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Research Article

Predictions for the spread, population density, and impacts of *Corbicula fluminea* in Ireland

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Abstract

In 2010, the Asian clam, *Corbicula fluminea*, was found for the first time in Ireland. The species is considered to be one of the most aggressive freshwater invaders causing strong economic and ecological impacts. This paper provides predictions for the spread, population density, and impacts of *Corbicula fluminea* in Ireland. Water chemistry datasets from the Republic of Ireland and from Northern Ireland were analysed to determine suitable waters for colonisation. Only 3 rivers and 6 lakes have pH levels considered too low (<5.6) for invasion of this species. *Corbicula fluminea* densities within a waterbody will depend on suitable substrate and food availability, with greater populations in canals, rivers and lakes with a higher trophic level. Boating and angling are likely to be the highest vectors of spread. Redevelopment of any canal sections will require risk assessment, to minimise spread. *Corbicula* is likely to cause negative economic effects by creating blockages in drinking and industrial water abstraction systems. The ecological impacts of *C. fluminea* are associated with their role as biofilters, and are therefore determined by their filtration rate and the overall population density in a given waterbody.

Key words: *Corbicula fluminea;* spread; Ireland; vectors; impacts

Introduction

The Asian clam (*Corbicula fluminea* Muller, 1774) (Figure 1) native to southern and eastern Asia, Australia, and Africa became highly invasive in the 20th century (reviewed in McMahon 1999; Karatayev et al. 2007). In 1938 *C. fluminea* was found for the first time in the Columbia River, Washington (USA) and it subsequently spread throughout 38 continental states, Hawaii, and northern and central Mexico (reviewed in McMahon 1999; Foster et al. 2011). North American records include, the Great Lakes (http://USGS.gov), Lake Owasco, New York State (Karatayev et al. 2012), the St. Lawrence River (Simard et al. 2012), and in Vancouver island, Canada (Kirkendale and Clare 2008). In the 1970s *C. fluminea* was introduced to Europe and South America where it was reported from Argentina (Ituarte 1981), Brazil (Veitenheimer-Mendes 1981), and Uruguay and is very likely to be present in Peru and Bolivia as well (Darrigran 2002). In Europe *C. fluminea* has already colonized France (Marescaux et al. 2010), Portugal, Germany, Belgium, the Netherlands (reviewed in McMahon 1999), Spain (Lois 2010), Hungary (Csanyi 1998–1999), Moldova (Munjiu and Shubernetski 2010), Serbia (Paunović et al. 2007), Britain (Howlett and Baker 1999), and in 2010 Asian clam was found for the first time in Ireland (Sweeney 2009). Currently *C. fluminea* is known to occur in the rivers Barrow, Nore (Caffrey et al. 2011) and Shannon (pers. obs.), all in the Republic of Ireland (http://www.fisheriesireland.ie).

Different vectors spread *Corbicula fluminea* at different spatial and temporal scales (Karatayev et al. 2007). It was suggested that *C. fluminea* was brought to North America in the 1930s by Asian immigrants as a food source (reviewed in Britton and Morton 1979), however the more recent introduction of this species into South

Figure 1. *Corbicula fluminea* from the River Barrow (Photograph by Frances Lucy).

America and Europe was via ballast water, due to increased international trade (reviewed in Karatayev et al. 2007). Once introduced into a new continent, secondary spread of *C. fluminea* is limited by environmental parameters but facilitated by transport for food and aquaculture, domestic shipping, transport of commercial fishing gear, fish stocking, sport fishing, and deliberate introduction (reviewed in McMahon 1982, 1999; Karatayev et al. 2007). In addition, *C. fluminea* can spread naturally downstream with the water currents and also upstream, although much more slowly (McMahon 1982, 1983, 1999; Prezant and Chalermwat 1984). The fast spread of *C. fluminea* to new waterbodies is also facilitated by its high reproduction potential (68,678 pediveligers adult-1 year-1) and self-fertilization, as a single individual can found a new population (McMahon 1999; McMahon and Bogan 2001).

Corbicula is known to be one of the most aggressive freshwater invaders having strong economic and ecological impacts (McMahon 1982, 1999; Phelps 1994; Karatayev et al. 2005a, 2007; Mackie and Claudi 2010). In the United States it has impacted municipal, agricultural, and industrial raw water systems (McMahon 1983, 1999). The most important economic impacts of *C. fluminea* include macrofouling of raw water systems (particularly those of fossil-fueled or nuclear power stations), and enhancement of sedimentation rates in canals (reviewed in McMahon 1999). The total damage caused by *C. fluminea* for US industries in 1986 alone, over two decades ago, was estimated at $1 billion (Isom 1986). The ecological impacts of *C. fluminea* are associated with its filtering activity. Asian clams occur in high densities over large areas, they can filter large volumes of water in short periods of time, subsequently depositing vast quantities of organic matter on the bottom, increasing benthic pelagic coupling, improving water clarity and competing with zooplankton for food. As an ecosystem engineer, *C. fluminea* imposes various impacts on habitat structure, biomineralization, oxygenation, and benthic and planktonic community structure (Karatayev et al. 2005a, 2007). Both the economic and ecological impacts of *C. fluminea* will depend on their population density in a given waterbody, which in turn depends on the prevalent substrate type, food availability, oxygen concentration, temperature regime and the waterbody morphometry (reviewed in Karatayev et al. 2005a).

The goals of this study are to predict the spread of *C. fluminea* across the island of Ireland (Republic of Ireland (ROI) and Northern Ireland (NI)), their potential population densities and economic and ecological impacts.

Methods

Study area

About 2% of Irish land surface (145,000 km^2) is comprised of inland surface waters. There are about 4,000 lakes with surface area greater than 0.05km^2 (Reynolds 1998). These are mostly natural with a small number of reservoirs created in the 19th and 20th centuries and serving urban areas. Thirteen lake types have been categorised for the EU water frame work directive (CEC 2000) with alkalinity, mean depth and size selected as main factors. In terms of productivity Irish lakes fit into two main types, soft-water oligotrophic and more productive limestone lakes (Reynolds 1998). Limestone lakes are mesotrophic or eutrophic with relatively high pH (7.5–8.5) and calcium content (90–260 mg/L) (EPA 2000). There are also a small number of hypertrophic lakes (EPA 2011). Stable stratification is unusual (Reynolds 1998); some of the larger Irish lakes (5 > 100km^2) are monomictic, while smaller lakes may partially stratify or remain mixed throughout the year. While small isolated mountain lakes are a common landscape feature, in general Irish lakes are an integral part of defined river basins.

There are about 14,000 km^2 of rivers and streams in Ireland, with a similar amount of smaller tributaries. Approximately 250 Irish catchments are >10 km^2, fewer than 100 are >100 km^2 (Reynolds 1998). The central plain of Ireland is dominated by carboniferous limestone with the thickest developments occurring in the axial regions of the Shannon basin (Hepworth Holland 2001). Rocks of carboniferous age occur at the surface or beneath quartenary deposits over nearly half the land area of Ireland (Hepworth Holland 2001), therefore influencing the pH and calcium levels in many river basins. The Shannon is Ireland's largest river basin, with several interconnected lakes, the largest being Lough Derg (117 km^2), Lough Ree (105 km^2) and Lough Allen (35 km^2). It is connected to the River Erne, providing a navigable waterway (The Shannon-Erne waterway) with a total length of 495 km. The largest lake on the island, Lough Neagh (385 km^2) occurs in Northern Ireland. Discrete isolated river systems occur in mountainous regions close to the western seaboard. There are also navigable canal systems (The Royal and Grand Canals and the Barrow Line) extending from Dublin westwards to the Shannon and the Barrow systems. Several disused canals exist in Northern Ireland with plans to potentially redevelop and open sections of these, e.g. the Ulster canal, in the future.

Abiotic limits for C. fluminea

To predict the spread of *C. fluminea* among waterbodies in Ireland we collected published data on abiotic parameters that are known to be limiting factors for the spread of this clam elsewhere (McMahon 1999; Karatayev et al. 2005a, 2007). *Corbicula fluminea* can colonize fresh waters, as well as brackish estuaries with salinities up to 17 psu (Table 1). According to various authors, the lower temperature limit for *C. fluminea* is between 0 and 2°C, and the upper temperature limit is 37°C (Table 1). The presence of *C. fluminea* in several lakes, streams, and canals in New York State (USA) that freeze in winter suggests that *C. fluminea* could survive low winter temperatures of about 0°C. Therefore, low or high temperatures are unlikely to be limiting factors for *C. fluminea* spread in Ireland due to its temperate oceanic climate.

In Mosquito Creek, Florida (USA) a population of *C. fluminea* was reported in waters with pH 5.6. Although, shell dissolution was suggested there as a major source of *C. fluminea* mortality, clams up to 3 years old were found in this creek (Kat 1982). Later research indicated that pH 5.6 was the lower limit for this clam (reviewed in Karatayev et al 2007). *Corbicula fluminea* are intolerant of even moderate hypoxia, therefore, they are usually restricted to littoral zones and to well oxygenated profundal areas (Fast 1971; McMahon 1999).

To assess the potential spread of *C. fluminea* in Irish freshwaters, we used Republic of Ireland (ROI) data from Irish Environmental Protection Agency (EPA Report 2010) and data for Northern Ireland (NI) from the Northern Ireland Environment Agency (NIEA) to compare abiotic parameters for all-Ireland waterbodies using limits for *C. fluminea* distribution. The EPA database contained mean, minimal and maximal values for water pH and conductivity (at 20°C, in μScm^{-1}) measured in 2007–2009. The NI database contained all sampling data from 2008-2010 (NIEA dataset, obtained by request), from which mean, minimal and maximal values for water pH and conductivity (at 20°C, in μScm^{-1}) were calculated. In total 1030 rivers and streams were assessed with 663 in the Republic of Ireland and 367 in Northern Ireland. We used pH and conductivity of water measured in 222 ROI lakes from 2007-2009 (EPA) and 68 NI lakes from 2008-2010 (NIEA). The lakes and rivers were monitored throughout the island of Ireland (ROI and NI), in 32 counties and in all eight river basin districts. We re-calculated calcium content in the water using the relationship between water conductivity and calcium content ($Ca = 0.141 (Conductivity)^{1.175}$) (Claudi and Mackie 1994).

Results

Potential spread

In ROI, the average (for 2007–2009) pH values were found at < 5.6 in only 3 of total 663 Irish rivers and streams (the Bunadaowen, Annalecka and Ballylow rivers). In addition, a pH less than 5.6 was found at some sites on the Liffey and Mourne Beg river systems, however, maximal pH on the same sites, as well as average pH on

Table 1. Environmental limits for *Corbicula fluminea*.

Factors	Parameters	References
Upper salinity limit (psu)	14 – 17	Evans et al. 1979; McMahon 1999
Lower temperature limit (°C)	0 – 2	Mattice 1979; Rodgers et al. 1979; Janech and Hunter 1995
Minimal temperature for reproduction (°C)	15	McMahon 1999; Rajagopal et al. 2000
Upper temperature limit (°C)	36 – 37	Dreier and Tranquilli 1981; Britton and Morton 1982
Lower pH limit	5.6	Kat 1982
Lower calcium limit (mg l^{-1})	3	Reviewed in Karatayev et al. 2007
Lower oxygen limit at 25-30°C (mg l^{-1})	1 – 3	Belanger 1991

Table 2. Potential vectors, their relevance and importance in facilitating *Corbicula fluminea* spread in Ireland.

Vector	Reference	Relevance to Ireland
Human-mediated:		
Sport fishing (discarded fish bait; transport in bilge water; fishing gear)	Ingram 1959; Britton and Morton 1979	High
Fish stocking and aquaculture	Britton and Morton 1979	High
Leisure craft	McMahon 1999	High
Transport with sand and gravel	Britton and Morton 1979; Sinclair and Isom 1963	High
Commercial shipping	McMahon 1999	Not relevant
Aquarium trade (release of unwanted specimens by hobbyists)	Abbott 1975	High
Introduction as food item	Britton and Morton 1979	Low
Tourist curiosity	Britton and Morton 1979	High
Natural spread:		
Downstream transport of pediveligers suspended in the water	McMahon 1999	High
Downstream transport of juveniles attached to floating objects	Counts 1986	High
Downstream transport of adults attached to the mucus dragline	McMahon 1999	High

Table 3. Known densities of *Corbicula fluminea* in different types of waterbodies and on different substrates.

Habitat	Density (m^{-2})	References
Waterbody		
Lakes	39 – 1278	Beaver et al. 1991
Reservoirs	30 – 796	Abbott 1979; Dreier and Tranquilli 1981; Karatayev et al. 2003
Rivers	315 – 3206	Rodgers et al. 1979; Belanger et al. 1985; Boltovskoy et al. 1997
Streams	54 – 974	Leff et al. 1990; Arias 2004
Canals	2255 – 16688	Eng 1979; Marsh 1985
Sediment type		
Rocks	0 – 377	Abbott 1979; Leff et al. 1990
Sand, silty sand	54 – 1215	Abbott 1979; Belanger et al. 1985; Leff et al. 1990
Shells	43	Karatayev et al. 2003

other sites of the same waterbody were ≥ 6.0. In Northern Ireland, the average pH values (2008–2010) for each of the 367 river and stream sites were > 5.6. Only four of these rivers (Derg, Essan Burn, Ben Crom, and Croaghs Burn) had minimum pH values ≤ 5.6, but the mean pH in each case was above the lower limit for *C. fluminea*. Therefore, we predict that *C. fluminea* will be able to colonize even these rivers, but populations there may be low and highly variable among sites and between years. We found that none of the 1,030 monitored rivers in the Republic of Ireland and Northern Ireland have calcium concentration < 7 mg l^{-1}, and hence above the limiting value of 3 mg l^{-1}. Therefore we predict that calcium concentration will not limit *C. fluminea* distribution in the rivers of Ireland.

Of the 222 ROI Irish lakes we analyzed for pH values, only 2 lakes (Loughs Cam and Dan) had average pH values (mean for 2007–2009) that were <5.6 (4.94±0.50; 5.31±0.23, mean +STDS). In NI, 4 out of 68 lakes monitored had a mean pH <5.6: White Lough (4.7±0.21); Loughnatorpoge (5.2±0.07); Meenabrock Lough (5.4±0.28) and Slawn Lough (4.9±0.07). These lakes we consider as having low probability for *Corbicula* colonisation. A few more ROI lakes (Tay, Acorrymore, Lettercraffoe, Bray Lower, Keel, Upper Lake Glendalough, and Enask Lake) and NI lakes (Silent Valley Reservoir and Lough Carn) had pH < 5.6 on a number of sampling occasions, but they had average pH > 5.6 (5.69 – 6.7). All other lakes had average pH higher that the minimal for *C. fluminea* and thus may be suitable for colonisation. The lowest calcium concentration in the 290 monitored Irish lakes (ROI and NI) was 5.33 mg l^{-1}, which was higher than the respective limiting concentration for *C. fluminea* (Table 1). Therefore we predict that calcium concentration will not limit *C. fluminea* distribution in Irish lakes.

Vectors

We identified potential vectors, their relevance and importance in facilitating natural and human-mediated spread of *C. fluminea* in Ireland (Table 2). From all vectors known to introduce and unintentionally spread *C. fluminea* in North America, only inland commercial shipping is absent in Ireland; all other vectors have high or low probability to spread the mollusc within and among isolated river and lake systems.

Discussion

Potential spread

We found that only 0.9% of 1,030 Irish rivers and 2.1% of 290 lakes throughout the island have lower probability to be colonized by *C. fluminea* due to their low average pH level. There are no rivers or lakes in Ireland that have a calcium level that will prevent *C. fluminea* from establishing reproducing populations. The complexity of geological succession and the erosion and deposition of glacial drifts during the ice age, not only resulted in the formation of Irish rivers and lakes, but has resulted in some limestone influence in the majority of Irish catchments due to their connectivity via surface and groundwaters. This is exhibited by above neutral pH (in most cases) and by the presence of calcium (>5.33 mg l^{-1}) in Irish freshwater samples (EPA and NIE datasets). Similarly when soils have free carbonate, high content of weatherable silicates or high base saturation, they generally give rise to circum neutral drainage waters (Giller and Malmqvist 1998). In other words due to geology and soils, water chemistry in almost all Irish rivers, lakes and canals is buffered to some extent and is thereby suitable for the introduction and spread of *C. fluminea*. The few exceptions to this are the named headwater rivers and lakes situated in non- limestone areas, which are naturally acidic, poorly-buffered and oligotrophic (in the case of lakes).

Vectors

The rapid spread of *Corbicula fluminea* in North America mostly have been associated with human activities, including accidental introduction in pleasure boat bilges, in bait buckets, with aquacultural species, and by aquarium hobbyists (Abbott 1975; Britton and Morton 1979; McMahon 1983, 1999; Counts 1986, Table 2). In addition, *C. fluminea* could be transported in sand and gravel mined from river beds colonized with this clam (Sinclair and Isom 1963). Deliberate introduction may include relocation as a tourist curiosity (McMahon 1983) and for water purification purposes (Dinges 1976). Natural spread at large is associated with downstream passive dispersal with water current (Jekinson 1979; Isom 1986). The main dispersal stage is the pediveliger/small juvenile (<2mm) (McMahon 1999). Pediveligers remain suspended and can be transported long distances on water currents prior to settlement. They can also be transported by means of the single long juvenile byssal thread acting as drag line (McMahon 1999). It was shown that the spread of *C. fluminea* as juveniles in bird feather or attached to bird's legs or in fish and waterfowl guts is very unlikely (Thompson and Sparks 1977; Isom 1986) and should be discounted as a significant dispersal factor for this clam (Counts 1986).

The rate of *C. fluminea* spread could be substantially higher that the spread of *D. polymorpha*. Because of *C. fluminea* is a hermaphrodite with a high reproduction capacity

(>68,000 pediveligers adult^{-1} year^{-1}) the introduction of a single individual may be sufficient to start a new population (McMahon 1999; McMahon and Bogan 2001). In Texas *C. fluminea* since the initial discovery in 1958 have colonized 180 counties (from 257 counties total in Texas) in less than 50 year and by 2010 was predicted to spread into all counties with sufficient waterbodies (Karatayev et al. 2005b).

A study on the downstream transport of zebra mussel larvae in small, medium and large Irish river systems demonstrated long-distance spread only in the larger, slow-moving rivers indicating that recruitment is principally supplied from substantial lake reservoirs upstream (Lucy et al. 2008). One factor is that zebra mussels do not form substantial populations in small or medium Irish rivers (reviewed in Lucy et al. 2008). The experience with *Corbicula*, however may be very different, river densities may be high (as already noted on the River Barrow, with maximum density estimated at 9,636 m^2; Caffrey et al. 2011) in rivers of all sizes and downstream transport could be from both lotic and lentic (upstream lake) sources, depending on the river basin.

Considering the connectivity and proximity of Irish river basins, existing canals (Grand and Royal) and the fact that most of the lakes and rivers are suitable for colonisation, we predict that the spread of *C. fluminea* will be rapid throughout the island freshwaters, and that most of the spread will be associated with the human activity. In addition, dredging and canalization of navigable waterways optimize conditions for passive downstream dispersal (McMahon 1982). In Northern Ireland, there are plans to redevelop the old Ulster canal, connecting the Erne system to Lough Neagh. The risk assessment for the spread of *Corbicula* via this pathway should be assessed because Lough Neagh is the largest waterbody in Northern Ireland, supplying Belfast with its major drinking water source and it also has an important eel fishery (Wood 1998). *Corbicula* is present in the Upper Shannon (Carrick on Shannon), which connects to the Erne via the Shannon-Erne waterway. Developing the canal could provide a major artery of spread to Northern Ireland, particularly since *C. fluminea* is known to have especially high densities in canals (Britton and Morton 1982; McMahon 1983; Karatayev et al. 2005a).

Most of the human-mediated vectors that were successful in spreading *C. fluminea* in North America are represented in Ireland as well (Table 2). Inland recreational activities in Ireland are enjoyed by Irish residents and apart from swimming can be placed in two broad categories, boating and angling. Leisure craft are widely used on the main navigations, while smaller lake boats (< 20m), used for angling, are moved by car- trailers between lakes. There are few restrictions on boater movement, although it is requested that boats from zebra mussel infested waters are steam-cleaned prior to launching in other waterways (http://www.inlandfisheries.ie). The rapid spread of zebra mussels between lakes in Ireland and internationally, has been widely attributed to boater movement (Padilla et al. 1996; Minchin et al. 2002). Both boat and shore angling may easily increase the spread of *Corbicula*, mediated through wet keep nets, landing nets, stink bags and waders. This is despite the detailed preventative biosecurity advice given for cleaning boats, footwear and equipment (http://www.fisheriesireland.ie).

The aquarium trade is a growing industry in Ireland as elsewhere, and thus release of unwanted specimens by hobbyists may potentially be a vector of *C. fluminea* spread in new catchments. Likewise, public awareness should be raised to prevent introductions of the molluscs picked as a tourist curiosity. We cannot disregard the deliberate introduction of *Corbicula* to Ireland for the purpose of cultivation for the food trade; moreover increased consumer demand may also play a role in their secondary spread.

Potential population densities

The ecological impacts of *C. fluminea*, as for any other invasive species, depend directly on their overall population density in a given waterbody. Therefore prediction of potential densities is important for estimating the overall ecological impact.

Corbicula fluminea can be found in a wide range of types of waterbodies, including lakes, reservoirs, rivers, canals, and even small streams (reviewed in McMahon 1999; Karatayev et al. 2005a). Beaver et al. (1991) found that *C. fluminea* abundance in Florida lakes generally increased with trophic state. Clam densities were 39 ± 17 m^{-2} in oligotrophic lakes, 368 ± 328 m^{-2} in mesotrophic lakes, and 1278 ± 1047 m^{-2} in eutrophic lakes. In two hypertrophic lakes the density of clams averaged 198 m^{-2} (Beaver et al. 1991). *Corbicula fluminea* sometimes may form high densities in certain areas of reservoirs, but their overall average density is usually lower in lentic than in lotic waters (Table 3). Anthropogenic inputs of phosphorus has resulted in the eutrophication of many Irish lakes and lowland river sections; in the ROI 39 lakes (17.7%) and 2,728 km of river channel (21%) rivers are classified as eutrophic with 82 lakes (36.9%) mesotrophic and 3 hypertrophic (EPA 2010). These would be considered to have high potential population densities. As the zebra mussel has reduced the trophic status of many Irish lakes to oligotrophic (44.1%, n=98) or mesotrophic following colonisation of many lakes since its arrival in the early 1990s (Lucy et al. 1995; EPA 2010), potential *Corbicula* densities in zebra mussel colonised waters are more difficult to predict.

One of the main factors that affects the distribution and abundance of *C. fluminea* within a waterbody is a substrate type (Leff et al. 1990; Karatayev et al. 2003). The best substrate for *C. fluminea* is sand, sometimes mixed with silt or clay (Table 3). *C. fluminea* are in much lower densities on rocks and in silt, and also usually avoid sediments under beds of submerged macrophytes (Karatayev et al. 2003). This may be the major limiting factor in many Irish river and littoral lake sites, due to the widespread presence of heterogenous boulder, cobble and gravel substrates. In fact there may be a patchy distribution within colonised rivers and lakes, with low densities in areas dominated by rocky and silty substrates. The temperature required for spawning (15°C) is the same as for the zebra mussel (reviewed in Lucy 2006) and not a limiting factor as it is normally reached annually in May, with lake and river temperatures normally remaining above this level until September. It is possible that the low oxygen limit (1–3mg/l) could occur in large lakes during stratification, and in lakes and rivers due to excess macrophytic growth or during a deoxygenating pollution incident.

Economic impacts

Since its introduction to the USA, *C. fluminea* has become one of the most important molluscan pest species (McMahon 1983), with an annual cost of $1 billion for control, replacement and repair (Pimental et al. 2005). Its numerous negative attributes have included living animals and shells that have clogged pipes and heat exchangers at power plants and other raw water users (McMahon 1983, 1999), reduced flow in irrigation canals (Prokopovich 1969), and specimens present in river gravels have even interfered with setting concrete (Sinclair and Isom 1963). The greatest economic impacts of *C. fluminea* in the US have been macrofouling of fossil-fueled and especially nuclear power stations, including several nuclear reactors have had to be closed down temporarily for the removal of *Corbicula* from the cooling systems (Isom 1986). Carried into raw water systems by intake pipes pediveligers and juveniles enter power plants, where they can accumulate in areas with the low water velocity (less than 1.2–1.5 m sec^{-1}) at densities over 20,000 m^{-2}. Settled juvenile in 6–12 months can grow to > 2 cm shell lengths capable of fouling small-diameter components (reviewed in McMahon 1999). As *Corbicula* brood their veligers within the mantle to the pediveliger stage, just a few individual adults can easily produce vast colonies in pumpwells without any additional external input of veligers. This makes control strategies aimed at adult elimination very important. Settlement takes place where sediments build up, usually in wet wells at the intake structure, eddies created at the ends of piping or at tees and bends, emergency systems or partially closed valves (Mackie and Claudi 2010). In several North American rivers that were dredged for sand and gravel, the high densities of *C. fluminea* incorporated in the cement, moving to the surface as the cement starts to set, weakening the structure (Sinclair and Isom 1961).

There are no nuclear plant or irrigation canals in Ireland. Most of the raw water sourced for Irish drinking water comes from surface water abstraction (EPA 2011), while a number of power plants extract cooling water from freshwater and estuarine sources. Therefore the potential economic damage in Ireland may include interference with power plant operation, drinking water abstraction from lakes and other industries using raw water, especially those that are already affected by *Dreissena polymorpha* fouling (Lucy 2009). For example, this may pose problems for the brewing industry, which is important to the Irish economy. In addition, high densities of *C. fluminea* in the sand and gravel illegally dredged for cement may decrease its quality.

Ecological impacts

Potential ecological impacts of *C. fluminea* on Irish waterbodies may be predicted based on the results of previous studies mostly conducted in the US (reviewed in McMahon 1999; Karatayev et al. 2005a, 2007). *Corbicula fluminea* filters large volumes of water and transports material removed from the water column to the benthos, providing a direct link between processes in the plankton and those in the benthos (benthic-pelagic coupling). In waterbodies where *C. fluminea* create high densities, such as streams, they may filter the volume of water equivalent to that of the entire waterbody from less than an hour to 4 days (Cohen et al. 1984; Lauritsen 1986; Leff et al. 1990; McMahon and Bogan 2001). The movement of large quantities of seston from the water column to the bottom induced changes in all aspects of freshwater ecosystems after their invasion (reviewed in McMahon 1999; Karatayev et al. 2005a, 2007). It was shown (reviewed in Karatayev et al. 2005a, 2007) that the filtering activities of *C. fluminea* causes water transparency to increase and decreases seston concentration, BOD, and phytoplankton density. With increased transparency, the photic zone for macrophytes greatly increases resulting in a greater portion of the waterbody covered with macrophytes. These ecological changes have already been observed in Irish lakes colonised by the zebra mussel, another filter feeder (Lucy et al. 2005). However, increased macrophyte beds may cover previously available substrate for *C. fluminea* and negatively affect their overall density in a waterbody. As it was shown in the North America, many benthivorous fishes consume *C. fluminea* including freshwater drum (*Aplodinotus grunniens* Rafinesque, 1819), catfish (Siluriformes), sunfish (Centrarchidae), and carp (Cyprinidae) (Isom 1986). Therefore the introduction of this clam may result in increased fish production (Phelps 1994). Cyprinids have already included the invasive zebra mussel in their diet (Millane 2009) and are thus likely to adapt to *Corbicula* as a new dietary item. Increased fish productivity may result in a negative feedback as there is some evidence suggesting that fish predation may be a major cause of reduction in *C. fluminea* density (Dreier and Tranquilli 1981; Robinson and Wellborn 1988). In Fairfield Reservoir, Texas fish predation reduced *C. fluminea* abundance 29 fold (Robinson and Wellborn 1988). In the Irish River Barrow, *Corbicula* is known to co-occur with lamprey (*Lampetra* spp.) (F. Lucy, pers. obs.), but the potential ecological impacts on these protected species (EU Habitats Directive) are unknown. The shells of *C. fluminea*, may accumulate in large quantities, alter the sediments and change the benthic community (Prokopovich 1969; Karatayev et al. 2005a). Overalls the ecological impacts of *C. fluminea* are associated with their role as biofilters, and are therefore determined by their filtration rate and the overall population density in a given waterbody (reviewed in Karatayev et al. 2005a). These ecological changes will be difficult to determine but sampling programmes for the water framework directive may, over time, indicate new trends in water quality, macrophytes, macroinvertebrates and fish populations in Irish waters invaded by *Corbicula fluminea*.

It is not possible to define the rate and patterns of spread, the population dynamics in different waterbodies or the subsequent impacts of the invasion of *C. fluminea* in Irish waters. Nevertheless, both the scientific history of *Corbicula* invasion in other countries and the abundance of suitable, proximal habitats determine that we should monitor and manage the spread of this new invader.

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