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Invasive Asian clams (*Corbicula fluminea*) recorded from 2001 to 2016 in Massachusetts, USA

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Abstract

Invasive Asian clams (*Corbicula fluminea*) recorded from 2001 to 2016 in Massachusetts were mapped to have a better understanding of the status of this species in this state. The map will help the general public in preventing the further spread of the clams to new water bodies by increasing the awareness of infested waters, as well as aid water resource managers track the extent of infestations in Massachusetts. The first sighting of Asian clams in Massachusetts was in a section of the Charles River in Watertown, MA. Currently there are 29 sites (representing 28 water bodies) reported to have the invasive Asian clam in Massachusetts. These recent infestations may reflect the warming temperature in this region because all clams were found in the warmer parts of the state where water temperature is above the clams' long-term incipient lower thermal limit. In an infested unnamed tributary in Forest Park, Springfield, MA, a high abundance of 6,124 clams/m^2 was recorded. The maximum shell length was 22.64 mm and most individuals were estimated to be about one year old.

Key words: invasive species mapping, invasive species management, warming temperature

Introduction

The Asian clam, *Corbicula fluminea* (O. F. Müller, 1774), is considered to be one of the most ecologically and economically important aquatic invasive species in global aquatic ecosystems (Sousa et al. 2008). The native range of *C. fluminea* is Eastern Asia and Africa but it has spread to Europe, North America, South America, and other areas of the world. Their invasive success and dispersion mainly relies on their natural characteristics including rapid growth, early sexual maturity, short life span, high fecundity, extensive dispersal capacities and their association with human activities (McMahon 2002). In North America, initial Asian clam establishment is thought to be due to transoceanic ballast water exchange and transport by Chinese immigrants as a food source (Johnson and McMahon 1998; Sousa et al. 2008). Since the introduction of *Corbicula fluminea* to the United States in 1938, it has spread into many of the major waterways (Counts 1986). By the 1960s the Asian clam had reached the Atlantic coast (McMahon and Bogan 2001). Asian clams have now established themselves in the United States above the 40° latitude line, where waters meet their temperature tolerance. Asian clam infestations continue to be dispersed through human activity, including ballast water transport and discharge, fish bait, release from aquariums, tourism boats (Sousa et al. 2008), and subsequently through natural water dispersal.

Asian clams have significantly reduced ecosystem services and caused economic damages. It has been reported to have cost the United States approximately $1 billion per year to control Asian clams since 1980 (Pimentel et al. 2005). This is due to the damage Asian clams cause to equipment, such as water intake pipes, electric power plant cooling systems, and sewage treatment plants (McMahon 2002; Muller and Baur 2011). The ecological damage Asian clams cause is also significant. Asian clams are filter feeders that consume large amounts of microscopic plants and animals, creating more competition for food sources among native aquatic life (Robinson 2004). Asian clams can attain densities greater than 6,000 clams per square meter (Robinson 2004; Sheehan et al. 2014) in rivers. Such expansive coverage alters the benthic community, and the clams sequester a large portion of the available carbon (Muller and Baur 2011). Native unionid mussel species have become threatened because they are being displaced by the Asian clam (Robinson 2004) although it is not always considered to be the case (McMahon and Bogan 2001).

Although Asian clams have had many negative impacts, there are also a few positive impacts that stem from their presence. Empty shells can be used by other species as shelters, and they are a food source for some species at higher trophic levels, such as cyprinid species (e.g. *Barbus* spp. and *Luciobarbus* spp., *Cyprinus carpio* Linnaeus, 1758) and pumpkinseed sunfish *Lepomis gibbosus* (Linnaeus, 1758) (Pereira et al. 2016 and references therein).

The goal of the present study is to map the sightings of Asian clams in Massachusetts and quantify the density and population size in an infested, unnamed tributary in Forest Park, Springfield, MA. The Asian clam map in Massachusetts will additionally make the general public aware of the presence of Asian clams in Massachusetts.

Methods

Mapping Asian clams in Massachusetts

The Massachusetts Department of Environmental Protection (MassDEP) Watershed Planning Program (WPP) is committed to protect, enhance and restore the quality and value of the waters of the Commonwealth with guidance by the Federal Clean Water Act. It works to secure the environmental, recreational, and public health benefits of clean water for the citizens of Massachusetts. As a result, a long-term statewide benthic macroinvertebrate biomonitoring program has been in place since 1973. Benthic community diversity is one of the indicators used by WPP staff to assess the health of a water body. Benthic samples have been collected from 823 different sites statewide and these sites are from 410 water bodies. The standard operating procedures, including sampling methodology, species identification, quality control and assurance, can be found in Nuzzo (2003). Sites with Asian clams were mapped as a data layer with ArcGIS® ArcMap™ 10.1 (ESRI, Redlands, California). To gain a more complete record of Asian clams in Massachusetts sightings also reported by Massachusetts Department of Conservation and Recreation (Jim Straub, personal communication) and U.S. Geological Survey (USGS) (Foster et al. 2016) staff were also included.

Abundance of Asian clams in an unnamed tributary in Forest Park, Springfield, Massachusetts

To examine the abundance of the Asian clam in a tributary to Porter Lake (inside Forest Park) in Springfield, MA, samples were collected from four stations along the stream (Figures 1, 2 and Table 1). This unnamed tributary drains to Porter Lake which is a 28 acre freshwater lake (Figure 2). Invasive purple loosestrife (*Lythrum salicaria*) has been found in this lake (Kennedy and Weinstein 2000) and there is also an unconfirmed report of invasive curly-leaved pondweed (*Potamogeton cripus*) (Carr and Kennedy 2008). Historically, this lake had a very dense growth of aquatic macrophytes (primarily *Ceratophyllum demersum*) and there are floating algal and duckweed mats at the western end (Kennedy and Weinstein 2000).

Sediment samples were collected from the tributary stream by MassDEP staff in August of 2016 using a Surber Square-Foot Sampler. The latitude and longitude of the four sampling stations from upstream to downstream were 42º04.790′ and −72º33.933′ (Station #1), 42º04.771′ and −72º33.982′ (Station #2), 42º04.733′ and −72º34.025′ (Station #3), and 42º04.682′ and −72º34.070′ (Station #4), respectively. This is a small wadable river and black coarse sands are major components of the sediment in these locations (Figure 3). Since the sediment composition in each of the sampling location is homogenous, only one sample was taken from each station. The top 10 cm of the sediment from each quadrat were collected and stored in a plastic container in the field and brought back to a freezer and kept at −32 °C. The sediment collected at each station was first filtered through a 500 µm sieve with tap water where most of the fine sediments were washed away. The rest of the sediment was transferred to a plastic tray where individual Asian clams and dead clam shells were picked by hand (Figure 4). At the end of picking, small particles were examined using a stereo microscope to determine if there were smaller individuals left. After all individual clams and dead shells from each site were extracted, the density of clams at that specific station was calculated as the number of clams per square meter. Shell length (maximum distance between the anterior and posterior across the valves)

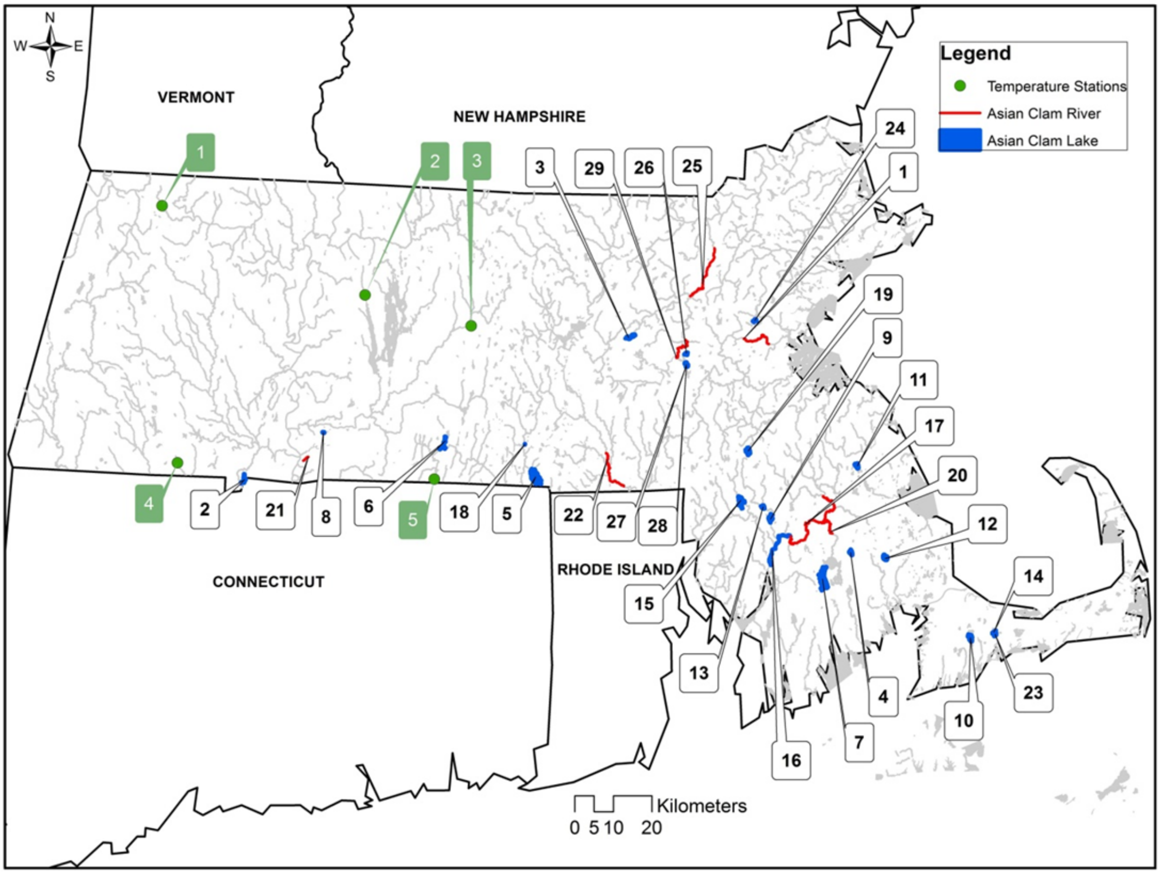

Figure 1. Distribution map depicting *Corbicula fluminea* in Massachusetts (See Supplementary material Table S1 for site descriptions; see also Figure 2 for more information about Site#18 where clam abundance was documented; The green circles are water temperature stations).

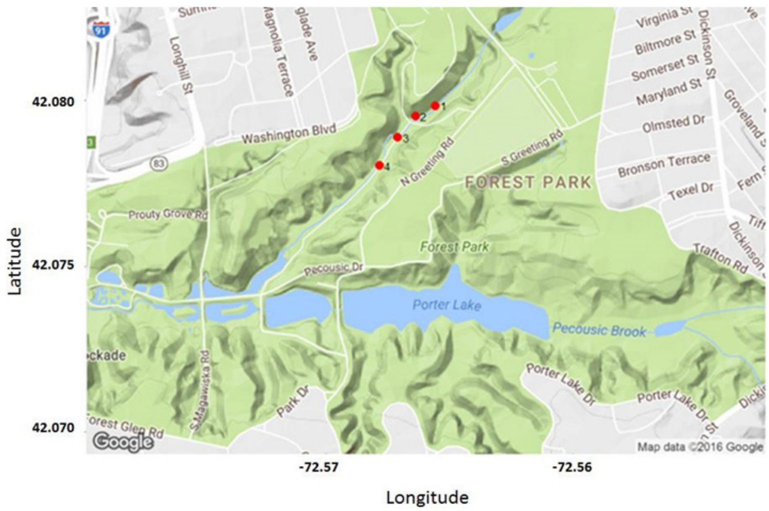

Figure 2. The four sampling stations along an unnamed tributary to Porter Lake in Springfield, Massachusetts (map made via ggmap, courtesy Kahle and H. Wickham 2013).

and height (maximum distance on the dorsal-ventral axis, across the shell middle axis) for each individual clam were measured with an electronic caliper (Mitutoyo Absolute digital caliper, 965 Corporate Boulevard Aurora, Illinois 60502). Each clam cohort was estimated using the modal progression of the Fish Stock Assessment Tool II. FiSAT is the official program used by the United Nations' Fisheries and

Figure 3. Sampling Station #1 along an unnamed tributary to Porter Lake in Springfield, Massachusetts. The white spots instream are empty *C. fluminea* shells (photo by WH Wong).

Figure 4. Live clams (Left) and dead empty shells (Right) collected from the sediment (the two photos are not in the same scale) (Photographs by WH Wong).

Table 1. Density of live Asian clams and dry weight of dead/broken shells in an unnamed tributary to Porter Lake in Springfield, Massachusetts.

Station	Station 1	Station 2	Station 3	Station 4
Density (Individuals/m^2)	7,104	6,932	6,416	4,047
Dry Dead Shell Weight (g/m^2)	512.3	159.3	51.7	4.3

Aquaculture Department to estimate population dynamics of finfish and shellfish. FiSAT II applies the maximum likelihood concept to separate the normally distributed components of size-frequency samples, allowing accurate demarcation of the component cohorts from the composite polymodal population size of finfish or shellfish (Mouthon 2001; Gayanilo et al. 2005). The dead shells (complete or broken) from the sediment of each site were also picked and the total weight of all dry shells was measured. All of the statistics were performed using SAS (Version 9.2, SAS Institute Inc. Cary, NC).

Results

The first documented sighting of Asian clams in Massachusetts was in a section of the Charles River in Watertown, Massachusetts in 2001 (Foster et al. 2016). Since then, Asian clams have been found in 23 other water bodies, including both rivers and lakes Figure 1 and Supplementary material Table S1). Asian clams were found in both brackish (Sampling #16) and freshwater sections (Sampling #17) of the Taunton River. Figure 1 shows the distribution of Asian clams throughout the state in rivers and ponds.

Table 2. The size of Asian clams at different stations in an unnamed tributary to Porter Lake in Springfield, Massachusetts.

Station		Station 1	Station 2	Station 3	Station 4
Shell length (mm)	Mean	6.92	6.88	6.44	6.11
	Standard deviation	2.82	2.72	2.11	1.40
	Maximum	22.64	18.72	15.46	12.69
	Minimum	2.56	3.43	2.49	3.04
Shell height (mm)	Mean	5.83	5.82	5.46	5.16
	Standard deviation	2.41	2.39	1.80	1.20
	Maximum	19.05	15.88	13.64	11.06
	Minimum	2.13	2.89	2.10	2.56

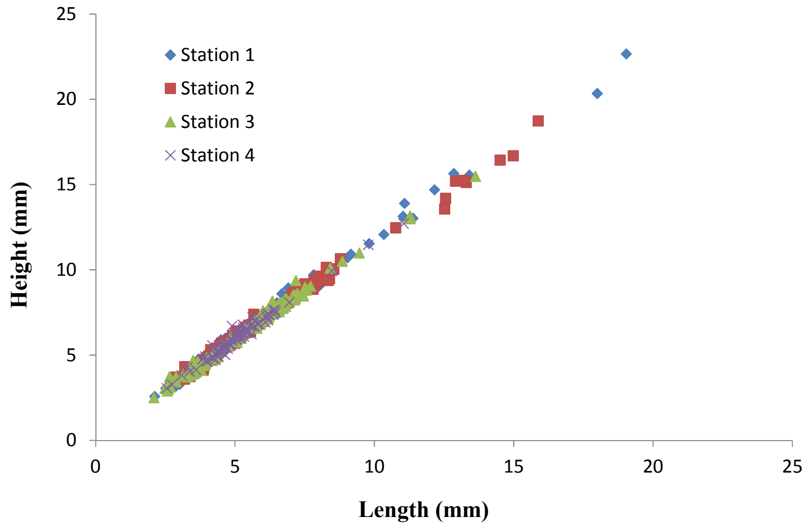

Figure 5. Shell length and height of *Corbicula fluminea* in Forest Park, Springfield, Massachusetts.

Supplementary material Table S1 provides the name of the water bodies, as well as the latitude and longitude of a sampling site, the agency(s) that reported the sighting, and the more specific report source(s). Based on MassDEP's own records, Asian clams were only detected from two out of the 410 water bodies statewide (Table S1). This ratio (2/410) is low because not every water body in the state is part of the benthic biomonitoring program.

In the unnamed tributary to Porter Lake in Forest Park, Springfield, Massachusetts in August of 2016, all four sites showed an extensive presence of Asian clams (Table 1). Many empty shells were observed, especially at Stations 1 and 2. The mean density of Asian clams was 6,124 individuals/m^2. The mean dry weight of dead shells including complete or broken shells was 181.9 g/m^2. The average shell length of clams from Sites 1 to 4 was 6.92, 6.88, 6.44, and 6.11 mm, respectively, and the corresponding height was 5.83, 5.82, 5.46 and 5.16 mm, respectively (Table 2). The shell length or height of clams from Station 4 was significantly less than that of clams from Stations 1 or 2 (Analysis of Variance, $P < 0.05$) but there was no significant difference between Station 3 and other sites (Analysis of Variance, $P > 0.05$). Analysis of Covariance shows that the significant difference of relationship between shell height and length ($F = 17946.6$, $P < 0.001$) was mainly contributed from the shell length ($P < 0.001$) but not from the stations ($P = 0.146$) (Figure 5). The maximum shell lengths from Stations 1 to 4 were 22.64, 18.72, 15.46, and 12.69 mm, respectively, while the corresponding dead shell lengths were 21.53, 20.28, 15.21, and 9.31 mm, respectively.

Since there was no significant difference in the size of clams among the three upstream sites, all individuals from Stations 1, 2, and 3 were pooled together to identify possible cohorts while clams from Station 4 were assessed separately. Two cohorts that were identified with clams from the three upstream stations with computed mean shell length of 6.98 mm and 17.13 mm, respectively (Figure 6).

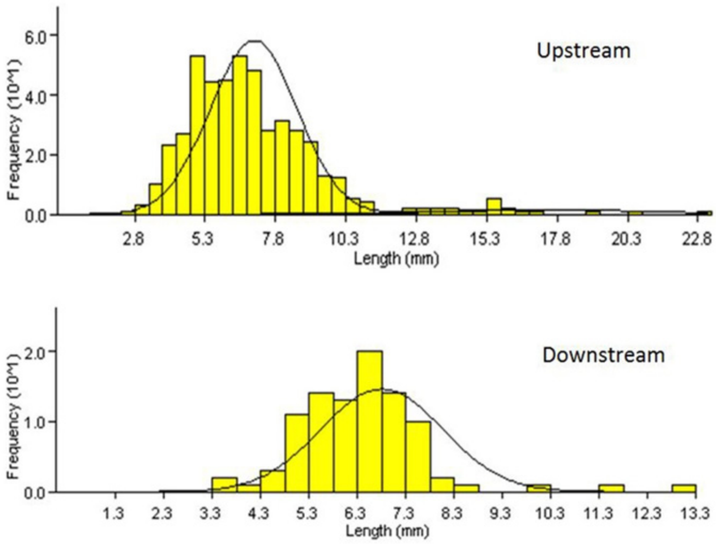

Figure 6. Frequency of *Corbicula fluminea* in upstream and downstream stations of an unnamed tributary inside of Forest Park, Springfield, Massachusetts (Cohort curve presented by FiSAT, Gayanilo et al. 2005). Note: the scales of X and Y axes between upstream and downstream are different.

The corresponding standard deviations for the small and large upstream cohorts were 1.55 mm and 3.83 mm, respectively. For the downstream station, only one cohort was identified with a computed mean shell length of 6.75 mm with a standard deviation as 1.26 mm (Figure 6).

Discussion

Asian clam infestation is an emerging issue for the Northeast states (Lake Champlain Basin Program 2016), even though it is the most widely distributed aquatic invader in the contiguous United States (McMahon and Bogan 2001). The first infestation of Asian clam in the State of Vermont was in the south-western part of Lake Bomoseen in the summer of 2016 (Ann Bove, personal communication). In the State of New Hampshire, Asian clams are already present in the lower Merrimack River and in several ponds (New Hampshire Department of Environmental Service 2016). In Massachusetts, there are a total of 29 sampling sites from 28 water bodies with Asian clams. Most of these water bodies are in the southern and eastern parts of the state (Figure 1). The rapidity with which Asian clams are expanding their range shows their success as an invasive species all over the state of Massachusetts. It is not surprising that the first Asian clam sighting in Massachusetts was in the Charles River. The Charles River is a recreational area frequently used by boaters, swimmers, and anglers. It is about 129 km starting from the outlet of Echo Lake, Hopkinton and ends in the City of Boston where it enters the Atlantic Ocean. The first Asian clam sighting was in the segment from Watertown Dam to the Boston University Bridge where boaters and canoers recreate year-round (Table S1). Infestations of non-native aquatic species often occur in recreational water bodies. For example, the first invasion of quagga mussels (*Dreissena rostriformis bugensis*) in the western United States was in the Las Vegas Boat Harbor Marina of Lake Mead (Moore et al. 2015). Lake Mead is ranked as one of the most visited national parks in the United States. The invasive quagga mussel was introduced into Lake Mead and rapidly spread to other areas of the western United States (McMahon 2011; Wong and Gerstenberger 2011). Likewise, the Asian clam is capable of spreading to other areas in Massachusetts via boaters, swimmers and anglers.

The present study demonstrates that the infestation of Asian clams in Massachusetts is not as severe as infestations in the southeast states (Foster et al. 2016). However, the density from the unnamed tributary to Porter Lake in Springfield, MA is moderate compared with others reported in the United States, such as 55 individuals/m^2 in Lake Seminole, GA (Patrick et al. 2017) and more than 10,000 clams/m^2 in New River, VA (Graney et al. 1980). Asian clams that were found upstream (Stations 1 and 2) were larger and more abundant than those found downstream

(Station 4). Based on the size structure, it is estimated that most Asian clams in upstream stations are up to two years old, while the age of most individuals from the downstream station is about one year (Mouthon 2001). The mass and maximum size of dead clam shells from upstream stations was greater than that from downstream stations. It appears that a few clams survive into a second year of life in the upstream stations and few if any appear to survive beyond the first year of life in the downstream station. This is possibly associated with different habitats along this tributary. Asian clams may prefer upstream stations because they are composed of coarse sands and soft mud, unlike downstream sites where the sediments are composed of coarse sands and hard clays. It also may be that larger individuals are more likely to be displaced downstream during flood events. This may explain the loss of the two-year old cohort in the downstream station where the hard clay, course sand substrate suggests higher flow rates that could have exposed larger-older clams to being hydrologically transported downstream during flood events. By contrast, the deeper course sand, soft mud substrata of the upstream sites may be indicative of a lower flow regime suggesting that the clams there are less hydrologically disturbed during flood events than the downstream station. To understand the density and size frequency of Asian clams in other infested waterbodies, and better determine their population dynamics in the Commonwealth of Massachusetts, successive monthly samples from multiple locations should be taken over a period of at least one year.

While the distribution of Asian clams is controlled both by habitat variables (e.g., substrate and pH) and climate variables (e.g., minimum temperature ≤ 2.0 °C in the coldest month (Mattice and Dye 1976)), climate variables are likely more important than the habitat variables (McDowell et al. 2014). Asian clam sightings in the southern and eastern parts of Massachusetts from 2001 to 2016, as well as recent discoveries of Asian clams in Vermont and New Hampshire, may be an indication of significant expansion in its range throughout the northeastern United States. In this region, warming temperatures have been recorded. They have been indicated by later freezing ice cover in the winter and earlier ice breakup in the spring in northeastern lakes (USEPA 2012). Based on the record of the Blue Hill Observatory (Iacono M, unpublished data), the winter (December, January and February) minimum daily temperature from 2001 to 2016 was significantly higher than the previous 16 years (1985 to 2000) (Wilcoxon two sample test, $N = 2888$, $P = 0.01$). This is probably the key reason Asian clams can establish themselves now in the United States above the 40° latitude line because waters remain above the clams' long-term incipient lower thermal limit (Mattice and Dye 1976). MassDEP has monitored water temperature in five rivers since 2012 where continuous water temperature data were collected every 30 min for each of the five monitoring stations (i.e., T1 to T5) (Figure 1). Based on data collected from November 1, 2013 to April 24, 2014, Stations T1 had significantly lower temperature than Stations T2 and T4; while the temperature of the late two stations were significantly lower than that in Stations T3 and T5 ($F_{4,\ 41880} = 407.25$, $P < 0.0001$) (Nuzzo R., unpublished data). Stations in the northern or western parts of the state have lower temperature due to their higher latitude and/or altitude. This pattern matches the distribution of invasive clams well. Almost all Asian clam sightings are in the southern or eastern parts of the state: the warmer the water, the more likely Asian calms can be found. Indeed, it is found that 17.9%, 25.0%, 25.2%, 31.0%, and 39.2% of the time between November 1, 2013 and April 24, 2014 in Stations T1, T2, T4, T5, and T3, respectively are above 2 °C (Nuzzo R, unpublished data). Therefore, the impact of climate change on the distribution of this species in Massachusetts and the northeast region should also be monitored because Asian clams are likely to expand well beyond their present distribution in the United States (McDowell et al. 2014).

Managing actions

The best approach to preventing the spread of aquatic invasive species is to use an integrated management strategy (Wong and Gerstenberger 2015). An urgent requirement for biosecurity to stop or significantly limit the spread of this invasive species is needed. For example, appropriate sign plates and decontamination equipment should be provided at infested water bodies for users to be aware of the infestation and the need to clean their boats before leaving the water body. Mapping infested water bodies in Massachusetts, such as the one (Figure 1) created in the present study, is helpful in keeping local residents and out-of-state travelers aware of the infestations before and after visiting their targeted lakes and rivers, as well as helping resource managers track the expansion or contraction of the infestation. There should be at least four parts to this plan: Firstly, the main means by which the species is being spread, whether it is human or natural causes, needs to be identified. Additionally, a means to slow or stop the spread needs to be created. This would include educational programs to raise public awareness, stricter boating codes, and new legislation

(Sousa et al. 2013). Secondly, the most vulnerable water bodies need to be identified in order for resources to be allocated in the most cost-effective manner. Thirdly, analysis needs to be completed to determine the potential ecological and economic impacts of the infestation of the Asian clams into new water bodies. Lastly, a plan for emergency response to an invasion needs to be created (Sousa et al. 2013). This would proactively limit the invasive potential of the species. The manner of dealing with Asian clams can be both reactive and proactive. Reactive methods are used on adult Asian clams and are more costly, an example of this would be using benthic barrier to control their populations (Sousa et al. 2013). Proactive methods target Asian clams in the larval stage, such as chemical treatments. Proactive methods tend to be more effective and versatile (Sousa et al. 2013).

It is more difficult to stop the spread of Asian clams in open waters, where treatment methods are more likely to negatively impact non-target species. Potassium treatments at specific levels have the potential of leaving non-molluscan wildlife and human health unharmed (Sousa et al. 2013). This makes potassium treatments a more attractive option when the survival of non-target molluscans is essential. There have also been more innovative means of control, such as BioBullets® and Zequanox® that have been created as molluscicides (Aldridge et al. 2006; Rackl and Link 2015); but these chemicals need to be tested to find out an optimum dose for treating Asian clam infestations. Benthic barriers may also be recommended and implemented in containing the Asian clam populations, although eradication may not occur and it is relatively expensive (Wittmann et al. 2012; Lake Champlain Basin Program 2016). More natural control options include plant extracts that are already used for other forms of pest management. Research thus far shows that thyme, an essential oil, and extracts used for *Eichornia* spp. treatment may have a strong potential of controlling Asian clams. The depletion of dissolved oxygen levels is also a method that is sometimes employed, which has been effective on Asian clams in Lake Tahoe (CA-NV) and Lake George (NY) (Sousa et al. 2013). The main challenge faced with any of these methods is the negative impacts caused to non-target species. This is why innovations such as BioBullets® and Zequanox® that are more efficient at affecting target species are growing. Hand removal, while time consuming, may be the most effective means of removing the invasive species with limited damage to the rest of the ecosystem.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Geo-referenced records of *Corbicula fluminea* in Massachusetts.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2017/Supplements/MBI_2017_Colwell_etal_Table_S1.xls