Research Article

Aquatic invasive species parrot-feather (*Myriophyllum aquaticum*) in Massachusetts, USA

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Citation: Becker YM, Wong WH (2023) Aquatic invasive species parrot-feather (*Myriophyllum aquaticum*) in Massachusetts, USA. *BioInvasions Records* 12(2): 477–492, https://doi.org/10.3391/bir.2023.12.2.12

Received: 2 January 2022
Accepted: 30 September 2022
Published: 26 March 2023

Handling editor: Carla Lambertini
Thematic editor: Tim Adriaens

Abstract

Parrot-feather (*Myriophyllum aquaticum*) is an aquatic plant in the water milfoil family native to South America. It is widely distributed across North America, Europe, Asia, Australasia, and Africa as an invasive species. Outside of its native range, parrot-feather is regarded as a troublesome weed, due to its ability to grow quickly and clog or stagnate shallow waterways. We report six sightings of parrot-feather in the state of Massachusetts, USA from 2006 to 2017 compiled from state-organized surveys. Approaches to control this invasive species, such as physical removal, chemical treatment, and potential biological agents, are also discussed in this report, with specific recommendations made to expand monitoring efforts in Massachusetts and control newly detected populations.

Key words: aquatic plant, monitoring, noxious weeds management, parrotfeather

Introduction

Parrot-feather (*Myriophyllum aquaticum* (Vell.) Verdc.) is an aquatic plant native to the Amazon River Basin in South America, but it has been introduced as an ornamental species around the world (Wersal et al. 2021). Today, the plant is found on nearly every continent (Lastrucci et al. 2018). Parrot-feather is a type of watermilfoil, classified within the same genus as Eurasian watermilfoil (*M. spicatum)* and variable milfoil (*M. heterophyllum*). These three species of watermilfoil, including parrot-feather, are included on the Massachusetts Prohibited Plant List on account of being invasive species; therefore, it is illegal to import, sell, or trade parrot-feather within the commonwealth of Massachusetts (Commonwealth of Massachusetts 2021). This document reports six sightings of *M. aquaticum* in the state of Massachusetts compiled from state-organized survey data stored by the Massachusetts Department of Environmental Protection (MassDEP), as well as biological information on *M. aquaticum* and a review of known and approved control methods for invasive populations. The introduction section below covers the basic biology of parrot-feather, its invasive range and

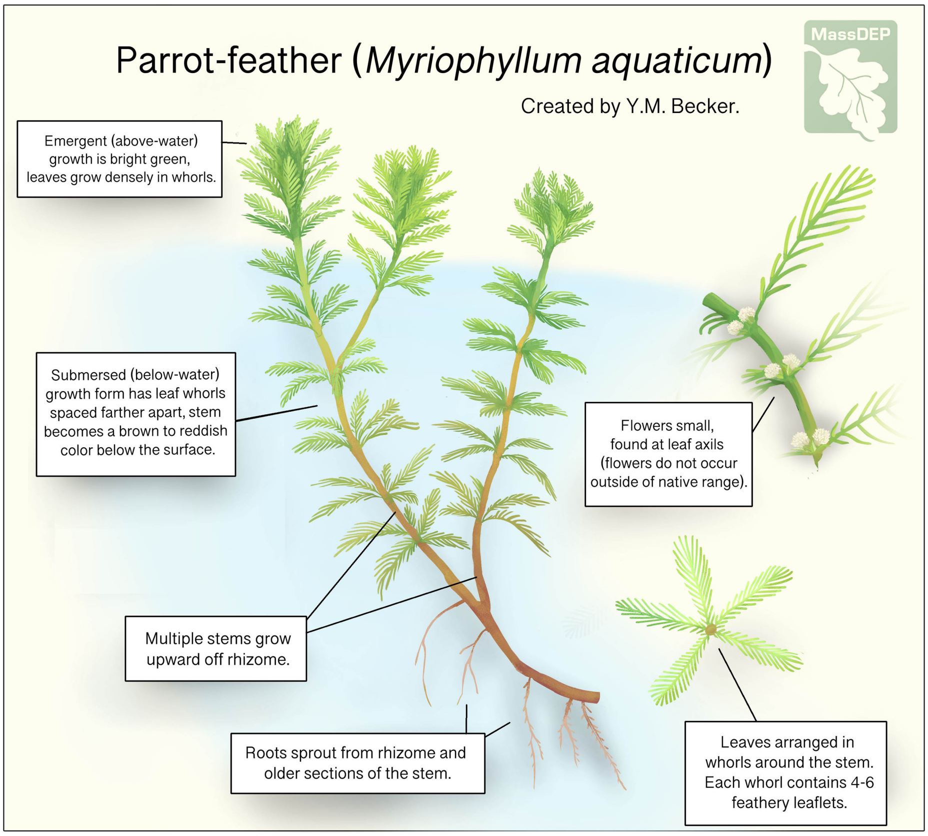

Figure 1. Illustration of parrot feather. Graphic created using Clip Studio Paint, with the help of visual references. (Haden 2018; Karwath 2005; King County NWCP 2018; Lurvey 2021; Orchard 1979; UF IFAS 2021; Vandenberghe 2015).

mechanisms of spread, as well as its ecological and human impacts, and control options. The subsequent Materials and Methods and Results sections report data collection and occurrence records of *M. aquaticum* in Massachusetts as well as detailed information about the six waterbodies (i.e., Jones River, Mill River, Satucket River, Great Pond (in Tisbury), Burchell's Pond, and Big West Pond) in which parrot-feather was found. Management and control options applicable to the reported populations are finally discussed.

Basic biology of parrot-feather

Considered an amphibious plant species, parrot-feather is heterophyllous in its growth, meaning that submerged leaves are different from leaves that emerge from the water (Wersal 2010; Wersal et al. 2021). The sections above water are solidly light-green to glaucous in color and dense with small pectinate or feather-like leaves arranged in whorls of five to six around the stem (Murphy 2007), while the submerged parts of the plant are much sparser, with longer, more filiform leaves around a stem that transitions into a deeper reddish-brown color below the water (Figures 1, 2). When present, flowers are small, white if female and yellow if male, and they grow along the stem at the axils of emergent leaves (Murphy 2007). In response to a change in position or in water level, the vegetation is able to

Figure 2. Photos of parrot-feather taken in Washington state, included as visual examples of a complete parrot-feather plant and densely growing populations (King County NWCP 2018). Specimen of a rooted fragment held in hand with roots and young stems growing off fragment (left). Examples of dense wild parrotfeather growth (right, top and bottom).

adjust and rapidly change; under experimental conditions, parts of the stem were observed to change from the emergent to the submersed form “in a matter of days” after a rise in water level (Wersal and Madsen 2011). The majority of the plant’s biomass appears to be positioned above the water, but the stems can extend downward up to 2 meters, where a rhizome is anchored to the sediment by thin roots (Cook 1985; Murphy 2007; Haberland 2014).

As a dioecious plant, parrot-feather has separate male and female flowers. The plant can be pollinated through wind and reproduces by seed, but sexual reproduction is thought to be a negligible means of reproduction outside of the plant’s native range, since the vast majority of invasive specimens collected appear to be female plants, and flowers are rarely seen (Cook 1985; Murphy 2007) Male plants are rare even within parrot-feather’s native habitat (Orchard 1979; Robles et al. 2011). Parrot-feather reproduces on a local scale by cloning, with mature plants producing numerous offshoots and allocating resources to younger plants in order to maximize their survival (You et al. 2013). Since the plant lacks tubers or any other kind of root specialized for nutrient storage and dispersal, these functions are served by the stolons connecting offshoots to their parents (Wersal et al. 2021). Parrot-feather can also reproduce via stem fragmentation, when dislodged or senescent pieces of stem fall into the sediment, where they begin to grow roots and new stems (Figure 2).

Invasive range and mechanisms of spread

The earliest recorded specimen of *M. aquaticum* in the United States was collected from New Jersey in 1890, having been introduced to the area as a garden ornamental (Wersal 2010; Wersal et al. 2021). By the 1940s, *M. aquaticum* was well established in the region of Southern New York, and populations could be found all the way on the west coast, in Washington state (Wersal et al. 2021). Today, this invasive species is established throughout the United States, especially along the coasts and in southern states east of Texas (USGS 2021).

After an initial introduction, parrot-feather is observed to secondarily spread to new habitats mainly by clonal growth and fragmentation (You et al. 2013; Murphy 2007). The species is capable of flowering and reproducing by seed, but this method of spread is not utilized outside of the plant's native range due to the non-occurrence of male introduced specimens (Murphy 2007). Either stem fragments or seeds from an established parrot-feather stand are prone to being carried downstream to colonize new areas, where a population then grows and expands producing clonal offshoots. Improperly quarantined boats and traveling waterfowl are also considered vectors for secondary spread, potentially enabling even broader dispersal of plant fragments to new waterways beyond the reach of simple downstream water movement (Murphy 2007; Kuehne et al. 2016). Boats in particular are known to be major vectors for the spread of aquatic plants in Massachusetts (MA DCR 2010).

Systems at the greatest risk of parrot-feather invasion are those which are shallow and prone to disturbance (Lastrucci et al. 2018). Regularly occurring mechanical disturbances facilitate stem fragmentation and create conditions that favor the dominance of *M. aquaticum* in shallow systems (Wersal and Madsen 2011). Since parrot-feather thrives in nutrient-rich environments, pollution and runoff are also risk factors for invasion (Xie et al. 2010; Wersal et al. 2021). Though populations will often fail to establish when faced with severe winters, parrot-feather is overall a hardy plant capable of withstanding moderate frost, short-term changes in water level, and even some degree of saltwater inundation (Wersal and Madsen 2011; Wersal et al. 2021). The plant can also overwinter in its submersed form beneath ice cover (Hussner 2008).

Ecological and human impacts

Myriophyllum aquaticum is known to be a competitive and fast-growing plant species, often dominating over native plant species to form dense, monospecific stands, as well as influencing animal species composition (Kuehne et al. 2016; Stiers et al. 2011; Lastrucci et al. 2018). Like other plant species which reproduce through clonal growth, *M. aquaticum* stands are prone to low genetic diversity (Lambertini et al. 2010). Though low genetic diversity does not reflect upon likelihood of invasion success, and clonal growth does not fully prevent the progression of evolution or the development of new somatic mutations in an invasive population (Roman and Darling 2007; Lambertini et al. 2010; Rollins et al. 2013), the replacement of genetically and taxonomically diverse plant populations with uniform clonal populations can threaten the long-term resilience of an ecosystem (Hughes et al. 2008).

Parrot-feather invasion has also been observed to bring about specific changes in macroinvertebrate and fish species composition. Studies have found certain non-native fish and arthropod species living in higher density in areas dominated by *M. aquaticum* as compared to non-invaded areas (Kuehne et al. 2016; Lastrucci et al. 2018). Notably, there is a well-established correlation between the density of *M. aquaticum* and the presence of mosquitoes, as densely growing parrot-feather stagnates waterflow, creating habitat for mosquitoes to breed (Hill 2003; Orr and Resh 1989; Lastrucci et al. 2018; Wersal et al. 2021). Increased mosquito abundance is a human health risk, given the dangers of mosquito-borne illnesses (Wersal and Madsen 2007; Wersal et al. 2021). In Massachusetts, mosquitoes are known to seasonally carry and spread several diseases, including West Nile virus and eastern equine encephalitis (Cambridge Public Health Department, n.d.). Flow blockages in waterways also negatively impact other species, preventing the movement of fish and inhibiting human recreational activities such as swimming and boating (Hill 2003; Lastrucci et al. 2018).

In spite of the risks posed by wild overabundant parrot-feather growth, *M. aquaticum* can also provide ecosystem services by shaping important microbial communities (Nakai et al. 2000; Sun et al. 2017). A study on waste treatment in constructed wetlands found that introducing *M. aquaticum* to wastewater has been observed to increase abundances of bacterial species involved in the nitrogen cycle, measured by a higher quantity of the bacterial genes responsible for nitrification and denitrification found in the sediment (Sun et al. 2017). Aquatic plants in general are thought to have similar interactions with microbial communities, but *M. aquaticum*'s role in this system is particularly well-documented (Sun et al. 2017). *Myriophyllum aquaticum*'s ability to rapidly produce large amounts of biomass make it an especially suitable candidate for wastewater remediation projects (Souza et al. 2013). Additionally, both *M. aquaticum* and a related milfoil species *M. spicatum* have been found to contain allelopathic chemicals capable of inhibiting blue-green algae growth (Nakai et al. 2000; Wu et al. 2008).

Myriophyllum aquaticum has also been found to be highly efficient in removing phosphorus, tetracycline, heavy metals, and other pollutants from water, whether for purposes of assessing pollutant concentrations or for ecological restoration (Harguinteguy et al. 2013; Souza et al. 2013; Luo et al. 2017; Colzi et al. 2018; Guo et al. 2019).

Control options

Physical control, either by hand or by machine, is a simple and intuitive way to reduce the amount of invasive vegetation in a short period of time. However, since parrot-feather is capable of reproducing by fragmentation, mechanically cutting or damaging parrot-feather stems could inadvertently facilitate the spread of the invasive species. Some physical control techniques such as drawdown, enacting floods, or benthic barriers, may also work, especially the early state of invasion for eradication, when the area affected is still small (MA DCR 2007; Metro Vancouver 2021). A study conducted in Portugal comparing mechanical and chemical control found that mechanical removal achieved immediate clearance followed by gradual regrowth back to initial density over the course of the next two years, while herbicide application using glyphosate was slow at first but provided better long-term control (Machado and Rocha 1998).

For large scale infestations, control options such as chemical treatment, physical removal, or biological control may be applied. Targeted application of chemical herbicides is a popular method of managing nuisance plants in Massachusetts. Many herbicides have been used with success, including glyphosate, endothall, diquat, 2,4-D, triclopyr, and imazapyr (Patten 2003; Hofstra et al. 2006; Souza et al. 2012). Success rates vary across different documented trials, and the effectiveness of a given herbicide application is likely to depend on characteristics of the site, the method of applying the herbicide, and the concentration and composition of the herbicide solution. Imazapyr is another chemical herbicide that is considered useful against parrot-feather. As imazapyr tends to break down after a short time when exposed to water and sunlight, it is typically used to control emergent vegetation (Tu et al. 2001). Field experiments comparing the efficacy of various herbicides have found imazapyr based treatments more effective than those using 2,4-D as a main ingredient (Kuehne et al. 2018). Another experiment using imazapyr combined with a non-ionic surfactant called Dyne-Amic® resulted in 100.0% parrot-feather mortality when applying high concentrations of the herbicide to four week old crops grown in mesocosms (Wersal and Madsen 2007). A field study in 2018 comparing the efficacy of imazapyr to 2,4-D and to a solution of imazapyr combined with carfentrazone (the latter chemical known to be ineffective on parrot-feather when used alone) found that 6 weeks after each treatment, the biomass of parrot-feather at the 2,4-D-solution-treated sites had only been reduced 23%, but at each of the sites where an imazapyr solution had been used, parrot-feather cover was reduced by 67–69%, a promising and significant, though incomplete, reduction (Kuehne et al. 2018). The concentrations of imazapyr and surfactant used in the 2018 field study exceeded those which were used by Wersal and Madsen (2007), and so the incomplete control in the 2018 study is accounted to variation in outdoor environmental conditions (Kuehne et al. 2018). The wild-grown parrot-feather may have also had greater resistance to the herbicide, being older and better established than the young plants used in Wersal and Madsen's (2007) mesocosm study. Regardless, a control rate of 67–69% is significant and speaks to the promise of imazapyr solutions as chemical control agents for parrot-feather infestations.

Imazapyr is approved for use by the EPA in controlling noxious plants, and for certain forms of agricultural pest control (US EPA 2006). It breaks down readily in water and sunlight, and it poses no health risk to birds, fish, or mammals (Tu et al. 2001; US EPA 2006). The risk of human exposure in areas where imazapyr is used is below the EPA's level of concern (US EPA 2006). For people working directly with imazapyr, risks resulting from inhalation and dermal contact are negligible, but the concentrated herbicide is considered an eye irritant, and protective clothing and especially eyewear are advised to be worn while applying the herbicide (US EPA 2006). The main ecological risk posed by imazapyr is the possibility of harm to nontarget plant species, as imazapyr is not selective in its ability to kill plant life (US EPA 2006). Therefore, chemical control by imazapyr should be considered only in situations where all alternative control methods would not be effective, and also where the outcome of not removing the invasive plant would be more detrimental than the harm done by eliminating non-target plant species. When increased mosquito habitat poses a significant public health risk, or where parrot-feather has already significantly outcompeted native aquatic macrophytes, the use of chemical herbicides may be justified. In any case, removal of invasive plants by chemical herbicides should always be followed up with repopulation of native species. Imazapyr should never be used in waterbodies where endangered or "listed" native plant species are known to live (US EPA 2006).

Meanwhile, it is worth noting that, in spite of experimentally demonstrated effectiveness of imazapyr on parrot-feather, they are not necessarily a good solution to parrot-feather invasion in every case. Clements et al. (2012) found that herbicide on alligatorweed (*Alternanthera philoxeroides*), another aquatic plant, can induce the plant to break into stem fragments capable of spreading downstream. Some agencies recommend against the use of chemical herbicides on the basis of low efficiency and potential devastating effects on other species and the environment if not used with care. When implementing any control program, one must ensure any actions being taken against invasive species will have large-scale benefits outweighing the harm they cause to the immediate environment.

Biological control may be considered in some situations as a means of reducing parrot-feather biomass. An ideal biological control agent is one that feeds on its target species sufficiently to suppress the target's growth and feeds exclusively or with strong preference on its target species, so that the control agent does not pose a risk to native or non-target species. Several organisms are known to feed on parrot-feather, including some insects and larger herbivores. While no parrot-feather specific biocontrol agent has been approved for release in the United States, insect biocontrol programs have seen successful in other parts of the world (Hill 2003).

Rather than by importing a non-native herbivore to graze on invasive species, one might also achieve management of invasive parrot-feather with the help of a native herbivore: the beaver. Field experiments by Parker et al. (2007) observed the effects of "beaver exclusion" on freshwater plant communities and found that removing beavers from certain plots lead to an extreme disparity in the abundance of the exotic *M. aquaticum*. Where beavers were permitted to graze and construct their nests, *M. aquaticum* biomass was reduced by 90%. This case serves as evidence that protecting native beavers can act as a preventative measure against noxious plant growth and ecological invasion. Massachusetts land-owners often seek to remove beavers from their property to prevent flooding caused by beaver dams, but removal of beavers is ecologically ill-advised due to the biodiversity value of the wetland habitats beavers create (Commonwealth of Massachusetts 2022). It is also possible to prevent beaver-induced flooding without removing or harming beavers, such as by the use of water level control devices (WLCD) also known as "beaver pipes" or "beaver deceivers" (Commonwealth of Massachusetts 2022; Beaver Solutions LLC 2022). It is illegal in Massachusetts to disturb beavers or their constructions without a permit, and while the Massachusetts Department of Fish and Wildlife provides a system for acquiring permits to remove beavers (MassWildlife n.d.), due to the many ecosystem benefits of beavers and their observed ability to quell the growth of invasive parrot-feather, it is worthwhile to aim for coexistence with beavers and to explore alternative means of water level control on properties where beaver construction poses issues.

Materials and methods

The data reported in this study were collected between 2006 and 2017 by various MassDEP (Division of Watershed Management) personnel, according to standard operating procedures (SOP) that might vary by year, monitoring focus, and specific waterbody. Data relating to sightings of *M. aquaticum* have been compiled from internal MassDEP sources by the authors of this paper. Per the Clean Water Act (CWA), an annual survey has been carried out since the 1970s in waterbodies across every state to monitor water quality (MassGIS 2022). The survey generates a dataset from every state, referred to as an "Integrated List of Waters" (ILW), which is turned in to the national Environmental Protection Agency (EPA) on a regular cycle. In Massachusetts, the data comprising the ILW is also uploaded for public download as GIS files (MassGIS 2022). Due to limitations

Table 1. Sightings and report agencies of infested waterbodies.

Waterbody	Watershed	Agency	Town	Year	Latitude	Longitude
Jones River	South Coastal	MassDEP	Kingston	2017*	41.995	−70.747
Jones River	South Coastal	MassDEP	Kingston	2006*	41.995	−70.747
Jones River	South Coastal	MassDEP	Kingston	2006*	41.995	−70.747
Jones River	South Coastal	MassDEP	Kingston	2006*	41.995	−70.747
Mill River	Charles	MassDEP	Norfolk	2015	42.122	−71.365
Satucket River	Taunton	MassDEP	East Bridgewater	2017**	42.022	−70.951
Satucket River	Taunton	MassDEP	East Bridgewater	2006**	42.022	−70.951
Satucket River	Taunton	MassDEP	East Bridgewater	2006**	42.022	−70.951
Great Pond	Islands	USGS NAS Database	Tisbury	2020	41.358	−70.654
Burchell's Pond (near Miacomet Pond)	Islands	USGS NAS Database	Nantucket	2016	41.246	−70.116
Big West Pond	Buzzards Bay	USGS NAS Database	Plymouth	2017	41.919	−70.116

* Sighting at the Jones River was first detected by MassDEP field staff in 2006 and further confirmed by Wai Hing Wong on July 18, 2017.
** Sighting at the Satucket River was first detected by MassDEP field staff in 2006 and further confirmed by Wai Hing Wong on July 7, 2017.

of funding, staffing, and time, not every body of water is assessed every year, and monitoring is focused on surveying certain target waterbodies. A standard operating procedure was developed for all field surveys by MassDEP, including field sheet development, species identification, and quality control and assurance. Monitoring at different waterbodies might be carried out by different staff and sometimes rely on volunteer efforts (MassDEP 2021), but species invasive species identification is generally verified by a biologist/taxonomist (Chase and Wong 2015).

The parrot-feather data in this report were collected by compiling MassDEP data from ILW surveys, and it is supplemented with sightings reported through other agencies, such as the U.S. Geological Survey's Nonindigenous Aquatic Species database (USGS NAS) (Table 1). Maps of known sites where parrot-feather has been detected were created using QGIS open-source software (OSGeo, Beaverton, Oregon) and ArcGIS® ArcMap™ 10.1 (ESRI, Redlands, California). More information about the six waterbodies with parrot-feather were collected from Lyons-Skwarto Associates (1970), Sutherland and Oktay (2010), Eichner et al. (2015), MVC (2020), JRLEHC (2022), and USGS (2022).

Results

Parrot-feather (*M. aquaticum*) was detected for the first time in Massachusetts in 2006, in the Jones River at Kingston (Table 1). Since then, it has been confirmed that a total of six waterbodies in the state, including three rivers and three lakes, are invaded by this species. The three rivers are the Jones River in Kingston, the Mill River in Norfolk, and the Satucket River in East Bridgewater. The lakes in which parrot-feather has been sighted are Great Pond in Tisbury, Burchell's Pond (an offshoot of Miacomet Pond) in Nantucket, and Big West Pond in Plymouth (Table 1). These waters are within five greater Massachusetts watersheds: South Coastal, Charles

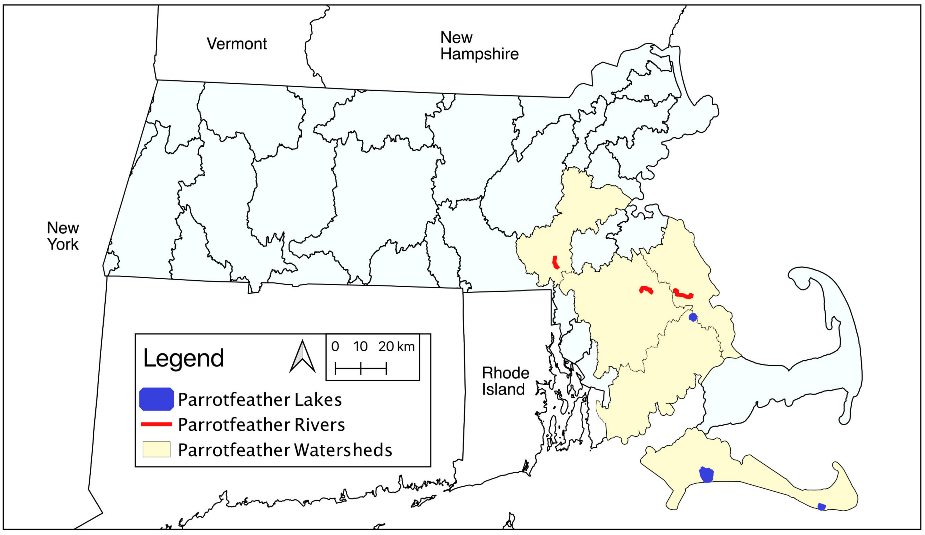

Figure 3. Map showing infested waterbodies by parrot feather at Massachusetts.

River, Taunton River, Islands, and Buzzards Bay (Table 1). Most of these waterbodies are in the southeastern region of the state. A map depicting all known infested waterbodies and watersheds in the state is included in this report (Figure 3).

The Jones River in Kingston has a main channel which runs 7.5 miles through several towns in the South Coastal watershed, with the local Jones River watershed encompassing thirty square miles. Silver Lake at the head of the Jones River is one of the largest natural lakes in the state, and it is used as a water supply for the town of Brockton. The Jones River is also an important waterway for anadromous fish, as herring spawn annually in the river.

Varying amounts of information are available regarding the other waterbodies where parrot-feather is reported to be seen. According to USGS, Mill River near Norfolk, MA, has a drainage area of 13.8 square miles. Satucket River in East Bridgewater has a drainage area of 34.8 square miles (USGS N.d). In 2001, prior to the sighting of parrot-feather dated to 2006, a survey conducted on Satucket River rated its ecosystem as containing "excellent fish habitat" (MassDEP 2001). Tisbury Great Pond on Martha's Vineyard has a surface of 662 to 800 meters, and a depth of 5 to 8 feet. A local report from 2020 rates the pond's water quality as poor to moderate, citing nitrogen pollution and low dissolved oxygen as sources of impairment.

Burchell's Pond is a small offshoot of Miacomet Pond on Nantucket, connected to the main body of water by a small tributary. The drainage area of Miacomet Pond is reported to include 970.6 acres. Detailed water quality monitoring carried out at Miacomet Pond for a period of 3.5 months in 2009 lead the monitoring team to the conclusion that Miacomet Pond is a eutrophic system, with excess nutrients most likely originating from nearby septic systems and a fertilized golf course.

Big West Pond is a pond in Plymouth, MA, with an area of 43 acres and a maximum depth of 16 feet. A report provided by the town of Plymouth from 1970 relates that the pond was eutrophic and dense with macrophyte growth (Lyons-Skwarto Associates 1970). A more recent report from 2015 states that the pond is not considered impaired, accounting to acceptable dissolved oxygen levels, but warns that nitrogen is still high due to septic system inputs, making the pond sensitive to phosphorus pollution (Eichner et al. 2015).

Discussion

Monitoring and prevention are needed to better manage this invasive species and prevent its further spread to other waters in Massachusetts. Like many invasive species, parrot-feather is most able to take hold and become invasive in bodies of water that are already at risk due to other factors – anthropogenic disturbance and excess nutrients in a system due to pollution are both conditions that benefit the proliferation of parrot-feather and eliminating these risk factors is an important step in preventing overabundant growth (Haberland 2014). In Massachusetts, cultural eutrophication, or eutrophication caused by pollution from human industry, is the primary water quality problem found in the state's freshwaters, with nutrient impairments directly or indirectly linked to approximately 48% of water quality impairments (MassDEP 2011) although phosphorus concentration has been declining in the past two decades thanks to remediation efforts (Wong et al. 2018).

Another step to avoid parrot-feather invasion is the prevention of dispersal through human activities. The DCR Lakes and Ponds Boat Ramp Monitoring Program identified boating and boat ramps as a vector for invasive plant spread in Massachusetts; through inspections of over 10,000 boats between 2004–2008, program monitors found that 19.5% of boats carried plant fragments, of which 41.2% were non-native (MA DCR 2010). Properly cleaning watercraft, swimming gear, and construction equipment before transporting items between waterbodies will prevent the accidental dispersal of plant fragments from infested systems. Additionally, care should be taken not to newly introduce exotic ornamental garden or aquarium plants to the wild, and the individual selection of native plants for outdoor home or commercial gardens should be encouraged and promoted to reduce this risk.

So far, monitoring for parrot-feather in Massachusetts has been carried out by conventional visual assessment and identification. With recent advancements in molecular technologies, monitoring by analyzing environmental DNA (eDNA) is becoming an increasingly accessible and valuable tool for detecting invasive species on a broad scale. Some experimental evidence suggests eDNA monitoring may not be as powerful for detecting plants as it is for animals, with detection of plant eDNA only occurring after plants begin to senesce (Kuehne et al. 2020). However, very little data exists on plant detection via eDNA, and the technology is yet very new. Specific identifiers and protocols for the detection of *M. aquaticum* have recently been developed, allowing for this species to be detected and identified through standard PCR-based methods (Shah et al. 2014).

Since there are only six waterbodies with confirmed invasive parrot feather, a rapid response is recommended in managing this invasive species at locations where it has been introduced in Massachusetts. Rapid response for eradication of the detected invasive species population alleviates the need for expensive invasive species control programs that would have to be enacted over the long-term. In Massachusetts, MA Department of Conservation and Recreation Lakes and Ponds Program has developed a guide on two different types of manual rapid response techniques to a small infestation of aquatic invasive species (MA DCR 2007): hand pulling and benthic barriers. Hand pulling is an inexpensive method favored for controlling small pioneer infestations, or where a large pool of volunteer labor is available. This technique is very species-specific and causes minimal damage to non-target species or other biota, many submerged non-native species spread by fragmentation, so extreme caution must be exercised when hand pulling to prevent additional spread. Although hand pulling is an inexpensive management technique, the use of SCUBA divers where necessary in deep water may increase the cost, and post-removal monitoring is essential to ensure success.

The installation of benthic barriers is also recommended to control small-scale growth of invasive parrot feather in Massachusetts (MA DCR 2007; Metro Vancouver 2021). Benthic barriers, or benthic mats, are flat structures typically made from a dark colored, gas-permeable synthetic material, such as plastic, geotextile, or landscaping fabric, anchored directly onto the ground by weights or a constructed rebar frame (Metro Vancouver 2021). They are designed to suppress plant growth along the bottom of a river or lakebed by preventing light from reaching a target area. This control method is most suitable for small, human-accessible areas such as around docks and swim beaches. This technique can be repeated over a long period of time if the mats are maintained and cleaned. The barrier needs to be securely anchored to the lake bottom or gases from decaying plants can build up beneath the barrier, causing it to rise off the bottom where it may create a hazard for boaters and swimmers. Caution must be used in selecting anchors so that they do not pose a hazard for swimmers and will not roll as gases build up. Also, benthic barriers tend to be non-specific and will smother all plant life where they are applied, so a site should be carefully surveyed to minimize harm to native plant species. It is also advised to make plans for the reintroduction of impacted native species after invasive growth has been sufficiently suppressed. Installation should be done on a day with appropriate weather conditions (calm and with no predicted storms) (MA DCR 2007).

In the case that an infestation of parrot-feather in Massachusetts grows to proportions beyond which physical removal or benthic barriers might be feasibly implemented as control options, chemical herbicide options may be considered. With the addition of non-ionic surfactants, imazapyr has been found to be highly successful in eradicating parrotfeather (Wersal and Madsen 2007; Kuehne et al. 2018), though care should be taken to mitigate harm to non-target plant species. It is also advisable to consider beavers as biological control, as they are native to Massachusetts, as reintroduction of beavers to waterways has experimentally shown to reduce parrot-feather biomass by 90% (Parker et al. 2007).

Based on the data we have compiled from MassDEP and USGS sources, parrot-feather arrived in the state only as recently 2006, and it seems to be gradually spreading to more ponds and rivers as the years go by. At this point in time, watershed managers and Massachusetts citizens committed to natural stewardship have the opportunity to respond quickly and control parrot-feather's spread, before the plant is overwhelmingly widespread in the state. With increased monitoring of infested locations and a rapid plan of response, it is possible to prevent parrot-feather from establishing itself widely in Massachusetts waterways.

Acknowledgements

The MassDEP's Michelle Waters-Ekanem Internship Program and Northeastern University's Co-Op Program were very supportive in completing this project. Comments from two anonymous reviewers and Dr. Carla Lambertini are valuable in improving the quality of an earlier version of this report. The views in this paper are those of the authors and do not necessarily reflect the views or policies of the Massachusetts Department of Environmental Protection (MassDEP).

Funding declaration

Data collection is partially funded by Massachusetts Department of Environmental Protection (MassDEP).

Author contribution

YMB and WHW drafted the paper together.

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