB.
- Summarizing scientific literature and research efforts that inform management options for EFB in Michigan.
- Identifying future directions for research relative to successful EFB management in Michigan.

This document references peer-reviewed journals and publications. Any chemical, company, or organization that is mentioned was included for its involvement in peer-reviewed, published, publicly shared information, not to imply endorsement of the chemical, company, or organization.

Biology and Ecology

I. Identification

European frog-bit is an herbaceous, free-floating, freshwater aquatic plant. Its leaves are entire, cordiform (heart-shaped) or slightly orbicular (circular), and arranged in a floating rosette (Figure 1). Its leaves are 0.47 – 2.4 in (1.2 – 6 cm) long and 0.51 – 2.5 in (1.3 – 6.3 cm) wide. Some leaves may be emergent when growing in dense floating mats. Its petioles (leaf stalks) are slender and have two translucent stipules at their base (Figure 2).

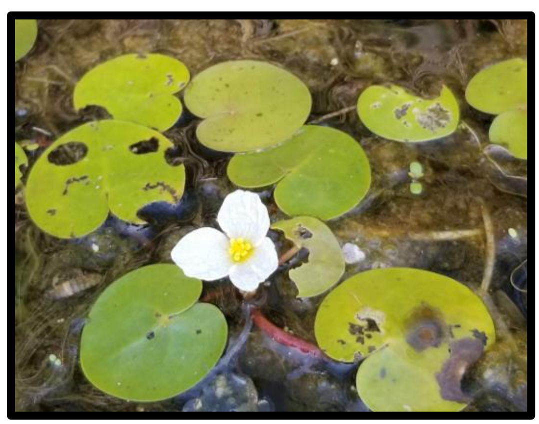

Figure 1. European frog-bit (*Hydrocharis morsus-ranae* L.) in bloom.

European frog-bit's roots hang below the rosette and are suspended in the water. In shallow water and on exposed muck, its roots may partially penetrate the substrate. Its roots are covered in fine root hairs and can be up to 19.7 in (50 cm) long (Cook and Lüönd 1982).

Figure 2. The arrows point to the two transparent leaf-like stipules at the base of the petioles of European frog-bit (*Hydrocharis morsus-ranae* L.). American frog-bit (*Limnobium spongia* (Bosc) Rich. ex Steud.) has only one stipule. Photograph by Paul Busselen, courtesy of Go Botany, New England Wildflower Society

European frog-bit's flowers have white to greenish sepals, white petals, and a yellow center (Figure 1). The petals of female flowers may have a reddish tinge. Flowering is erratic in its native and invasive range and may be influenced by small fluctuations in temperature (Cook and Lüönd 1982). Its flowers are short-lived and bloom from June to September in North America (Gardner 2008; Cahill et al. 2021a).

European frog-bit's fruits are green globose (spherical) berries that contain as many as 74 seeds (Scribailo and Posluszny 1985). Its seeds are dark brown, broadly ellipsoidal, 0.04 – 0.05 in (1 – 1.3 mm) long, and covered with blunt spiraling tubercles. European frog-bit also produces specialized vegetative reproductive structures, called turions (Figure 3), at the nodes of stolons. Turions are ellipsoidal and typically produced in late summer and early fall in its native and invasive range (Cook and Lüönd 1982; Catling et al. 2003).

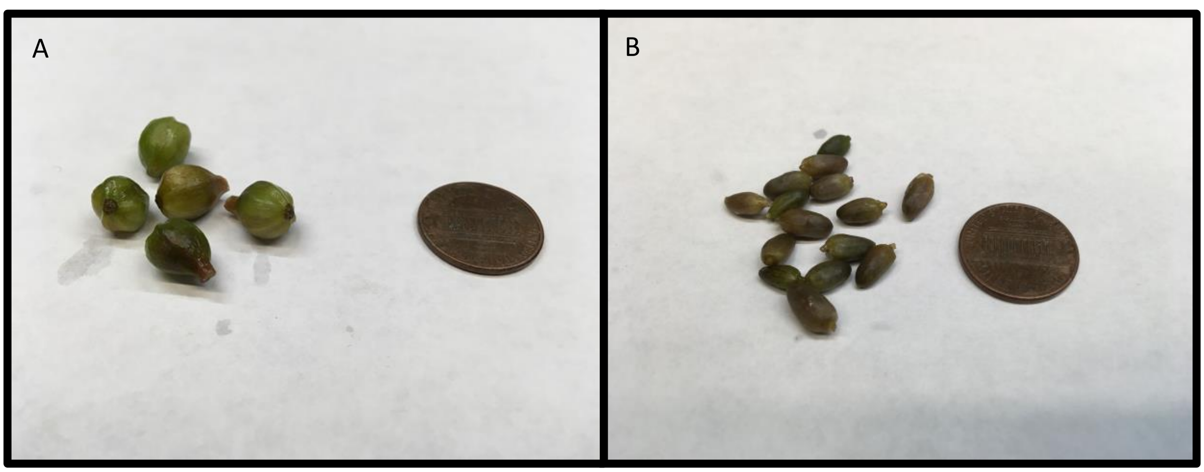

Figure 3. European frog-bit (*Hydrocharis morsus-ranae* L.) A) fruits and B) turions.

Species that can be mistaken for EFB include: American frog-bit (*Limnobium spongia* (Bosc) Rich. ex Steud.), American white waterlily (*Nymphaea odorata* Aiton), and water-shield (*Brasenia schreberi* J.F. Gmel). *L. spongia* is not found in Michigan and has only one stipule on its petioles compared to EFB's two (Figure 2). *L. spongia* also has larger aerenchyma (spongy tissue) spaces on the undersides of its leaves (Catling and Dore 1982). *N. odorata* has circular leaves that are 8 – 12 in (20.3 – 30.5 cm) long and have a distinctive slit on one side compared to EFB's 0.47 – 2.4 in (1.2 – 6 cm) long heart-shaped leaves. *B. schreberi* can be distinguished from EFB by its maroon flowers and oval leaves that have a coating of gelatinous slime on their underside.

European frog-bit seedlings can be difficult to distinguish from duckweed species: common duckweed (*Lemna minor* L.) and greater duckweed (*Spirodela polyrhiza* (L.) Schleiden). The roots of duckweed species arise from the underside of their leaves while the roots of EFB arise from the base of a rosette or leaf petiole (Catling et al. 2003).

II. Detection

European frog-bit is typically found in calm to slow moving waterbodies in areas protected from wind and wave action (e.g., shorelines, wetlands, inlets). In the Great Lakes region, dense floating mats of EFB are typically found in the floating vegetation zone or in sheltered openings of the emergent vegetation zone (Figure 4; Halpern 2017; Wellons 2018). European frog-bit detection efforts are best conducted from early summer to early fall when its leaves are floating on the surface of the water (Catling et al. 2003; Cahill et al. 2021a). When growing in the floating and submerged vegetation zones, EFB can typically be detected via visual searches from a boat or land. More intensive sampling may be required for detection when EFB is growing among emergent vegetation.

Figure 4. Floating mat of European frog-bit (*Hydrocharis morsus-ranae* L.) in a canal on Harsens Island, Michigan.

Remote sensing technology can be used to detect and distinguish EFB. In the South Nation River in Ontario, EFB mats were distinguished at an overall accuracy of 72.8% (Kappa 66.0%) for unsupervised fuzzy and object-based image analysis (Proctor et al. 2012). The unsupervised analyses occasionally mistook EFB for other free-floating and floating-leaved plants (i.e., *N. odorata*, *L. minor*, yellow water-lily (*Nuphar lutea* (L.) Sm.), coontail

(*Ceratophyllum demersum* L.), floating pondweed (*Potamogeton natans* L.)) and sometimes for mixed forest along the shoreline. Supervised processing performed better (overall accuracy 87.4%, Kappa 84.3%), but required image processing experts to develop classification rules at every step. Proctor et al. (2012) did not report the time required for supervised or unsupervised processing of imagery.

Typically, a patch of EFB would have to be 5 pixels in size to be detected with remotely sensed imagery. Unmanned aerial systems would likely be required to gather imagery at a resolution fine enough to detect smaller EFB patches or individual EFB plants. It is also difficult to detect EFB interspersed among emergent wetland vegetation (e.g., cattails (*Typha* spp. L.), common reed (*Phragmites australis* (Cav.) Trin. ex Steud.), bulrush (*Schenoplectus* spp. (Rchb.) Palla)). Researchers at Boise State University are currently evaluating the use of multi-temporal UAV-collected imagery for EFB detection (Cahill and Monfils 2021a).

Genetic markers have been developed for detecting genetic material shed by EFB into the environment and these markers have been used to successfully identify EFB from laboratory-generated water samples (Scriver et al. 2015). Given the near shore habitat that EFB occupies and its easily distinguishable features, it may not be efficient to utilize this approach for EFB detection. However, it could improve the true positive detection of EFB when it is growing undetected in stands of emergent and floating vegetation or in an inaccessible portion of a waterbody. This approach could also reduce the need for labor-intensive field surveys until EFB is positively detected in an area.

III. Life History and Spread/Dispersal

European frog-bit's sexual reproductive strategy is not fully understood. Some have reported that it has both monoecious (possessing male and female flowers) and dioecious (possessing male or female flowers) genotypes (Catling and Dore 1982; Cook and Lüönd 1982; Scribailo and Posluszny 1984; Martine et al. 2015) while others have reported that it is only monoecious (Lindberg 1873; Dore 1968; Halpern 2017). Lindberg (1873) and Cook and Lüönd (1982) suggested that EFB might appear dioecious due to the difficulty of untangling individual plants from one another.

European frog-bit flowers are imperfect (possessing either male or female reproductive structures) and short-lived, lasting one day once they open (Cook and Lüönd 1982; Catling et al. 2003). Flowering is erratic and may be influenced by small fluctuations in temperature (Cook and Lüönd 1982). The ideal temperature for flowering is unknown. Not all EFB individuals or colonies flower in a given year (Catling et al. 2003). Male and female flowers produce nectar that is visited by a variety of insect pollinators (Scribailo and Posluszny 1984). After the female flower is fertilized and the fruit begins developing, the peduncle recurves so that the fruit ripens in the water (Cook and Lüönd 1982; Scribailo and Posluszny 1984). Once ripe, internal pressure causes the sides of the fruit to split, releasing the seeds into the water. The seeds sink to the substrate and remain there until germination begins (Scribailo and Posluszny 1984; Scribailo and Posluszny 1985).

In addition to sexual reproduction, EFB can reproduce asexually. Clonal daughter plants, called ramets, are produced from terminal buds at the tips of stolons (Sculthorpe 1967). At the end of the growing season, EFB produces modified stolon buds, called turions (Cook and Lüönd 1982). Turions ripen at the water's surface, overwinter on the substrate, and typically germinate and sprout at the water's surface when the water warms (Adamec 2011).

Native Range:

In its native range, EFB is a summer annual that can reproduce sexually and asexually (Cook and Lüönd 1982). In an oxbow lake in southern Poland, EFB biomass and density increased from May through September and declined in October (Toma 2013). Seed production is considered rare (Arber 1920; Sculthorpe 1967; Cook and Lüönd 1982; Preston and March 1996). Seeds collected in Europe germinated when water temperature reached 59°F (15°C; Serbanescu-Jitariu 1972 in Catling et al. 2003) but little else is known regarding seed germination in the native range.

Asexual reproduction through stolon buds and turions is considered the primary form of reproduction in EFB's native range. When water temperature is between 59°F (15°C) and 77°F (25°C) turion development is initiated by photoperiod. The higher the water temperature, the shorter the photoperiod needed to initiate development. When water temperatures are below 50°F (10°C) and above 77°F (25°C) turion initiation becomes independent of photoperiod. Below 50°F (10°C) turion development does not occur and above 77°F (25°C) turion development is immediate (Cook and Lüönd 1982).

Turion freezing temperature and survival are influenced by exposure to frost. In the Czech Republic, dormant turions that were hardened off by natural winter frosts, similar to what they would experience in the fall prior to breaking away from stolons, had a 76% survival rate. Non-hardened turions that were kept at 36.5°F (2.5°C), representative of the water temperature at the bottom of lakes and rivers during winter in temperate climates, froze at 25.5°F (-3.6°C) and did not germinate (Adamec and Kučerová 2013).

Water temperature and light are the primary drivers of turion germination (Terras 1900; Arber 1920; Sculthorpe 1967). In the United Kingdom, germination rate was greatest at 68°F (20°C) and did not occur below 50°F (10°C; Richards and Blakemore 1975). Germination rate was highest with greater light intensity and duration and germination did not occur in the dark.

Invasive Range:

Similar to its native range, EFB in North America can reproduce sexually and asexually. At Rondeau Provincial Park in southern Ontario, EFB started flowering in mid-June, reached peak bloom in mid-July, and was mostly finished by mid-August (Scribailo and Posluszny 1984). Homoptera (Aphidae) and Diptera (*Hydrellia* and *Notiphila* spp.) were most frequently observed visiting the flowers but hoverflies (Syrphidae) and sweat bees (Halictidae) were considered the primary pollinators. In Michigan, EFB has been documented flowering from June to September (Cahill et al. 2021a; Monfils et al. 2021). Researchers at Lake Superior

State University are assessing the phenology of EFB in Munuscong Bay, Michigan (Cahill and Monfils 2021a).

The reproductive status of EFB populations in North America has been studied in Michigan, New York, and Ontario. Flowering and fruiting were documented across EFB's distribution in Michigan (Cahill et al. 2021a; Monfils et al. 2021). Greater than 90% of seeds collected from populations in Michigan germinated in *ex-situ* trials (Cahill et al. 2021a). In Lake Champlain, New York, artificially pollinated plants produced fruits, indicating sexual reproduction is possible but it was not observed in the field (Martine et al. 2015). In Lake Opinicon, Ontario, EFB mats of intermediate density (~2000 g/m^2) produced the most seeds (2000 – 3000 per m^2). In a laboratory experiment, 69% of seeds collected from Lake Opinicon germinated when exposed to a 15-hour photoperiod and a 79/59°F (26/15°C) temperature regime for 12 months. Although the Lake Opinicon population produced abundant viable seeds, few seedlings were found in the lake. A similar situation was observed in a Lake Erie coastal wetland; 250 seeds per m^2 were produced but only two seedlings were found the following growing season (Scribailo and Posluszny 1984).

Turion production is considered EFB's primary strategy for persisting overwinter in its invasive range. Turions typically develop on stolon nodes in the late summer and early fall, detach from the plant in the fall, and overwinter on the substrate (Catling and Dore 1982; Catling et al. 2003). In Michigan, EFB rosettes with turions have been documented on exposed substrate as early as June and July (Cahill et al. 2021a; Monfils et al. 2021). In 2020, turion deposition in the Saginaw Bay occurred from August 11 to November 18. An average of 49.8 turions per 0.0324 m^2 (equivalent to 1,537 turions per m^2) were produced (Cahill et al. 2021a). In Lake Opinicon, turion production reached as high as 1,000 turions per m^2 (Burnham 1998). In coastal wetlands of the Upper St. Lawrence River, turion production differed between vegetation zones, with a median of 208 per m^2 in the emergent vegetation zone, 32 per m^2 in the floating vegetation zone, and in all but one sample that contained 80 turions, zero in the submerged vegetation zone (Halpern 2017).

In southeastern Ontario, turions germinate from late April to early May and by mid-May plants are fully developed (Catling et al. 2003). The rosette that develops from a single turion can give rise to over 10 ramets, each of which can produce 10 turions of their own (Scribailo and Posluszny 1984). A single turion can grow to cover an area of 1.2 yd^2 (1 m^2) in just one season (Cook and Lüönd 1982; Catling et al. 2003).

Little research has been conducted on the long-term viability of EFB turions. Burnham (1998) found that turions decayed after being kept at 39.2°F (4°C) for 16 months. Arber (1920) stated that turions can remain viable for up to 2 years but did not describe the methodology of the experiment. Turions collected from the Saginaw Bay of Michigan remained viable after one-week and one-month of desiccation but did not survive a six-month exposure to winter conditions (Cahill et al. 2021a).

In addition to differences in vegetative reproduction, Halpern (2017) noted differences in EFB density and biomass accumulation between wetland vegetation zones and in a controlled setting with different combinations of light and depth. Density was greatest in the emergent and floating vegetation zone and significantly less in the submerged vegetation zone. Shoot, root, and total biomass were greatest in the floating vegetation zone and similar between the other zones. European frog-bit produced the most biomass in full sun and shallow (11.8 in; 30 cm) to moderate depths (17.7 in; 45 cm). Halpern (2017) also found differences in EFB morphology and nutrient content between wetland zones: roots were longest in the floating and submerged vegetation zones, root:shoot ratio was highest in the floating vegetation zone, leaves were narrowest in the submerged vegetation zone, and nitrogen content was highest in the emergent vegetation zone.

European frog-bit's free-floating habit allows it to drift on the water's natural flow within and between connected waterbodies. Turions and seeds may also drift with flowing water. Much of EFB's initial spread in North America is attributed to drifting (Catling and Dore 1982). Some EFB colonies may have intentionally or accidently been introduced by duck hunting clubs to provide refuge and food for waterfowl (Catling and Dore 1982). European frog-bit plants, turions, and seeds may be transported on boats, trailers, and other boating equipment that isn't properly washed and dried following use in an infested waterbody. This mode of dispersal is attributed to much of EFB's recent spread (Catling et al. 2003) but has not been investigated. Wildlife can also contribute to the spread of EFB. Plants can become entangled in the bills and feet of waterbirds and subsequently transported to new waterbodies (Catling and Dore 1982). Seeds and turions may be transported through endozoochory (transport in the digestive tract); however, their viability after passing through the digestive tract is unknown. Although it is difficult to determine, the improper disposal of waste from water gardens and aquariums may also contribute to EFB's spread (Catling and Dore 1982; Catling et al. 2003; Maki and Galatowitsch 2004).

IV. Habitat

Native Range:

European frog-bit is native to Europe and Asia (Figure 5; Cook and Lüönd 1982). It is critically endangered in Spain and the Czech Republic, endangered in Norway and Switzerland, vulnerable in the United Kingdom, and protected in parts of France (Lansdown 2014). Habitat loss is regarded as the primary cause of EFB's decline in Switzerland and the United Kingdom (Sager and Clerc 2006). Elsewhere in its native range it is widespread and abundant (Lansdown 2014).

European frog-bit tolerates a wide range of climatic conditions across its native range (Catling et al. 2003). It is found in fresh to slightly brackish water with low salinity (≤ 2 ppt; Luther 1951 in Sculthorpe 1967) and favors mesotrophic to oligo-mesotrophic conditions (Cook and Lüönd 1982; Murphy 2002). It has also been found in eutrophic conditions (Suominen 1968; Pitkänen et al. 2013). It occurs in calm to slow moving water with high conductivity (>300 µS cm^{-1}), near neutral pH (7.0 – 8.0), and organic substrate (Husák and Gorbik 1990; Murphy 2002; Sager and Clerc 2006; Steffen et al. 2014). European frog-bit inhabits small waterbodies and inlets, bays, and coves of larger waterbodies and is frequently found in ditches, channels, canals, backwaters, peat diggings, and oxbow lakes (Cook and Lüönd 1982; Belyakov and Garin 2018; Meseldžija et al. 2019; Gecheva et al.

2019; Rybak et al. 2020). Associated species include *Typha* spp., tufted sedge (*Carex elata* Mack.), grass-like sedge (*Carex panicea* L.), swamp sawgrass (*Cladium mariscus* (L.) Pohl), *L. minor*, floating fern (*Salvina natans* (L.) All.), *S. polyrhiza*, *N. lutea*, arrowhead (*Sagittaria sagittifolia* L.), common bladderwort (*Utricularia vulgaris* L.), *P. natans*, small pondweed (*Potamogeton pusillus* L.), shining pondweed (*Potamogeton lucens* L.), reed manna grass (*Glyceria maxima* (Hartm.) Holmb.), star duckweed (*Lemna trisulca* L.), *C. demersum*, and water soldiers (*Stratiotes aloides* L.; Husák and Gorbik 1990; Murphy 2002; Sager and Clerc 2006; Steffen et al. 2014; Efremov et al. 2019).

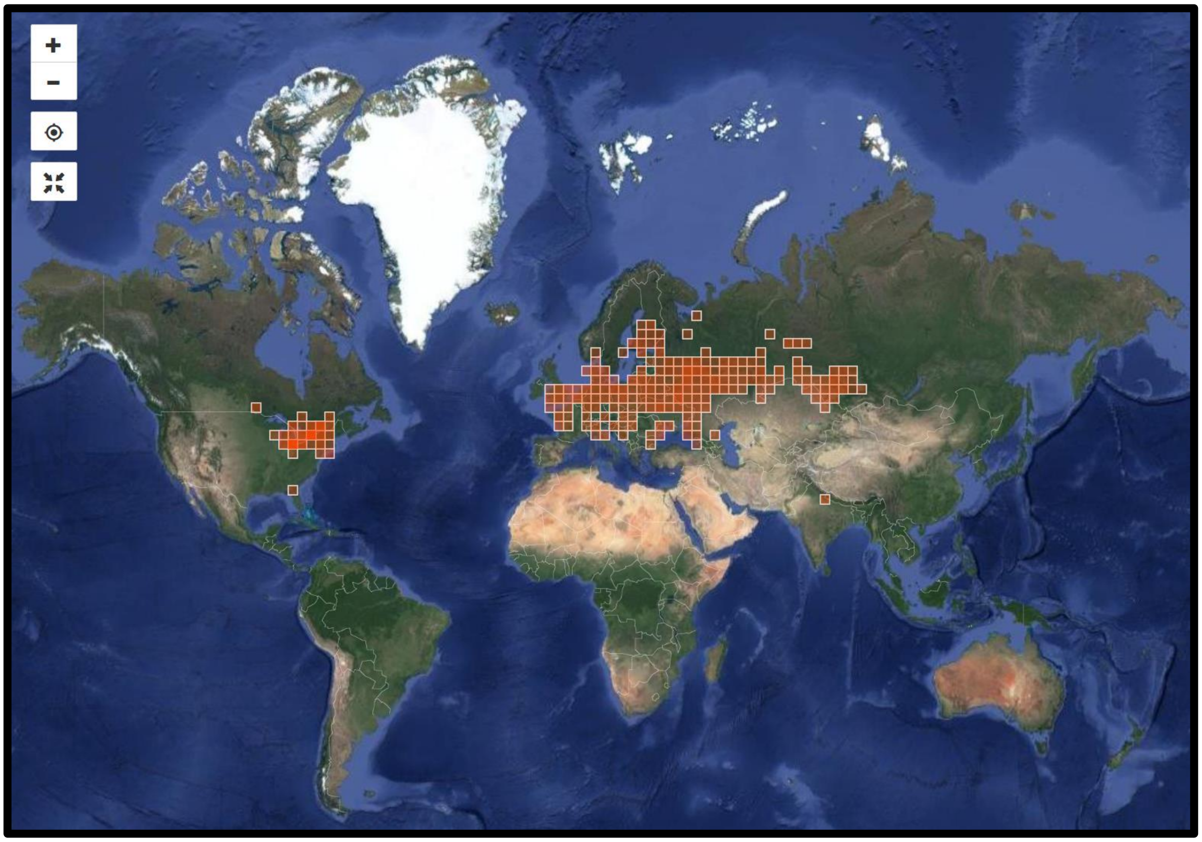

Figure 5. Global distribution of European frog-bit (*Hydrocharis morsus-ranae* L.). Source: iNaturalist, downloaded 01 September 2021.

Invasive Range:

In North America, EFB has been documented in Ontario, Quebec, New York, New Jersey, Vermont, Ohio, Michigan, Maine, Pennsylvania, Washington state, Florida, and Wisconsin (Dore 1968; Roberts et al. 1981; Catling et al. 2003; Gardner 2008; Marsden and Hauser 2009; Lamont et al. 2014; Jacono and Berent 2021; MISIN 2021; iNaturalist 2021; Figure 6). Similar to its native range, the EFB established in North America appears tolerant to a wide range of climatic conditions (Catling et al. 2003). It often occurs in nutrient rich water but a range of trophic levels, including oligotrophic conditions, are suitable for establishment (Catling et al. 2003; Zhu et al. 2008). European frog-bit typically occurs in waterbodies with a near neutral pH (6.5 – 7.8; Catling and Dore 1982).

European frog-bit can be found in wetlands associated with lakes, rivers, and streams, as well as artificial waterbodies such as canals, channels, ditches, and ponds (Catling and Dore 1982; Catling et al. 2003). Within wetlands, it can colonize the emergent, floating, and submerged vegetation zones. In a laboratory experiment conducted by Halpern (2017), EFB biomass production was greatest in full sun exposure and 11.8 – 17.7 in (30 – 45 cm) of water. In the Cedar Point National Wildlife Refuge, EFB was collected on wet muck at the edge of a diked marsh. Additional colonies were documented along the marsh's shoreline as well as floating within the marsh (Gardner 2008).

In Great Lakes coastal wetlands, EFB is associated with *T. angustifolia* and hybrid *Typha* (Halpern 2017; Monks et al. 2019). Stands of *T. angustifolia* and hybrid *Typha* may shelter EFB from wind, wave, and seiche activity and their decay may provide EFB with a readily available nutrient source (i.e., nitrates, ammonium, phosphorus). Other species associated with EFB in North America include *L. minor*, northern watermilfoil (*Myriophyllum sibiricum* Kom.), Eurasian watermilfoil (*Myriophyllum spicatum* L.), *P. pusillus*, Vasey's pondweed (*Potamogeton vaseyi* Robb.), *S. polyrhiza*, *U. vulgaris,* broadleaf cattail (*Typha latifolia* L.), *P. australis*, native *Phragmites* sp., and reed canary grass (*Phalaris arundinacea* L; Spicer and Catling 1987; Catling et al. 1988; Catling et al. 2003; Monks et al. 2019; Central Michigan University Herbarium – CMC).

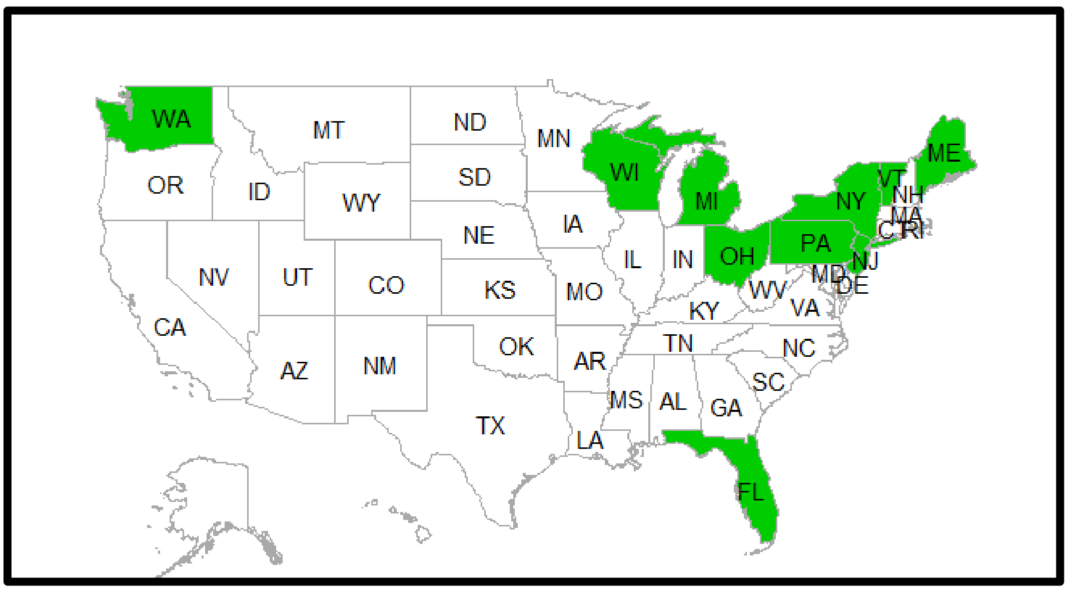

Figure 6. State-level distribution of European frog-bit (*Hydrocharis morsus-ranae* L.) in the United States.

V. Effects from EFB

An impact assessment of established nonindigenous species in the Great Lakes Basin ranked EFB's potential environmental and socio-economic impacts as moderate and its potential beneficial impacts as low (Sturtevant et al. 2014). A risk assessment conducted by the Michigan Department of Agriculture and Rural Development classified EFB as a high-risk invasive species for its establishment/dispersal, impact, and geographic potential (Weibert 2015). A survey in Michigan found that conservation professionals and recreational waterbody users aware of EFB were most concerned with potential EFB impacts to native wetland flora and fauna (Cahill et al. 2021b). The impacts of EFB on Great Lake coastal wetlands is currently being evaluated by researchers at Central Michigan University, Michigan Natural Features Inventory, and Lake Superior State University (Cahill and Monfils 2021a).

a. Negative Effects

European frog-bit can form dense, entangled, floating mats that cover the surface of the water. These mats have the potential to negatively impact the human use of waterbodies by clogging navigation and irrigation channels and inhibiting recreational and commercial activities (Catling et al. 2003). These impacts may result in decreased waterfront property values (Zhu et al. 2018). Research is needed to quantify the social and economic impacts of EFB invasion.

Dense mats of EFB have the potential to reduce light, temperature, dissolved oxygen, and nutrient availability in the water column (Zhu et al. 2008; Johnson 2018; Monfils et al. 2021). The annual decomposition of EFB mats may further deplete dissolved oxygen, which can be harmful to fish and macroinvertebrates (Catling et al. 2003).

Studies examining the impact of EFB on aquatic plant communities have yielded inconsistent results. Catling et al. (1988), Zhu et al. (2014), and Monfils et al. (2021) documented reduced aquatic plant diversity associated with high abundance of EFB. Halpern (2017) found that EFB surface coverage and aquatic plant species richness and diversity were negatively correlated in one of six Lake Ontario wetlands studied. When samples from all six wetlands were pooled, EFB surface coverage and aquatic plant diversity had a significant, weak, negative correlation (Halpern 2017). Thomas and Daldorph (1991), Houlahan and Findlay (2004), and Trebitz and Taylor (2007) found no effect of EFB on aquatic plant species richness, cover, or diversity. Further studies are needed to elucidate the impact of EFB on native aquatic plant communities at varying densities and spatial scales.

Dense mats of EFB may also negatively impact fish, wildlife, and invertebrate communities. Catling et al. (1988) observed fewer snails, crustaceans, and insect larva on EFB mats compared to stands of native aquatic plants in New York and Ontario. In Lake Oneida, New York, EFB altered the macroinvertebrate community assemblage (Zhu et al. 2015). In a Lake Erie coastal wetland, Johnson (2018) observed a greater abundance of mobile orders of macroinvertebrates in EFB dominated areas compared to areas not dominated by EFB. A preliminary study in Munuscong Bay documented fewer fish species and lower fish abundance in areas invaded by EFB compared to areas without EFB (Daly 2016). More fish species tolerant of low dissolved oxygen levels and fewer species sensitive to low dissolved oxygen levels were documented in areas dominated by EFB compared to areas dominated by other aquatic plant species and open water in Lake Erie and Lake Huron coastal wetlands (Johnson 2018; Monfils et al. 2021). Further research is needed to evaluate the potential for EFB to impact native aquatic fauna.

European frog-bit may alter aquatic fungal and bacterial communities. A study in Poland found fewer fungi species on EFB than several aquatic plant species, including *L. minor* and *C. demersum* (Czeczuga et al. 2004). Dissolved organic matter leached from EFB negatively impacted bacterial growth in a controlled setting (Anesio et al. 2000). Catling et al. (2003) reported that no bacteria species have been documented on EFB.

b. Positive Effects

European frog-bit may benefit some wildlife and invertebrate species by providing food and refuge (Catling et al. 2003; Zhu et al. 2018). In Lake Oneida, New York, areas with EFB had greater chironomid abundance and benthic macroinvertebrate diversity compared to areas without EFB (Zhu et al. 2015).

European frog-bit's ability to store pollutants in its tissue makes it a viable bioindicator and candidate for phytoremediation. Several studies have demonstrated EFB's uptake of heavy metals (e.g., lead, zinc, nickel, copper) and nutrients (e.g., nitrogen, phosphorus) from polluted environments (Maleva et al. 2004; Polechońska and Samecka-Cymerman 2016; Polechońska et al. 2017; Engin et al. 2017; Polechońska and Samecka-Cymerman 2018; Gałczyńska et al. 2019; Polechońska and Klink 2021). Caution must be exercised when using EFB for phytoremediation given its capacity for rapid reproduction and dispersal and potential social, economic, and environmental impacts.

European frog-bit contains chemical compounds thought to have medicinal uses, including spermidine and saponins (Villanueva et al. 1985; Kotelnaya et al. 2019).

Current Status and Distribution in Michigan

European frog-bit was introduced into North America in 1932 when it was intentionally planted in an arboretum in Ottawa, Ontario. It was first detected outside of the arboretum in 1939 in the Rideau Canal, which was connected to the original planting site (Minshall 1940). From there EFB spread into the St. Lawrence and Ottawa Rivers (Minshall 1940; Dore 1968). By 1972, it was found in eastern Lake Ontario (Catling and Dore 1982). European frog-bit was first reported in the United States in New York in 1974 (Roberts et al. 1981). It has since been documented in Ontario, Quebec, New York, New Jersey, Vermont, Ohio, Michigan, Maine, Pennsylvania, Washington state, Florida, and Wisconsin (Dore 1968; Roberts et al. 1981; Catling et al. 2003; Gardner 2008; Marsden and Hauser 2009; Lamont et al. 2014; Jacono and Berent 2021; MISIN 2021; iNaturalist 2021).

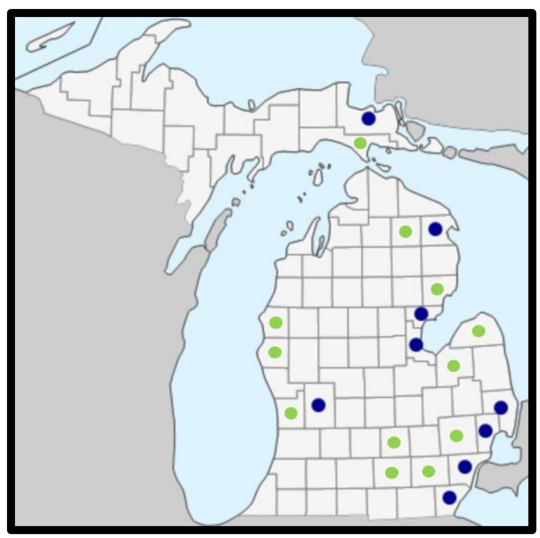

Figure 7. Blue dots indicate counties in Michigan where a specimen of European frog-bit (*Hydrocharis morsus-ranae* L.; EFB) has been collected and included in Michigan Flora. Green dots indicate counties where EFB was documented by MISIN, but not by Michigan Flora. County map developed by Michigan Flora online (Reznicek et al. 2011)

European frog-bit was first documented in Michigan in 1996 at the Ford Yacht Club in Wayne County (Reznicek et al. 2011). It is now established in 21 counties (Figure 7). It is established along the Huron-Erie Corridor in Monroe, Wayne, Macomb, and St. Clair counties; Saginaw Bay in Arenac, Bay, Tuscola, Huron, Iosco counties; Thunder Bay in Alpena County; northwest Lake Huron in Mackinaw County; Munuscong and Raber Bay in Chippewa County; Grand River in Ottawa County; Pentwater River in Oceana County; and Lincoln River in Mason County. Inland populations of EFB are also established in Alpena, Montmorency, Kent, Oakland, Wayne, Ingham, Jackson, and Washtenaw counties.

Management of EFB

The European Frog-bit Collaborative was established in Fall of 2018 to advise the development of the EFB Adaptive Management Framework. Meetings and correspondence of the EFB Collaborative include a diverse network of federal and state agencies, Cooperative Invasive Species Management Areas, non-governmental organizations, and universities. Meetings of the EFB Collaborative guided and informed the development of a coordinated and assessable EFB Adaptive Management Framework (Cahill and Monfils 2021b). The Adaptive Management Framework aims to eliminate EFB's impact to the Great Lakes Basin ecosystem and economy by preventing spread to new areas of the state and reducing the impacts of established infestations. The first complete implementation of the EFB Adaptive Management Framework occurred from February 2020 to March 2021. The second year of EFB Adaptive Management Framework implementation was initiated in March 2021.

I. Prevention

According to the modeling efforts of the Michigan Department of Agriculture and Rural Development, all of Michigan and 79% of the United States is suitable for EFB establishment (Weibert 2015). Since EFB spreads quickly once it is established, it is imperative to take the proper measures toward prevention. European frog-bit is a prohibited species in Michigan under the Natural Resources and Environmental Protection Act 413 of 1994. Under this act it may neither be grown nor sold in the state. Additionally, the transport and sale of EFB are prohibited in Washington, Oregon, Idaho, Minnesota, Wisconsin, Indiana, New York, Vermont, New Hampshire, and Maine (Halpern 2017).

European frog-bit may act as an aquatic hitchhiker, so boaters, anglers, and hunters can unintentionally contribute to its spread. The Clean Boats, Clean Waters program, a cooperative program of Michigan Lake and Stream Associations, Inc. and Michigan State University Extension, produced a video that provides instructions for decontaminating equipment to reduce the spread of invasive species such as EFB between waterbodies. The following actions may prevent and limit the dispersal of EFB:

- Build a coalition of local, state, and Great Lakes regional partners to monitor for EFB and other aquatic invasive species
- Build a coalition of states that have classified EFB as a restricted or prohibited species

- Identify and monitor waterbodies that have a high-risk of invasion using known distribution and dispersal knowledge
- Provide boat washing stations for high-traffic public lake accesses
- Develop and sustain a water recreation vehicles and trailers inspection program
- Increase stakeholder awareness of available prevention and control methods
- Actively manage sites where EFB is found

II. Management/Control

It is imperative that treatment of invasive aquatic plants is paired with a scientifically sound monitoring program that is designed to assess the management objectives. The EFB Collaborative developed a standard tool to evaluate EFB status and progress towards management objectives, and track baseline data on EFB phenology, habitat associations, and occurrence at managed sites (Cahill and Monfils 2020). A data management system to enter, store, and manage pre- and post-treatment monitoring data is available via the MISIN Treatment Tracker application.

Consideration of EFB's distribution in wetlands, lakes, canals, and other waterbodies is crucial when developing a management plan. European frog-bit can become increasingly difficult to manage once it is established throughout the major wetland vegetation zones (Halpern 2017). Dense mats in the floating vegetation zone are often the target of management actions; however, turions and free-floating plants can reestablish from the emergent and submerged vegetation zones, respectively. Free-floating plants in the submerged vegetation zone are likely to disperse to new areas through wind, waves, and current and should therefore be considered a management priority (Halpern 2017). A coordinated management strategy that targets EFB in the emergent, floating, and submerged vegetation zones simultaneously may be required to reduce EFB's reestablishment and dispersal potential.

Treatment timing is another important consideration when developing a management plan for EFB. To reduce its reestablishment and spread potential, management actions should be conducted prior to seed and turion development.

Management of other invasive aquatic plants may facilitate the expansion and growth of EFB infestations. The formation of dense EFB infestations in areas previously managed for *P. australis* has been documented in Lake Erie coastal wetlands (Judd and Francoeur 2019; Robichaud and Rooney 2021). European frog-bit has been observed growing in the open water and among the dead stalks of *T. angustifolia* and *Typha x glauca* in Munuscong Bay and *P. australis* in Saginaw Bay following management of these emergent species. Management techniques or plans that target EFB and these emergent invasive plants simultaneously may provide more effective EFB control (Halpern 2017; Wellons 2018; Monks et al. 2019).

Physical and chemical management techniques have been used to control EFB infestations in Michigan (Table 1). Outside of Michigan, manual removal has been the most commonly used method for EFB control. In Vermont, manual removal, supplemented with metal and bamboo rakes, was used to control EFB in the Charlotte Town Farm Bay and Shelburne Lower LaPlatte (Lewis Creek Association 2011; Lewis Creek Association 2013). Manual removal has also been used on small isolated EFB populations in the Adirondack region of New York (Oles and Flint 2007).

Table 1. Summary of management techniques used to control European frog-bit (*Hydrocharis morsus-ranae* L.) in each infested region of Michigan and the year that management started in each region. Techniques with a (+) between them indicate they were part of an integrated management strategy, not that they were implemented at the same time.

Region	**Managed Since**	**Control Technique(s) Used**
Saginaw Bay (Arenac, Bay, Tuscola, Huron, and Iosco counties)	2010	Manual removal, diquat treatment + manual removal
Eastern Upper Peninsula (Chippewa and Mackinaw counties)	2013	Manual removal
Northeast Lower Peninsula (Alpena and Montmorency counties)	2015	Manual removal, diquat treatment
West Michigan (Kent, Ottawa, Oceana, and Mason counties)	2016	Flumioxazin treatment, flumioxazin treatment + diquat treatment + manual removal, manual removal
Southeast Lower Peninsula - Inland (Macomb, Oakland, and Wayne counties)	2019	Flumioxazin treatment, manual removal
Mid Lower Peninsula (Ingham, Washtenaw, and Jackson counties)	2020	Manual removal
Southeast Lower Peninsula - Coastal (Macomb, Monroe, St. Clair, and Wayne counties)	Unknown	Unknown

a. Chemical

Newbold (1975) and (1977) list diquat, paraquat, chlorthiamid, terbutryne, cyanatryn, and dichlobenil as providing effective single season control of EFB. Hauteur and Canetto (1963) reported that amitrole controlled EFB in ditches and canals of France but required retreatment the following year. In Europe, diquat at 1 and 10 ppm and endothall at 5 ppm were effective for controlling EFB in stagnant drainage ditches (Holz 1963; Renard 1963). Diquat applied at concentrations of 74 – 1,153 μg/L significantly reduced EFB biomass relative to an untreated control in a mesocosm experiment (Sesin et al. 2018). Diquat and flumioxazin reduced EFB abundance in the year of treatment relative to untreated control comparisons in Michigan (Monfils et al. 2021). Only three of the aforementioned herbicide active ingredients (i.e., diquat, endothall, flumioxazin) are approved for aquatic use by the United States Environmental Protection Agency (EPA). Further research is needed to evaluate the efficacy and optimal use patterns of chemical treatments for controlling EFB.

Many herbicides are used to control the closely related *L. spongia*, but it is uncertain if EFB is equally susceptible. Herbicides commonly used for *L. spongia* control include diquat, imazapyr, penoxsulam, imazamox, triclopyr, and 2,4-D (Madsen et al. 1998). Ongoing research by University of Hartford and SePRO is investigating the efficacy of flumioxazin, florpyrauxifen-benzyl, and imazamox for EFB control in lab and greenhouse trials (C. McGlynn, New York State Department of Environmental Conservation, personal communication). A summary of herbicide active ingredients that are approved for aquatic use by the EPA and have shown some effectiveness for EFB or *L. spongia* control is in Table 2.

Table 2. Summary of effective herbicide active ingredients for European frog-bit (*Hydrocharis morsus-ranae* L.; hereafter EFB) control to date that are approved for aquatic use by the United States Environmental Protection Agency. Also included are herbicide active ingredients that are used for American frog-bit (*Limnobium spongia* (Bosc) Rich. ex Steud.) control that could be effective against EFB. For each active ingredient, example trade names, whether it's approved for aquatic use in Michigan (MI), whether EFB is listed on its label, advantages, disadvantages, and the cited literature are listed. Directions on the pesticide label should always be followed and the state Departments of Environment, Great Lakes, and Energy and Agriculture and Rural Development should be consulted for up to date regulations, restrictions, permitting, licensing, and application information. Table modeled after the MNFI Glossy Buckthorn Factsheet (MNFI 2012).

Herbicide	Approved in MI	Listed on Label	Pros	Cons	References
Endothall (e.g. Aquathol®)	Yes	No	• 5 ppm controlled EFB in stagnant drainage ditches	• Has not been systematically evaluated for EFB control in field or lab trials • May harm non-target species (Broad-spectrum herbicide) • May be toxic to aquatic organisms • Prohibited for use in waterbodies < 600 ft from a potable water intake • May have post-treatment restrictions on water use	(Holz 1963; WDNR 2012)
Diquat (e.g. Reward®)	Yes	No	• 1 and 10 ppm controlled EFB in stagnant drainage ditches • 74 – 1,153 µg/L significantly reduced EFB biomass in mesocosm trials • 0.94, 1.87, and 3.75 lb/ac reduced *L. spongia* biomass by 99 – 100% in lab trials • Provided a single season reduction in EFB abundance at a site in Michigan • Lists *L. spongia* on label	• May harm non-target species (Broad-spectrum herbicide) • Toxic to aquatic invertebrates • Ineffective in turbid water or conditions with a lot of wave action • Post-treatment restrictions on drinking and irrigation water	(Holz 1963; Renard 1963; WDNR 2012; Sesin et al. 2018; Monfils et al. 2021)
Triclopyr (e.g. Renovate®)	Yes	No	• 0.76, 1.51, 3.02 lb/ac reduced *L. spongia* biomass by 78 – 95% in lab trials • Less harm to non-target species (Selective herbicide) • Lists *L. spongia* on label	• Has not been systematically evaluated for EFB control in field or lab trials • Post-treatment restrictions on potable and irrigation water	(Madsen et al. 1998; WDNR 2012)
2,4-D (e.g. Navigate®)	Yes	No	• 0.96, 1.93, and 3.85 lb/ac reduced *L. spongia* biomass by 53 – 80% in lab trials • Less harm to non-target species (Selective herbicide)	• Has not been systematically evaluated for EFB control in field or lab trials • May be toxic to fish and invertebrates • May have post-treatment restrictions on swimming and irrigation water	(Madsen et al. 1998; WDNR 2012)

Herbicide	Approved in MI	Listed on Label	Pros	Cons	References
Imazamox (e.g. Clearcast®)	Yes	No	• Lists *L. spongia* on label	• Has not been systematically evaluated for EFB control in field or lab trials • May harm non-target species (Broad-spectrum herbicide) • Restricted concentration when near potable water intakes • Post-treatment restrictions on potable and irrigation water	(WDNR 2012)
Imazapyr (e.g. Habitat®)	Yes	No	• Lists *L. spongia* on label	• Has not been systematically evaluated for EFB control in field or lab trials • May harm non-target species (Broad-spectrum herbicide) • Post-treatment restrictions on potable water	(WDNR 2012)
Penoxsulam (e.g. Galleon® SC)	Yes	No	• Less harm to non-target species (Selective herbicide) • Lists *L. spongia* on label	• Has not been systematically evaluated for EFB control in field or lab trials • Post-treatment restrictions on irrigation water	(WDNR 2012)
Flumioxazin (e.g. Clipper®)	Yes	No	• Provided a single season reduction in EFB abundance at a site in Michigan • Lists *L. spongia* on label	• May harm non-target species (Broad-spectrum herbicide) • Toxic to fish and aquatic invertebrates • Post-treatment restrictions on irrigation water	(WDNR 2012; Monfils et al. 2021)

b. Physical or Mechanical Control

Manual removal has been effective for single season control of EFB on a small scale (Martine et al. 2015; Monfils et al. 2021). Manual removal is time and labor-intensive and often requires repeated visits to maintain control (Bailey and Calhoun 2008; Kelting and Laxson 2010; Zhu et al. 2015). Catling et al. (2003) recommended that manual removal should occur in the spring and early-summer, once germinating turions are floating on the surface of the water but before dense mats form. If done too late in the year, manual removal can proliferate the spread of stolon buds and turions (Catling et al. 2003). Manual removal of EFB has been shown to have no impact on surface or benthic macroinvertebrates (Zhu et al. 2015) but its effect on native aquatic plants is unknown. Ongoing research led by Lake Superior State University is assessing short- and long-term responses of plants, macroinvertebrates, and fishes to hand-harvesting of EFB (Cahill and Monfils 2021a).

Over a five-year period in the Town Farm Bay in Vermont, 55.9 tons (50,711.63 kg) of EFB were removed at a cost of $79,000 and 6,208 hours, reducing EFB cover to less than 6%. Annual spring maintenance visits were required to maintain control of the Town Farm Bay population (Lewis Creek Association 2013). At the Alpena Wildlife Sanctuary in Michigan, 10,000 lbs (4,536 kg) of EFB were removed in both 2015 and 2016 and 3,000 lbs (1,361 kg) were removed in 2017. Removal effort was similar across 2015 – 2017, suggesting that the manual removal was effective. Similarly, in Munuscong Bay and Raber Bay, Michigan, over 10,000 lbs (4,536 kg) of EFB has been removed since 2013 with similar effort but reduced biomass returns each year.

Shading can be a time and cost-efficient method for EFB control in areas where recreational and commercial activity is limited (Zhu et al. 2014). The effectiveness of shading with floating cloth for EFB control has been demonstrated in greenhouse and field trials (Zhu et al. 2014). In greenhouse trials, 100% shading completely removed EFB and shading between 50% – 80% significantly reduced EFB biomass. One hundred percent shading completely removed EFB in field trials and 70% shading significantly reduced EFB biomass. Shading does have the potential to negatively impact native aquatic plant and macroinvertebrate communities (Zhu et al. 2014; Zhu et al. 2015).

Water level drawdowns may effectively control EFB, but they are only possible in waterbodies with artificially controlled water levels. To be effective, drawdowns would likely need to occur overwinter or in the spring/early summer (Catling et al. 2003). European frog-bit's ability to survive on mud flats for months at a time (W. Keiper, Michigan Department of Environment, Great Lakes, and Energy, personal communication) may lessen the efficacy of spring and early summer drawdowns. The length of time needed for drawdowns to be effective is unknown. Drawdowns can have many negative effects on aquatic ecosystems, particularly to native aquatic plants and macroinvertebrates (Madsen 2000; Harman et al. 2005).

Mechanical harvesting has been employed to control EFB in the Rideau Canal in southeastern Ontario (Spicer and Catling 1987). Research is needed to evaluate its efficacy as well as its potential to disperse free-floating individuals, seeds, and turions, further spreading EFB. Non-target impacts to native plant, fish, and invertebrate species is also a concern when using mechanical harvesting to control an invasive plant population (Engel 1990; Madsen 2000).

Researchers at Loyola University Chicago are currently evaluating the effectiveness of combined EFB management and hybrid *Typha* management techniques (Cahill and Monfils 2021a). Wellons (2018) documented no significant treatment effects on EFB from above water harvest of hybrid *Typha*, below water harvest of hybrid *Typha*, above water harvest of hybrid *Typha* combined with EFB manual removal, and below water harvest of hybrid *Typha* combined with EFB manual removal. Monks et al. (2019) found that above water *Typha* removal accompanied by below water cutting significantly reduced EFB cover compared to above water *Typha* removal and untreated control plots.

c. Biological

Many organisms are known to consume EFB, including water-birds, rodents, insects, snails, and fish (Catling and Dore 1982; Sviridenko et al. 1988 in Catling et al. 2003; Catling et al. 2003). Few studies have evaluated these species' potential as biological control agents (i.e., Sanders et al. 1991; Zhu 2014; Halpern 2017).

Zhu (2014) conducted field and laboratory experiments to test the utility of snails as biological control agents for EFB. Zhu sampled EFB at sites across the Great Lakes region, collected snails that were on the EFB samples, and quantified the amount of EFB leaf damage at each site. A significant weak correlation between the number of snails and the amount of leaf damage at each site was detected; however, when a single outlier was removed the correlation was no longer significant. In the laboratory experiment, Zhu tested the impact of the tadpole physa (*Physa gyrina* Say) on parameters associated with EFB growth (e.g., number of roots, stems, and leaves; biomass). There were no significant differences between EFB plants with and without snails. Zhu (2014) concluded that snails are unlikely to serve as biological control agents and that further studies are needed to find species that could, particularly in EFB's native range.

In a laboratory setting, Halpern (2017) investigated the use of the waterlily leafcutter moth (*Elophila obliteralis* (Walker)), a semi-aquatic moth native to eastern North America, for control of EFB. Halpern introduced *E. obliteralis* larva to young EFB plants at varying densities and measured their impact on vegetative reproduction and productivity. When five larvae were introduced per EFB plant, clonal production was significantly reduced compared to untreated controls. Total biomass was significantly reduced when one, three, and five larvae were introduced per plant. Artificially enhancing the abundance of *E. obliteralis* early in the growing season may serve as a viable biological control option for EFB management (Halpern 2017); however, this has not been verified in the field.

Grass carp (*Ctenopharyngodon idella* Val.) are also known to consume EFB; however, it is not a preferred food source (Sanders et al.1991). The utility of *C. idella* as a biological control agent is not feasible as they can have detrimental impacts to ecosystems and are a prohibited species in Michigan.

No bacteria, viruses, or plant parasites have been recorded on EFB. The plant does, however, host a variety of rusts, smuts, and molds, but their effects on EFB have not been studied (Catling et al. 2003).

Researchers at the United States Geological Survey's Great Lakes Science Center are investigating the potential of a gene silencing approach for controlling EFB, similar to their ongoing work with *P. australis* (K. Kowalski, United States Geological Survey's Great Lakes Science Center, personal communication).

d. Indirect Management

No indirect management techniques have been investigated for the control of EFB at the time of this report. European frog-bit establishment may be prevented by altering flow regimes. In waterbodies that have artificially controlled flow regimes, such as some canals and ditches, the flow of water could be increased to make conditions unsuitable compared to the calm, slow moving waterbodies that EFB typically prefers. However, this could result in the further spread of EFB plants and propagules.

Research Needs

I. Biology and Ecology

In eastern North America, EFB has been documented in Ontario, Quebec, New York, New Jersey, Vermont, Ohio, Michigan, Maine, Pennsylvania, Florida, and Wisconsin (Dore 1968; Roberts et al. 1981; Catling et al. 2003; Gardner 2008; Marsden and Hauser 2009; Lamont et al. 2014; Jacono and Berent 2021; MISIN 2021; iNaturalist 2021). Plant specimens from each population should be collected and deposited in herbaria to allow for future genetic analysis. Genetic analysis of the relationships between established EFB populations may provide insight into EFB's introduction and dispersal pathways and aid in the development of more efficient education, prevention, and monitoring programs.

European frog-bit is established in 21 counties in Michigan: Alpena, Arenac, Bay, Chippewa, Huron, Ingham, Iosco, Jackson, Kent, Mackinaw, Macomb, Mason, Monroe, Montmorency, Oakland, Oceana, Ottawa, St. Clair, Tuscola, Washtenaw, and Wayne counties (MISIN 2021). Occurrences outside of its known distribution in Michigan are likely, particularly along the coastline of Lake Huron between the known occurrences in St. Clair and Huron counties and Iosco and Alpena counties. Surveys in these areas would elucidate the full extent of EFB's distribution in Michigan and potentially shed light on its pathways of dispersal. There is also a need for comprehensive surveys in areas surrounding each high-risk infestation. Further understanding of EFB's distribution could alter statewide goals and approaches for EFB management in Michigan.

To date, modeling of suitable EFB habitat has been at the coarse regional scale in North America. Using a trio of climate variables (plant hardiness zones, precipitation, Köppen-Geiger climate classes), Weibert (2015) predicted that 79% of the United States and all of Michigan could be suitable for EFB. Understanding local characteristics (e.g., depth, pH, turbidity, flow velocity) that characterize EFB occurrence in its invasive range will improve predictions of EFB spread and guide monitoring efforts. Researchers at Boise State University, Central Michigan University, and the Michigan Natural Features Inventory are developing species distribution models for EFB (Cahill and Monfils 2021a).

Turions and seeds are typically produced in the late-summer and early fall (Dore 1968; Catling et al. 2003). European frog-bit rosettes with turions have been documented on exposed substrate as early as June and July in Michigan (Cahill et al. 2021a; Monfils et al. 2021). Understanding EFB's seasonal growth and reproductive pattern in Michigan could help guide the timing of management efforts so that the spread of propagules is reduced. Ongoing research by Central Michigan University is investigating the phenology of EFB growth, flowering, and fruiting across its Michigan distribution. Researchers at Lake Superior State University are assessing the phenology of EFB in Munuscong Bay, Michigan (Cahill and Monfils 2021a).

Temperature and photoperiod are known to influence turion and seed germination (Serbanescu-Jitariu 1972 in Catling et al. 2003; Richards and Blakemore 1975; Cook and Lüönd 1982). Turions are reported to remain viable for 16 months to 2 years (Arber 1920; Burnham 1998). Turions remain viable after one-week and one-month of desiccation (Cahill et al. 2021a). Little else is known regarding the triggers of turion and seed germination or their long-term viability. The potential for regrowth through seeds and turions is important to understand when controlling populations of EFB.

European frog-bit populations in Ontario and Michigan produce viable seeds (Scriabilo and Posluszny 1985; Burnham 1998; Cahill et al. 2021a). Delineation of seed producing populations in the Great Lakes region could provide insight into the role of seed production in EFB reproduction and dispersal.

Much of EFB's spread between connected waterbodies in North America is believed to be a result of plants and propagules drifting on the water's natural flow, and its overland dispersal is believed to be a result of hitch-hiking on boats and boating equipment (Catling et al. 2003). Elucidating the pathways and vectors of EFB spread could inform management, monitoring, and prevention efforts. Understanding how far and for how long turions and seeds can float before sinking could help predict the natural spread of EFB. Similarly, understanding the tolerance of EFB plants, turions, and seeds to desiccation are crucial for predicting over-land dispersal and developing effective watercraft decontamination procedures.

Dense mats of EFB have been shown to impact native aquatic flora and fauna and water quality (Catling et al. 1988; Zhu et al. 2015; Dray 2016; Johnson 2018; Monfils et al. 2021) but information on its impacts at varying densities and scales is lacking. Anecdotal reports suggest EFB has detrimental social and economic impacts. Understanding EFB's ecological, social, and economic impacts at varying levels of infestation can help managers prioritize sites for management and contribute to the cost-benefit analysis of managing an invasive population. The impacts of EFB on Great Lake coastal wetlands is currently being evaluated by researchers at Central Michigan University, Michigan Natural Features Inventory, and Lake Superior State University (Cahill and Monfils 2021a).

II. Detection

Genetic markers have been developed for detecting EFB genetic material shed into the environment (Scriver et al. 2015) but they have not been evaluated in the field. This approach may not be prudent for EFB detection, given its near-shore habitat and easily distinguishable features. Sampling for genetic material shed into the environment by EFB could improve the efficiency of early detection, especially when it is growing in stands of emergent and floating vegetation or in an inaccessible portion of a waterbody.

Remote sensing technology, at a 2.4 m resolution, has been used to detect and distinguish EFB infestations (Proctor et al. 2012). Using this resolution, populations that do not form dense mats may go undetected because an EFB plant is smaller than the resolution of the imagery. Imagery gathered by unmanned aerial systems would likely be required to gather imagery at a resolution fine enough to detect individual EFB plants or small EFB mats. European frog-bit is also difficult to detect using remote sensing when it is growing interspersed among emergent vegetation. The use of multi-temporal UAV-collected imagery is currently being evaluated for EFB detection by researchers at Boise State University (Cahill and Monfils 2021a).

III. Management

Diquat, endothall, and flumioxazin have been found to control EFB (Holz 1963; Renard 1963; Sesin et al. 2018; Monfils et al. 2021). Ongoing lab and greenhouse trials by University of Hartford and SePRO are investigating the efficacy of flumioxazin, florpyrauxifen-benzyl, and imazamox for EFB control (C. McGlynn, New York State Department of Environmental Conservation, personal communication).

Understanding how ramet, turion, and seed production and viability are impacted by chemical treatment could lead to more effective management strategies. If ramets, turions, or seeds are not impacted by treatment or if production of these reproductive structures is enhanced following treatment, repeated applications will likely be required to maintain control.

On a small scale, manual removal is considered an effective technique for EFB control (Martine et al. 2015; Monfils et al. 2021) but often requires repeated visits (Zhu et al. 2015). Mechanical harvesting has also been employed for EFB management (Spicer and Catling 1987). Researchers at Lake Superior State University are assessing the short- and long-term impacts of hand-pulling on EFB and native wetland biota (Cahill and Monfils 2021a).

Combinations of *Typha* harvesting techniques and EFB management techniques are currently being evaluated by Loyola University Chicago (Cahill and Monfils 2021a). Thus far, above water *Typha* removal accompanied by below water cutting significantly reduced EFB cover compared to untreated control plots (Monks et al. 2019). The efficacy of mechanical management techniques for EFB control as well as their potential to disperse seeds, turions, and ramets requires further investigation. Research into more efficient methods and devices for mechanical management of EFB could be beneficial.

Halpern (2017) demonstrated the utility of *E. obliteralis* larva for control of young EFB plants in lab trials. Studies that examine the efficacy of *E. obliteralis* in the field as well as its non-target impacts are needed. Other species, such as snails (Zhu 2014), have been evaluated but their impact to EFB was not severe enough to be useful for management. A variety of rusts, smuts, and molds are also found on EFB (Catling et al. 2003). The impact of these species on the productivity and reproductive output of EFB might be worthy of investigation. Further research exploring potential biological control agents, particularly in EFB's native range, could provide a long-term control option. Researchers at the United States Geological Survey's Great Lakes Science Center are investigating the potential of a gene silencing approach for controlling EFB (K. Kowalski, United States Geological Survey's Great Lakes Science Center, personal communication).

Future Directions for Michigan and EFB Management

European frog-bit is a free-floating aquatic plant native to Europe and Asia (Cook and Lüönd 1982). In North America, it has been documented in Ontario, Quebec, New York, New Jersey, Vermont, Ohio, Michigan, Maine, Pennsylvania, Washington state, Florida, and Wisconsin (Dore 1968; Roberts et al. 1981; Catling et al. 2003; Gardner 2008; Marsden and Hauser 2009; Lamont et al. 2014; Jacono and Berent 2021; MISIN 2021; iNaturalist 2021). European frog-bit's rapid reproductive and dispersal ability as well as its potential for ecological, social, and economic impacts make it a concern to natural resource managers in the Great Lakes region.

Prevention – Prevention of new colony establishment is likely the most cost-effective approach to EFB management. Potential pathways of EFB dispersal include waterway currents, fish and wildlife, and transportation of plants and propagules by recreational waterbody users. The development of education and outreach programs designed to raise stakeholder (e.g., lake associations, anglers, waterfowl hunters) awareness of prevention and control methods may reduce the human-mediated spread of EFB. Likewise, a sustainable boat washing and inspection program, particularly at high-risk waterbodies, could aid in containing its spread. Active management to eradicate or suppress established high-risk EFB populations could reduce the likelihood of dispersal through human and non-human mediated vectors.

Monitoring – Early detection of an EFB introduction makes eradication a more realistic option. Adding EFB to existing monitoring programs will assist in early detection and increase the potential of eradication. A cohesive monitoring and reporting system involving local municipalities, non-profit organizations, lake associations, recreation clubs and organizations, and waterfront property owners, would increase the number of known EFB locations and enable early detection and rapid response to new colonies. Connecting waterfront property owners and boaters with resources such as MISIN could improve early detection efforts. Working with herbaria for confirmation, documentation, and vouchering will provide verifiable long-term data that can be used to examine changes in macrophyte communities.

European frog-bit monitoring would benefit from a direct and targeted monitoring strategy. To develop a targeted monitoring strategy, EFB occurrences and associated environmental variables could be modeled to identify suitable waterbodies for establishment. Human use patterns, such as whether a waterbody has a public boat access, could also be included in the distribution models. Suitable waterbodies that have a high-risk of EFB introduction could then be prioritized for monitoring.

Networking data – Statewide monitoring methods would benefit from creating or participating in systems that centralize and provide open access to diversity data (e.g., MISIN, Michigan Clean Water Corps [MiCorps] Data Exchange Network – Great Lakes Commission, Early Detection and Distribution Mapping System [EDDMapS], USGS Nonindigenous Aquatic Species Database [USGS NAS], Biodiversity Information Serving Our Nation [BISON], Global Biodiversity Information Facility [GBIF], Integrated Digitized Biocollections [iDigBio]). These databases house biological specimen or observation data including species location, verification, photographs, density, and even links to genetic data. Efforts within the state of Michigan have agencies contributing to regional databases (e.g., MISIN) but participation is not consistent and data standards are not established across programs. Currently state databases are not always networked within an agency, across the state, throughout the region, or relative to national efforts.

Participation in a national or global information network will standardize data collecting practices, record comparable data using designated data standards across projects, ease data acquisition, avoid data redundancies, and promote projects with a larger scope of study than the original project for which the data sets were initially collected. Information networks that are continually linked to other resources and updated can be used to develop effective and efficient monitoring and management plans. When information networks are not linked or periodically synchronized, a person collecting information must independently identify, locate, and consolidate data from separate and often difficult-to-access sources. The result is that information is missed and data collection becomes redundant and inefficient.

Networking with and contributing to state, regional, national, and international databases will advance research in areas that could improve the way invasive aquatic species are managed. Researchers can easily access the data and use it to model suitable habitat, model distribution, research population genetics across many spatial scales, predict new introductions, study changes due to climate change, or locate areas most beneficial for new projects or collections. The public could also use these data to know which species they may encounter when visiting specific waterbodies.

Rapid response – The ability to rapidly respond to reports in new or high-value locations submitted by the public or through a regular monitoring strategy is essential to battling invasive species. Invasive species are easier to treat prior to establishment and when an infestation is small. If the procedure to manage an infestation takes several years to achieve action, the infestation may have grown beyond realistic management. The Michigan Departments of

Environment, Great Lakes, and Energy, Natural Resources, and Agriculture and Rural Development have developed a response plan that outlines the steps to take when a new aquatic invasive species occurrence is reported and serves as a guide for determining when and what type of response is needed (DEQ et al. 2014). The workflow begins at reporting the occurrence to the appropriate personnel, who determine the threat level of the species and verifies the species identification. Next a risk assessment is completed to determine if a species is a candidate for a response. If a response is deemed appropriate, options are assessed, and the response is planned and implemented. Finally, a report is made and adaptive management of the population is initiated. Although it is called a rapid response, it may not end rapidly.

Management – When managing EFB, it is important to delimit the extent of the infestation, contain already established populations, mitigate the impact of EFB in invaded high-value sites, and protect uninvaded high-value sites. The EFB Adaptive Management Framework has been developed to guide EFB management decision-making in Michigan (Cahill and Monfils 2021b).

Educating residents on the identification, legal restrictions, and potential negative impacts of EFB could aid in the detection of infested sites, assist in preventing new occurrences, and alert managers prior to the establishment of dense floating mats.

Measuring effective control – The effectiveness of a management action for EFB control can be quantitatively assessed by documenting any regrowth, reduction in EFB biomass or cover, or reductions in turion and seed production. Pairing a management plan with a monitoring program, inclusive of pre- and post-treatment assessments in treated and reference areas, is crucial for determining the efficacy of any management action. A standard protocol and data management system for pre- and post-treatment monitoring have been developed and implemented in Michigan to evaluate EFB control efforts (Cahill and Monfils 2020; Monfils et al. 2021).

The goal of aquatic invasive species management strategies is to preserve or restore ecologically stable aquatic communities. Minimal chemical, biological, and physical controls should be required to maintain these communities. Any management plan should involve the integration of prevention and control methods that consider factors impacting the long-term ecological stability of an aquatic community.

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Table 3. Objectives, strategic actions, leads, and expected outcomes of European frog-bit (*Hydrocharis morsus-ranae* L.; hereafter EFB) management.

Objective	Strategic Action	Who is leading effort in Michigan?	Expected Outcome
Guidance and Outreach for EFB Management			
Increase public awareness of prevention methods	• Coordinate and collaborate with local and regional stakeholders managing water bodies with an infestation or high likelihood of introduction • Educate public on identification, prevention, and early-detection	• Michigan State University Extension • Michigan Lake and Stream Associations, INC. • CISMA's • EFB Collaborative's Education and Outreach Working Group	• Increase public awareness of EFB • Increase the frequency and use of boat washing stations • Protect high-value sites • Contain established populations
Provide technical guidance to those interested in EFB management	• Develop a framework to prioritize management of EFB infestations • Educate stakeholders on available control methods	• CISMA's • EFB Collaborative's Education and Outreach Working Group	• Increase management efforts
EFB Monitoring and Data Management			
Develop a mechanism for detecting, monitoring, and reporting AIS species	• Develop a system of identifying waterbodies with high likelihood of introduction • Survey waterbodies with high likelihood of introduction	• Cooperative Lakes Monitoring Program (CLMP) • EGLE – Water Resources Division (WRD) • MISIN • MiCorps • EFB Collaborative's Delimitation Surveying Working Group	• Develop a more thorough and up-to-date statewide distribution of EFB • Evaluate dispersal pathways and vectors
Develop standard operating procedures for monitoring treatment efficacy	• Develop guidelines for pre/post-treatment monitoring to determine treatment efficacy	• CMU (Monfils et al.)	• Develop best management practices for EFB control
Contribute regularly to regional, national, and global diversity information networks	• Consolidate Michigan biological and abiotic data • Standardize resources • Standardize data collection • Network existing data • Regularly synchronize data	• MISIN • MiCorps Data Exchange Network • iDigBio • NAS - USGS • BISON • GBIF	• Develop adaptive monitoring strategy that responds to up-to-date distribution • Promote AIS research of regional, national, and global extents • Prevent data redundancies
Educate public on identification and reporting of AIS in Michigan	• Target users of water bodies that are infested or have a high-likelihood of introduction	• MISIN • MiCorps • CISMA's • Management agencies • EFB Collaborative's Education and Outreach Working Group	• Increase public awareness of AIS • Identify water bodies that need professional confirmation of AIS

Research Needs for EFB Management			
Chemical: Evaluate the effectiveness of current chemical treatments	• Study the effectiveness of chemical treatments for reducing/eliminating EFB	• EGLE – WRD • EFB Collaborative's Management Assessment Working Group • University of Hartford • SePRO	• Determine whether or not chemical treatment is a cost-effective management approach • Effective treatment of EFB resulting in containment, suppression, or eradication
Biological: Establish biological control methods	• Identify and study the effectiveness of any potential biological control species or mechanisms	• USGS Great Lakes Science Center	• Increase long-term control success
Mechanical: Evaluate effectiveness of current mechanical controls	• Study the effectiveness of mechanical harvesting for reducing/eliminating EFB	• Loyola University Chicago	• Determine whether or not mechanical removal is a cost-effective management approach • Effective treatment of EFB resulting in containment, suppression, or eradication
Physical: Evaluate effectiveness of current physical controls	• Study the effectiveness of hand-pulling, shading, and water level draw-down for reducing/eliminating EFB	• EFB Collaborative's Management Assessment Working Group	• Determine whether or not physical controls are a cost-effective management approach • Effective treatment of EFB resulting in containment, suppression, or eradication

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