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Research Article

North American range extension of the invasive Asian clam in a St. Lawrence River power station thermal plume

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Editor's note:
This special issue of *Aquatic Invasions* includes papers from the 17th International Conference on Aquatic Invasive Species held in San Diego, California, USA, on August 29 to September 2, 2010. This conference has provided a venue for the exchange of information on various aspects of aquatic invasive species since its inception in 1990. The conference continues to provide an opportunity for dialog between academia, industry and environmental regulators within North America and from abroad.

Abstract

Similar to the zebra mussel (*Dreissena polymorpha*) and the quagga mussel (*Dreissena bugensis*), the Asian clam (*Corbicula fluminea*) is an invasive bivalve that has colonized many waterbodies in the United States and Europe. So far, low water temperature and ice formation during winter appear to have limited its northern distribution, especially in Eastern North America. This paper documents the recent discovery of a *Corbicula fluminea* population in the St. Lawrence River, in the thermal plume produced by the Gentilly-2 nuclear power plant (Bécancour, Québec, Canada). Based on a benthic samples obtained during November 2009 from 21 sites, both upstream and downstream of the power plant outlet, average density (± standard error) of this non-indigenous species was 368 ± 176 living individuals/m². Additional samples collected in 2010 showed an increase in density to 3,380 ± 1,315 living individuals/m² downstream the power station, and established the range limit at 4 km downstream. The species was present only downstream of the power plant and its distribution appears to be associated with the warm water plume. The influence of the thermal plume at 4 km from the power station was however fairly limited. The size of individuals varied from < 1 mm to 24 mm in length. These results confirm the establishment of the species in the St. Lawrence River, thereby extending the northern boundary of its distribution in North America.

Key words: *Corbicula*, invasive species, bivalves, St. Lawrence River, power plant, warm water plume

Introduction

The introduction of non-native invasive species is the second-largest threat to the maintenance of biodiversity throughout the world (Convention on Biological Diversity 1992). Invasive species can also induce serious economic impacts, i.e., up to 5% of gross income worldwide (Pimentel et al. 2007). In recent years, following trade globalization and increases in the volume of international maritime traffic (Nentwig 2007), several invasive aquatic species have made their way into waterways of Canada and Québec, through the Great Lakes and St. Lawrence basin (Mills et al. 1993). In this basin, more than 87 species belonging to different taxonomic groups have been introduced, including the round goby (*Neogobius melanostomus* Pallas, 1811), the bloody red shrimp (*Hemimysis anomala* G.O. Sars, 1907), and the European tench (*Tinca tinca* L., 1758; DeLafontaine and Costan 2002). Presently, invasive aquatic species threaten more than half of the Canadian fish identified by the Committee on the Status of Endangered Wildlife in Canada (Dextrase and Mandrak 2006). Moreover, species of indigenous freshwater mussels have drastically declined in the last two decades following the arrival of the zebra mussel (*Dreissena polymorpha* Pallas, 1771) and the quagga mussel (*Dreissena bugensis* Andrusov, 1897; Ricciardi et al. 1998) in the late 1980s, both introduced via ballast water discharge (Hebert et al. 1989, May and Marsden 1992, Carlton 2008).

Some introduced species represent a greater risk of invasion than others (Williamson 1996). This includes species that have high reproductive and dispersion rates, those with high phenotypic plasticity that are tolerant to a wide range of environmental conditions, or "engineer" species that have the capacity to alter physical and chemical characteristics of ecosystems (Karatayev et al. 2009; Sakai et al. 2001). Because aquatic mollusks commonly possess several of the above characteristics, this group is recognized as being over-represented as invasive aquatic species (Karatayev et al. 2009; Sousa et al. 2009). The Asian clam, *Corbicula fluminea*, Müller 1774 (Order: Verenoida, Family: Corbiculidae), is a good example of an invasive mollusk: present in four continents, it is considered to be among the most invasive species in the world (McMahon 1983). Its success as an invader is due in part to its high level of energy efficiency, high growth rate, early maturity, high fecundity and dispersal potential (McMahon 1983). During the reproductive period, an adult of this self-fertilizing hermaphroditic bivalve can produce from 97 to 570 juveniles per day (MacMahon and Bogan 2001). These juveniles can be passively transported by water currents or attached to a dispersing agent, facilitating invasion downstream in a drainage basin or in remote areas (MacMahon and Bogan 2001). Although *C. fluminea* is sensitive to certain environmental stressors, such as low water temperatures or hypoxia, its high reproductive potential allows this bivalve to be extremely resilient, and its populations recover quickly from episodes of catastrophic mortality (MacMahon and Bogan 2001; Werner and Rothhaupt 2008; Vohmann et al. 2010). Invasive Asian clams can cause damage to ecosystems and modify invaded habitats to the point where indigenous species can no longer survive (Gonzalez et al. 2008; Sousa et al. 2009). Notably, in situation of high population density, filter feeding by this bivalve increases water clarity by removing large amounts of planktonic food, fostering the spread of macrophyte algae (Sousa et al. 2009).

During its invasion history, the range of the Asian clam has spread rapidly. The first living population in North America was discovered in 1938 in the Columbia River basin, Washington, U.S., but empty shells were reported on Vancouver Island back to 1924 (Counts 1981; McMahon 1983). By 1953, the species was regarded as a nuisance in North America, and by 1970 it had colonized nearly 2,000 linear km of watercourses in the United States (Sinclair and Isom, 1961; McMahon 1983). On a worldwide scale, *C. fluminea* spread to Western Europe (Portugal, France and Germany in early 1980, England in 1998; Mouthon 1981; Aldridge and Müller 2001), South America (Darrigran 2004), and more recently in Eastern European countries (Beran 2006; Bodis 2007). Because of limited survival of Asian clam exposed at water temperature below 2°C for extend period of time (Mattice and Dye 1976), low water temperatures and winter ice formation have historically limited the distribution and impacts of *C. fluminea* in northern latitudes. Nevertheless, recent reports have extended the distribution range of the species further north, namely Vancouver Island, Canada, in 2008 (Kirkendale and Clare 2008), New York State in 2008 (Marsden and Hauser 2009), and Ireland in 2010 (Caffrey et al. 2011).

Our interest in the Asian clam, and more specifically its capacity to invade northern temperate regions, originates from the recent discovery of the species in the freshwater portion of the St. Lawrence River, in the thermal plume of a power-generating station near Bécancour, Québec, Canada. Earlier reports on the species in the Great Lakes basin suggested that Asian clam populations at the limit of their northern range were either associated with warm water outflows from thermal/nuclear power station or simple temporary summer populations unable to survive through winters (Clarke 1981; French and Schloesser 1991). This paper documents the first population of *C. fluminea* in the St. Lawrence River, near the Gentilly-2 power plant of Hydro-Québec, and aims at further understanding the biological and ecological significance of this new discovery in Eastern Canada, in the light of its northern location and climate. Aquatic invasions are an important environmental risk that must be seriously considered, given the very high rate of native species extinction in freshwater ecosystems (Ricciardi and Rasmussen 1999).

Methods

The Gentilly-2 nuclear generating station (46°39'56"N, 72°35'64"W) is located on the south shore of the St. Lawrence River, downstream of the port of Bécancour and Trois-Rivières city, Québec, Canada (Figure 1). Normal water temperatures at this location are approximately 22.5°C in July, 2.5°C in November and 3.5°C in April (Hydro-Québec 2006). However, water temperatures drop below 1°C during the winter months (St. Lawrence Observatory, 2010). The plume of discharged water from the power plant creates a microclimate that modifies physical characteristics of the fluvial ecosystem downstream of the station. Gentilly-2 discharges approximately 25 m^3/sec of warm water into the river, and the thermal plume is detected up to 5.6 km downstream of the discharge channel when the reactor is operating at full power. The average deviation in temperature between the generating station headrace and discharge channel is 11.1°C (Hydro-Québec 2006). Downstream of the discharge channel, the thermal influence declines from 8°C to 1°C as the distance from the generating station increases to 3 to 4 km (Figure 1; Hydro-Québec 2006). The extent of the zone of thermal influence varies according to the tide and the month of year, being larger at high tide than low tide, and larger in July than in November or April (Hydro-Québec 2006). At the municipality of Bécancour, the average and spring tidal ranges are 0.6 m and 0.8 m, respectively. Maximum current speed at Bécancour is 7.4 km/h (Fisheries and Oceans Canada 2010).

The first evidence of a *C. fluminea* population in the Bécancour region was provided by the discovery of two empty shells (including one complete specimen, 16 mm in length), found on 20 July 2009, near the Gentilly-2 warm water discharge channel (Figure 2a, b). On 12 and 13 November 2009, benthos was sampled at 21 different sites (Figure 1) using a Petersen-type grab sample (305 × 305 mm) at a depth of roughly 2.4 ± 0.2 m (standard error). The sampled sites were scattered upstream and downstream of the generating station to see whether living specimens were present on either side of the discharge channel. All the sample sites downstream of the generating station (sites 1 to 10) were located in or near the Gentilly-2 thermal influence zone (Figure 1). Temperatures were measured at 20–25 cm below the surface at all the sites. Sediment samples were sorted in the laboratory using a 0.053 mm sieve. The samples were preserved in ethanol, and were then sorted using a stereomicroscope in the laboratory, to identify visible living and dead specimens.

Sampling was also conducted during August 2010; although these samples have not all been sorted and analyzed, preliminary information for a second year of sampling is available. In 2010, we sampled 56 sites along the thermal plume and further downstream, i.e., up to 15 km downstream the power station. We used a 0.5 mm sieve in the thermal plume (16 sites) and a 1mm sieve further down in the thermal plume (40 sites). Finally, in late October 2010, 16 thermographs were dropped at the bottom of the riverbed at different locations in and outside the thermal plume of the power station. Six thermographs were retrieved in summer 2011, thus permitting to report the water temperature at exact locations where *C. fluminea* was present.

Results

Substratum composition at the sampled sites was mostly a mixture of silt, clay, sand, gravel and organic matter. In November 2009, the average water temperature during sampling ranged from 6.3°C to 6.9°C outside the thermal plume from the power station. The temperature at the discharge canal outlet at site 1 was 18.3°C, but gradually decreased further down in the thermal plume (e.g. site 5 = 15.5°C, site 6 = 13°C and site 8 = 10°C, 1.5 km downstream), and was still at 8°C in sites 9 and 10 (about 2 km downstream, Table 1). No living *C. fluminea* specimens were found in the samples collected from sites 11 to 21, upstream from the power station outlet, although one empty shell was found at site 20. On the other hand, a living population of *C. fluminea* was found downstream of the power station (Table 1). For sites located downstream of the discharge channel (sites 1 to 10), an average of 34 ± 16 (standard error) live individuals were harvested in each grab, for an estimated density of 368 ± 176 individuals/m^2 in 2009. More specimens were found at the discharge channel outlet (sites 1, 4 and 5) at an average density of 1058 ± 466 individuals/m^2. In other sites, the average density was 72 ± 12 individuals/m^2. Live specimens were observed at the furthest site, 2.25 km downstream the power station (site 10).

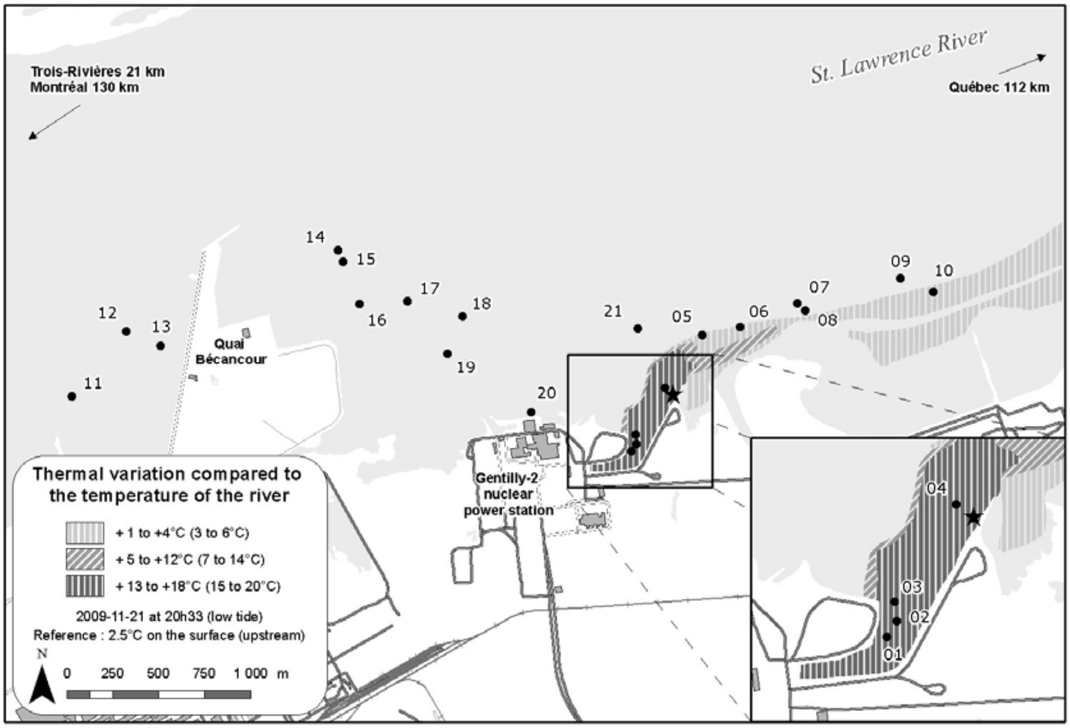

Figure 1. Location of sampling sites in the vicinity of the warm water plume from the Gentilly-2 nuclear power station (see enlargement) and in the St. Lawrence River, near Bécancour, Québec, Canada. The star identifies the site where *C. fluminea* was first observed in July 2009 (see specimen, Figure 2). The different thermal zones created by hot water discharged by the power station are hatched in grey, and are based on data obtained from Hydro-Québec (2006). The boundaries of the hot water plume vary with tidal conditions and month; this figure shows the period where the plume appears to be at its narrowest (Hydro-Québec 2006).

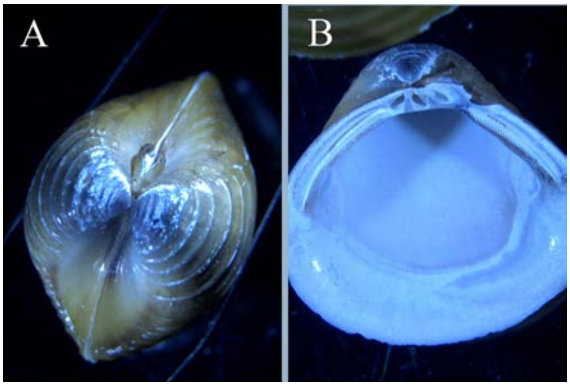

Figure 2. First specimen of the Asian clam, *Corbicula fluminea*, harvested from the discharge channel of the Gentilly-2 power station located on the south shore of the St. Lawrence River in Bécancour (Québec, Canada; July 2009). The specimen measures 16 mm in length. **A** - Dorsal view of the shell; **B** - Lateral view. Photograph by André Martel.

Figure 3. Some *Corbicula fluminea* specimens harvested from a sampling station near the Gentilly-2 power station located on the south shore of the St. Lawrence River (Bécancour, Québec, Canada; November 2009). Photograph by Annie Paquet.

Table 1. *Corbicula fluminea* densities at each of the 21 stations sampled in the vicinity of the warm water plume from the Gentilly-2 nuclear power station in the St. Lawrence River, near Bécancour, Québec, Canada (Figure 1). Sites 1 to 10 are in the thermal plume downstream the nuclear power station and sites 11 to 21 are upstream. Latitude and longitude of each station is provided (North American Datum 1983). N - number of live individuals per m^2.

Station ID	Latitude, N	Longitude, W	N
1	46.3953	-72.34978	1593
2	46.39568	-72.34946	108
3	46.39613	-72.34957	54
4	46.39848	-72.34767	398
5	46.40117	-72.34525	1184
6	46.40165	-72.34258	54
7	46.40297	-72.33861	54
8	46.40262	-72.33804	108
9	46.40446	-72.33146	32
10	46.40387	-72.32908	97
11	46.39648	-72.38953	0
12	46.39983	-72.38594	0
13	46.39922	-72.38346	0
14	46.40377	-72.37088	0
15	46.40432	-72.37131	0
16	46.40175	-72.36958	0
17	46.40204	-72.36619	0
18	46.40145	-72.36223	0
19	46.39958	-72.36314	0
20	46.39693	-72.35704	0
21	46.40132	-72.34981	0

The results obtained from the samples taken in August 2010, although preliminary, revealed that density increased from 2009 to 2010. The average density in 2010 was 3380 ± 1315, with samples originating from about the same area sampled in 2009, although extending further downstream and using a 0.5 mm sieve. The average density for 8 stations situated within 0.5 km of the power station was 5,339 ± 2,500, while that of sites located from 0.5 to 3 km in the thermal plume was 1421 ± 273 (0.5 mm sieve). The range limit of the population in 2010 was about 4 km downstream the central, and density in this area was 78 ± 43 (1 mm sieve). Five thermographs placed at 1.7, 2.4, 3.0, 3.5 and 4.0 km downstream the power station registered daily average temperatures that were bellow 2°C during respectively 40 %, 28 %, 91 %, 60 % and 90 % of recording winter days (December 15 to March 31). One thermograph outside the thermal plume temperature was bellow 2°C for 95 % of winter days.

Discussion

The population of Asian clams observed in the freshwater tidal portion of the St. Lawrence River is the northernmost documented occurrence of the species in Eastern North America. This population benefits from thermal influence of the nuclear power station. Nevertheless, the species was still present at 4 km downstream the power station in 2010, where the influence of the thermal plume was found to be relatively limited in winter. Results from thermographs deposited in the bottom of the St. Lawrence during winter 2010, suggest that water temperature dropped bellow 2°C for 40 % of winter days at 1.5 km from the power station and for 90 % of winter days at 4 km from the power station. Results from 2011 should allow us to determine whether or not the population remains restricted to warmer area of the St. Lawrence, in the immediate vicinity of Gentilly, or, by contrast, is expanding significantly further downstream, outside the warm water plume.

Others populations of *Corbicula fluminea* have been discovered at higher latitudes, but in regions where climate is milder, such as in England in 1998 (Norfolk; Aldridge and Müller 2001), in Ireland in 2010 (River Barrow, St. Mullin; Caffrey et al. 2011), and in western Canada in British Columbia in 2008 (lacustrian system near Victoria, Vancouver Island; Kirkendale and Clare 2008). In colder regions of northern Europe and North America, where water temperatures drop below 2°C in winter for extended period of time, experimental work of Mattice and Dye (1976) predicted a limited invasion of Asian Clam or a confinement to sites under thermal influence of power stations (Schöll 2000). Accordingly, in North Eastern North America, the Asian clam had most commonly been found either in warmer areas or areas influenced by thermal pollution in Lake Erie (Clarke 1981), Lake Sainte-Claire (French and Schloesser 1991), Connecticut River (Morgan et al. 2003) and, more recently, in the Champlain Canal of Lake Champlain in 2008 (Marsden and Hauser 2009). Nevertheless, populations of *C. fluminea* have now also been discovered in cooler regions, away from power stations, e.g., in northwestern Poland, in the Czech Republic and in Germany (Domagała et al. 2004; Schmildlin and Baur 2007; Stańczykowska and Kołodziejczyk 2009). Moreover, a recent occurrence of an Asian clam population was also found in Lake George (New

York), where temperature drops below 2°C during several weeks and which is located at higher latitude than most documented population of *C. fluminea* in Eastern North America (M. Modley and Darrin Freshwater Institute, personal communication). This population has likely been established for at least three years (M. Modley and Darrin Freshwater Institute, personal communication). Müller and Baur (2011) and MacMahon and Bogan (2001) underlined that the latest northern discoveries and recent experiments on Asian clam populations raise questions about the ability of this species to tolerate colder conditions than initially established, or for longer period.

Previous researches suggested that although *C. fluminea* can live outside zones of thermal influence during summer and fall, most individuals die when water temperatures drop below 2°C for extended periods of time in northern regions (Graney et al. 1980; French and Schloesser 1991; Mattice and Dye 1976). In Lake Constance, in Germany, only 0.1 % of a *C. fluminea* population established in 2003 survived when the water temperature dropped below 2°C for a two-month period (Werner and Rothhaupt 2008). Similarly, in 2000, some specimens of *C. fluminea* were found in shallow water in the Sainte-Claire Lake delta in Ontario, but none survived into 2001 (Dave Zanatta, personal communication). Based on those results we should suspect *C. fluminea* population to remain only under the thermal influence of the power station and not to invade other areas of the St. Lawrence. Nevertheless, in the Clinton River in Michigan (Janech and Hunter 1995), in Lake George (M. Modley and Darrin Freshwater Institute, personal communication) and in the Czech Republic (Stańczykowska and Kołodziejczyk 2009) a significant proportion of *C. fluminea* individuals seemed to tolerate low winter water temperatures. Those studies suggested that even if Asian clam populations suffer extensive winter mortality, the small number of survivors could possibly produce offsping that would be better tolerant to rigorous climates (Janech and Hunter 1995; Stańczykowska and Kołodziejczyk 2009). Challenged by the northern distribution of *C. fluminea* in Europe, Müller and Baur (2011) experimentally tested the lower temperature tolerance of Asian clam by using specimens collected in March from a remnant of the Rhine River. After 9 weeks of exposure to temperature of 2°C and 0°C, survival rates of clam were respectively 47.5 % and 17.5 %, with larger size clams having a higher probability to survive. Müller and Baur (2011) suggested that *C. fluminea* is more tolerant to cold waters than previously assumed, but still suggested that exposition to water bellow 2°C for more than two months should lead to high level of mortality, as observed in Lake Constance (Werner and Rothhaupt 2008). Considering the low genetic diversity of *C. fluminea*, and low mutation rates, tolerance to cold water would likely results from high phenotypic plasticity of the species (McLeod 1986). Because water temperatures in the St. Lawrence River fall below 2°C in winter for several months, a further extension of Asian clam outside the Gentilly-2 thermal influence zone would bring more questions about the possible tolerance of this species to cold environment.

Although *C. fluminea* appears to be establishing itself in northern regions, episodes of high mortality caused by cold temperatures should nevertheless limit population densities, reducing their ecological impacts (Werner and Rothhaupt 2008). The average density recorded for the Gentilly-2 population in 2009 was fairly low (368 ± 176 individuals/m^2), but comparable to that recorded in the Czech Republic (100 individuals/m^2; Beran 2006). Results from 2010, however, with average density at 3,380 ± 1,315 individuals/m^2, suggest that population size could still increase and that 2009 was possibly an early stage of invasion. For comparison purposes, population density of *C. fluminea* population reached 2,500 individuals/m^2 in England, while the highest density recorded was 131,000 individuals/m^2 in California (Aldridge and Müller 2001; Beran 2006). In colder regions, significant variations in density have been observed according to months, years or sites of sampling, e.g. between 4 and 1,454 individuals/m^2 in Sainte-Claire Lake (French and Schloesser 1991), between 45 and 11,610 individuals/m^2 in the Connecticut River (Morgan et al. 2003, 2004) and between 32 and 21,496 individuals/m^2 in this study. In Lake George, despite water temperatures between -1°C and 2°C in winter, the preliminary data suggests an average density of 3,069 individuals/m^2 with a maximum of 6,359 individuals/m^2 (M. Modley and Darrin Freshwater Institute, personal communication). For a better understanding of the population dynamic of Asian Clam in the St.

Lawrence, as well as the density we should expect in this region on the long term, detailed data should be collected to estimate growth and reproduction. Although most specimens found measured less than 5 mm (Figure 3), the largest specimen in 2009 measured 24 mm, suggesting that the population has been established for approximately three years (see Sinclair and Isom 1961).

The discovery of the Asian clam in the St. Lawrence River raises many questions. First, what is the source population of the individuals that colonized that region? Several hypotheses exist. The species may have been introduced by ballast or waste water discharged by ships from the United States, South America, Europe or Asia (Sousa et al. 2008). It may have been imported for aquariums, as fishing bait, for consumption, or with other species intended for aquaculture (Elliott and zu Ermgassen 2008; Kirkendale and Clare 2008; Sousa et al. 2008). We also have to determine whether the Bécancour population of Asian clam is the only one currently living in the St. Lawrence River, or whether other populations are settled further upstream, responsible for releasing larvae that establish themselves in the power station. Other sites of the St. Lawrence River affected by industrial warm water were sampled in November 2010, but based on preliminary data, *C. fluminea* does not appear to be present (Simard et al. unpublished data). Assuming that the population of Asian clams in the Gentilly-2 thermal plume is the only one in the province, it is questionable whether its eradication should be considered, keeping in mind the extreme resilience of the species. The most realistic solution lies in the possible closure of the power plant, which will undergo repairs from 2012 onwards, limiting warm water into the discharge canal. Mats laid over the lake bottom have recently been used in Lake Tahoe and Lake George in an attempt to suffocate and eradicate the clam under a benthic barrier (Wittmann et al. 2008; M. Modley, personal communication), but given the size of the St. Lawrence River and considering water current, such a solution would be extremely complex logistically. *C. fluminea* appears very tolerant to chlorination and molluscicide agents, while these products would harm other species in the ecosystem (Bidwell et al. 1995).

Conclusion

The *Corbicula fluminea* population discovered in the St. Lawrence River needs to be studied in more detail in order to better understand its population dynamics and its impact on the aquatic ecosystems of the St. Lawrence River. Based on previous works of Mattice and Dye (1976), the species should not be able to survive Québec's cold winters outside the hot water discharges from the nuclear power plant or other factories. A recent publication nevertheless suggested that a certain percentage of individuals would be tolerant to water temperature of 0°C, and therefore a population could eventually establish in this cold region (Müller and Baur 2011). Climate change is likely to favor the success of the Asian clam in northern regions. In the eventuality that the Asian clam population becomes established outside the thermal plume of the Gentilly-2 power station, potential risks are that *C. fluminea* threatens the heat exchange, drainage and channel systems of riverside industries or could compete with vulnerable indigenous mollusk populations. Monitoring of this highly invasive mollusk in Québec’s waterways is important.

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