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State of Michigan's

Status and Strategy for Water Lettuce (*Pistia stratiotes* L.) Management

Scope

Pistia stratiotes L. (water lettuce, hereafter WL) occurs on every continent except Antarctica and is one of the world's worst weeds (Holm et al. 1977). Water lettuce is on the Michigan Departments of Environmental Quality, Natural Resources, and Agriculture and Rural Developments "Watch List," a list of priority invasive species that pose an immediate and significant threat to Michigan's natural resources. Water lettuce grows and reproduces rapidly and can form thick floating mats that have the potential to negatively impact native biodiversity and reduce the recreational and commercial utility of waterbodies (EPPO 2017). This document was developed by Central Michigan University and reviewed by Michigan Departments of Environmental Quality and Natural Resources for the purposes of:

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

Figure 1. Water lettuce (*Pistia stratiotes* L.) resembles an open head of lettuce. Photograph by G.E. Crow, courtesy of Michigan Flora Online (Reznicek et al. 2011)

Water lettuce is free-floating aquatic plant that has pale-green obovate to spatulate leaves that are arranged in a floating rosette (Figure 1). Leaves are 4 – 8 in (10 – 20 cm) long and 4 in (10 cm) wide (Khan et al. 2014). They are longitudinally ribbed and densely covered in fine whitish hair-like trichomes, giving them a velvety appearance.

Roots are numerous and feathery and can be up to 20 in (50 cm) long. The roots hang below the plant and are suspended in the water column (Figure 2). Water lettuce can also survive for extended periods of time in shallow water and on moist substrates with its roots semi-anchored.

Water lettuce produces stem-like stolons that arise from leaf axils. Stolons can be up to 24 in (70 cm) long (Weldon and Blackburn 1967) and often entangle to create floating mats. At the ends of stolons, WL produces clonal daughter plants.

Figure 2. Floating rosette of water lettuce (*Pistia stratiotes* L.). Photography by Forest and Kim Starr [CC BY 3.0 (http://creative commons.org/licenses/by/3.0)], via Wikimedia Commons

The inflorescence of WL is a reduced spike of tiny pale-green flowers clustered around a short fleshy stalk (spadix) and hidden in leaf axils (Figure 3). Individual flowers are single sexed (either male or female) and the inflorescence is monoecious (possessing male and female flowers). The inflorescence consists of 3 – 9 male flowers and one female flower (Buzgó 2006). The spadix is surrounded by a white leaf-like bract (spathe). Water lettuce can have several inflorescences per rosette, each of which arise from a separate leaf axil. Its fruit is a green, ovoid to ellipsoid, many-seeded berry. Seeds are thin, have a wrinkled surface, and are golden-brown in color when mature (Dray and Center 1989).

Figure 3. Water lettuce (*Pistia stratiotes* L.) in flower. Photograph by Malcolm Manners [CC BY 2.0 (https://creativecommons.org/licenses/by/2.0/)], via Flickr

Water lettuce is the sole member of the genus *Pistia* and is unlikely to be confused with other species. The species most like WL is another invasive free-floating aquatic plant found in North America, water hyacinth (*Eichhornia crassipes* [Mart.] Solms). *E. crassipes* has showy lavender flowers on an erect stalk compared to WL's inconspicuous pale-green flowers that are clustered on a spadix and hidden in leaf axils. In temperate regions of North America, WL flowers in late summer to early fall. When not in flower, WL can be distinguished by its rosette of fleshy leaves covered in hair-like trichomes compared to the smooth glossy leaves and inflated petioles of *E. crassipes*.

II. Detection

Water lettuce can be found in dense floating mats (Figure 4), interspersed among floating and emergent vegetation, or floating in the open water. It is typically found in calm to slow moving waterbodies such as lakes, ponds, rivers, canals, and wetlands (Cilliers et al. 1996; Adebayo et al. 2011; Hussner 2014; Shapovalov and Saprykin 2016). In Michigan, WL is generally found from August – November. Flowering has been observed in October, when surface water temperatures are ~75°F (24°C; Cahill et al. 2018). Water lettuce flowers are inconspicuous and not required for identification. Its thick, ridged, and hairy leaves, as well as its free-floating habit, differentiates it from associated species in the Great Lakes region. When growing in dense floating mats or in the open water WL can typically be detected via visual searches from a boat or land. More intensive sampling may be required for detection when WL is growing among emergent and/or floating vegetation.

Figure 4. Water lettuce (*Pistia stratoites* L.) mat covering the surface of a pond. Photograph by Yuriy Kvach [CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/deed.en)], via Wikimedia Commons

Remote sensing can be used to detect and distinguish WL. Water lettuce has a higher visible green and red reflectance than most associated species (e.g., *E. crassipes*, alligator weed (*Alternathera philoxeroides* (Mart.) Griseb.)) throughout the growing season (Everitt et al. 2003; Everitt et al. 2011). Water lettuce infestations have been distinguished using aerial color-infrared (CIR) photography and videography combined with computer image analysis (Everitt et al. 2003). Color-infrared photography had an overall unsupervised accuracy of 86.3% (81.4% kappa) with WL having a 80% user's accuracy and 85.7% producer's accuracy. The color-infrared videography had an overall unsupervised accuracy of 83.8% (76.3% kappa) with WL having a 76.5% user's accuracy and 92.9% producer's accuracy. Classification errors were primarily caused by confusion with mixed aquatic and riparian vegetation. Quickbird satellite imagery at 2.8 m resolution has also been used to distinguish WL and *E. crassipes* infestations (Everitt and Yang 2007). The overall accuracy of the supervised classification was 94.4% (93.3% kappa) with WL having a 100% user's and producer's accuracy. The overall accuracy of the unsupervised classification was 80% (75.4% Kappa) with WL having a 90% user's accuracy and 81.8% producer's accuracy.

Genetic markers have been developed for detecting genetic material shed by WL into the environment and these markers have been used to successfully identify WL from laboratory-generated water samples (Scriver et al. 2015). Given the near shore habitat that WL occupies and its easily distinguishable features, it may not be efficient to utilize this approach for WL detection. However, it could improve the true positive detection of WL 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 after WL was positively detected in an area.

III. Life History and Spread/Dispersal

Water lettuce's native distribution is a matter of debate and an area of ongoing research (Renner and Zhang 2004; Evans 2013). Several continents have been included in descriptions of its native range, including South America (Cordo et al. 1978; Dray and Center 1989), Africa (Holm et al. 1977), northern Australia (Gillett et al. 1988), Asia (Habeck and Thompson 1997), and North America (southern Florida; Evans 2008). Evans (2013) argued that paleo-botanical, historical, and ecological evidence demonstrates that WL is native to neo-tropical America, northern Africa, and southern Asia. In addition, Evans states that WL fossil records from Florida, historic WL observations from 1765 – 1774, and the presence of specialized insect species and an endemic snail species (*Aphaostracon pycnus*) that use WL as part of their life cycle supports the notion that WL is native to southern Florida (Evans 2013).

Water lettuce is monoecious (male and female reproductive structures on same individual; Haynes 1988) and has imperfect flowers (possessing either male or female reproductive structures). Flowers may be wind or insect pollinated (Haynes 1988; Parsons and Cuthbertson 2001). The insect species that pollinate WL are unknown but its floral traits suggest it is fly pollinated (Gibernau et al. 2010). Once a female flower is fertilized, the peduncle bends sideways and pulls the developing fruit under the surface of the water. Here, the fruit disintegrates and a mucilaginous envelope of seeds is released (Buzgó 1994). The seeds float for 1 – 2 days and then fall to the substrate (Holm et al. 1977; Neuenschwander et al. 2009; CABI 2018). Water lettuce dies back completely in drought or freezing conditions and regenerates from buried seeds in the seed bank (Buzgó 2006; Neuenschwander et al. 2009). The long-term viability of WL seeds is unknown.

Water lettuce is also capable of rapid vegetative reproduction, producing clonal daughter plants at the ends of stolons (Haynes 1988). A single parent plant can produce up to 15 clonal daughter plants and up to four generations of rosettes can be connected via stolons (Dray and Center 2002). Parent and daughter plants can become easily detached through fragmentation (Haynes 1988). Water lettuce does not produce persisting vegetative organs (Buzgó 2006; Neuenschwander et al. 2009).

The vectors and pathways of WL dispersal have not been well studied. The accidental or deliberate release of plants from aquariums and water gardens is typically considered the primary means of WL introduction (MacIsaac et al. 2016; EPPO 2017). Secondary spread can occur by daughter plants breaking away from parent plants and drifting on current or wind-driven flow. Seeds may also spread on the water's flow before they sink to the substrate. Plants and seeds may attach to watercraft, trailers, and other boating equipment and be transported to uninfected waterbodies (Neuenschwander et al. 2009). Likewise, plants and seeds may become attached to animals, particularly waterfowl, and subsequently transported to new locations (Millane and Caffrey 2014). Seeds may also be ingested by wildlife and transported to new waterbodies but their viability after passing through the digestive tract is unknown.

Tropical and subtropical regions:

In tropical and subtropical regions WL acts as a perennial and can reproduce sexually (i.e., seed production) and asexually (i.e., vegetative; Mitra 1966; Bua-ngam and Mercado 1975; Holm et al. 1977; Dray and Center 1989; Harley 1990). In general, seed production is considered less important than clonal reproduction (Hill 2003). However, aside from a reintroduction or drift of free-floating plants from other infested areas, the germination of seeds in the seed bank is the only way that WL can reestablish following unsuitable conditions (e.g., drought, freezing temperatures). Seed production differs across its tropical and sub-tropical distribution, ranging from 1 – 42 seeds per fruit (Mitra 1966; da Silva 1981 in Kurugundla 2014; Dray and Center 1989; Harley 1990; Kurugundla 2014). Seeds collected from sub-tropical Australia took 20 – 44 days to germinate in constant or intermittent light (12 h light/12 h dark) and 27 – 56 days to germinate under constant darkness (Harley 1990). Ninety percent of seeds germinated in constant or intermittent light and 60% germinated in constant darkness. Scarifying the seed coat reduced germination time to 9 – 21 days in constant or intermittent light and 21 – 48 days in constant darkness but did not impact the percentage of seeds that germinated (Harley 1990). Water lettuce seeds collected from southern China were found to have 73.3% and 62.5% germination rates after experiencing rapid and slow desiccation, respectively (Kan and Song 2008).

Dray and Center (1989) studied the production and germination of WL seeds at the Loxahatchee National Wildlife Refuge, Florida. In April, the WL mat was composed of 237.6 ramets/m^2 and produced 768.8 inflorescences/m^2, 156.8 fruits/m^2, and 528.2 seeds/m^2. Fruits contained 1 – 20 seeds and the seed bank beneath the mat contained 4,196 seeds/m^2. The first 0 – 2 in (0 – 5 cm) of substrate contained 75% of the seed bank and no seeds were found below 6 in (15 cm). Eighty-four percent of seeds collected from plants, 92% of seeds from the first 0 – 2 in (0 – 5 cm) of substrate, and 84% of seeds from the 2 – 6 in (5 – 15 cm) substrate layer germinated when exposed to 25°C and constant light. Seeds collected from the seed bank began germination immediately while the seeds collected from plants began germination in 7 – 14 days (Dray and Center 1989).

Differences in WL's seasonal growth pattern have been observed across its tropical and subtropical distribution. In Ghana, WL increased biomass from September to December, flowered from November to January, and senesced from December to February (Hall and Okali 1974). Biomass increased rapidly between March and April but declined from May to August. In Egypt, biomass increased from May to September and senesced in October (Eid et al. 2016). In Florida, WL increased biomass from April to August, flowered from November to January, and senesced from September to March. No sexual reproduction was observed in the Florida study (Dewald and Lounibos 1990). In addition to climate (Eid et al. 2016) and weather (Hall and Okali 1974), WL growth may be influenced by nutrient availability (Hall and Okali 1974), salinity (Haller et al. 1974), pH (Pieterse et al. 1981), plant density (Tucker 1983), insect herbivory (Odum 1957), and disease (Pettet and Pettet 1970).

Water lettuce has a high growth rate in tropical and subtropical regions (Sharma and Sridhar 1981). In Florida, low density WL populations doubled their biomass in four days and reached a max dry weight biomass of 1,000 g/m^2. Plants in higher density populations have reduced growth rates (Reddy and DeBusk 1984).

Temperate regions:

Water lettuce has been reported in several countries with temperate climates, including Belgium, Czech Republic, Germany, Hungary, the Netherlands, Romania, Russia, Slovenia, Japan, Canada, and the United States (Figure 5; Adebayo et al. 2011; Hussner 2012; Tamada et al. 2015; MacIsaac et al. 2016). Water lettuce acts as an annual throughout much of its temperate distribution and populations typically die-out once the cold season beings.

Little is known regarding the reproductive status of WL in temperate regions. In Michigan, WL is generally found from August – November and has been documented flowering in October, when surface water temperatures are ~75°F (24°C; Cahill et al. 2018). Winter exposure experiments near Lake St. Clair and the Detroit River revealed no overwintering vegetative survival or seed set, suggesting that annual reintroduction is to blame for its continued persistence in the region (MacIsaac et al. 2016). Climate models, using air and water temperature variables, predicted that the Great Lakes basin is not currently suitable for WL establishment and won't be under climate change projections for the mid- or late-21st century (Garwood et al. 2014). An introduced population in the Netherlands flowered and produced ripe seeds during an abnormally warm summer but WL was not found during the following summers (Pieterse et al. 1981). In a controlled study of seeds collected from the Netherlands, germination rate was highest between 73 – 77°F (22.5 – 25°C), decreased at 86°F (30°C), and did not occur at or below 64°F (17.5°C). Germination rate increased as light intensity increased. Seed viability was not affected by an 8-week exposure of 39°F (4°C) in water and seeds remained viable following exposure to 23°F (-5°C) for up to 4-weeks in ice. No germination occurred following an 8-week exposure of 23°F (-5°C) in ice (Pieterse et al. 1981).

Water lettuce has established populations in thermally abnormal waterbodies (e.g., warm water discharge ponds, thermal springs) of Germany, Slovenia, and Japan (Šajna et al. 2007; Hussner et al. 2014; Tamada et al. 2015). The populations in Germany and Slovenia flowered from April – September and produced ripe seeds at the end of September. Seeds collected from the populations in Germany, Slovenia, and Japan germinated under controlled conditions, with water temperatures between 68 – 84°F (20 – 29°C), but no seedlings were observed in the field. In the Hussner et al. (2014) study, seeds exposed to 41°F (5°C) for 2, 6, and 10 weeks had significantly lower germination rates at 71.6°F (22°C) compared to seeds kept at 71.6°F (22°C). The germination rate of seeds exposed to 25°F (-4°C) was also significantly lower than that of seeds exposed to 71.6°F (22°C) and their germination rates decreased as exposure duration increased. Seeds exposed to 0°F (-18°C) did not germinate.

Seed production is typically regarded as the only mechanism that would allow WL to persist in temperate climates, as vegetative portions of WL are susceptible to frost and die back completely in areas where a cold season occurs (Neuenschwander et al. 2009). However, WL plants can survive over winter in thermally abnormal waterbodies and plants still develop at temperatures as low as 50°F (10°C; Šajna et al. 2007; Hussner et al. 2014; Tamada et al.

2015). During the winter the older and larger rosettes die and decay while smaller and younger rosettes survive. The erect leaves of older and larger rosettes are more exposed to winter conditions compared to the smaller, low-laying leaves that are on or close to the surface of the warm water. Hussner et al. (2014) recorded winter temperatures between 54 – 59°F (12 – 15°C) on flat floating leaves while the temperature of the larger erect leaves ranged from 43 – 57°F (6 – 14°C). In addition to the shape and size of the plants, Tamada et al. (2015) suggested that the microclimate around the plants may impact overwintering success. During January and February, the air temperature above the large decaying leaves was similar to the air temperature above the water's surface without WL, reaching a low of 40°F (4.2°C). In contrast, the air beneath the large decaying WL leaves, where the small overwintering WL plants were found, was consistently warmer than the air above the leaves, reaching a low of 54°F (12.1°C).

In established overwintering populations in temperate regions, WL abundance fluctuates across seasons. Populations are reduced during the winter and gain biomass during the spring and summer (Hussner et al. 2014; Tamada et al. 2015). In Slovenia, biomass averaged 114 g/m^2 in December, 308 g/m^2 in April, and 609 g/m^2 in August (Šajna et al. 2007).

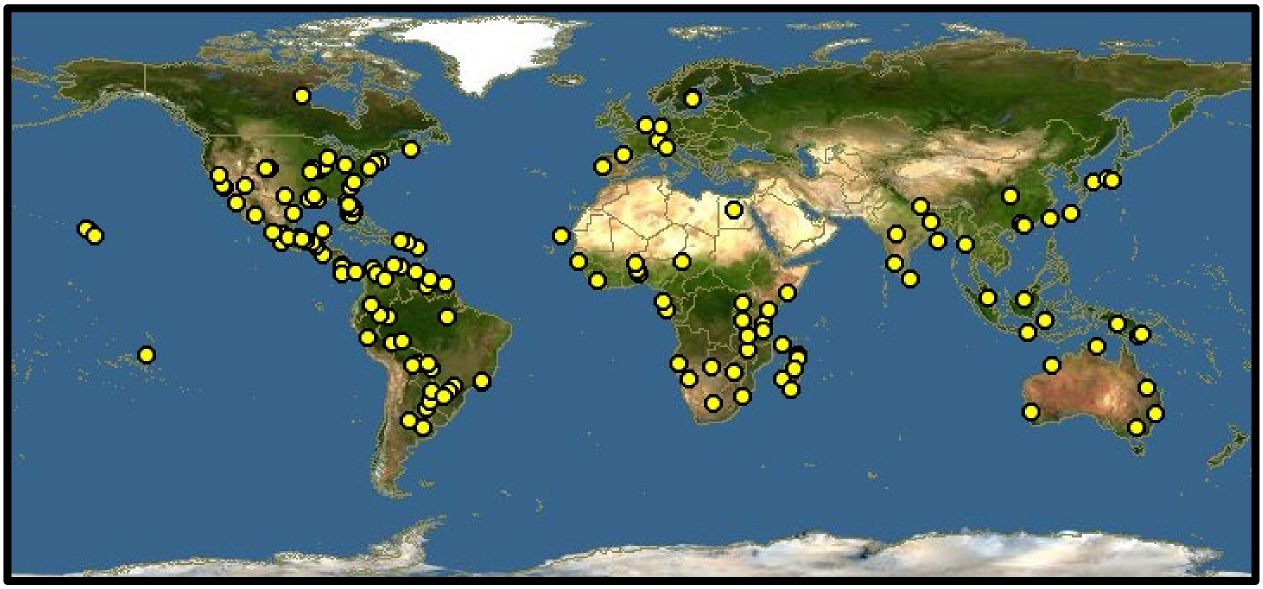

Figure 5. Global distribution of water lettuce *(Pistia stratiotes* L.). Source: http://www.discoverlife.org

IV. Habitat

Tropical and subtropical regions:

Water lettuce can be found across the tropical and subtropical regions of the world (Figure 5). A complete list of countries where WL occurs was provided by the European and Mediterranean Plant Protection Organization (EPPO 2017). Water lettuce grows in a variety of aquatic habitats, e.g., slow-moving rivers, streams, lakes, reservoirs, wetlands, seasonal waterbodies, floodplains, ponds, irrigation channels, canals, and rice fields (Bua-ngam and

Mercado 1976; Cilliers et al. 1996; Howard and Harley 1998; Thomaz et al. 1999; Tamire and Mengistou 2013; Khan et al. 2014; Bhadha et al. 2015; Gul et al. 2017). It thrives in disturbed habitats, such as areas of increased nutrient loading, pollution, deforestation, and flow regulation (Neuenschwander et al. 2009). It can be found in any depth of water but is typically found along the shallow margins of waterbodies over silty or mucky substrate. This species can also survive on moist muck or sand for several weeks (Weldon and Blackburn 1967).

Water lettuce can tolerate oligotrophic, mesotrophic, and eutrophic conditions (Thomaz et al. 1999; Perdomo et al. 2008; Neuenschwander et al. 2009) but performs best in waterbodies with high nutrient loading (Henry-Silva et al. 2008). It is tolerant to a broad range of pH values but prefers slightly acidic water (Sharma and Sridhar 1981; Dewald and Lounibos 1990; Tamire and Mengistou 2013; Eid et al. 2016; GISD 2018). Water lettuce typically occurs in warm water with temperatures as high as 95°F (35°C; Neuenschwander et al. 2009). Plants collected from a WL population in Florida had a low tolerance to salinity; 0.17 – 1.66% salinity reduced growth and 2.5 – 5% salinity caused mortality (Haller et al. 1974).

Temperate regions:

Water lettuce has been documented in several countries that have a temperate climate (Figure 5; EPPO 2017). These introductions occur in rivers, streams, creeks, reservoirs, lakes, bays, coves, and small artificial waterbodies in urban areas, such as drainage channels, canals, and ponds (Pieterse et al. 1981; Šajna et al. 2007; Adebayo et al. 2011; Hussner et al. 2014; Tamada et al. 2015; Shapovalov and Saprykin 2016). It can tolerate pH values between 4.0 – 10.0 (Pieterse et al. 1981) and can be found in any depth of water. It is typically found along the shallow margins of waterbodies intermixed with emergent vegetation such as cattails (*Typha* spp.) or entangled with submerged vegetation such as coontail (*Ceratophyllum demersum* L.; Shapovalov and Saprykin 2016). Water lettuce collected from temperate areas of Japan was able to survive in 6 practical salinity unites (Upadhyay and Panda 2005).

Adebayo et al. (2011) detected WL at eight locations in the Detroit River and Lake St. Clair. Water temperature at the sites was between 50 – 51.8°F (10 – 11°C) and at each site WL co-occurred with *E. crassipies*. Species associated with WL in temperate regions include duckweeds (*Lemna* spp., *L. minor* L.), *C. demersum*, pondweeds (*Potamogeton* spp., *P. nodosus* Poir.), spiny water nymph (*Najas marina* L.), pickerel weed (*Pontederia cordata* L.), yellow water-lily (*Nuphar advena* (Aiton) W.T. Aiton), *Salix* spp., Eurasian water-milfoil (*Myriophyllum spicatum* L.), water chestnut (*Trapa natans* L.), *E. crassipies*, eel-grass (*Vallisneria americana* var. *biwaensis* (Miki) Lowden), reed canary grass (*Phalaris arundinacea* L.), narrowleaf cattail (*Typha angustifolia* L.), and hybrid cattail (*Typha* x *glauca*; Šajna et al. 2007; Adebayo et al. 2011; Hussner et al. 2014; TEMP-7737; CHIC18090; 0035597MOR; NY02457010; NY02457168; v0254231WIS; v0200837WIS).

The only known overwintering WL populations in temperate regions are found in Germany, Slovenia, and Japan. Here, WL occurs in thermally abnormal waterbodies, such as ponds, rivers, streams, and wetlands that receive warm water discharge (Šajna et al. 2007; Hussner et al. 2014; Tamada et al. 2015). The water temperature in these waterbodies is considerably higher than areas that do not receive warm water discharge: a median of 64.8 – 69.3°F (18.2 – 20.7°C) in Germany, average of 71.4°F (21.9°C) in Japan, and above 62.6°F (17°C) year-round in Slovenia. The waterbodies are eutrophic to hypereutrophic, have an average pH of 7.6, and a conductivity of 423 – 461 µS/cm (Šajna et al. 2007). Nutrient concentrations in these waterbodies are as follows: nitrate at 1590 – 2530 µg/L, nitrite at 103.8 µg/L, ammonia-nitrogen at 159.5 µg/L, phosphate at 20 – 110 µg/L, and orthophosphate at 351.3 µg/L (Šajna et al. 2007; Hussner et al. 2014).

V. Effects from WL

Most of what is known regarding the economic, social, and ecological impacts of WL invasion come from tropical and subtropical regions of Africa and to a lesser extent South America and Asia. Few studies have addressed its impacts on temperate ecosystems (e.g., Šajna et al. 2007; Hussner 2014). Most impacts to native flora and fauna are inferred from its ability to form thick mats, alter water chemistry, and for its similarity to other damaging free-floating invasive species (i.e., *E. crassipes*, giant salvinia (*Salvinia molesta* D.S. Mitch.)) and are not directly supported by data. Studies investigating the impacts of WL have focused on its impacts when growing at high densities; less is known about its impact when interspersed among native vegetation. The following is a summary of what is known regarding the impacts of WL, particularly when growing in thick floating mats.

a. Negative Effects

Water lettuce's rapid growth rate and biomass potential make it a serious concern to water resource managers and lend to its listing as one of the world's worst weeds (Holm 1977; Reddy and DeBusk 1984; Dewald and Lounibous 1990). It can form thick mats that cover the surface of lakes, reservoirs, wetlands, and ponds and clog slow-moving rivers, streams, channels, and canals. Water lettuce mats can interfere with all aspects of water utilization, including agricultural production, navigation, flood control, and irrigation (Howard and Harley 1998; Hill 2003; EPPO 2017). Floating mats can create dams in culverts and against bridges and can reduce the efficiency of hydroelectric power generation (Howard and Harley 1998; Neuenschwander et al. 2009). Water lettuce may also impact recreational water usage, such as fishing and swimming opportunities (Šajna et al. 2007), but this has not been quantified. Controlling an established WL infestation can be a costly endeavor. It is estimated that WL and *E. crassipes* control cost $107 per acre in Florida annually (Adams and Lee 2007).

Similar to other invasive free-floating plants that form thick mats (e.g., *E. crassipies, S. molesta*), WL has the potential to alter the physical and chemical properties of waterbodies. Reduced wind and wave driven turnover can lead to thermal stratification of the water column under WL mats (Sculthorpe 1967; Attionu 1976). This combined with shading of phytoplankton and submerged aquatic plants can reduce dissolved oxygen levels, increase carbon dioxide levels, and increase alkalinity underneath and around thick mats (EPPO 2017). In a stream in Slovenia, dissolved oxygen levels decreased by more than 50%, reaching only 2.5 mg/L, when measured beneath WL mats (Šajna et al. 2007). Water lettuce mats can also decrease water temperature and pH, increase siltation, and give water a foul odor (Weldon and Blackburn 1967; Attionu 1976; Sridhar and Sharma 1980; Sridhar and Sharma 1985; Howard and Harley 1998; Chamier et al. 2012). They also have the potential to increase water loss through evapotranspiration, which can be particularly impactful in closed systems (e.g., ponds, reservoirs; Sharma 1984; Howard and Harley 1998). Infestations of WL can alter the availability and cycling of nutrients such as nitrogen and phosphorous (Howard and Harley 1998; EPPO 2017). The accumulation of WL detritus beneath thick mats may cause increased nutrient and sediment loading (Dray and Center 2002).

The impact that WL has on aquatic flora has not been empirically evaluated. Reduced light availability beneath thick WL mats may reduce native aquatic plant diversity and abundance, particularly for submerged species. Over a ten-year period in the Erft River of Germany, native aquatic plant diversity and abundance declined, which was attributed to increases in abundance of WL and *V. americana* var. *biwaensis* (Hussner 2014). In Slovenia, WL mats that persisted over the winter were anecdotally linked to declines in *C. demersum*, *M. spicatum*, *N. marina*, and *T. natans*. This species can also be problematic in rice fields, where it creates damaging conditions to rice and competes for space and nutrients (Bua-ngam and Mercado 1976; Khan et al. 2014). Substances extracted from WL have been found to have allelopathic properties that inhibit the growth of algae and some terrestrial plant species (Aliotta et al. 1991; Bich and Kato-Noguchi 2012).

The altered composition and structure of aquatic plant communities and the physiochemical changes that are associated with WL invasion may negatively impact native fish, wildlife, and invertebrate species. Water lettuce may limit fish and wildlife access to breeding grounds, shelter, food, and other resources that are found at the margins of waterbodies (Howard and Harley 1998). In the Minjiang River of China, mats of *E. crassipes* and WL were associated with decreased plankton abundance and diversity (Cai 2006). By decreasing the flow of water, thick mats can increase siltation in rivers, reservoirs, and wetlands (Hill 2003), potentially covering fish and invertebrate habitat (Neuenschwander et al. 2009). Water lettuce also poses a threat to wildlife species of conservation concern, including the endangered snail kite (*Rostrhamus sociabilis*) by limiting its access to foraging habitat (Rodgers et al. 2001).

Another concern of WL invasion is that it provides habitat for several disease carrying species (Holm et al. 1977). Most notably, WL harbors malaria carrying mosquito species in the genera *Anopheles* and *Mansonia* (Lounibos and Dewald 1989; Neuenschwander et al. 2009) and snail species that host schistosomiasis (Pointier et al. 1988; Cogels et al. 1997).

b. Positive Effects

Water lettuce is a promising candidate for the phytoremediation of polluted aquatic environments and containment waters (Maine et al. 2001). It can remove heavy metals such as cadmium, mercury, chromium, copper, and zinc; while experiencing minimal toxic effects or a decline in reproduction (Maine et al. 2001; Skinner 2007; Mishra and Tripathi 2008; Nurhayati et al. 2010). Water lettuce's uptake of heavy metals could also make it useful as a bioindicator for water pollution (Galal and Farahat 2015). Dried WL leaves can be used as efficient oil sorbents in water (Yang et al. 2014). This species can also accumulate nitrogen and phosphorous from nutrient enriched water (Aoi and Hayashi 1996; Sooknah and Wilkie 2004; Lu et al. 2010). Forni et al. (2006) found that WL can remove two antimicrobial drugs, sulfonamide and quinolone, from contaminated water; however, the plants died three weeks after being exposed to the highest concentration.

The use of aquatic invasive plants for production of biogases, such as biodiesel, biohydrogen, and biomethane, as alternatives to fossil fuels has gained attention in recent years (Wilkie and Evans 2010; Kaur et al. 2017). Water lettuce's chemical composition and excessive growth rate make it ideal as a feedstock for bioenergy production and several studies have demonstrated its potential on a small scale (e.g., Pantawong et al. 2015; Corneli et al. 2017; Kumar et al. 2017). Water lettuce's high nutrient content also gives it potential as a fertilizer and as cattle feed; however, its uptake and storage of heavy metals is a concern (Neuenschwander et al. 2009; Khan et al. 2014).

Traditional medicine, particularly in the Ayurvedic system, commonly use WL for the treatment of various ailments. Medicinal substances derived from WL may act as antifungals, antimicrobials, diuretics, antidiabetics, etc. (Joy et al. 2001; Premkumar and Shyamsundar 2005; Abu Ziada et al. 2009; Pallavi et al. 2011). Khan et al. (2014) provided a review on WL's pharmacological and medicinal properties.

Current Status and Distribution in Michigan

The first documentation of WL in North America was in Florida in 1765; however, its status as an invasive species in Florida has been debated (Evans 2013). Currently, WL has been reported in Alabama, Arizona, California, Colorado, Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Kansas, Louisiana, Maryland, Michigan, Minnesota, Mississippi, Missouri, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Virginia, Texas, Wisconsin, Mexico, Ontario, and Quebec (Dray and Center 2002; Booth 2016; EPPO 2017; Thayer et al. 2018; MISIN 2018).

Water lettuce has been reported at some point in eight counties in Michigan, all in the southern Lower Peninsula: Monroe, Wayne, Kalamazoo, Ingham, Washtenaw, Oakland, Lapeer, and

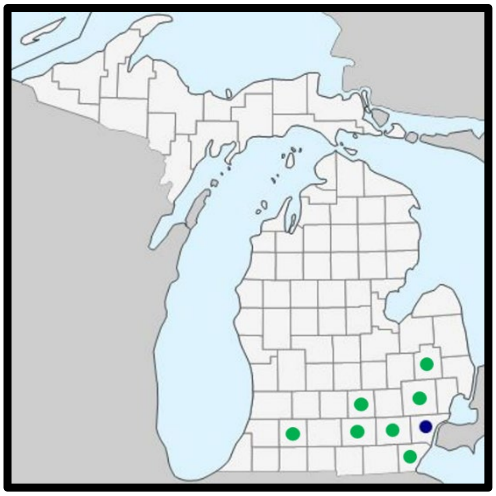

Figure 6. Blue dots indicate counties in Michigan where a specimen of water lettuce (*Pistia stratiotes* L.) has been collected and included in Michigan Flora. Green dots indicate counties where water lettuce was documented by the Midwest Invasive Species Information Network, but not by Michigan Flora. County map developed by Michigan Flora online (Reznicek et al. 2011)

Jackson (Figure 6). Most WL introductions are short-lived and either die-out overwinter or are eradicated. The only population that may be re-occurring is in the Frank and Poet Drain in Wayne County. In 2017, WL was documented in Watkins Lake in Jackson/Washtenaw County, First Sisters Lake in Washtenaw County, and in the Frank and Poet Drain in Wayne County. All WL at these sites was removed (Cahill et al. 2018).

Management of WL

I. Prevention

Water lettuce is not included on the USDA's Federal Noxious Weed List but it is noxious/regulated in Alabama, California, Connecticut, Florida, Louisiana, South Carolina, Texas, Wisconsin, and Manitoba. It is included on the "Watch List" of the MDNR, MDEQ, and MDARD, a list of invasive species that have either never been documented in Michigan or have a limited distribution and pose an immediate and significant threat to Michigan's natural resources. Water lettuce is currently allowable for sale and possession in Michigan. If it is found outside of cultivation, contact the MDEQ Water Resources Division – Aquatic Nuisance Control Program.

Risk classifications vary across WL's temperate distribution, ranging from low to high-risk. A New Zealand risk assessment model, modified for the United States and Canada, classified WL as a high-risk species (Gordon et al. 2012; Gantz et al. 2013). A risk assessment of potential Great Lakes invaders classified WL's introduction potential as high, potential environmental and socioeconomic impacts as moderate, and potential beneficial impacts as moderate (Fusaro et al. 2016). A species assessment conducted in Wisconsin, recommended that WL be classified as prohibited in the state for its potential for survival, dispersal, and impacts (WDNR 2017). In New York, WL received a moderate ranking for invasiveness, primarily due to its potential for ecological impacts and dispersal ability but given that the climate throughout most of the state is unsuitable for establishment its invasiveness was considered "not assessable" (Jordan et al. 2008). A risk assessment conducted for Ireland, classified WL invasion as a low-risk; although, it was estimated that projected increases in water temperature due to climate change could create suitable conditions for WL establishment in the next 50 – 100 years (Millane and Caffrey 2014).

Since WL spreads quickly once it is established, it is imperative to take the proper measures toward prevention. This species may act as an aquatic hitchhiker, so boaters, anglers, and hunters can unintentionally contribute to its spread. Watercraft, trailers, and boating equipment should be washed and dried before transporting between waterbodies and any attached plant material should be disposed of away from shore. 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 WL, between waterbodies: https://www.youtube.com/watch?v=IWobcoWchsI&feature=youtu.be. To prevent spread within a waterbody or between connected waterbodies, recreational boaters should avoid areas where WL occurs or reduce speeds when traveling through infested areas. Water garden and aquarium enthusiasts should purchase native or non-invasive species whenever possible. Unwanted plants should be disposed of properly and never released into the environment. The following actions may prevent and limit the dispersal of WL:

- Classify WL as a “prohibited species” in Michigan under the Natural Resources and Environmental Protection Act 413
- Build a coalition of local, state, and Great Lakes regional partners to monitor for WL and other aquatic invasive 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
- Encourage water garden and aquarium enthusiasts to use native or non-invasive species
- Educate water garden and aquarium enthusiasts on the proper disposal of unwanted plants and waste
- Actively manage sites where WL is found

II. Management/Control

A management strategy that incorporates ecological knowledge and several control techniques – called integrated pest management – into an adaptive management framework of setting management objectives, monitoring, and plan adaptation over time is often considered the most effective approach for controlling invasive species. 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. Monitoring data should be collected using a standardized protocol, inclusive of pre- and post-treatment assessments in managed and unmanaged reference locations, so statistical inferences on treatment impact can be made.

Early detection and rapid response to a WL introduction is crucial. Excluding thermally abnormal waterbodies (Šajna et al. 2007; Hussner et al. 2014; Tamada et al. 2015), it is unlikely that WL can vegetatively overwinter as adult plants in temperate regions like Michigan. Detecting and responding to a WL introduction prior to seed set could prevent the establishment of a persistent population. Water lettuce’s rapid vegetative reproduction and persistence in the seed bank make it exceedingly difficult to manage once it becomes established.

Globally, WL has been managed with chemical, physical, mechanical, and biological control techniques (Neuenschwander et al. 2009; Khan et al. 2014; EPPO 2017). Biological control agents (e.g., *Neohydronomus affinis*, *Spodoptera pectinicornis*), chemical treatments (e.g., diquat, 2,4-D, glyphosate), water level manipulations, and mechanical removal have been used for WL control in North America. In Michigan, WL distribution is limited and introductions are manually removed. The following is a summary of control methods tested to date and their results.

a. Chemical

The herbicides diquat, 2,4-D, and glyphosate are the most widely used chemical treatments for invasive free-floating plants (Howard and Harley 1998; Neuenschwander et al. 2009). Langeland et al. (2009) listed diquat, imazapyr, carfentrazone, and penoxsulam as providing excellent WL control, imazamox as providing good WL control, and copper and glyphosate as providing fair WL control. Paraquat, terbutyrn, and chlorsulfuron have also been effective for WL control (Patnaik 1971; Madin 1984; Cilliers et al. 1996) but are not approved for aquatic use by the United States Environmental Protection Agency (EPA). Most data available on treatment efficacy for WL control come from laboratory or small-scale pond trials; few studies have quantitatively assessed the *in-situ* efficacy of herbicide treatments for WL control (e.g., Weldon and Blackburn 1967). See Table 1 for a summary of EPA approved herbicide active ingredients that have shown some effectiveness against WL in laboratory or field trials.

As plants die and decompose following an herbicide treatment dissolved oxygen levels in the water are reduced (Howard and Harley 1998). In calm and stagnant waterbodies this can create noxious conditions for aquatic organisms (Minnesota Pollution Control Agency 2009). Applying an herbicide prior to the formation of thick WL mats or pre/post-treatment harvesting of plants may prevent the depletion of dissolved oxygen.

Table 1. Summary of effective herbicide active ingredients for water lettuce (*Pistia stratiotes* L.; hereafter WL) control to date. For each herbicide active ingredient, example trade names, whether the active ingredient is currently approved for aquatic use in Michigan, whether WL is listed on the pesticide label, advantages, disadvantages, and the cited literature are listed. Directions on the pesticide label should always be followed and the state Departments of Environmental Quality 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).

	Approved	**Listed on Label**	**Pros**	**Cons**	**References**
Diquat (e.g. Reward®)	Yes	Yes	• 14.3 oz/ac + Induce® (1 qt/ac) provided 100% control 15 DAT in pond trials • 2 – 3 qt/ac + Pro-Mate® Kinetic® (0.25% v/v) provided >95% control in mesocosm trials • 0.5 and 1 lb ai/ac + Sun Wet™ (0.5% v/v) reduced biomass by ≥98% in mesocosm trials • 0.04 – 0.36 qt/ac + Cide-Kick® (0.25 v/v) reduced biomass in mesocosm trials	• Has not been systematically evaluated for WL control in field trials • 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 potable and irrigation water	(Thayer and Haller 1985; Langeland et al. 2002; WDNR 2012b; Mudge and Netherland 2014a; AERF 2018)
2,4-D + Diquat	Yes + Yes	No + Yes	• 15.2 oz ae/ac of 2,4-D + 8 oz ai/ac of diquat + Sun Wet™ (0.5% v/v) reduced biomass by ≥98% in mesocosm trials	• Has not been systematically evaluated for WL control in field trials • May harm non-target species (Broad-spectrum herbicide) • May be toxic to fish and invertebrates • Diquat is ineffective in turbid water or conditions with a lot of wave action • Post-treatment restrictions on potable and irrigation water • May have post-treatment restrictions on swimming and irrigation	(WDNR 2012b; Mudge and Netherland 2014a; AERF 2018)
Triclopyr + Diquat	Yes + Yes	No + Yes	• Combinations of 0.74 or 2.9 lb/ac triclopyr and 0.25 or 0.54 lb ae/ac diquat reduced biomass by >80% • Can be used to manage mixed populations of *E. crassipes* and WL	• Has not been systematically evaluated for WL control in field trials • May harm non-target species (Broad-spectrum herbicide) • Toxic to aquatic invertebrates • Diquat is ineffective in turbid water or conditions with a lot of wave action • Post-treatment restrictions on potable and irrigation water	(Langeland and Smith 1993; WDNR 2012b)

	Approved	Listed on Label	Pros	Cons	References
Endothall (e.g. Aquathol® K)	Yes	No	• 1.5, 3, and 4.5 lb/ac + Induce® (1 qt/ac) provided 80% control 15 DAT in pond trials	• Has not been systematically evaluated for WL control in field trials • Rapid regrowth following treatment in pond 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	(Thayer and Haller 1985; WDNR 2012b; AERF 2018
Glyphosate (e.g. AquaPRO®)	Yes	Yes	• 2 lb ae/ac + Sun Wet™ (0.5% v/v) reduced biomass by ≥61% 8 WAT in mesocosm trials • 2.7 lb ae/ac + Induce® (0.25 v/v) provided 100% control 5 WAT in greenhouse trials • 4 and 6 lb/ac + Induce® (1 qt/ac) provided 100% control 30 DAT in pond trials • Biodegrades and binds to soil faster than many other aquatic herbicides	• Has not been systematically evaluated for WL control in field trials • Only effective on actively growing plants • Rainfall following application may impact efficacy • May harm non-target species (Broad-spectrum herbicide) • Post-treatment restrictions on potable water	(Thayer and Haller 1985; Emerine et al. 2010; Souza et al. 2011; WDNR 2012b; Mudge and Netherland 2014a; AERF 2018)
Flumioxazin (e.g. Clipper®)	Yes	Yes	• 3.1 and 6.12 oz ai/ac + Sun Wet™ (0.5% v/v) provided ≥98% control in mesocosm trials	• Has not been systematically evaluated for WL control in field trials • May harm non-target species (Broad-spectrum herbicide) • Toxic to fish and aquatic invertebrates • Post-treatment restrictions on irrigation	(WDNR 2012b; Mudge and Netherland 2014a; AERF 2018)
Carfentrazone-ethyl (e.g. Stingray®)	Yes	Yes	• 0.04, 0.27, 0.49, 2.73, and 4.81 oz/ac + Freeway® (0.25% v/v) reduced biomass in greenhouse trials • 0.4, 0.8, 1.2, 1.6, and 2.4 oz/ac + Cygnet Plus® (0.25% v/v) reduced biomass in greenhouse trials • Less harm to non-target species (Selective herbicide)	• Has not been systematically evaluated for WL control in field trials • Moderately toxic to fish	(Koschnick et al. 2004; UF/IFAS 2018a; AERF 2018)

	Approved	Listed on Label	Pros	Cons	References
Imazamox (e.g. Clearcast®)	Yes	Yes	• 1.5 and 3 oz ai/ac + Sun Wet™ (0.5% v/v) reduced biomass 8 WAT in mesocosm trials • 0.5, 1, 2, 3, 4, and 8 oz/ac + Induce® (0.25% v/v) reduced biomass 5 WAT in greenhouse trials • May selectively manage WL	• Has not been systematically evaluated for WL control in field trials • Slow acting • May harm non-target species (Broad-spectrum herbicide) • Restricted concentration when near potable water intakes • Post-treatment restrictions on potable and irrigation water	(Emerine et al. 2010; WDNR 2012b; Mudge and Netherland 2014a; AERF 2018)
Imazamox + Carfentrazone-ethyl	Yes + Yes	Yes + Yes	• 1 oz ai/ac of imazamox + 0.24 oz ai/ac of carfentrazone-ethyl + Inergy® (1% v/v) reduced biomass 8 WAT in mesocosm trials • Produces injury symptoms faster than imazamox alone • May selectively manage WL	• Has not been systematically evaluated for WL control in field trials • Slow acting • May harm non-target species (Broad-spectrum herbicide) • Moderately toxic to fish • Restricted concentration when near potable water intakes • Post-treatment restrictions on potable and irrigation water	(WDNR 2012b; Mudge and Netherland 2014b; UF/IFAS 2018a; AERF 2018)
Imazamox + Flumioxazin	Yes + Yes	Yes + Yes	• 1 oz ai/ac of imazamox + 0.26 oz ai/ac of flumioxazin + Inergy® (1% v/v) reduced biomass 8 WAT in mesocosm trials • Produces injury symptoms faster than imazamox alone • May selectively manage WL	• Has not been systematically evaluated for WL control in field trials • Slow acting • May harm non-target species (Broad-spectrum herbicide) • Toxic to fish and aquatic invertebrates • Restricted concentration when near potable water intakes • Post-treatment restrictions on potable and irrigation water	(WDNR 2012b; Mudge and Netherland 2014b; AERF 2018)
Imazapyr (e.g. Habitat®)	Yes	Yes	• 8 oz ae/ac + Induce® (0.25% v/v) provided 98% control 5 WAT in greenhouse trials	• Has not been systematically evaluated for WL control in field trials • May harm non-target species (Broad-spectrum herbicide) • Post-treatment restrictions on potable water	(Emerine et al. 2010; WDNR 2012b; AERF 2018)

	Approved	Listed on Label	Pros	Cons	References
Penoxsulam (e.g. Galleon® SC)	Yes	Yes	• 0.5 oz ai/ac + Inergy® (1% v/v) reduced biomass 8 WAT in mesocosm trials • 0.5 oz ai/ac + Aqua-King Plus® (1% v/v) + Thoroughbred® (0.5% v/v) reduced biomass 8 WAT in mesocosm trials • 0.63 and 1.25 oz ai/ac + Sun Wet™ (0.5% v/v) reduced biomass 8 WAT in mesocosm trials • May selectively manage WL	• Has not been systematically evaluated for WL control in field trials • Slow acting • Post-treatment restriction on irrigation	(WDNR 2012b; Mudge and Netherland 2014a,b; AERF 2018)
Penoxsulam + carfentrazone-ethyl	Yes + Yes	Yes + Yes	• 0.5 oz ai/ac of penoxsulam + 0.24 oz ai/ac carfentrazone-ethyl + Inergy® (1% v/v) reduced biomass in mesocosm trials (63-72% control) • Produces injury symptoms faster than penoxsulam alone • May selectively manage WL	• Has not been systematically evaluated for WL control in field trials • Slow acting • Moderately toxic to fish • Post-treatment restrictions on irrigation	(WDNR 2012b; Mudge and Netherland 2014b; AERF 2018)
Penoxsulam + Flumioxazin	Yes + Yes	Yes + Yes	• 0.5 oz ai/ac of penoxsulam + 0.26 oz ai/ac of flumioxazin + Inergy® (1% v/v) reduced biomass in mesocosm trials (63-73% control) • Produces injury symptoms faster than penoxsulam alone • May selectively manage WL	• Has not been systematically evaluated for WL control in field trials • Slow acting • May harm non-target species (Broad-spectrum herbicide) • Toxic to fish and aquatic invertebrates • Post-treatment restrictions on irrigation	(WDNR 2012b; Mudge and Netherland 2014b; AERF 2018)
Bispyribac-sodium (e.g. Tradewind™)	No	Yes	• 0.84 and 1.7 oz ai/ac provided up to 99% control 8 WAT in mesocosm trials • Less harm to non-target species (Selective herbicide)	• Has not been systematically evaluated for WL control in field trials • May require repeated applications to control regrowth • Only effective on actively growing plants • Should not be used on moving water or on waterbodies with an outlet • Post-treatment restrictions on livestock and irrigation	(WDNR 2012b; Glomski and Mudge 2013; AERF 2018)

*Weeks after treatment (WAT), days after treatment (DAT)

b. Physical or Mechanical

Manual removal by hand or with rakes and seining using fishing/cargo nets are used to control small recently introduced WL populations or to clear patches of WL for access to water (Diop and Hill 2009; DAF 2016; GISD 2018). For large infestations, the mat typically needs to be cut into small sections using knives or ropes and then pulled to shore (Howard and Harley 1998; Khan et al. 2014). This is a time and labor-intensive process that has the potential to proliferate the spread of WL via fragment and seed dispersal if done after flowering has occurred (Hill and Coetzee 2017). Following removal, WL can repopulate through the seed bank, plants that are missed during removal, or plants that drift from inaccessible areas (Neuenschwander et al. 2009). In Botswana, a combination of water level manipulation and physical removal were used to control WL in seasonal waterbodies. The water level was raised twice a year, allowing the seeds in the seed bank to germinate. Once the seeds germinated and were floating on the water's surface they were manually removed. Repeating this process year after year depleted the seed bank and eradicated WL from the waterbodies (Kurugundla 2014).

Hand pulling has been used on a potentially reoccurring population in the Frank and Poet Drain of the Detroit River, Michigan. In 2014 and 2015 thousands of pounds of WL was removed from the drain. In 2016 and 2017 all WL plants were removed, totaling 120 lbs (54 kg) and 7 lbs (3 kg), respectively. It is unknown whether the reoccurring presence of WL in the Frank and Poet Drain is a result of an established seed bank, drift from other infested locations, or reoccurring introductions (Cahill et al. 2018).

Mechanical harvesters that cut and collect vegetation can be employed for WL control on larger scales (Rodgers et al. 2001; Khan et al. 2014; Hill and Coetzee 2017). Like manual removal, mechanical harvesting can result in the further spread of WL, typically only provides temporary control, and should be done prior to flowering. Mechanical removal has the potential to negatively impact native biodiversity, particularly to plants growing among WL and invertebrate species living on WL. Mechanical harvesting can also increase turbidity.

Floating diversion booms have been deployed on slow moving rivers to collect WL plants as they drift downstream (Neuenschwander et al. 2009). They can be used to protect infrastructure, maintain access to open water, or contain an isolated population. In heavily infested areas booms must be frequently cleared of plant material (Howard and Harley 1998). Following any type of physical or mechanical removal WL plants should be disposed of away from shore to prevent reintroduction.

Water level manipulation can be used to control WL in areas that are inaccessible to herbicide applicators or mechanical harvesters. Every three years in the Rodman Reservoir in Florida, a combination of flooding and drawdowns is used to manage hundreds of acres of WL. The reservoirs water level is raised so that mats of WL drift into upland areas and is then quickly reduced so that the mats become stranded on dry ground (UF/IFAS 2018b). Water level manipulation can be damaging to native aquatic organisms (Madsen 2000; Harman et al. 2005) and is only possible in reservoirs and other artificially controlled waterbodies. The efficacy of water level manipulation for WL control has not been evaluated.

c. Biological

Water lettuce is utilized by a diverse assemblage of insect species. It is consumed by at least 44 species worldwide: 21 in the neotropics, 11 in Asia, 9 in North America, 5 in Africa, and 5 in Australia (Dray et al. 1993; Dray and Center 2002). Dray et al. (1993) documented six insect species feeding on WL in Florida: *Petrophila drumalis* (Dyar), *Synclita obliteralis* (Walker), *Samea multiplicalis* Guenée, *Rhopalosiphum nympharae* L., *Draeculacephala inscripta* Van Duzee, and *Tanysphyrus lemnae* (F.). Only some of these species fed exclusively on WL. Most species that are exclusive to WL occur in South America and include (but not limited to) *Argentinorhynchus breyeri* Brethes, *A. bruchi* (Hustache), *A. squamosus* (Hustache), *A. bennetti* O'Brien and Wibmer, *A. kuscheli* O'Brien and Wibmer, *A. minimus* O'Brien and Wibmer, *N. affinis* Hustache, *N. elegans* O'Brien and Wibmer, *Pistiacola cretatus*, *P. fasciatus* O'Brien and Wibmer, *P. drumalis* (Dyar), and *Spodoptera pectinicornis* (Hampson) (Cordo and Sosa 2000). Few of these species have been pursued as potential biological control agents (Table 2).

Surveys for fungal pathogens inhabiting WL have found few species (Barreto et al. 2000). Barreto and Evans (1996) documented *Cercospora pistiae* Nag, Raj, Govindu and Thirumalachar damaging WL in Argentina but considered it an unpromising biocontrol agent. *Botrytis pistiae* Baccarini, *Phyllosticta stratiottis* F. Tassi, *Corticium rolfsii* Curzi, *Rhizoctonia solani* Kuhn, *Sclerotium rolfsii* Saccardo, and *Ramularia* spp. are also associated with WL (Barreto et al. 1999; Fernandes and Barreto 2005). In laboratory trials, Yirefu et al. (2017) documented *Alternaria alternata, A. tenuissima, Fusarium oxysporum, F. equiseti,* and *Neofusicoccum parvum* causing severe leaf necrosis on WL. *A. alternata* and *Sclerotinia sclerotiorum* (Lib.) de Bary have both been effective against WL (Table 2; Mohan Babu et al. 2004; Waipara et al. 2006).

Table 2. Summary of biological control agents that have shown some effectiveness for water lettuce (*Pistia stratiotes* L.; hereafter WL) control to date. For each agent, the species name, native distribution, advantages, disadvantages, and cited literature are listed. Table modeled after the MNFI Glossy Buckthorn Factsheet (MNFI 2012).

Species	**Native Distribution**	**Pros**	**Cons**	**References**
Neohydronomus affinis Hustache (weevil)	South America	• Successful eradication or suppression at sites in Australia, Africa, and South America • Can achieve 100% control in 1 – 2 years in tropical regions • Reduced abundance by 90% at sites in Florida and Louisiana • Reduced plant size, number of leaves, and growth rate at sites in Florida • Two weevils per plant reduced plant size and four weevils plant caused mortality in laboratory trials • Specific to WL in the United States (Florida), Australia, Africa, and South America • Has been used as a biocontrol in the United States (Florida, Louisiana, Texas)	• Long-term control using *N. affinis* has not been achieved in the United States • May harm some native species (i.e. *Lemna*, *Spirodela*, *Limnobium, Azolla*) • Less effective in cool temperatures and in eutrophic conditions • Has not been evaluated for use in temperate climates	(Cilliers 1989; Thompson and Habeck 1989; Harley 1990; Dray and Center 1993; Cilliers et al. 1996; Dray and Center 2002; Ajuonu and Neuenschwander 2003; Mbati and Neuenschwander 2005; Neuenschwander et al. 2009; Diop et al. 2010; Moore and Hill 2012; Cabrera Walsh et al. 2017)
Argentinorhynchus breyeri Brèthes (weevil)	South America	• High densities can cause mortality • May be specific to WL	• Requires waterbody to dry to complete its life cycle • Has not been evaluated as a biocontrol in the United States • Has not been evaluated for use in temperate climates	(Cordo and Sosa 2000; Neuenschwander et al. 2009)
Samea multiplicalis Guenée (pyralid moth)	North America, Central America, South America	• High densities combined with cool temperatures (i.e. slow WL growth) can reduce WL mats • Feeds on several aquatic invasive/ non-native plants in the United States (e.g. *E. crassipes*, *S. minima* Baker, *S. molesta*)	• May feed on native plant species • Populations are sporadic • Can't sustain control throughout the growing season • Has not been evaluated for use in temperate climates	(Sands and Kassulke 1984; Dray et al. 1993; Center 1994; Dray and Center 2002)

Species	Native Distribution	Pros	Cons	References
Lepidelphax pistiae Remes Lenicov (planthopper)	Argentina	• High densities stunted growth and caused mortality in laboratory trials • Reduced biomass, cover, plant size, and clonal reproduction in field trials in Argentina • Specific to WL in Argentina • Did not reduce the effectiveness of *N. affinis* • Currently being evaluated for its environmental safety and utility as a biocontrol agent in the United States by the USDA/ARS Invasive Plant Research Laboratory	• Has not been evaluated in temperate climates • Not approved for release in the United States	(Marino De Remes Lenicov and Cabrera Walsh 2013; Cabrera Walsh et al. 2014; Cabrera Walsh and Maestro 2014; Cabrera Walsh and Maestro 2016; Marino De Remes Lenicov et al. 2017; Tipping et al. 2017)
Sclerotinia sclerotiorum (Lib.) de Bary (fungus)	Worldwide	• Caused 100% mortality 54 DAT* in laboratory trials in New Zealand	• Can infect a wide range of organisms (Broad host range) • Damaging pathogen to several crop species (e.g. soybeans, legumes, sunflowers) • Has not been evaluated as a biocontrol in the United States	(Waipara et al. 2006)
Alternaria alternata (fungus)	Worldwide	• Caused severe leaf necrosis in laboratory trials • Caused 98% mortality 21 DAT in controlled trials in India	• Can infect a wide range of organisms (Broad host range) • Common outdoor allergen • Has not been evaluated as a biocontrol in the United States	(Mohan Babu et al. 2004; Yirefu et al. 2017)

*Weeks after treatment (WAT), days after treatment (DAT)

d. Indirect Management

No indirect management techniques were investigated for the control of WL at the time of this report. Although competitive exclusion of WL by the introduction of a competitively superior species might have potential as an indirect management strategy, many of the species that outcompete WL (e.g., *E. crassipies*, *S. molesta*) are damaging invasive species themselves. The taller *E. crasspies* can shade out WL and was documented displacing WL in Florida when left unmanaged (Chadwick and Obeid 1966; Dray et al. 1988; Agami and Reddy 1990). In rice fields in the Philippines, competition for light and nutrients by heart-shaped false pickerelweed (*Monochoria vaginalis* (Burm. f Presl)) and barnyard grass (*Echinochloa crus-galli* (L.) Beauv.) reduced WL biomass (Bua-ngam and Mercado 1976).

Research Needs

I. Biology and Ecology

Currently, WL has been documented in Alabama, Arizona, California, Colorado, Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Kansas, Louisiana, Maryland, Michigan, Minnesota, Mississippi, Missouri, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Virginia, Texas, Wisconsin, Mexico, Ontario, and Quebec (Dray and Center 2002; Booth 2016; EPPO 2017; Thayer et al. 2018; MISIN 2018). Populations reported in temperate areas are typically ephemeral and are removed or die-out during the winter months. Repeated occurrences in the Detroit – St. Clair River system of Michigan may be a result of a persistent soil seed bank, drift from an upstream source, or reoccurring introductions. Investigation of the genetic relationships between WL populations on the American and Canadian side of the Detroit – St. Clair River system could provide insight into its pathways and vectors of introduction and dispersal. Understanding WL's pathways and vectors of introduction and dispersal could help prevent new introductions and aid in the development of more efficient education, prevention, and monitoring programs.

To date, modelling of suitable WL habitat in the Great Lakes basin has used air and water temperate variables in lakes (Garwood et al. 2014). Further understanding local site characteristics (e.g., current velocity, water chemistry, associated vegetation) that characterize WL occurrence, particularly in temperate climatic zones, will improve predictions of WL spread and help guide monitoring efforts. Human dimension variables such as human population density and density of pet stores that sell WL in the area could also improve model predictions.

Given WL's sensitivity to frost and freezing conditions it is unlikely that vegetative overwintering occurs in the Great Lakes region (Neuenschwander et al. 2009; MacIsaac et al. 2016). Viable seed production is probably the only mechanism for WL to persist in the Great Lakes region but it has not yet been observed (Adebayo et al. 2011; MacIsaac et al. 2016). Understanding the conditions that trigger WL flowering and seed development, like Pieterse et al. (1981) observed during an abnormally hot summer in the Netherlands, should be investigated to determine if these conditions are met in the Great Lakes region. It is possible that WL is sexually reproducing in the Great Lakes region undetected, as WL flowers are inconspicuous, fruits develop under the surface of the water, and the seeds sink to the substrate (Buzgó 1994; Buzgó 2006). Water lettuce plants that are removed from waterbodies in the Great Lakes should be searched for flowers and fruit and the sediment below reoccurring populations should be searched for seeds. If seeds are found, germination experiments could be conducted to determine if they are viable.

If WL produces viable seeds in the Great Lakes region, it is possible that seeds could remain viable overwinter and germinate the following year. Water lettuce seeds can tolerate frost and survive temperatures as low as 23°F (-5°C) for 4 weeks (Pieterse et al. 1981). Water lettuce seeds from the Netherlands did not germinate below 68°F (20°C) and the highest germination rate was between 73 – 77°F (22.5 – 25°C), conditions that could be met in the Great Lakes region. Germination can occur in complete darkness and germination rate increases with increased light intensity (Pieterse et al. 1981; Harley 1990). Further understanding of the environmental conditions that trigger and regulate seed germination could provide insight into the likelihood of WL establishing persistent populations in the Great Lakes region.

Water lettuce seeds can persist through drought and freezing conditions (Pieterse et al. 1981; Kan and Song 2008) but their long-term viability is unknown. Multi-year management efforts would likely be needed to maintain control of an established WL population if seeds can remain viable in the seed bank.

A climate model, using variables associated with air and water temperatures in lakes, projected that the Great Lakes region will remain unsuitable for WL establishment until at least the late-21st century (Garwood et al. 2014). Further climate modelling that incorporates finer scale data, such as water temperatures in shallow wetlands, along the margins of waterbodies, or in steams, could refine the projections. Projected climate change impacts, such as decreases in ice cover in the winter and earlier ice breakup in the spring, increases in water temperature, and an extended growing season, may create more suitable conditions for WL introduction, establishment, and spread. Furthermore, the impact that climate change will have on WL fruit and seed production, vegetative reproduction, and seed germination should be investigated.

Water lettuce infestations have the potential to negatively impact native plant and wildlife diversity, alter the physical and chemical characteristics of waterbodies, and impose severe limitations on recreational and commercial water usage (Neuenschwander et al. 2009; EPPO 2017). Most studies that document the impacts of WL occur in tropical and subtropical regions; few have taken place in temperate climates. In Slovenia and Germany, WL mats were anecdotally associated with declines in submerged aquatic plants (*C. demersum*, *M. spicatum*, *N. marina* L., and *T. natans*; Šajna et al. 2007; Hussner et al. 2014). Its impact when growing in mixed communities has not been investigated. Understanding WL's potential for ecological, social, and economic impacts in the Great

Lakes region can help managers prioritize sites for management and contribute to the cost-benefit analysis of managing an invasive population.

II. Detection

Remote sensing can be used to detect and distinguish WL infestations (Everitt et al. 2003; Everitt and Yang 2007; Everitt et al. 2011). Typically, a population would have to be 5 pixels in size to be detected with remotely sensed imagery. Classifications using imagery at 2.8 m spatial and spectral resolution can be used to detect WL mats greater than 10 m in size, but populations that don't form large mats may go undetected. Imagery gathered by unmanned aerial systems would likely be required to gather imagery at a resolution fine enough to detect smaller WL mats or individual WL plants. It may also be difficult to detect WL interspersed among emergent vegetation with similar spectral signatures or at course spatial or spectral resolutions using remote sensing.

Genetic markers have been developed to detect WL genetic material shed into the environment (Scriver et al. 2015). These markers were successful at detecting WL genetic material in laboratory generated water samples but have not been evaluated in the field. Sampling for genetic material shed into the environment by WL 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. However, investment into this approach for WL detection may not be efficient, as WL is an easily distinguishable species and is often found near shore.

III. Management

Several herbicides have been effective for controlling WL in laboratory and pond trials (Table 1). Of those, diquat, endothall, glyphosate, flumioxazin, carfentrazone-ethyl, imazamox, imazapyr, and penoxsulam are approved for aquatic use in Michigan. Little research has been published on the *in-situ* efficacy of chemical treatments for WL control that is inclusive of untreated controls and pre- and post-treatment monitoring. Studies that evaluate the short and long-term efficacy of chemical treatments, as well as the impact these treatments have on native aquatic plants, fish, and invertebrate communities are needed. Untreated control comparisons and quantitative pre- and post-treatment monitoring are required to properly measure the efficacy of any treatment.

Mechanical and physical techniques are used to control WL. Manual removal has been successful for eradicating or managing recently introduced populations and small isolated populations (Diop and Hill 2009; Kurugundla 2014; DAF 2016; GISD 2018). Mechanical removal is used on larger WL infestations (Rodgers et al. 2001; Khan et al. 2014; Hill and Coetzee 2017). Research is needed to evaluate the efficacy of manual and mechanical removal as well as their potential to enhance the spread of WL plants and seeds. Water level manipulation has also been used to control WL infestations in Florida (IFAS 2018); however, research is needed to evaluate its efficacy and impact to native flora and fauna.

Biological control programs, primarily using *N. affinis*, have been successful in controlling WL in other countries but have produced mixed results in the United States (Table 2). A promising biological control agent, *L. pistiae*, showed effectiveness in field and lab trials against WL and is currently being evaluated for use in the United States by the USDA/ARS Invasive Plant Research Laboratory. Two fungi, *Sclerotinia sclerotiorum* and *Alternaria alternate,* were effective against WL in lab trials but have not been evaluated for WL control in the field and are not approved as biological control agents for WL in the United States. Research into potential biological control agents that would be effective in temperate climates is needed.

Understanding WL's potential for sexual reproduction in the Great Lakes region is crucial for management. If viable seeds are produced management should occur prior to seed development. If WL is able to form a seed bank, its persistence in invaded waterbodies and dispersal potential (i.e., transport by wildlife) could be greater than previously thought. Understanding how ramet and seed production is impacted by treatment could lead to more effective management strategies. If ramets or seeds are not impacted by treatment or if production of these reproductive structures is enhanced following treatment, repeated actions will likely be required to maintain control.

Future Directions for Michigan and WL Management

Water lettuce is a free-floating aquatic plant found on all continents except Antarctica (EPPO 2017). In North America, it has been documented in in Alabama, Arizona, California, Colorado, Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Kansas, Louisiana, Maryland, Michigan, Minnesota, Mississippi, Missouri, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, South Carolina, Virginia, Texas, Wisconsin, Mexico, Ontario, and Quebec (Dray and Center 2002; Booth 2016; EPPO 2017; Thayer et al. 2018; MISIN 2018). Water lettuce's distribution in the Great Lakes region is limited but its potential for adverse impacts coupled with the possibility of climate change creating more suitable conditions for its establishment make it a management concern in the Great Lakes region.

Prevention – Prevention of new colony establishment is likely the most cost-effective approach for WL management. Potential vectors of WL introduction and dispersal include dumping of aquarium and water garden plants, waterway currents, fish and wildlife, and transportation of plants and seeds by recreational waterbody users. Classifying WL as a "prohibited species" in Michigan under the Natural Resources and Environmental Protection Act 413 could reduce accidental or deliberate introductions from the aquarium and water garden trade. The development of outreach and education programs designed to raise stakeholder and public (e.g., lake associations, anglers, aquarium enthusiasts) awareness of WL impacts and prevention and control methods may reduce the human-mediated spread of WL. Likewise, a sustainable boat washing and inspection program, particularly at high-risk waterbodies, could aid in containing its spread. Active management to eradicate or contain WL infestations could reduce the likelihood of dispersal through human and non-human mediated vectors.

Monitoring – Early detection of a WL introduction makes eradication a more realistic option. Adding WL 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 WL 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.

Water lettuce monitoring would benefit from a direct and targeted monitoring strategy. To develop a targeted monitoring strategy, WL occurrences and associated environmental variables could be modelled to identify suitable waterbodies for establishment. Human dimension variables, such as whether a waterbody has a public boat access and the density of pet shops that sell WL in the area, could also be included in the distribution models. Suitable waterbodies that have a high-risk of WL 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, Weed Map – Cooperative Weed Management Area, Michigan Clean Water Corps (MiCorps) Data Exchange Network – Great Lakes Commission, Nonindigenous Aquatic Species Database – USGS (NAS – USGS), 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. Preliminary efforts within the state of Michigan have agencies contributing to regional databases (e.g., MISIN, Cooperative Weed Management Area, Nonindigenous Aquatic Species Database), 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 aquatic invasive 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 water bodies.

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 Environmental Quality, 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 (MDEQ 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 WL, it is important to delimit the extent of the infestation, eradicate recently detected introductions, contain already established populations, and protect high-value sites. An integrated pest management plan combined with an adaptive management framework is likely the most effective approach for controlling WL.

Educating residents on the identification, legal restrictions, and potential negative impacts of WL 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 WL control can be quantitatively assessed by documenting any regrowth, reduction in WL biomass or cover, or reductions in seed or ramet 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.

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 water lettuce (*Pistia stratiotes* L.; hereafter WL) management.

Guidance and Outreach for WL Management			
Objective	**Strategic Action**	**Who is leading effort in Michigan?**	**Expected Outcome**
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.	• Increase public awareness of WL • Increase the frequency and use of boat washing stations • Protect high-value sites • Contain established populations
Provide technical guidance to those interested in WL management	• Develop framework to prioritize management of WL infestations • Educate stakeholders on available control methods		• Increase management efforts
WL Monitoring and Data Management			
Develop a mechanism for detecting, monitoring, and reporting AIS species	• Develop a system of identifying water bodies with high likelihood of introduction • Survey waterbodies with high likelihood of introduction	• Cooperative Lakes Monitoring Program (CLMP) • MDEQ – Water Resources Division (WRD) • MISIN • MiCorps	• Develop a more thorough and up-to-date statewide distribution of WL • 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 WL 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	• Increase public awareness of AIS • Identify water bodies that need professional confirmation of AIS
Research Needs for WL Management			
Chemical: Evaluate the effectiveness of current chemical treatments	• Study the effectiveness of chemical treatments for reducing/eliminating WL		• Determine whether or not chemical treatment is a cost-effective management approach

			• Effective treatment of WL resulting in containment, suppression, or eradication
Biological: Establish biological control methods	• Identify and study the effectiveness of any potential biological control species		• Increase long-term control success
Mechanical: Evaluate effectiveness of current mechanical controls	• Study the effectiveness of hand-pulling and mechanical harvesting for reducing/eliminating WL		• Determine whether or not physical/mechanical removal is a cost-effective management approach • Effective treatment of WL resulting in containment, suppression, or eradication
Physical: Evaluate effectiveness of current physical controls	• Study the effectiveness of water level manipulation for reducing/eliminating WL		• Determine whether or not physical controls are a cost-effective management approach • Effective treatment of WL resulting in containment, suppression, or eradication

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