State of Michigan's
Status and Strategy for Curly-leafed Pondweed (*Potamogeton crispus* L.)

Scope

Invasive curly-leafed pondweed (*Potamogeton crispus* L., hereafter CLP) has invaded the state of Michigan since 1910 (Stuckey 1979). This document was developed by Central Michigan University and reviewed by Michigan Departments of Environmental Quality and Natural Resources for the purposes of:

- Summarizing the current level of understanding on the biology and ecology of CLP.
- Summarizing current management options for CLP in Michigan.
- Identifying possible future directions of CLP management in Michigan.

This document used the current information available in journals, publications, presentations, and experiences of leading researchers and managers to meet its goals. Any chemical, company, or organization that is mentioned was included for its involvement in published, presented, or publically shared information, not to imply endorsement of the chemical, company, or organization.

Biology and Ecology

I. Identification

Curly-leafed pondweed is a submersed perennial plant with slender, laterally compressed stems (Figure 1). The stems are rectangular with a furrow on the broader sides, 0.01 – 0.1 in (0.5 – 2.5 mm) wide, with many branches (Holm et al. 1997). Like the rest of the members in its genus, CLP has rhizomes (i.e.,horizontal root-like stems) 10 – 13 ft (3 – 4 m) long that are branched (Holm et al. 1997).

Figure 1. A flowering curly-leafed pondweed (*Potamogeton crispus*). Photograph by Frank Koshere, courtesy of Wisconsin Department of Natural Resources

There are both spring and winter forms of CLP leaves. Both forms have alternately arranged leaves attached directly to the stem and are widest near the stem to oblong. The spring leaves have mildly serrated and wavy edges, 0.3 – 0.6 in (0.75 – 1.5 cm) wide, and up to 10 cm long (Holm et al. 1997). The leaves are bright to dark green in color and may have a reddish tint. There are usually only 2 parallel vein(s) on each side of the red midrib, however specimens have been observed with 1 or 3 (Scribailo and Alix 2006). The winter form are blue-green in appearance, flat-margined, narrower than the spring version, and have a dull reddish-brown midrib (Wehrmeister 1978). There is often ice coverage when the winter leaves are present, so it is less likely to observe that leaf type.

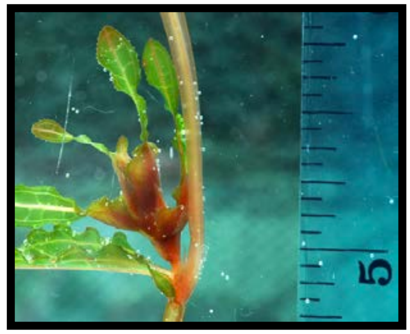
Figure 2. A developing turion of curly-leaf pondweed (*Potamogeton crispus*). Photograph by Frank Koshere, courtesy of Wisconsin Department of Natural Resources

Turions are formed at the base of the leaf and are composed of a modified stem and leaves (Figure 2; Wehrmeister 1978). The turions produced are 1.5 in (4 cm) long, brittle, thorny, and either green or brown.

The flowers are clustered in 3 – 5 whorls arranged in a spike 0.4 – 0.8 in (1 – 2 cm) long (Wehrmeister 1978). The individual flowers are 0.08 – 0.25 in (2 – 7 mm) long and 0.06 – 0.1 in (1.5 – 3 mm) wide with one dark olive to brown, curly modified leaf. The fruit is smooth to containing small tuber-like swellings or projections (Harris and Harris 1994). Each fruit has one seed and each spike produces an average of 3-4 seeds (Catling and Dobson 1985).

Species that are often mistaken for CLP include: white-stemmed pondweed (*Potamogeton praelongus* Wulfen) and *P. x undulatus* Wolfg., a hybrid of CLP and *P. praelongus*. The serrated leaves of CLP differentiate it from the other two species, which have smooth margins. Curly-leafed pondweed also has smaller leaves and more defined wavy leaf margins than the other species (Scribailo and Alix 2006).

II. Detection

Curly-leafed pondweed is easily detectable in early spring as it will be one of the few plants readily growing and the first submersed plant to reach the surface. Detection can occur as soon as it is possible to navigate the body of water (Wehrmeister 1978). Before April, CLP leaves could be in their winter, non-undulated form. In late April, the plants reach the surface and the floral spike can be used in identification, because it is likely the only aquatic flower in bloom. In early July, CLP will begin to die out. Detection during the summer die out will be inconsistent and less effective.

In examining Michigan herbaria collections and descriptions (AUB, BLH, CMC, EMC, MICH, MSC, UMBS, WMU), CLP has been collected from May to October, but few specimens were collected in September and those collected in August were sometimes described as “not abundant.” This may indicate that although CLP begins dying back in early July, it may not die out to undetectable levels until August in Michigan.

Remote sensing cannot be reliably used to detect submerged species like CLP. Water absorbs the wavelengths of light most often used to detect and distinguish plant species. Sago pondweed (*Stuckenia pectinata* (L.) Börner.) is indistinguishable from water crowfoot (*Ranunculus fluitans* Lam.) based on reflectance alone, but could be distinguished if objectbased image processing techniques that examined texture and shape are used at depths less than 15.7 in (40 cm; Visser et al. 2013). The value of detecting CLP at depths less than 15.7 in (40 cm) is minimal, since CLP is easily detected by man at this depth and can be hidden from sensors by overhanging vegetation.

Higher resolution imagery would not improve the detection ability. The imagery used in Visser et al. (2013) was gathered at a resolution less than 1m that can be achieved only manually in a labor-intensive manner like in the study or possibly with unmanned aerial systems.

III. Life History and Spread/Dispersal

Curly-leafed pondweed is a perennial that reproduces both sexually and asexually via turions. Unlike most plants CLP is dormant during the summer, while it is in the form of a turion (Figure 2), and vegetative in the winter and spring (Wehrmeister 1978).

Germination is triggered by a decrease in water temperature; therefore, an unusually hot summer would cause turions to germinate later in the season and a cool summer will cause the turions to germinate earlier (Sastroutomo 1981). After the turions germinate, the plant produces its winter foliage. The winter form of CLP can withstand extremely low light levels and low temperatures, however, unusually long periods of ice cover and deep snowpack have been observed to limit the viability of the winter form (Heiskary and Valley 2012).

When the ice melts and the water warms in March, the stems rapidly produce the spring leaf forms; by April the spring form is the dominant leaf form. The spring foliage dies off between late-May and mid-August.

In mid-April the flower buds and turions form. The flowers form at the tips of the shoots that grow above the water. The turions and fruits mature in July and August, depending on the water temperature; colder water slows the maturation (Catling and Dobson 1985). The germination rate of the fruits is extremely low and varied depending on the population studied (Catling and Dobson 1985). Curly-leafed pondweed fruits have little influence on the growth of an established population, however they are effective in terms of dispersal of CLP to new areas.

Once the turions are mature they can be dropped by the plants or knocked off by a physical force, and sink to the bottom. Green turions are more likely to germinate than brown turions (Sastroutomo 1981). The turions remain dormant until they germinate in late September through November. The Redwood-Cotton Rivers Control Area in Minnesota cites that turions can remain dormant and viable for up to five years, but primary sources were not cited and this information has not been confirmed (RCRCA 2003).

Curly-leafed pondweed is a popular aquarium plant. The dumping of aquarium water into a natural body of water is one vector of introduction of CLP. Although owning this plant is prohibited or restricted in the many states including Michigan, there are means to acquire it through online purchases, both directly or from contamination of another purchase (Maki and Galatowitsch 2004).

Other vectors of dispersal are ballast water, waterfowl, and improper boat cleaning between bodies of water. The stems, turions, or fruit can be caught in ballast water, animal feet or feathers, or boat props and deposited unintentionally in unaffected bodies of water. Waterfowl also eat CLP fruit and can disperse it through their feces (Catling and Dobson 1985).

IV. Habitat

Curly-leafed pondweed is one of the world's most widespread aquatic plant species (Holm et al. 1997). Although it is found worldwide, CLP is native to only Eurasia (Stuckey 1979).

Curly-leafed pondweed usually grows in silt or clay sediment, however, it has been found in gravel or sand (Catling and Dobson 1985). It grows in most freshwater ecosystems including estuaries, reservoirs, lakes, rivers, and even small ditches (Stuckey 1979). It grows best in eutrophic conditions and has been found to be very resistant to pollution, growing in waters too polluted for other plants. Growth can occur at depths ranging from 1.6 – 11.8 ft (0.5 - 3.5 m; Stuckey 1979).

Curly-leafed pondweed is an advantageous weed, meaning if an area has been disturbed it will take advantage of the lack of competition and proliferate. Due to CLP's high tolerance for pollutants and this advantageous nature it often dominates in water bodies too polluted for plant other life. Another instance of disturbance that may cause CLP proliferation is the treatment of a lake for other nuisance weeds. If a species is knocked down or eradicated one season, the next season CLP will be more abundant than before (Madsen 2009).

V. Effects from CLP

a. Negative Effects

The spring leaf form of CLP develops in April and quickly reaches the surface where it flowers. The spring leaf form prevents light from reaching most native plants that have only begun to germinate. This creates a CLP monoculture or CLP dominated oligoculture. As an aquatic invasive species that forms large mono- or oligocultures along rivers and lakeshore it has the potential cause the following

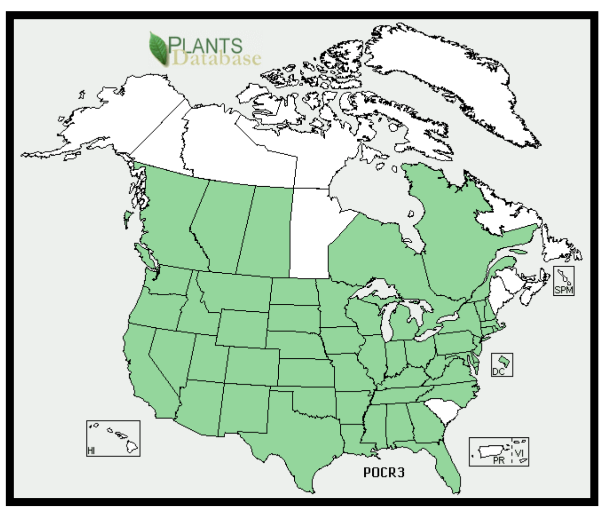

Figure 3. Distribution of curly-leafed pondweed (*Potamogeton crispus*) in North America. Populations have been reported in one county in Maine in 2004 (IPANE 2014). Map provided by USDA PLANTS Database (2014)

ecological and economic issues, but CLP has not been studied in relation to these effects specifically:

- Impede irrigation or flow
- Promote deposition of sediment
- Impact recreation activity
- Decrease open spawning habitat
- Decrease in native plant species

The summer die off of CLP allows more light to reach the substrate, but native species growth after CLP die-back is minimal (Nicholson and Best 1974).

The summer die off also depletes dissolved oxygen levels. These anoxic conditions can cause fish kills and harm other aquatic organisms. These die offs also produce nuisance odors and eutrophication of lakes.

Thick stands of CLP also impede water flow which could affect irrigation channels (Catling and Dobson 1985). Water recreation can also be impeded and swimming in it can irritate the skin.

b. Positive Effects

Curly-leafed pondweed has been found to be extremely resistant to pollutants and heavy metals, not only surviving but also up taking these pollutants. In China CLP has been used to remediate bodies of water containing pollutants and heavy metals such as mercury, iron, lead, nickel, manganese, magnesium, silicon, calcium, phosphorus, and copper (Ali et al. 2000; Mi et al. 2008; Cohen and Robbins 2011). In the laboratory, CLP was recorded to accumulate 125 μg g^{-1} after 96 hours of exposure to a 10 μM mercury $^{2+}$ solution. Unfortunately, the annual die-off of CLP redeposits the pollutants and heavy metals back into the water body unless the plants are removed and disposed of in another manner. No studies were found at the time of this report detailing recolonization or management of these water bodies after treatment for the pollutants and heavy metals with CLP.

Current Status and Distribution in Michigan

Curly-leafed pondweed is found in 47 of the 48 contiguous United States (Figure 3). The first specimen of CLP was found in Philadelphia in 1840’s (Stuckey 1979). The species then spread along the east coast, eventually making its way into the eastern then western Great Lakes. Curly-leafed pondweed had spread to most of the United States by 1975 (Stuckey 1979; Bolduan et al. 1994). The only states where CLP has not been detected are South Carolina, Alaska, and Hawaii (UGA Center for Invasive Species and Ecosystem Health 2014). As of 2004 CLP was found in one county in Maine (IPANE 2014).

Curly-leafed pondweed was first recorded in the western Great Lakes in 1900, after already being well established in the eastern Great Lakes. In Michigan, CLP was first recorded in 1910 in Van Buren County in Lake Michigan (Stuckey 1979). In 1926, CLP was reported in inland Michigan lakes in Ottawa and Van Buren Counties; these lakes were directly connected to Lake Michigan (MSC; Stuckey 1979). By 1935 CLP had spread up the Kalamazoo River and as far north as Holland and as far west as Kalamazoo County, invading lakes not directly connected to the Great Lakes (Stuckey 1979).

Curly-leafed pondweed is currently found in inland lakes of 34 counties in Michigan, distributed both in the upper and lower peninsulas (Figure 4). It is considered widespread throughout the state and region.

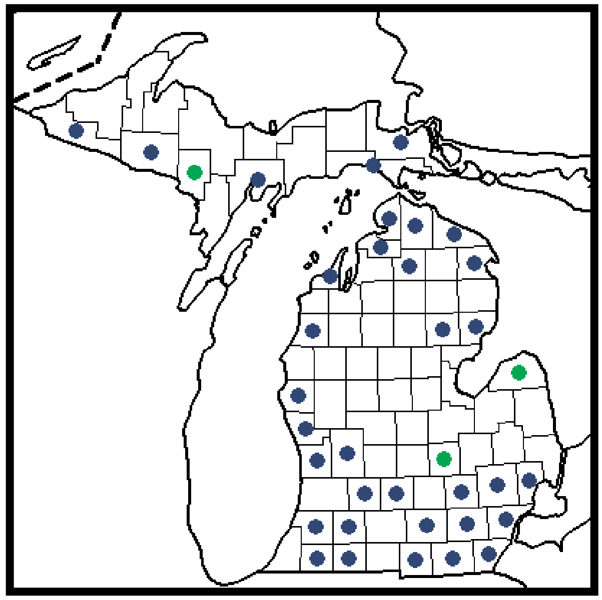

Figure 4. The distribution of curly-leafed pondweed (*Potamogeton crispus*) throughout Michigan. Blue dots indicate a collected specimen verified by Michigan Flora. Green dots indicate reports documented by the Midwest Invasive Species Information Network (2014). County map developed by the Michigan Flora Online (Reznicek et al. 201111)

Management of CLP

I. Prevention

Like other invasive species, CLP is difficult to control once established and is considered widespread in Michigan. Therefore, prevention of new populations in uninfected waters is the most economical management approach. In Michigan CLP is considered a “Restricted species” per Part 413 of the Natural Resources and Environmental Protection Public Act 451 of 1994, as amended (MDARD 2014). This categorization means that any CLP plants, fragments, seeds or a hybrid or genetically engineered variant is restricted and that the growth, purchase, sale, and distribution has restrictions and permitting requirements. Studies at the Great Lakes Commission and University of Notre Dame are underway to examine trade of aquatic invasive species.

While not considered a federal noxious weed, CLP is on the noxious weed lists or identified as an invasive species in six states: Alabama, Connecticut, Maine, Massachusetts, Vermont, and Washington (USDANRCS 2014). These classifications range from class C to B noxious weeds in Alabama, Vermont, and Washington; invasive in Connecticut and Maine; and prohibited or banned in Massachusetts and Connecticut.

Preventing the introduction of CLP is very similar to preventing most aquatic invasive species from spreading. Little can be done regarding CLP movement by birds, however it is still important to limit all of the other human mitigated transport possibilities as much as possible. The following actions may prevent and limit the dispersal of CLP:

- Build a coalition of local, statewide, and Great Lakes regional partners to monitor for CLP and other aquatic invasive species
- Improve monitoring and enforcement of distribution and sale of CLP among aquaria and horticulture industries (Maki and Galatowitsch 2004)
- Educate aquarium owners on the hazards associated with dumping aquatic tanks into natural bodies of water and the spread of invasive species
- Provide boat washing stations for high-traffic public lake accesses
- Develop and enforce a sustainable water recreation vehicles and trailers inspection program
- Identify and protect high-value, uninfested sites

II. Management/control

Curly-leafed pondweed can be devastating to native species, real estate values, and recreational activities. For this reason it is important to control its dominance within the body of water.

Although presented separately here, a management plan developed by integrating ecological knowledge, several management techniques, monitoring, and plan adaptation over time – called integrated pest management – is the most effective approach to controlling invasive species. Several herbicides have been shown to be effective at long-term control of CLP, but eradication is difficult after establishment. Bottom barriers have shown effectiveness at combating CLP in small areas, and mechanical harvesting of CLP can be effective if timed correctly.

a. Chemical

1. Submerged CLP

Effective in the laboratory – Single and repeated doses of 25 ppm of gibberilic acid and 6-benzyladenine (6-BA) completely arrested turion growth in laboratory experiments. Ten repeated treatments, 3 days apart of 6-BA at a concentration of 2.5 ppm also effectively arrested turion growth (Wang et al. 2012).

Diquat treatments also reduced turions (Poovey et al. 2002). Applied three times during the spring, once at 2 ppm then twice at 1 ppm, diquat reduced turion numbers by 85%. Diquat was not as effective in terms of biomass reduction; shoots were only reduced 60% and roots were reduced from 60-90% (Poovey et al. 2002).

Fluridone has reduced CLP turion development when exposed continually to 4 - 6 ppb for at least 56 days (Poovey et al. 2010). Several booster treatments were necessary to maintain the concentration of fluridone in the laboratory throughout the time period. Fluridone did not significantly reduce growth of other parts of CLP.

Poovey et al. (2010) emphasized the early spring and cool water timing of application when CLP is immature as essential to effectiveness.

Effective in the field - Repeated, early season, low concentration endothall treatments when water temperatures were 50° – 59°F (10° – 15°C) were effective at controlling CLP (Johnson et al. 2012). Johnson et al. (2012) used target concentrations of 0.75 - 1.00 ppm and applied only to the areas where CLP existed. The cover area of CLP was noticeably reduced after two years of treatment and significantly reduced after 4 years of treatment. Endothall applied to mid-spring waters with temperatures of 68°F (20°C) were also been found to reduce the root and shoot biomass upwards of 90%, however once the water reached 25°C in late spring the biomass reduction drops to 60% (Poovey et al. 2002).

A companion study examined the effects of the treatment on non-target species. The repeated, early season, low dose endothall treatments did not have a significant effect on the species native to the Minnesota lakes treated (Jones et al. 2012). The exact species composition of the study lakes could be different than lakes in Michigan, but all of the species studied are also found in Michigan.

Endothall had significant effects at low concentrations of at and below 0.5 ppm on Eurasian water milfoil (*Myriophyllum spicatum* L.), Illinois pondweed (*Potamogeton illinoensis* Motong.), and sago pondweed (*Stuckenia pectinata*). Other plants were affected by doses higher than 0.5 mg L^{-1} including coontail (*Ceratophyllum demersum* L.), elodea (*Elodea canadensis* Michx.), wild celery (*Vallisneria americana* L.), wide-leafed cattail (*Typha latifolia* L.), and smartweed (*Polygonum hydropiperoides* Michx.). Pickerelweed (*Pontederia cordata* L.) and spatterdock (*Nuphar advena* Aiton) were not affected by endothall treatments (Skogerboe and Getsinger 2002).

Flumioxazin may be effective when applied in early spring to early summer in concentrations of 100 to 400 ppb, if the pH of the water is less than 8.5 (DiTomaso and Kyser 2013).

Acrolein is a nonselective herbicide and algaecide that kills CLP and many other plants on contact. It is not legal to apply acrolein in Michigan.

2. Exposed soil

Effective in the field - Imazamox can be used on submerged CLP in water or on exposed soil on a depth-regulated water body to control CLP. For in water treatments, 50-100 ppm is applied from early spring to early summer to target areas. To apply on exposed soil in a downdraw situation, treat the soil with 64 oz of product per acre (8 oz a.e. $acre^{-1}$) in late winter, at least 14 days before water will be reintroduced into the system. The first flush of water should not be used for irrigation purposes (DiTomaso and Kyser 2013).

Adjuvants are additives that are added to herbicides that, in some instances, will improve herbicide effectiveness; there are some aquatic herbicides that include adjuvants in the mixture. There are only four adjuvants approved at this time for aquatic use in Michigan: agri-dex, cygnet plus, polyan, and topfilm. All four are drift/sink adjuvants; all but topfilm are nonionic surfactants and topfilm is a grain-based emulsifier. Aquatic herbicides will list possible adjuvants to mix with on their label, but whether or not adjuvants cause a significant difference in herbicide performance is dependent on the herbicide, herbicide concentration, environmental conditions, and target species.

Three adjuvants are not approved for aquatic use in Michigan for their adverse effects on fish and macroinvertebrates: cide-kick II, subcide, and sure-fact.

Table 1. Summary of effective herbicide treatments on curly-leafed pondweed (*Potamogen cripus*) to date. For each herbicide, example brand names, target concentration or rate, any recommended adjuvants, treatment timing, advantages, disadvantages, and the cited literature was listed. The first column indicated the type of herbicide application or part of the plant that was treated. Directions on the pesticide label should always be followed and the state Department of Environmental Quality and Department of Natural Resources should be consulted for up to date regulations, restrictions, permitting, licensing, and application information. Table modeled after Michigan Natural Features Inventory's Glossy Buckthorn Factsheet (2012)

	Herbicide	**Target Dosage/ Rate**	**Adjuvant**	**Timing**	**Pros**	**Cons**	**References**
Submersed	**6-benzyladenine** (plant hormone)	25 ppm or 2.5 ppm multiple doses			• Arrests turion growth completely with a single, high concentrated dose • Arrests turion growth completely with repeated, low concentrated doses	• Has not been tested in the field • Not listed on either the aquatic approved or not approved list for Michigan	(Wang et al. 2012)
Submersed	**Acrolein** (e.g. Magnacide® H)	Up to 15ppm over 30min to 8 hours			• Reduce CLP by 100% • Breaks down quickly in the environment • Controls only submersed weeds and algae • Lists species name on label	• Not legal for use in Michigan • Danger to fish populations • Cannot be used near animal or human drinking water intakes • Prohibited in swimming areas • Kills most submersed aquatic plant species	(Unrau et al. 1965; Baker Petrolite Corporation 2013)
Submersed	**Diquat** (e.g. Alligare®)	1-2 ppm		Spring Multiple applications 14 days apart	• Reduces turions by 85% • Reduces shoot biomass by 60% • Reduces root biomass by 60 – 90% • No fishing of swimming restrictions • Lists genus name on label • Approved for aquatic use in Michigan (permit and licensing required)	• May harm non-target species (Broad-spectrum, contact herbicide) • Toxic to aquatic insects • Cannot apply near fisheries • Needs repeat applications	(Poovey et al. 2002; Alligare 2009)

	Herbicide	Target Dosage/ Rate	Adjuvant	Timing	Pros	Cons	References
Submersed	**Endothall** (e.g. Aquathol®)	0.75-1.00 ppm		Early spring, when water temperatures are between 10°-15°C	• Reduces root and shoot biomass by 90% • Affects other invasive species including *Myriophyllum spicatum* • Does not affect native plants at low concentrations • Lists species name on label • Approved for aquatic use in Michigan (permit and licensing required)	• Affects some native species at high concentrations • Needs repeat applications for reproduction control • May harm non-target species (Broad-spectrum, contact herbicide) • Prohibited for use in water bodies < 600 ft from a potable water intake	(Skogerboe and Getsinger 2002; Poovey et al. 2002; United Phosphorus, Inc. 2011; Johnson et al. 2012; Jones et al. 2012)
Submersed	**Gibberilic acid** (plant hormone)	25 ppm			• Arrests turion growth completely	• Has not been tested in the field • Not listed on either the aquatic approved or not approved list for Michigan	(Wang et al. 2012)
Surface Water or Submersed	**Flumioxazin** (e.g. Clipper®)	100-400 ppb	Spray adjuvants suitable for aquatic environme nts	Early spring to early summer	• Lists species name on label • Approved for use in Michigan (permit and licensing required)	• Ineffective in water with a pH above 8.5 • Toxic to aquatic insects • May harm non-target species (Broad-spectrum, contact herbicide)	(Valent 2012; DiTomaso and Kyser 2013)
Surface Water or Submersed	**Fluridone** (e.g. Sonar ®)	4-6 ppb		Early spring	• Suppresses growth and turion formation relative to concentration • Low toxicity to fish • Does not accumulate in zooplankton • Approved for use in Michigan (permit and licensing required)	• Has not been tested in the field • Needs repeat applications for control • Ineffective in high water movement areas • Ineffective to areas less than 5 acres • Requires at least 56 days of exposure to be effective • May harm non-target species (Broad-spectrum, contact herbicide)	(Madsen 2009; Poovey et al. 2010; Lake Restoration, Inc. 2014)

	Herbicide	Target Dosage/ Rate	Adjuvant	Timing	Pros	Cons	References
Submersed or Exposed Soil	**Imazamox** (e.g. Clearcast®)	Submersed: 50-100 ppb Dewatered Bed: 8oz/acre	Spray adjuvants suitable for aquatic environments	Early spring to early summer	• Lists species name on label • Approved for aquatic use in Michigan (permit and licensing required)	• Expose soil with water downdraw for highest efficiency • Cannot refill water for 14 days after treatment • Water downdraw can lead to the invasion of other exotic species • May harm non-target species (Broad-spectrum, systemic herbicide)	(DiTomaso and Kyser 2013; SePRO 2013)

b. Physical or Mechanical

Bottom barriers of semipermeable mesh reduce CLP by 95% when managed correctly (Mayer 1978). They are best used in areas of frequent recreation area and are not practical for a lake-wide solution. The barrier impedes sunlight penetration to the substrate and all rooted aquatic plant photosynthesis. Submerged plants wither and die. Semipermeable mesh effect only the rooted aquatic vegetation directly underneath the mesh. Since CLP grows in thick monoculture mats, this method is unlikely to cause much harm in populations of non-target species (Mayer 1978). Bottom barriers must be installed properly, regularly maintained, and occasionally replaced to work effectively and be safe for swimmers and boats. The barriers must be removed every winter and replaced in the spring to prevent sediment accumulation on top of the barrier, allowing plants to take root. If removed without replacement, new infestations of aquatic invasive species are likely.

Mechanical harvesting has a great effect on the current season presence of CLP, but curly-leafed pondweed must be harvested before turions are dropped from the plants to effectively control CLP for multiple seasons it. Harvesting in mid-June reduced the amount of new turions in the sediment by 90%, with 10% of the turions being dropped or knocked off before harvesting (Johnson and Fieldseth 2014). Harvesting earlier in the season could reduce the new turions in the sediment even more, however, a deep reaching harvester must to be used to ensure that all plants are cut and all turions harvested (Johnson and Fieldseth 2014).

Drawing down the water in a lake, pond, or river segment can also be used to control CLP, but is not feasible in most intances. The downdraw exposes the area where CLP naturally roots. While the water is drawn down herbicides such as imazamox can be applied to the sediment for additional control methods. The downdraw method can be detrimental to local flora and fauna due to the extreme alteration of the environment.

c. Biological

Many fish feed on the different parts of CLP including the turions, stems, and leaves. Considered an invasive species in most of North America, the common carp has been noted to destroy populations of CLP in one Pennsylvania Lake (Nichols and Shaw 1983). The carp uprooted the plants looking for benthic organisms, increasing the turbidity of the water. During spawning, the fish also damaged the plants. The common carp is an invasive species in the Great Lakes region, and its introduction into an ecosystem has dire consequences to native fauna, reducing overall diversity.

Two species were identified as being predators of the *Potamogeton* genus, the waterlily aphid *Rhopalosiphum nymphaeae* L. and the aquatic beetle *Donacia provosti* Fairmaire (Zheng et al. 2005). These species do not exclusively feed on CLP and have not been reported to reduce production of CLP, thus are not practical for biological control.

At the time of this report no other biological controls were investigated.

III. Indirect Management

Reducing nutrient loading of water bodies may impair CLP establishment, because CLP grows best in eutrophic environments. Promotion and maintenance of natural shorelines and native vegetation on water front property can reduce nutrient loading in water bodies. Native grasses and wildflowers feature deep and extensive root systems that stabilize the soil, prevent erosion, and reduce nutrient run-off. The use of native plants is preferred in shoreline landscaping because they are well adapted to the climate and soil conditions of that ecosystem and require very little maintenance once established (Henderson et al. 1998). The root systems take time to established, sometimes even years, and there are local government regulations that must be followed before planting (Henderson et al. 1998).

Research Needs

In order to better understand CLP ecology, monitoring, and management in Michigan, the following research needs should be addressed: turion viability, ecological impacts of CLP spring booms and summer crashes, analysis of relationships with other invasive species, testing of chemical treatment techniques including herbicide temperature, further investigation into chemical treatments with hormones, effectiveness of biodegradable bottom barriers, and continued research into biological controls.

I. Biology and Ecology

The turions of CLP have been reported but not confirmed to remain viable for five years (RCRCA 2003). The conditions of the viability test were not described, so it is unknown if turion viability differs in saturated, dried, frozen, or other conditions. Knowing turion viability will help to develop effective long-term management plans that account for regrowth of turions.

The ecological impacts of CLP on aquatic flora and fauna during CLP spring booms and summer crashes has yet to be quantified. Determining the effects of CLP on fish populations and vegetation during CLP fluctuations could provide more definitive and quantitative costs to CLP populations.

In general, there is a lack of literature on specific ecological and economic impacts of a specific aquatic invasive plant species. Most impacts are grouped by growth forms of the species, but the impacts are not quantitatively measured. It is more difficult to justify management of an invasive species when quantitative impact data is lacking.

II. Monitoring

Monitoring and documentation of CLP yearly fluctuations in variation in abundance could help identify trends and develop treatment strategies. Understanding and testing the cyclic growth and co-treatment of CLP, Eurasian water milfoil, and starry stonewort (*Nitellopsis obstusa* (N.A.Desvaux) J.Groves) could aid in developing a comprehensive and integrated management plan.

III. Management

Investigation of the effects of herbicide temperature on treatment could improve treatment effectiveness. The application of cooled herbicide has been shown to penetrate CLP to a greater depth than traditional application.

Biofilms, communities of bacteria, algae, fungi, and protozoan that accumulate on surfaces in aquatic environments, and their relationship to herbicide effectiveness has not been investigated thoroughly. There is research on the role biofilm communities play in remediation and toxic clean-ups (Singh et al. 2006) and the effects of certain herbicides on biofilms (e.g. Kosinski 1984; Wolfaardt et al. 1995; Lawrence et al. 2001; Gustavson et al. 2003; Schmitt-Jansen and Altenburger 2005), but little directly addressing the relationship between biofilm and herbicide effectiveness, and the effects of killing the biofilm prior to herbicide application. There could also be ecological impacts of killing biofilm prior to herbicide application for non-target species or duration of the herbicide in the system (e.g. Kosinski 1984; Wolfaardt et al. 1995; Lawrence et al. 2001).

In laboratory applications, the plant hormones 6-benzyladenine (6-BA) and gibberilic acid, were found to be very effective in controlling the production of CLP turions; however, field tests have yet to be conducted (Wang et al. 2012). It is unknown how these treatments will affect non-target species during CLP treatment.

Biodegradable bottom barriers of jute or hemp to control CLP have yet to be tested for effectiveness to control CLP. Biodegradable bottom barriers have less maintenance and labor requirements than traditional bottom barriers (Caffrey et al. 2010). Other, inorganic matting has been proven effective to reduce CLP growth (Mayer 1978), but studies of the hemp mats has revealed that effectiveness needs to be tested on a species by species basis (Hofstra and Clayton 2012). Overall effectiveness, timing of mat placement (e.g. spring, summer after die back), and length of time for optimal treatment is unknown for CLP.

Future Directions for Michigan and CLP Management

Curly-leafed pondweed has been found in Michigan since 1910. Reported populations are found in 34 counties throughout Michigan, 5 in the Upper Peninsula and 29 in the Lower Peninsula. Curly-leafed pondweed is very resilient and can grow in almost any water body including streams, rivers, lakes, and ditches; as well as very polluted waters. The most common way for

CLP to spread is through the dispersal of their turions, which can be moved from water body to water body through natural channels, on boat props, in ballast water, or through the dumping of fish tanks. The fruit of CLP rarely germinates; however, the seeds can survive passing through a bird's digestive system and be viable when excreted near a new body of water.

Prevention - Once a CLP population is established and has produced turions it is difficult to permanently eradicate a population. Preventing CLP introduction is the best way to ensure a water body remains uninfected. Once an area has been infected by CLP, early detection would make eradication a more realistic option.

Considering the widespread nature of CLP in Michigan, efforts may be better served by protecting uninfested waters. A cohesive monitoring and reporting system involving local municipalities, non-profit organizations, lake associations, irrigation channel supervisors, and waterfront property owners, would increase knowledge of CLP locations and enable early detection responses to new colonies. The instigation of boat washing or inspection program with education components at waters uninfested with CLP could aid the prevention of the spread of this species.

Other methods to limit dispersal of CLP are educating the horticulture, aquaculture, and aquaria industries and the general public on identification and the ecological impacts of CLP. Connecting waterfront property owners with resources such as MISIN may improve early detection efforts.

Monitoring – Since CLP is highly widespread, it is important to identify high-valued sites to focus monitoring efforts. To achieve that goal, both infested and uninfested sites must be identified. Adding CLP to existing Michigan lake and stream monitoring programs should increase the possibility of early detection and create a more realistic distribution of CLP.

The implementation of a strategic-random, stratified-random, or targeted monitoring strategy can establish a more accurate statewide distribution of CLP. A targeted strategy would involve the most preparation and research, but may be the most efficient in the field. To develop a targeted monitoring strategy, the current known distribution and predictive modeling would be used to extrapolate sites that have a high-likelihood of infestation. The likelihood of infestation of sites would be determined by evaluating potential pathways and dispersal trends of CLP, like that Abigail Fursaro and Alisha Dahlstrom Davidson (Wayne State University) are currently applying as a part of the Great Lakes Restoration Initiative to identify hot spots for new aquatic invasive species to be introduced. For CLP, factors to be considered are watershed-path distance to known populations, public access points, estimated lake activity, waterfowl migration routes, and presence of other invasive species (i.e. Eurasian water milfoil, starry stonewort).

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, MiCorps Data Exchange Network – Great Lakes Commission, VertNet, Nonindigenous Aquatic Species Database - USGS, Biodiversity

Information Serving Our Nation (BISON), and Global Biodiversity Information Facility (GBIF)). 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 or standard throughout programs. In addition, 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, produce comparable data 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 was collected. Information networks that are continually linked to other resources and updated can be used to develop effective and efficient monitoring and management plans. In turn, monitoring plans can inform the resources on their findings and create an adaptive strategy to combat invasive species. When information networks are not linked or periodically synched, a person collecting information must independently identify, locate and consolidate data from separate and often difficult to access sources. The result is information is not accessed and data collection becomes redundant and inefficient.

Networking with and contributing to state, regional, national and internationals 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 this data to know what species they may be exposed to when recreating 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 if the infestation is small. If the procedure to manage an infestation takes several years to achieve action, the infestation may have grown beyond realistic management. Maine Department of Environmental Protection has developed a rapid response protocol that attempts to treat infestations of certain aquatic invasive species within 30 days of a newly detected aquatic invasion (MDEP 2006). The workflow begins at confirmation of report, and then delineation of infestation, containment, and primary evaluation. Next steps are treatment selection, plan refinement, and implementation. The infestation should be monitored and evaluated regularly for several seasons to evaluate the treatment and control any reemerging growth. Although it is called a rapid response, it may not end rapidly.

Management - Since CLP is highly widespread, high-value sites are the highest management concentration.

The most viable ways to control CLP is through chemical and physical means after developing an integrated pest management plan. Aquatic herbicides including endothall, diquat, and imazamox are the most effective for general applications. Aquatic herbicides including flumioxazin and imazamox are effective for specific types of application and in specific environments. Chemical treatments are a part of a long-term integrated management plan as the turions are viable for at least 5 years and only diquat, fluridone, and some hormone treatments have shown a reduction of turion development in the laboratory.

Measuring effective control - Documenting year-to-year regrowth, reduction of CLP percent cover, and/or reduction of turion growth after the application of control treatments are the best ways to quantitatively assessed CLP control. Reduction in the production of turions largely inhibits the spread of CLP to other areas in a body of water and could reduce the return of CLP after its mid-summer die-off. Assessing the reduction of turion development would be the ideal controls aiming for long-term management and possible eradication.

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 an integration of prevention and control methods that consider factors that affect the long-term ecological stability of an aquatic community.

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Table 2. Objectives, Strategic Actions, Leads, and Expected Outcomes of CLP Management

Guidance and Outreach for Curly-leafed Pondweed 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 partners of water bodies with an infestation or high likelihood of infestation • Educate public of identification, early-detection, and prevention • Promote boat-washing programs in water bodies with an infestation or high likelihood of infestation	• AIS Core Team • Lake Associations • Michigan Inland Lakes Partnerships • MSU extension	• Increase public awareness of CLP • Increase the frequency and use of boat washing programs • Protect high-value sites • Contain established populations
Prevent other new introductions of CLP	• Educate local and regional aquaria and horticulture businesses about AIS • Reduce sale of CLP in aquaria and horticulture industries	• MDARD • Great Lakes Commission	• Elimination of purposeful and accidental sale of CLP
Provide technical guide to those interested in management	• Creation of a CLP technical guide and prioritization tool		• Increase management efforts
Monitoring and Data Management			
Develop a mechanism for monitoring and reporting AIS species	• Develop a system of identifying water bodies with high likelihood of infestation • Survey water bodies with high likelihood of infestation	• AIS Core Team • MISIN • BISON • Michigan Water Corps	• Develop a more thorough and up-to-date statewide distribution of CLP
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 • Weed Map - CWMA • MiCorps • VertNet • 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 and high-likelihood of infestation	• MISIN • Michigan Water Corps	• Increase public awareness and early detection of AIS • Identify water bodies that need professional confirmation of AIS

Research Needs for Management			
<u>Chemical:</u> Develop chemical treatments that will increase management success and minimize the ecological and economical effects	• Investigate non-target effects of 6-benzyladenine and gibberilic acid treatments • Test effectiveness of 6-benzyladenine and gibberilic acid • Evaluate other systemic herbicides for reducing turion development		• Develop effective strategies to reduce turion development to be used in combination for control or eradication
<u>Biological:</u> Establish biological control methods that will increase control and minimize effects of CLP	• Evaluate the validity of using *Rhopalosiphum nymphaeae* (L) and *Donacia provost* as a biological control including effectiveness, captive breeding, non-target effects		• Develop more effective and economical treatment options for established populations • Decrease effects on non-target species
<u>Mechanical:</u> Determine the most effective and economical mechanical methods to mediate the effects of CLP	• Determine or confirm turion and seed viability • Investigate the effectiveness of hemp bottom barriers		• Identify the length of time turions are viable to better gage effectiveness of long-term control plans • Determine a less maintenance approach to bottom barriers for high traffic areas

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