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State of Michigan's

Status and Strategy for Carolina Fanwort (*Cabomba caroliniana* A. Gray) Management

Scope

Carolina fanwort (*Cabomba caroliniana* A. Gray, hereafter CFW) is a submerged aquatic plant that is invasive in Australia, Europe, Asia, and parts of North America (Wilson et al. 2007). In the United States, CFW has established invasive populations in the Northeast, Pacific Northwest, and Midwest, but has only recently been recognized as a management concern in Michigan (Higman et al. 2010; MISIN 2017). An earlier version of this document was a product of an Environmental Protection Agency - Great Lakes Research Initiative 205(j) grant between the Michigan Department of Environmental Quality and Central Michigan University (CMU) in 2014 (Hackett et al. 2014). It was significantly revised by CMU and partners on the Michigan Invasive Species Grant Program 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 CFW.
- Summarizing scientific literature and research efforts that inform management options for CFW in Michigan.
- Identifying future directions for research relative to successful CFW 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

Carolina fanwort is a perennial aquatic plant with heterophyllous leaves (Ørgaard 1991). It gets its name from its submerged, fan-like leaves. These leaves have an opposite, sometimes whorled arrangement, 2 – 5 cm (0.75 – 2 in) wide, and are finely subdivided with the first division from a single point (Godfrey and Wooten 1981; eFloras 2014). The floating leaves, if present, are peltate with a notched base and alternate arrangement, 0.4 – 3 cm (0.2 – 1.2 in) long, 1 – 4 mm (0.04 – 0.2 in) wide, and entire (eFloras 2014). Carolina fanwort has solitary flowers on an unbranched peduncle. In North America, CFW has been reported to flower from late June to October or November (Wilson et al. 2007). Flowering specimens in Michigan have been collected for herbaria from late-June to the end of September (University of Michigan Herbarium – MICH; Western Michigan University Herbarium - WMU). Flowers bloom above water, have six white to purplish sepals and petals, and are 6 – 15 mm (0.25 – 0.6 in) across. Fruits contain three seeds and are less than 7 mm (0.25 in) long. Visitation of ponds in New Jersey established prime flowering time as July to September with seeds appearing soon after flowering begins (Riemer 1968). Tarver and Sanders (1977) reported seeds maturing 28-31 days after fertilization.

Species that are often mistaken for CFW in North America include: watermilfoil (*Myriophyllum* spp.), coontail (*Ceratophyllum demersum* L.), water-marigold (*Bidens beckii* Torr. Ex Spreng.), and white water crowfoot (*Ranunculus* spp. with white flowers including *R. longirostris* Godr. and *R. trichophyllus* Chaix). Without flowers, submerged CFW may resemble watermilfoil, coontail, or water-marigolds since they all have finely divided submerged leaves. The leaves of watermilfoil branch from a central stem, unlike the fan-like division of CFW. Coontail's submerged leaves are arranged in whorls of five or more and have teeth on their margins. Coontail is also stiff and brittle and holds its shape out of water, unlike CFW. The submerged leaves of water-marigold are opposite like CFW, but they branch at the stem, lacking the petiole of CFW. The emergent leaves of water-marigold have an opposite arrangement, while the floating leaves of CFW have an alternate arrangement. The flowers of white water crowfoot resemble that of CFW and both have finely divided leaves. White water crowfoot has 5 petals, unlike the 6 sepals and petals of CFW, and the finely divided leaves of white water crowfoot have an alternate arrangement.

There are four other accepted species in the genera *Cabomba*: *C. aquatica* Aubl., *C. furcata* Schult. & Schult. f., *C. haysenii* Wiersema, and *C. palaeformis* Fassettl, but no sightings of these have been reported in Michigan. All species are native to Central and South America. In the United States, *C. furcata* has been introduced to Puerto Rico and Florida (USDA 2017). *Cabomba aquatica* and *C. furcata* are common aquaria plants and CFW has been misidentified as *C. aquatica* in stores (Maki and Galatowitsch 2004; Hussner et al. 2013; Verbrugge and Van Valkenburg 2014).

II. Detection

Carolina fanwort can be found in large dense mats or interspersed among native macrophytes, often at depths from 2 – 4 m (6 – 12 ft; Schooler et al. 2006; Matthews et al. 2013). The finely dissected opposite, or sometimes whorled, submerged leaves of CFW distinguish it from similar species. When in flower, the white, 6-part flower, is distinct. Methods used to collect CFW for detection and identification include rake-tosses (Cahill et al. *in prep*), SCUBA/snorkeling with transects or quadrats (Schooler et al. 2006; Schooler 2009; Bickel and Schooler 2015; Cahill et al. *in prep*), and quadrat sampling without SCUBA/snorkeling assistance (Gangstad 1992).

Aerial photographs have been used with botanists or local experts to distinguish emergent and floating aquatic vegetation (e.g., Husson et al. 2013). Submerged aquatic vegetation at water depths greater than 40 cm (16 in) cannot be distinguished using remote sensing technology at this time even when processed with object-based image analysis (Visser et al. 2013). Water absorbs the wavelengths commonly used to remotely sense vegetation (i.e. visible and near infrared). Remote sensing detection would also be limited in its ability to distinguish CFW in mixed stands of other aquatic vegetation.

Attempts to identify markers for CFW to use for field detection have proved difficult (Scriver et al. 2015). Markers that have been tried either amplified non-target species as well or there were too many species-specific mutations for the marker to get consistent results (Scriver et al. 2015). Markers have been identified for related *C. aquatica* (Barbosa et al. 2015). If it is possible to detect and differentiate CFW with eDNA, this could improve the true positive detection of CFW when it is growing undetected in mixed stands of aquatic vegetation or in an inaccessible portion of a waterbody. Environmental DNA detection procedures could also reduce the need for labor-intensive field surveys until after CFW was positively detected in an area

III. Life History and Spread/Dispersal

In its native range, CFW is considered a perennial that overwinters as stem and rhizome fragments (eflora 2014) or continuously flowers and grows throughout the year (Schneider and Jeter 1982). A CFW population may flower over many months but an individual flower opens for only two days. On the first day, the female genitalia of the flower are curved outward, toward the nectaries at the base of the petals. Insects (e.g., honeybees, flies, wasps) will spread pollen from other flowers to these curved genitalia while retrieving nectar. When the flowers open on the second day, the female genitalia are standing straight in the center of the flower and the pollen-bearing genitalia is curved toward the nectaries to spread pollen to the insects (Tarver and Sanders 1977; Schneider and Jeter 1982). Seeds mature in fertilized flowers 28 to 31 days after fertilization (Tarver and Sanders 1977). Seeds are unlikely to germinate unless dried, suggesting that seeds are a mechanism CFW uses to overcome fluctuating water levels (Tarver and Sanders 1977; Schooler et al. 2009).

Carolina fanwort phenology varies throughout its invasive range. In Kasshabog Lake, Ontario CFW overwinters as fragments, begins to grow in early spring, and flowers from late June to November (Noël 2004 in Wilson et al. 2007). Similarly, Riemer and Ilnicki (1968) documented CFW populations in New Jersey overwintering as fragments, resuming growth in early spring, and flowering from late June to September. In tropical regions of Australia, CFW flowers continuously throughout the year (Wilson et al. 2007) and in cooler regions of Australia CFW overwinters as fragments (Mackey and Swarbrick 1997).

Seeds are produced in parts of CFW's North American invasive range, but germination has not been documented (Riemer and IInicki 1968; Wilson et al. 2007). After laboratory trials under suitable growing conditions resulted in no CFW seed germination, Riemer and IInicki (1968) postulated that CFW does not produce viable seeds in New Jersey. Similarly, CFW seeds produced in Kasshabog Lake, Ontario are not viable (Noël 2004 in Wilson et al. 2007). Seeds and seedlings have been found in tropical regions of Australia (Schooler et al. 2006; Matthews et al. 2013).

In late fall the lower portions of CFW stems defoliate, become brittle, and break apart, facilitating asexual spread (Riemer 1965). There is evidence that CFW reproduces almost exclusively asexually throughout its invasive range (Ørgaard 1991; Xiaofeng et al. 2005). Asexual reproduction is facilitated through rhizome-like stem growth and stems that readily fragment (Riemer and IInicki 1968; Ørgaard 1991). A fragment with at least one node is required for regeneration (Bickel 2016). In laboratory trials, a free-floating fragment of a single node (i.e., portion of stem where one pair of leaves attaches) had a 30% chance of reestablishing; a single node in substrate had a 50% chance of reestablishing; a free-floating fragment of more than one node had a 50% chance of reestablishment; and a fragment of more than one node placed in substrate had a 100% chance of reestablishment (Bickel 2016). Fragments can spread through connected water bodies. Practical scenarios executed by Bickel (2014) show regeneration of CFW fragments after days out of water (42 hours). Fragment clumping and humid weather reduce CFW fragment desiccation and can greatly enhance the survival of CFW fragments out of water (Bickel 2014). It is likely that recreational activity in North America has facilitated spread between unconnected water bodies (McCracken et al. 2013; Bickel 2014).

Carolina fanwort is a popular aquarium plant and was marketed throughout the 20th century (Les and Mehrhoff 1999). It has been hypothesized that aquarium waste is a vector of introduction and cause of CFW's global spread. Instances of aquarium waste introduction are difficult to verify without first-hand accounts or molecular data from past commercial sources (McCracken et al. 2013).

There are three documented phenotypes of CFW: green, purple/red, and purple (Bultemeier et al. 2009). It has been postulated that the phenotypic variation is a result of differential light and temperature conditions (Wain et al. 1983; Hanlon 1990; Leslie 1986; Martin and Wain 1991; Ørgaard 1991). Bultemeier et al. (2009) found that all three phenotypes (green, purple/red, and purple) exhibit differential responses to a wide range of aquatic herbicides. Green CFW was the least susceptible to herbicide treatment while the purple/red and red phenotypes were more susceptible. Invasive populations in the northern United States are composed of green CFW (Bultemeier et al. 2009).

IV. Habitat

Carolina fanwort is native to the southeastern United States and parts of South America (Ørgaard 1991). It is primarily found in lakes, ponds, and slow-moving streams with soft sediment at depths from 2 – 4 m (6 – 12 ft; Schooler et al. 2006; Matthews et al. 2013).

Carolina fanwort has been introduced in an array of habitats outside its native range including Australia, Japan, New Guinea, Malaysia, China, the Netherlands, Belgium, Hungary, England, Canada, and the United States (outside of native range; Les and Merhoff 1999; Wilson et al. 2007; MISIN 2017). It has been rapidly expanding its range in the Netherlands (Matthews et al. 2013), and is so problematic in Australia that it was ranked as one of the twenty species on the inaugural weeds of national significance list (Thorp and Lynch 2000). Researchers from these two countries have published a large percentage of the recent CFW research (e.g., Schooler 2009; Cabrera-Walsh et al. 2011; Dugdale et al. 2013; Matthews et al. 2013; Bickel 2014).

In its invasive range, CFW is commonly found in water less than 3 m (10 ft) deep but can be found in depths of up to 10 m (32 ft; Schooler et al. 2006; Wilson et al. 2007). Water pH is the most powerful predictor of CFW colonization potential (Jacobs and MacIsaac 2009;

Bickel 2012; Bickel and Perrett 2014; Bickel and Schooler 2015; Bellinger and Davis 2017). Carolina fanwort grows best in soft water systems with low alkalinity and acidic pH (4-6; Riemer 1965; Gangstad 1992; James 2011) but can also colonize waterbodies with pH levels as high as 8.8 (Matthews et al. 2013). Waterbodies with higher pH may not support as dense of CFW populations (Bickel and Perrett 2014).

Carolina fanwort has been documented in oligotrophic to mesotrophic, and eutrophic systems (Lyon and Eastman 2006; Wilson et al. 2007). Bickel (2012) found nutrient levels in water, a condition of eutrophic systems, have no effect on CFW, only nutrients in the substrate. Oligotrophic systems that have sufficient nutrients in their soil can support CFW (Bickel 2012). Olsen et al. (2015) and Huang et al. (*in press*) found excess nitrogen in the water inhibited or collapsed CFW growth.

V. Effects from CFW

a. Negative Effects

In habitats with suitable growing conditions, CFW can produce dense mats that exclude native vegetation (Sheldon 1994; Mackey and Swarbrick 1997; Lyon and Eastman 2006). Along with excluding native flora, these mats reduce the amount of sunlight reaching the sediment, increase epiphytic algal biomass, and alter the macro-invertebrate assemblage (Hogsden et al. 2007). A laboratory study found that CFW did not outcompete native vegetation when grown in mixed communities, but it could establish itself faster in newly disturbed substrate (Bickel and Perrett 2014), leading to the formation of dense mats.

Carolina fanwort is not an important food plant for fish, macroinvertebrates, or waterfowl, but has been consumed occasionally by waterfowl and rarely by macroinvertebrates (McAtee 1939; Rodrigues et al. 2014; Grutters et al. 2015). If CFW displaces native macrophyte species that are important food sources for macroinvertebrate and fish and wildlife species it could potentially create a gap in the food web.

Dense mats of CFW discourage swimming and recreational boating and result in reduced angler success in heavily infested areas (Gangstad 1992). Carolina fanwort gives an unpleasant flavor and discoloration to water, increasing the cost of treatment up to $50 per cubic meter (Australian Department of the Environment and Heritage 2003). Removal of CFW has been found to improve water quality by reducing dissolved nitrogen, dissolved phosphorus, and turbidity (Anderson et al. 1996).

b. Positive Effects

Several laboratory studies on CFW and closely related species (i.e., *C. furata*) have shown potential for the plants to remove heavy metals (i.e., lead, copper, chromium) and pharmaceuticals from the water column (Yaowakhan et al. 2005; Dileepa et al. 2012; Othman et al. 2014; Mackul'ak et al. 2015; Nur Fadzeelah et al. 2015). These positive effects may prompt the development of bioremediation efforts using CFW but caution must be exercised when using live plants given the ease of unintentional fragmentation and spread of CFW.

Current Status and Distribution in Michigan

Considered native to the southeastern United States and parts of South America, CFW has established invasive populations in the United States, Canada, Australia, Europe, and Asia. In the United States, CFW has established invasive populations in the Northeast, Midwest, and parts of the Pacific Northwest.

W.J. Beal planted CFW in the Michigan State University botanic garden pond circa 1890 (Beal 1900). It is not known whether invasive populations in Michigan are a result of that introduction or later ones. Carolina fanwort was first collected from the wild in Michigan in June 1935 from Kimble Lake and Portage Creek in Kalamazoo County (Reznicek et. al. 2011; WMU). The Midwest Invasive Species Information Network (MISIN 2017) reported populations of CFW in eight additional counties in western Lower Peninsula. On the western side of the Lower Peninsula there is a large concentration of reported sightings in lakes within Kalamazoo County and surrounding counties (i.e., Barry, Branch, Calhoun, St. Joseph, Van Buren). A smaller group of sightings have been reported in the Kent County area. Carolina fanwort has been found in Reeds and Fisk Lakes near Grand Rapids and Brower Lake near Rockford.

The only populations of CFW reported in southeastern Michigan are in Oakland County. It has been found in Lake Wau-Me-Gah and Lake Sherwood (MISIN 2017).

The northernmost reported sightings are in Indian Lake near Howard City and Mecosta Lake in Mecosta County. The isolation of these populations from larger groupings may indicate that CFW is spreading northward in the state from the first collected populations in Kalamazoo and St. Joseph Counties or that there was a new introduction. Population genetics studies could shed light upon the dispersal and introductions of CFW within the region.

The first population in Ontario, Canada, was discovered in Kasshabog Lake in 1991 (McDonald 2002). McCracken et al. (2013) compared the genetics of native populations in the southern United States, invasive populations in the northern United States, the invasive population in Ontario, and individuals from the commercial trade. Their results suggest that the CFW population in Ontario is likely the result of invasion from the northern United States and that there has been at least 3 separate introductions in the northeastern United States originating from the southern United States or the commercial trade (McCracken et al. 2013).

Management of CFW

I. Prevention

Carolina fanwort becomes very difficult and expensive to control once it is established; the single year management cost at a heavily infested site in the Netherlands was over €350,000 (US$480,000; Matthews et al. 2013). Preventing CFW introduction into uninfected waterbodies is more practical than managing it post-colonization.

Carolina fanwort is a "Prohibited species" in Michigan under the Natural Resources and Environmental Protection act 451 of 1994. Under this act it may neither be sold nor grown in the state. Unfortunately, CFW can easily be mistaken for other species that are not prohibited in the aquaria trade (Maki and Galatowitsch 2004; Hussner et al. 2013; Verbrugge and Van Valkenburg 2014). Building a coalition of local and regional partners with this same designation for CFW may help improve enforcement of this act. The following actions may prevent and limit the dispersal of CFW:

- Build a coalition of local, statewide, and Great Lakes regional partners to monitor for CFW and other aquatic invasive species
- Build a coalition of states that have classified CFW as a restricted or prohibited species
- Expand existing coalitions to include organizations that may soon encounter CFW as an aquatic invasive species
- Improve monitoring and enforcement of the distribution and sale of CFW among states that restrict or prevent its distribution (Maki and Galatowitsche 2004; Hussner et al. 2013; Verbrugge and Valkenburg 2014)
- Educate aquarium owners and industry on CFW identification and the hazards associated with the improper disposal of aquarium waste and the spread of invasive species (Hussner et al. 2013; Verbrugge and Valkenburg 2014)
- Provide boat washing stations for high-traffic public lake accesses (Bickel 2014)
- Develop and sustain a water recreation vehicles and trailers inspection program (Bickel 2014)
- Identify water bodies with high-risk of infestation using known distribution and dispersal knowledge

II. Management/Control

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.

a. Chemical

Herbicides recommended for use against CFW include 2, 4-D n-butyl ester, diquat, carfentrazone-ethyl, endothall, flumioxazin, fluridone, penoxsulam, and triclopyr (Table 1; DiTomaso et al. 2013). Dyes have also been used as a non-herbicidal treatment to limit photosynthesis of CFW.

In laboratory trials, Bultemeier et al. (2009) evaluated the response of the three CFW phenotypes (i.e., green, purple/red, purple) to selected herbicides. Flumioxazin was most effective, reducing photosynthesis of all three phenotypes to zero (Bultemeier et al. 2009). Cahill et al. *in prep* conducted a controlled study in Barton Lake, Michigan to investigate the effect an early summer flumioxazin treatment on CFW. In this study, flumioxazin significantly reduced CFW biomass relative to controls at 8 weeks post-treatment. Although flumioxazin provided effective control, proportional percent cover of CFW was not significantly different pre- and post-treatment relative to controls, indicating CFW remained the dominant plant in the macrophyte community throughout the growing season (Cahill et al. *in prep*).

Bultemeier et al. (2009) found endothall amine salt to be effective against CFW. In laboratory trials, endothall amine salt reduced photosynthesis of all three phenotypes to below 50% of untreated controls. Hunt et al. (2015) also demonstrated the effectiveness of endothall amine salt for CFW control in laboratory trials, reducing CFW biomass by 83, 100, and 100% at application rates of 0.5, 1.5, and 3 mg ae L^{-1}, respectively. Field trails have yet to verify the efficacy of endothall amine salt for CFW control.

Fluridone at 20 ppb reduced CFW biomass by 80% in a growth chamber study; however, this concentration of fluridone also severely limited growth of the native macrophyte water marigold (*Megalodonta beckii*; Nelson et al. 2002). Mackey (1996) reported that fluoridone has been used on CFW infestations in Australia but has provided minimal and inconsistent control. In Michigan, it is unusual to be issued a permit to apply fluoridone at concentrations more than 6 ppb.

Hunt et al. (2015) evaluated the efficacy of 2 mg ai^{-1} of carfentrazone-ethyl at 2, 12, 24, and 72 hours of exposure. Across all concentration-exposure time treatments, carfentrazone-ethyl achieved a maximum of 65% CFW biomass reduction. All treatments had visual observations of regrowth post-treatment although regrowth was not quantitatively measured. Hunt et al. (2015) note that low light during the herbicide trails may have impacted the effectiveness of the carfentrazone-ethyl. Inkson et al. (2014) described qualitative results of carfentrazone-ethyl treatments for control of CFW infestations using various application techniques at 9 sites in Australia. Treatments of carfentrazone-ethyl reduced CFW at all 9 target sites to 1% of their original density at 2 – 3 years post-treatment.

Price and Collins (2016) described the use of 2, 4-D n-butyl ester treatments injected into the substrate as one of many management treatments and events used to control CFW in Darwin River, Northern Territory, Australia (e.g., flower cutting, shading, drawdown, salt water flooding). Carolina fanwort was reduced from 11 km to 1 km of the river. The authors stated that the remaining 1 km of CFW was likely resistant to 2, 4-D n-butyl ester treatments.

James (2011) found lime application to be an effective method for CFW control in a laboratory setting. In soft water experimental tanks lime additions of 55 and 160 μM resulted in an increase in pH (9,10) and a 36% and 8% reduction of shoot biomass, respectively. No analysis was performed on how this increase in pH would affect native macrophytes. Lime addition would be most effective in areas where maintenance of native flora is not a primary concern and a large increase in pH is feasible.

Table 1. Summary of herbicide treatments used on Carolina fanwort (*Cabomba caroliniana*) 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. 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 MNFI (2012). Much of the information below is summarized from Ditomaso et al. 2013

Herbicide	Target Dosage/ Rate	Adjuvant	Timing	Pros	Cons	References
2, 4-D n-butyl ester (Navigate ®)	Not reported		Spring to early summer	• Effective if injected in substrate • Less harm to non-target species (Selective, systemic herbicide) • Approved for aquatic use in Michigan (permit and licensing required)	• Ineffective when broadcast in water column • Repeat treatments likely needed • Resistant CFW populations found • May not be management method responsible for successful field treatment • Toxic to fish	(Applied Biochemists 2002; Price and Collins 2016)
Diquat (e.g. Reward®)	0.1 to 0.25 ppm		Late spring to early summer	• Approved for aquatic use in Michigan (permit and licensing required)	• Ineffective in turbid water or conditions with a lot of wave action • May harm non-target species (Broad-spectrum, contact herbicide) • Toxic to aquatic invertebrates	(Syngenta 2007; Bultemeier et al. 2009)
Carfentrazone-ethyl (e.g. Shark®)	2 ppm		Late spring to summer	• Degrades quickly (half-life 8.3 days) • Shows symptoms in 2-hours; plant death in 7-28-days • No signs of bioaccumulation in soil, fish, or mammals • No-observed-effects below 810 mg/kg in birds • Toxic to algae • Reduced biomass by 65% or less at twice the recommended concentration in laboratory experiments with shade	• Pre-treatments of glyphosate were needed to kill non-target vegetation in field trials • Prohibited for use in flowing water • Harms non-target species (Broad-spectrum, contact herbicide, e.g. arrowhead, duckweed) • Toxic to fish, mollusks, and crustaceans, although no mortalities of trout in tests (deoxygenation of water) • Not on either the aquatic approved or not approved list for Michigan	(FMC Australasia Pty Ltd 2011; MACSPREAD Australia and FMC 2012; Inkson et al. 2014; Hunt et al. 2015)
Endothall (e.g. Aquathol®)	1-2 ppm for 2 days		Spring to early summer. 48 hour exposure	• Shows symptoms within 3-7 days • Reduces biomass by >86% when treated in laboratory • Approved for aquatic use in Michigan (permit and licensing required)	• May harm non-target species (Broad-spectrum, contact herbicide) • Prohibited for use in water bodies <600 ft. from a potable water intake	(Bultemeier et al 2009; United Phosphorus, Inc. 2011; Hunt et al. 2015)

Herbicide	Target Dosage/ Rate	Adjuvant	Timing	Pros	Cons	References
Flumioxazin (e.g. Clipper®)	100-400 ppb		Spring to early summer. 24 hour exposure	• Reduced photosynthesis to zero 144 hours after treatment in laboratory study • Reduced biomass relative to untreated controls in field study • Approved for aquatic use in Michigan (permit and licensing required)	• May harm non-target species (Broad-spectrum, contact herbicide) • Toxic to aquatic invertebrates	(Bultemeier et al. 2009; Valent 2012; Cahill et al. *in prep*)
Fluridone (e.g. Sonar®)	6-15 ppb for 5-7 weeks		Early spring. 5-7 weeks	• Reduces biomass by >80% after 84 days at 0.02 ppm in laboratory trials • Approved for aquatic use in Michigan (permit and licensing required)	• Minimal control in field trials • May harm non-target species (Broad-spectrum, systemic herbicide) • Restricted concentrations near potable water intakes	(Mackey 1996; Nelson et al. 2002; SePRO 2013a)
Penoxsulam (e.g. Galleon®)	100-200 ppb for 4-6 weeks		Spring to early summer	• Less harm to non-target species (Selective, systemic herbicide)	• Not on either the aquatic approved or not approved list for Michigan	(DiTomaso et al. 2013; SePRO 2013b)
Triclopyr (e.g. Renovate®)	0.5 to 2 ppm		Spring to early summer	• Does not affect many monocot species • Less harm to non-target species (Selective, systemic herbicide) • Approved for aquatic use in Michigan (permit and licensing required)	• Restricted concentrations near potable water intakes	(DiTomaso et al. 2013; SePRO 2013c)

b. Physical or Mechanical Control

The fragmentary nature of stems makes physical removal of CFW challenging without facilitating further spread. Physical removal by divers or suction can be effective, but it is time consuming and expensive (Wilson et al. 2007). In the United States and Australia, mechanical harvesting has only provided temporary control (Wilson et al. 2007). Mackey and Swarbrick (1997) reported that it only took three weeks for a CFW population to regrow to its initial size following mechanical harvesting. Mechanical control techniques are not encouraged in areas where further spread is a concern.

In the Netherlands, the Hydro-venturi system is a new experimental method being used for CFW control. The system uses water pressure to dislodge whole plants from the sediment and then collects them when they float to the surface (Matthews et al. 2013). This avoids most fragmentation and is less intrusive than conventional dredging. The Hydro-venturi system did not work well near shores and displaced sediment into the water, reducing clarity and increasing turbidity. Its use is most appropriate in artificial channels or canals with large infestations (Matthews et al. 2013).

Lake or reservoir drawdown can reduce or eliminate CFW population dependent on weather conditions (Dugdale et al. 2013; Matthews et al. 2013), but may promote seed germination (Schooler et al. 2009). In Australia, a 2 – 3 month lake level drawdown during the winter did not eradicate CFW and left viable stems and crowns as a source of recolonization (Dugdale et al. 2013). Effectiveness of drawdown is also dependent on the harshness of weather conditions and amount of CFW standing crop during the time the sediment is exposed. Carolina fanwort can survive and repopulate if established in dense mats or if the weather is either too humid during a summer drawdown or too warm during a winter drawdown (Dugdale et al. 2013; Bickel 2014). Drawdown is not practical for many waterbodies and can negatively impact native macrophytes.

Shading with tarps can effectively eliminate CFW in small confined areas such as ponds or dams (Schooler 2008). Shading is an inexpensive option that doesn’t enhance fragment dispersal. It is not a species-specific solution and will also impede other species in the shaded area. An ongoing study in Barton Lake, Michigan is evaluating the efficacy of biodegradable benthic barriers for CFW control (Monfils et al., CMU, unpub. data). Over the course of a single growing season the benthic barriers reduced CFW biomass and total macrophyte percent cover relative to controls. Additional monitoring over subsequent years is required for assessing long-term efficacy and the re-colonization of native macrophytes.

c. Biological

There are three insect species that have been identified as possible biological control agents for CFW: *Hydrotimetes natans* Kolbe, an aquatic weevil, *Paracles spp.,* a pyralid moth (Schooler et al. 2006; Schooler and Julien 2008; Cabrera-Walsh et al. 2011), and *Parapoynx diminutalis* Snellen, another pyralid moth (Schooler et al. 2009). Host specificity, effectiveness, and captive rearing have yet to be fully investigated for any of these species.

In its native South American range, *H. natans* completes its entire life cycle on CFW. Larva feed primarily on the basal stems and adults on upper leaves and stems. It has not colonized any other aquatic macrophytes during tests and appears to be host specific (Cabrera-Walsh et al. 2011). Predation from the weevil is thought to weaken CFW stems, reducing competitiveness in the deeper part of its growth range.

Paracles spp. is native to South America where its caterpillars feed on new CFW foliage and is thought to directly limit productivity at all depth zones by damaging photosynthetic parts of the plant (Schooler et al. 2006). Laboratory tests of various stages of *Paracles* spp. life cycle in the presence of CFW and other species revealed no oviposition preference for CFW. Australian experts have deprioritized *Paracles* spp. as a potential biological control agent because of the lack of preference or exclusivity it has for CFW (Schooler et al. 2009).

P. diminutalis is native to Southeast Asia and east Africa, where it is documented to feed on several aquatic plants. It has not been found in South America but has been introduced into the southeast United States and Panama. *P. diminutalis* have gilled larvae that feed on the new shoots of CFW stems, stunting CFW growth. Research on this species as a potential biological control agent is focused on learning more about its population, habits, and distribution (Schooler et al. 2009).

While the potential biological control species are thought to limit CFW growth, their effectiveness as control agents for CFW needs further testing. *H. natans, Paracles* spp*.,* and *P. diminutalis* are not known to survive in temperate climates. More investigation is necessary to determine whether these species could effectively reduce CFW competitiveness without becoming problematic invasive species themselves.

III. Indirect Management

No indirect management techniques have been investigated for the control of CFW at the time of this report. Maintenance of a healthy native ecosystem of flora and minimizing substrate disturbance are the best methods for preventing the colonization, but it is no guarantee of exclusion (Bickel and Perrett 2014).

Research Needs

I. Biology and Ecology

Invasive CFW populations in North America have not been observed to produce viable seeds (Wilson et al. 2007). A seed germination study could confirm the viability of seeds in Michigan populations. Without viable seed production, eradication appears to be possible in small water bodies if fragment dispersal is contained. If viable seeds are produced, CFW persistence (i.e., seeds in the seed bank) and inter-waterbody dispersal (e.g., endozoochory) could be greater than previously thought.

Understanding the genetics of invasive CFW populations will inform future monitoring and management strategies. Wain et al. (1983) used gel electrophoresis to determine allele frequencies at 12 loci and found high genetic similarity between the 3 CFW ecotypes. Given the advancements of genetics in the last 30 years, further research on the different ecotypes of CFW may reveal different conclusions. Understanding the genetic composition of invasive CFW populations has substantial implications for management when considering the differential sensitivity to herbicides the three CFW phenotypes exhibit (Bultemeier et al. 2009).

Analysis of the population genetics of Michigan populations may be able to pinpoint pathways of dispersal (e.g., aquarium waste, fragments from unconnected water bodies). This testing would contribute to a better understanding of origin, dispersal, and phenotype of Michigan populations. Without population genetic analysis, it is unknown if the more isolated populations of CFW were established by human or animal dispersal from existing populations or a novel introduction from improper disposal. This knowledge would allow for the development of more efficient tactics to prevent the dispersal of the species.

Given the difficulty in detecting early occurrences of invasive aquatic plants, eDNA may be a viable method to use for detection. There are currently no techniques in place to detect CFW from water samples taken in the field. Environmental DNA could improve the efficiency of early CFW detection.

Carolina fanwort can produce dense mats that exclude native vegetation, alter macroinvertebrate assemblages, and increase epiphytic algal biomass (Sheldon 1994; Mackey and Swarbrick 1997; Lyon and Eastman 2006; Hogsden et al. 2007). In addition to the ecological effects of CFW introduction, CFW gives an unpleasant flavor and discoloration to water and discourages the recreational use of infested waterbodies (Gangstad 1992; Australian Department of the Environment and Heritage 2003). Further research is needed to describe the effects invasive CFW has on fish communities, as well as its economic and recreational impacts in the Great Lakes Basin. Quantifying the effects of invasive CFW will help prioritize invasive populations for management.

II. Management

Flumioxazin is the only chemical treatment that has been shown to effectively control CFW in laboratory and field trials (Bultemeier 2009; Cahill et al. *in prep*). Endothall amine salt and lime have effectively controlled CFW in a laboratory setting (Bultemeier et al. 2009; James 2011; Hunt et al. 2015); but further testing is needed to evaluate their efficacy in the field. Further studies that evaluate the short and long-term efficacy of other chemical treatments, as well as the impact these treatments have on native macrophyte, fish, and invertebrate communities are needed. The integration of untreated controls and pre- and post-treatment comparisons in field studies are crucial for supporting the efficacy of any management treatment.

Mechanical harvesting may provide temporary CFW control (Mackey and Swarbrick 1997; Wilson et al. 2007). Future research should investigate the potential for mechanical harvesting to proliferate CFW fragment dispersal.

Shading and biodegradable benthic barriers have been shown to effectively control localized patches of invasive CFW over a single growing season (Schooler 2009; Monfils et al., CMU, unpub. data). Further research and monitoring is required to evaluate the long-term efficacy of shading and benthic barriers for CFW control and the recolonization of native macrophytes post-treatment. Water-level drawdown can reduce or eliminate CFW population dependent on weather conditions and the density of the infestation (Dugdale et al. 2013). Future studies should investigate the potential for water level drawdown to promote CFW seed germination (Schooler et al. 2009). The use of water-level drawdowns for CFW control may not be a worthwhile management strategy if CFW rapidly recolonizes via seedlings.

H. natans and *P. diminutalis* have potential as biological control agents for CFW (Schooler et al. 2009; Cabrera-Walsh et al. 2011). Further research is needed to determine whether these species could effectively reduce CFW without becoming a problematic invasive species themselves and whether they could survive in temperate climates.

Future Directions for Michigan and CFW Management

Carolina fanwort is an aquatic macrophyte that was first introduced into Michigan in the 1890s (Beal 1900). For almost a century it existed in the state without being considered a significant threat to native flora. Carolina fanwort has developed invasive populations in the Northeastern, Midwestern, and Pacific-Northwestern United States, Australia, Asia, and Europe. It has invaded climates with a wide range in temperature and aquatic conditions, prompting governments in many parts of the world to invest in research.

Prevention – Prevention of new colony establishment is the most cost effective approach to CFW management. The aquarium industry is believed to have been the original pathway for CFW introduction, thus should be targeted for education and enforcement of current state regulations of prohibited plant species. Increased enforcement of current restrictions placed on the distribution and sale of CFW could prevent new introductions (Maki and Galatowitsch 2004; Hussner et al. 2013; Verbrugge and Valkenburg 2014). Collaborations between states with similar regulations of CFW and other aquatic invasive species could prove beneficial. Expanding existing coalitions to include organizations that may soon face CFW as an invasive species may also prevent spread.

Carolina fanwort can easily attach to boats or trailers and be transferred to uninfested waters (Bickel 2014). The instigation of a sustainable boat washing or inspection program from waters infested with CFW could aid in reducing the spread of this species.

Monitoring – Early detection would make eradication a more realistic option. Adding CFW 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 CFW 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.

Carolina fanwort monitoring would benefit from a direct and targeted monitoring strategy. To develop a targeted monitoring strategy, CFW occurrences and associated environmental variables could be modeled to identify suitable waterbodies for establishment. Suitable waterbodies that have a high-risk of CFW introduction could then be prioritized for monitoring, like Davidson et al. (2015) provided for a suite of invasive macrophytes in the Great Lakes Basin.

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; Nonindigenous Aquatic Species Database – USGS; Biodiversity Information Serving Our Nation (BISON); and 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 be exposed to 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 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. The 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 re-emerging growth. Although it is called a rapid response, it may not end rapidly.

Management – When managing CFW, it is important to delimit the extent of the infestation, contain already established populations, and protect high-value sites. When determining the best integrated pest management plan, factors such as phenotypes and whether the population reproduces sexually or asexually should be taken into consideration. Population genetics, as well as chemical and mechanical control research could help develop more effective management plans.

Measuring effective control: Following the treatment of CFW, the effectiveness of treatment can be quantitatively assessed through documenting any year-to-year regrowth, reduction in CFW biomass, height, or percent cover. 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 affecting the long-term ecological stability of an aquatic community.

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

Objective	Strategic Action	Who is leading effort in Michigan?	Expected Outcome
Guidance and Outreach for Carolina fanwort Management			
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	• AIS Core Team • Lake Associations • Michigan Inland Lakes Partnerships	• Increase public awareness of CFW • Increase the frequency and use of boat washing programs • Contain established populations
Prevent new introductions of CFW	• Educate local and regional aquaria about AIS	• MDARD • Great Lakes Commission	• Reduce sale of invasive CFW in Michigan • Reduce misidentification of CFW as other related species • Elimination of purposeful and accidental sale of CFW
Provide technical guidance to those interested in CFW management	• Framework to prioritize management of CFW populations • Educate stakeholders on available control methods		• Increase management efforts
CFW 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 • Identify eDNA markers for CFW	• AIS Core Team • MISIN • BISON • Michigan Water Corps • eDNA researchers	• Develop a more thorough and up-to-date statewide distribution of CFW • Evaluate dispersal pathways and vectors
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 • Lake associations • Management agencies	• Increase public awareness of AIS • Increase early detection of AIS • Identify water bodies that need professional confirmation of AIS

Research Needs for CFW Management			
Chemical: Develop treatments to increase long-term control or eradication success	• Develop guidelines for pre-, post-treatment, and control monitoring to determine treatment efficacy	• AIS Core Team • Integrated Invasive Aquatic Plant Management Team	• Effective treatment of infestation resulting in possible eradication of invasive CFW
Biological: Establish biological control methods that will increase control and minimize effects of CFW	• Investigate viability of *H. natans* and *P. diminutalis* as biological controls • Search for biological control species that can be effective in temperate climates		• More effective treatment options for already established populations • Decrease management effects on non-target species
Mechanical: Evaluate effectiveness of current mechanical controls	• Explore methods that limit spread through stem fragmentation		• Determine whether or not long term mechanical removal is a cost-effective management approach
Physical: Evaluate effectiveness of current physical controls	• Study the effectiveness of shading (e.g., benthic barriers) for reducing/eliminating CFW • Study the potential for water-level drawdown to promote CFW seed germination	• Integrated Invasive Aquatic Plant Management Team	• Determine whether or not physical controls are a cost-effective management approach

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