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Research Article

The distribution of the Asian clam *Corbicula fluminea* and its potential to spread in Ireland

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Abstract

The Asian clam *Corbicula fluminea* was first recorded from the Barrow River in Ireland in April 2010. There are five separate concentrations known to exist. Four of these were found during 2010 to 2012 within Ireland's largest river, the Shannon. The abundance and polymodal length frequencies indicate that the likely seminal site in Ireland is from the Barrow where it may have been present since, or before, 2006. There is a concern the species will continue to expand and modify aquatic communities. All concentrations are linked by a connected navigation system thereby implicating leisure craft as a pathway. However, anglers might be spreading the species since most sites where they are now known are associated with angling. This account reviews the evidence for these potential pathways, for this 'r' strategist. The abundance and distribution in the lower Shannon River, and possible impacts on lake ecosystems are discussed.

Key words: spread, lake, river, pathway, distribution, non-indigenous, invasion

Introduction

The Asian clam *Corbicula fluminea* (O.F. Müller, 1774) is native to southern and eastern Asia, Australia, northern Africa and south-east Russia (Žadin 1952). It rapidly spread during the last century as a non-indigenous species (NIS) to the Americas (McMahon 1983; Beasley et al. 2003). In Europe *Corbicula fluminalis* (O.F. Müller, 1774) appeared during the Pleistocene interglacial period, commonly occurring in deposits in The Netherlands, North Sea and south-eastern Britain (Miller et al. 1979; Meijer and Preece 2000). More recently both species became introduced to Europe (Paunović et al. 2007). *C. fluminea* was first reported by Mouthon (1981), from the Tagus River in Portugal and the Dordogne, France, in 1980. It was later recorded from The Netherlands in 1985 (Bij de Vaate and Greijdanus-Klaas 1990). It is presently widely distributed in continental Europe from Austria (Fischer and Schultz 1999), Belgium (Swinnen et al. 1998), the Czech Republic (Beran 2006), France (Vincent and Brancotte 2002), Germany (Weitere et al. 2009; Hasloop 1992), Hungary (Csányi 1999), Portugal (Sousa et al. 2007), Serbia (Paunović et al. 2007), Slovakia (Vrabec et al. 2003), Spain (Pérez-Bote and Fernández 2008; Lois 2010; Pérez-Quintero 2008) and Switzerland (Schmidlin et al. 2012). It has spread via many of the watersheds including the Rhine (Bij de Vaate 1991) and the Rhone (Mouthon 2001), the Elbe (Beran 2006), the Danube in Bulgaria (Hubenov et al. 2013), the Danube delta in the Ukraine (Son 2007), Romania (Scolka and Gomoiu 2001) and in the Prut River Basin in Moldovia (Munjiu and Shubernetski 2010).

Corbicula fluminea was first recorded in Britain from the Chet River, Norfolk in 1998 (Howlett and Baker 1999; Baker et al. 1999). Since then the species has colonised many of the adjacent Broads rivers (Aldridge and Müller 2001). In 2004 it was found in the tidal region of the Thames River (Davison 2006). Elliott and zu Emergassen (2008) studied it in more detail. It was later found in the New Bedford River in the

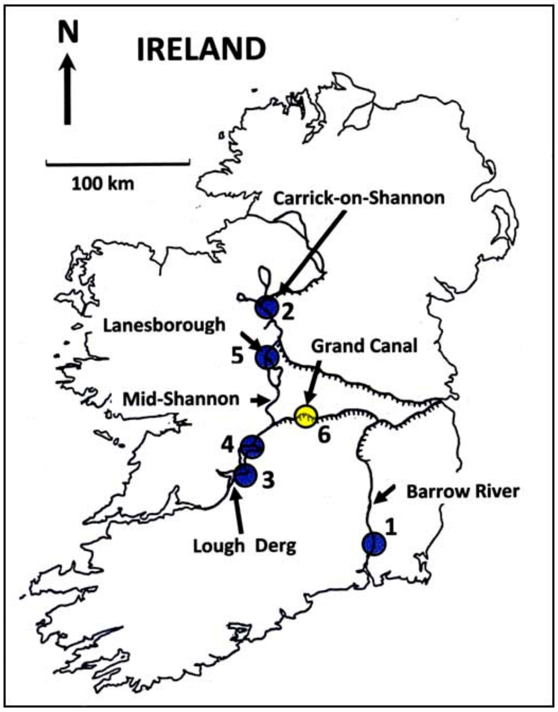

Figure 1. Current known distribution of Asian clams in Ireland. **1** Barrow and Nore rivers, **2** Carrick-on-Shannon, **3** Dromineer Bay in Lough Derg, **4** Upper Lough Derg, **5** Upper Lough Ree near Lanesborough and **6** at Cornalour Lock on the Grand Canal. See also Figure 5 for principal study areas, and Table 1S.

British midlands (Willing 2007). It was found in the Trent and Mersey canals in 2011 (Willing 2011) and is likely to spread more widely *via* the inland waterways.

In April 2010 the Asian clam was found for the first time in the Barrow River in south-east Ireland (Sweeney 2009). It was studied by Caffrey et al. (2011) who found it to be widely distributed at densities to ~9,000 m^{-2} in the upper tidal freshwater areas of the river. It was also found at lower densities in the tidal area of the confluent Nore River (Figure 1). Shell length frequency distributions indicate a presence since at least 2006. In 2010 it was found on the upper Shannon River at Carrick on Shannon (Hayden and Caffrey 2013) where densities of 400 to 750 m^{-2} were estimated. This account reports on a rapid assessment of its abundance and distribution from three further regions on the lower Shannon River during 2011 and 2012 and an observation from a canal system that connects the Shannon River to the Barrow Estuary (Figure 1). The different modes of spread in Ireland are discussed.

Methods

The colonised areas

Loughs Ree and Derg are the most downstream lakes on the Shannon River. The Shannon catchment drains 11, 250 km^2, this is ~17% of the Irish land surface area. Water transparency is reduced by humic acids from peat runoff. This becomes buffered to produce alkaline conditions as a result of outcrops and exposed boulders of carboniferous limestone. The fall of water from the source of the Shannon to the sea is 120 m with a 30 m drop at a hydroelectric dam situated at the head of the Shannon Estuary. In addition the data collected by Caffrey et al. (2011) from the Barrow River and Hayden and Caffrey (2013), from elsewhere on the Shannon River, were examined for Asian clam abundance and distribution.

Recreational craft activities predominate through the Shannon lakes and interconnected river sections during the summer months (Minchin et al. 2006). The Shannon waterway connects to Lough Erne in Northern Ireland via the Shannon-Erne Waterway, through sixteen locks, and to Dublin, on the east coast via the Grand Canal and with Waterford, in the south-east, via the Barrow Navigation. The three Shannon assessment areas studied are 9 (Lough Ree), 10 (mid-Shannon) and 11 (Lough Derg) of Minchin and Zaiko (2014). Lough Ree lies at 38m above sea-level with a maximum depth of 35 m and mean depth of 6.2 m. It has a volume of 0.65 km^3 and surface area of 105 km^2. Shallow bays, small shoals and islands of eroded glacial till occur throughout the length of the lake and there are streams and rivers entering on either side. A lake fen area of interconnected alkaline lakes connects to the south-east of Lough Ree (Bowman 1999). Lough Derg is 33 m above sea level, has a maximum depth of 37 m and average depth of 7.5 m. It has a volume of 0.88 km^3 and surface area of 188 km^2. Shallow bays with small rivers and streams lie on either side of a central axis that passes over a series of deeper water depressions of 30+ m from half-way along its length (Bowman 1999). The river section connecting Lough Ree to Lough Derg has depths of 1.6 to 16 m with river bed sediments ranging from fine silt and peat to stones and bedrock, according to river depth and width. There is winter flooding of callows on either side of this river section due to the low river gradient. The Shannon River connects to the Grand Canal. This was built in 1804 and has forty-three locks over a distance of 131 km. It

Figure 2. Basket dredge used to retrieve Asian clams during 2011 and 2012, scale is 50 cm.

passes through glacial boulder-clay, peatland and limestone bedrock. The canal area examined was from the Shannon River to where the canal meets the upper section of the Barrow waterway, a distance of 85 km. This canal is dredged to a depth of 1.2m but has deeper sections (Figure 1).

The sampling methods

Sampling took place from January 2011 to November 2012. This consisted of 1,046 stations. Substrata ranging from fine mud to stones were sampled over a depth range of 1.2 m to 37 m. Asian clams were initially found using a vertical tow net that scooped sediment into the net (Minchin 2014). A basket dredge was made using a Sunnex® stainless steel wire meshed basket of 260mm open diameter, 300mm height and 180mm bottom diameter, all surfaces had a diagonal mesh of 5mm. One side was weighted with a tied-in lead sheet. A bridle with a net float was attached to the upper half of the basket rim to ensure a correct sampling position. A 1m chain section was attached to the leading part of the bridle (Figure 2). The dredge was deployed from a 10m vessel at ~1 knot with ~3 to 4 times the depth of line paid-out. Once paid out, the engine was placed in neutral to allow the dredge to cut a groove of sediment. Care was taken to prevent burial of the dredge. On retrieval, samples were flushed in lake water, rinsed and washed in a 2mm bar mesh, sieve, and any Asian clams removed.

The basket-dredge determined the relative distribution of Asian clams. A Van-Veen grab, with an 18 cm × 14 cm ($0.025m^{-2}$) bite, was used to evaluate densities in areas where Asian clams exceeded 100 per dredge haul. Stations where Asian clams were obtained are shown in Table 1S.

Asian clams were measured for shell-length, the longest diameter from the anterior to the posterior margins of each shell.

Surface temperatures were measured at the Derg Marina, Ballina, Killaloe at the southern end of Lough Derg at a depth of 0.5 m, and in the Dromaan Deep temperatures to depths of 24 m were obtained at various time intervals during the year using an oceanographic reversing thermometer and Nansen bottle

Calculating the abundance and distribution range of different assessment regions

The biopollution method of (Olenin et al. 2007) requires that a set of defined regions (assessment areas) are determined for a specific time period, so that temporal trends can be followed. Three assessment areas were based on those determined along the entire length of the Shannon River waterway (Minchin and Zaiko 2014). The assessment period in the Shannon was for the years 2010 to 2012, and for the Barrow region was 2010 based on the data of Caffrey et al. (2011). The biopollution method requires an evaluation of the abundance and distribution range (ADR)

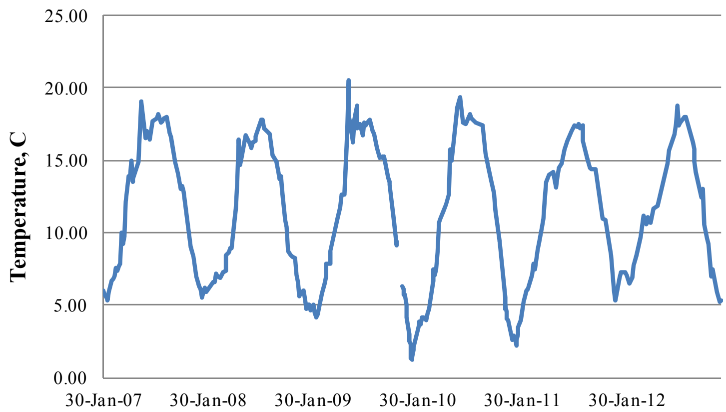

Figure 3. Near surface water temperatures at Ballina at the southern end of Lough Derg. Growth is considered to take place once 10°C and reproduction from 15°C.

Table 1. Classes of abundance and distribution according to Olenin et al. (2007).

Abundance	Distribution scale			
	Single locality	Several localities	Many localities	All localities
Low	A	A	B	C
Medium	B	B	C	D
High	B	C	D	E

before determining the different levels of impact on communities, habitats and ecosystem function as was undertaken for the zebra mussel in the Shannon (Minchin and Zaiko 2014). Here the ADR alone is used, as this is easily achieved, based on the survey information gathered. The ADR has three levels of abundance: *present* where a NIS made up only a small part of a community; *common* where its abundance was frequent but less than half of the abundance of the native community, *abundant* should it exceed half the native abundance, and dominate. The mean frequency of Asian clams were assessed according to the following distribution scales: *local*, where it appeared only in one place; *several localities* where it was present in less than half of the stations where it may be expected; *many localities* where it was found in more than half of the available localities; *all localities* where all substrata, where it may be expected, are occupied. However, in the case of the Shannon, the invasion of the zebra mussel *Dreissena polymorpha* dominated many substrates to form a high proportion of the invertebrate biomass (Minchin et al. 2002; Minchin and Zaiko 2014). The unionid *Anodonta anatina* was formerly dominant in shallows where the Asian clams now frequently occurs having been extirpated by being smothered by the zebra mussel. The *A. anatina* was formerly the principal suspension feeder now replaced by the zebra mussel and the Asian clam. For this study the following criteria were used for the abundance levels of *C. fluminea*: *present*: <10; *common* 10-100 and *abundant* >100 per basket dredge haul. The stations within each assessment unit were scored for clams at these three different levels of abundance to determine its relative distribution. Sampling was supplemented with a Van-Veen grab in areas where concentrations of Asian clams were located using the dredge.

A five-point scale consisting of combinations of each level of Asian clam abundance and its frequency of occurrence can be deduced accordingly: where there are low numbers in one or several localities (A); in low numbers in many localities, or is common in one or several localities, or high numbers in one locality (B); in low numbers in all localities, common in many localities or in high numbers in several localities (C); is common in all localities or is abundant in many localities (D); or is abundant in all localities (E) according to the scheme in Table 1. The method can be applied to a single species as in the case of an invasive bryozoan in the Canary Islands (Minchin 2012), the zebra mussel in the Shannon River (Minchin and Zaiko 2014) or where it has been developed for a phytoplankton species, *Protoperidinium minimum,* in the Baltic Sea (Olenina et al. 2010) or for several species as in the case of a review of the impact of alien invertebrates in the Baltic Sea (Zaiko et al. 2011), or in marinas in Northern Ireland (Minchin and Nunn 2013). Here we use the ADR on a single species but do not quantify the levels of its impact on communities, habitats or ecological functioning.

Results

Temperature

Temperatures of 0.9ºC were measured beneath ice during January 2010 at a depth to 2.5 m in Dromineer Bay. The temperatures measured in the glacial trench, along the main axis of the lake, in the Dromaan Deep at 24 m ranged from 2.4ºC during the cold period to 16.4ºC in late July over the years 2010 to 2012. Long-term temperature records were made at Ballina, south of Lough Derg and ranged from 1.2 to 20.5ºC (Figure 3).

Sediments

Greatest numbers of Asian clams were obtained from sandy-muds and mud. Few were recovered from crumbed peat deposits. Asian clams recessed in clay and some were attached to concretions, pebbles and stones. The size distributions varied according to substrate type with smaller Asian clams retrieved from fine sediments at the northern entrance to Lough Derg. Variations in the surface shell colour of Asian clams in the river section suggest movement by river currents or by pedal activity. In some regions a dark staining of the shell surface was prevalent, although recent growth on the shell could be unstained (Figure 4).

Lough Ree

At the northernmost part of Lough Ree, below the bridge at Lanesborough, twenty-seven *C. fluminea* were obtained from thirty stations from depths of 1m to 6m. Asian clams occurred in mud, crumbed peat and amongst stones. No Asian clams were found in the river above the Lanesborough Bridge. Retrieved Asian clams had one prominent mode at 2–7 mm. The largest Asian clam was 24 mm (Table 2). No Asian clams were found elsewhere throughout Lough Ree despite samples taken from river delta shallows to depths of 30+ m. The overall ADR value for the Lanesborough population in Lough Ree was ADR = A, i.e. low numbers in several localities (Table 3).

Figure 4. Discoloration of Asian clams indicating displacement.

The mid-Shannon River

Asian clams were retrieved only in the lower third of this assessment area from below the town of Banagher to the entrance of Lough Derg. The number of clams collected in samples varied. There was a concentration at 4m above the bridge at Portumna which extended below this same bridge to 16 m depth. Within this linear kilometre Asian clams locally attained density estimates of 1,500–4,500 m^{-2}. Asian clams, of up to 12 mm, were occasionally found byssally anchored to vacant shells of the unionid *Anodonta anatina* and to stones. The ADR for this region is B, i.e. common in several localities (Table 3).

Lough Derg

Asian clams were found in the northern third of Lough Derg along the main axis of the lake (Figure 5). This distribution was continuous from the lower mid-Shannon River. On either side of this axis Asian clams were sparsely distributed, but were absent within the inner parts of bays on both sides of the lake. Estimates of densities within this region ranged from individuals to >300 m^{-2} (Table 2) occurring on fine muds to stones with most on mud and shell sand.

A separate concentration, almost half way down the lake, was present in Dromineer Bay at a depth of 5 m to 6 m. This concentration was to one side of the main lake axis with a diffuse westward distribution to the deeper water at 24 m. To the south of this region no further Asian clams were obtained despite ~200 sampling stations. The ADR for Lough Derg is B, i.e. common in several localities (Table 3).

Table 2. Asian clams sampled in Ireland. Shell measurements are of shell height* otherwise are of shell length.

Population concentration	Year	Size range (mm)	Number of distinct modes	Dominant mode(s) (mm)	Depth Range (m)	Estimated max density /m^2	Ratio shells to live Asian clams	Possible date of arrival
Upper-Shannon River	2010	3-22*	2	5, 11*	-	~750	unknown	<2008
Lanesborough	2012	2-24	4?	5	1-6	<10	18/27	2009
Mid-Shannon/upper Derg	2011	3-26	3	6,14,18	1-20	>3000	-	2008
	2012	4-24	3	15-17	1-26	>1800	45/2012	2009
Dromineer/Dromaan	2011	3-30	2	6,12	1-24	>300	-	2007
	2012	4-21	4	6,12,17	5-23	>300	9/633	2008
Grand Canal	2012	-	-	-	1.2-2.4	0	2/0	unknown
Freshwater tidal Barrow	2010	5-32*	4?	16-19, 20-23, 30+*	x ±3.0	9,636	unknown	≤2006
Freshwater tidal Nore	2010	5-24*	2?	9, 21*	x±3.0	336	unknown	<2008

Table 3. Estimated abundance and distribution values for different assessment areas and using data from Caffrey et al. (2011) and Hayden and Caffrey (2013); x = water depth ± tidal range.

	No Asian clams	<10 Asian clams (present)	10-100 Asian clams	100+ Asian clams (abundant)	Stations presence/total	Overall ADR
Upper-Shannon River (4)	205	?	?	?		-
Lough Ree (9)	294	12	0	0	12/306	A
Mid-Shannon River (10)	122	54	40	1	95/217	B
Lough Derg (12)	322	124	36	4	164/486	B
Grand Canal	0	0	0	0	0/37	Not present
Freshwater tidal Barrow	2	4	?	17	21/23	'D'
Freshwater tidal Nore	4	2	?	4	4/10	'C'

Table 4. Possible transmission modes of *Corbicula fluminea* to each concentration.

Population concentration	Leisure craft	Angling sites	Wading birds	Other possible modes
Lower Barrow	berths, no anchorage	few	frequent	deliberate release, ships ballast, dredge spoil
Carrick-on-Shannon	3 marinas, anchorage	extensive angling stands	present	unknown
Lanesborough	2 marinas, anchorage	well known angling centre	present	unknown
Banagher	2 marinas	angling centre	present	unknown
Grand Canal (shells)	no marina, berthage	angling	some	unknown
Portumna	2 marinas, no anchorage	international angling centre	present	unknown
Dromineer	3 marinas, anchorage	some angling activity	present	unknown

The Grand Canal

Two vacant shells of 7 and 8 mm were found at Cornalour Lock, some 20 km from the Shannon River on the Grand Canal. No living specimens were found nor were shells recovered at any other canal site. It is unlikely a population is established at this site.

Discussion

Modes of dispersal

There is no direct evidence as to how the Asian clams arrived or have spread within Ireland (Table 4). The high density population in the tidal reaches of the Lower Barrow and Nore rivers (Caffrey et al. 2011) has been presumed to have formed the seminal Irish population. The current distribution within the waterways, which can be fully accessed by leisure craft, implicates a spread with boats from the Barrow Estuary. However, it is possible it could have arrived from an area where *Corbicula* has not yet been found. The four Shannon concentrations indicate separate inoculations, whether these are sourced from the Barrow remains unknown. All Asian clam concentrations, except for the Dromineer Bay population in Lough Derg, were close to angling sites. The Lough Ree population occurred below a warm water discharge from a power station that attracts anglers fishing for cyprinids. The area below Banagher is regularly fished and the banks close to Portumna support international angling events using baits. The shells found in the Grand Canal were at a site where anglers from Britain regularly fish. Anglers fishing from banks normally follow a catch-and-release policy, with fish being stored in keep nets, until the angling day is complete and the fish released. Keep nets may be immersed over several hours and during this time young Asian clams may adhere to a net. Nets are normally stored in a waterproof bag until their reuse, perhaps at a different angling site. The occurrence of the Dromineer concentration is not easily explained as angling in this region is with artificial lures. There are several possible vectors distributing Asian clams in Ireland (Table 5). The Asian clam poses difficulties for managers because it is likely to compromise water quality status according to the criteria of the Water Framework Directive. All that can be practically achieved is to reduce the rate of spread by managing transmission processes. To this end Barbour et al. (2013) have shown under trial studies that a 10% bleach solution was partly successful, the broad spectrum disinfectant Virkon ® at a 2% solution resulted in 93% mortality. One of the difficulties in controlling this species is that a small number, perhaps an individual, might be capable of creating a new population, since individuals can be self-fertile (Kraemer et al. 1986; Williams and McMahon 1989; Sousa et al. 2008).

Sampling using a basket dredge over expansive areas was efficient and easily undertaken where there were soft sediments. Stony substrates could also be sampled but there was the risk of dredge damage. The ADR status was '**A**' for the Lough Ree assessment area and '**B**' for the mid-Shannon and Derg assessment areas. Higher values may be expected in the future. These findings contrast with the Barrow River population (Caffrey et al. 2011) where densities ranged from 1m^{-2} to >9,000m^{-2} over a large area.

Based on their 23 stations, Asian clams were abundant at 17 stations, present at four and absent at two. Using the ADR definition '*common in all localities or abundant in many localities'* an ADR of '**D**' is the likely level for 2010. For the Nore the ADR is most probably '**C**' (Table 3), based on ten stations. The ADR method does not rely on precise measurements but enables a reasoned classification to five separate classes.

A rapid simplified method to evaluate the state of NIS when monitoring for both the Water Framework Directive (EC 2000) and the Marine Strategy Framework Directive (EC 2008) is needed (Olenin et al. 2010). Using the ADR enables cost effective monitoring. However, undertaking the requirements to provide an overall biopollution level requires previously gathered environmental data as Wittfoth and Zettler (2013) will have indicated. They evaluated the status of three lagoons on the German Baltic coast and found no difficulties in calculating an ADR for each species examined.

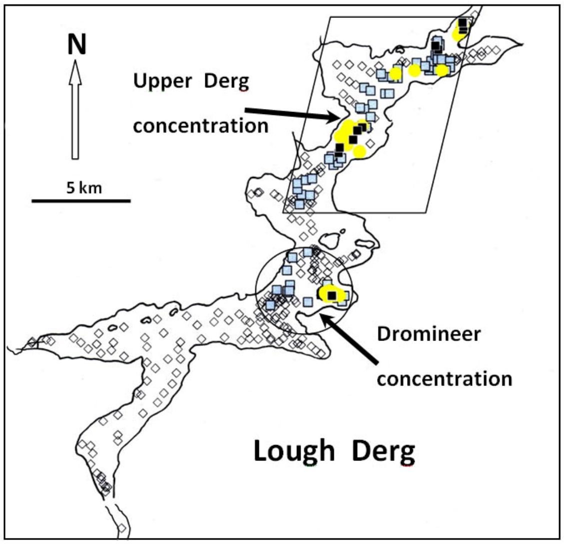

Figure 5. Lough Derg showing two separate Asian clam concentrations. Open diamonds-not found; blue <10; yellow circles 10-99; black squares>100 individual s collected in basket dredge per station.

In this study four separate concentrations were found on the Shannon. The Lough Ree concentration was confined to a small area of ~35 hectares. *C. fluminea* has a life span of up to three years within its native range and in North America (Morton 1977; Eng 1979), although, more recent studies indicate that it may survive up to five years (McMahon 2000). On account of its comparatively short life duration it remains unclear the year the founders of each concentration arrived. The Asian clam size distributions, and the small proportion of shells obtained, would suggest an arrival to the Shannon in, or before, 2007. In the mid-Shannon region Asian clams first occur 1.5 km downstream of Banagher. Asian clams were scattered downstream of this site extending into Lough Derg and this may represent one or more inoculations. The Dromineer concentration was highly localised and discharges from the nearby

Table 5. Vectors that may be capable of transmitting Asian clams in Ireland, either presently or at a future time. Levels of certainty based on Minchin (2007).

Pathway	Inoculation sites	Probability	Comment
1.Natural spread	Many available sites	**Direct evidence:** Drift in flowing water by means of produced threads **Direct evidence:** Local pedal locomotion **Possible**: Carriage by birds **Possible:** Entanglement with drift plant materials	-Downstream spread with 'drag-lines' and to deeper water (Preznat and Chalermwat 1984) -Capable of pedal movement and upstream (McMahon 1991) -Birds might transmit Asian clams (McMahon 1982) from the intertidal region of the Barrow -Drift plant materials common in autumn and winter (Sousa et al. 2008)
2.Angling, commercial fishing and stocking of fish	Many angling lakes and angling occurs in currently infested areas Stocking is regularly undertaken	**Likely:** bags for holding keep nets may prevent desiccation **Possible**: used as angling bait **Possible:** unapproved movement of contaminated equipment within Ireland and from Britain or Europe **Unlikely:** might be carried with water in which stock-fish are carried	-Threads may become entangled on anglers keep nets -Not known to be currently used as bait -There is unapproved fishing and angling by nationals and non-nationals -Hatcheries are unlikely to hold Asian clams
2.Weed cutting craft	Macrophytes are regularly cut on canals	**Likely:** transmission on cut weeds	-Weed is easily distributed as fragments on cutting arrays and rotary belts
3.Recreational craft	Asian clams have not been found associated with recreational craft to-date	**Likely:** overland transmission of small craft **Possible:** widely travelled during summer period **Possible:** Asian clams have been found in partly submerged tyre fenders on a barge in France **Possible:** anchors frequently snag weed in shallow water, vessels with anchors held on the hull are more likely to transmit **Possible:** Lodged in weed traps of engine cooling systems **Unlikely**: entrainment with ballast water **Unlikely:** entrainment in toilet water	-Seasonal movements of trailers with outboards seen with snagged weed. Asian clams can withstand long periods of emersion (Byrne et al. 1988) -the entire waterways are regularly used in summer -Spread with tyre-fenders can be controlled by drill holes in the lowest part -Weed is often snagged in anchors -Weed accumulates in weed traps especially on canals and shallows -Some yachts carry small amounts of ballast water -No pelagic stage so unlikely to become entrained
4. Dredging	Many rivers under management	**Likely:** transmission of gravels for river improvements and other developments	-River improvements continually being managed for salmonids
5. Introduction for food	Many available sites for stocking	**Possible**: Asian clams are eaten by the Asian community	-Presently not known to be eaten in Ireland
6.Ornamental plants	Ornamental plants often in delta areas and marinas	**Unlikely:** sites where Asian clams are found are not presently associated with ornamental plant establishment	-Introduction with ornamental plants, unless released to the wild are unlikely to result in a population
7. Aquarium releases	Probably close to human habitation	**Likely:** not presently known to be imported or used as an aquarium species but likely to be used in cold water aquaria and in ponds in the future	-May be used in school nature studies and by aquarium enthusiasts. Elsewhere known as golden clams, good luck clams and prosperity clams

Nenagh River may have flushed Asian clams from the shallows to depths of 24m. It is expected that the concentration in the upper region of Lough Derg will eventually merge with the Dromineer population and the range of the Asian clams extend further down-lake.

Temperatures measured to the south of Lough Derg indicate a short growing season within the main body of the lake (Figure 3). However, within the shallow bays during prolonged periods of solar radiation temperatures can attain at least 23ºC. As a result there are likely to be periods during the year where temperatures exceed those measured at the Ballina station. Growth on the Connecticut River in North America was found to take place once temperatures were above 10ºC (Morgan et al. 2003). However, others indicated a wider range over which growth began ranging from 9–15ºC (Mattice and Wright 1986; French and Schloesser 1991). Should it take place once >10ºC then in the Shannon there is a seven month growing period, April to October. Temperatures >15ºC are needed for reproduction (McMahon 2000; Rajagopal et al. 2000). In Lough Derg this is a comparatively small window of about four months. Elsewhere *C. fluminea* can have up to three reproductive events in a year (Doherty et al. 1987; Darrigran 2002). It is currently unknown how many reproductive events take place in the Shannon but at least one such event has taken place in each of the most recent years.

Mattice and Dye (1976) claimed the lowest thermal tolerance for *C. fluminea* to be 2ºC. Horning and Keup (1964) reported >95% mortality following a week of temperatures close to 0ºC beneath ice on the Ohio River. This lower tolerance limit was questioned by Janech and Hunter (1995) and then by Morgan et al. (2003) because populations they were studying survived when temperatures of 0 to 2ºC occurred for almost two to three months in winter. Müller and Baur (2011) showed in laboratory studies Asian clams survived short periods with low mortality at 0ºC but mortality progressively increased to 80% after nine weeks of exposure at 0ºC. They found increased survival according to Asian clam size. Condition is known to decline at temperatures of 2ºC over a period of one month (French and Schloesser 1996), and so explain why larger individuals seem more tolerant of prolonged low temperatures as these probably have more reserves. In Lough Derg Asian clams survived temperatures of 0.9ºC for almost two weeks below ice in the shallows of Dromineer Bay. At this time the lowest recorded temperature in the deeper areas of Lough Derg at 24 m was 2.4ºC. Mortalities were low during this winter, as few shells were recovered by the dredge or grab the following summer (Table 2). While it is possible that the sampling may not have recovered all of the vacant shells present, these may have been buried deeper than the dredge operating level, this seems unlikely. However, the two shells found in the Grand Canal might have represented living individuals that might have succumbed to low temperatures, when there was ~30 cm of ice cover. It is unlikely that winter temperatures in Ireland will result in a purge of Asian clams in the Shannon. All indications are that water properties in Irish waters are suitable for Asian clam growth and reproduction (Costello et al. 2004) with some exceptions (Lucy et al. 2012). Nevertheless, some lakes may not attain sufficiently high temperatures for reproduction should they become introduced.

Figure 6. Thread of a 4mm Asian clam that may be used as a drag-line for dispersal by water currents.

Asian clam distributions in Lough Derg

The density of Asian clams, while variable, occurred along the central axis of the northern third of Lough Derg (Figure 5). On either side of this axis few Asian clams were recovered but none were found within shallow bays on either side. The exception was Dromineer Bay. Since Asian clams lack a pelagic stage, but can be dispersed with currents downstream aided by threads (Figure 6), the distribution along the main axis of the lake may reflect the main downstream flow through the lake.

Possible ecological consequences

Asian clams can attain high levels of abundance in lotic environments as reported by Caffrey et al. (2011) and have a wide range of impacts (Karatayev et al. 2007). Their abundance and distribution may be expected to increase in the mid-Shannon assessment unit. In lentic environments a low to moderate abundance may be expected in shallows, according to Fast (1971) Asian clams do not occur within the hypolimnion of stratified lakes. This may be due to the relatively low tolerance of Asian clams to hypoxia. Matthews and McMahon (2000) reported that respiration becomes impaired at dissolved oxygen levels of 1–3 mg l^{-1}. In well oxygenated lakes Asian clams have been found at depths of ~100m, with the greatest known depth being 143m in Lake Mead, USA (Peck et al. 1987). Indeed, Karatayev et al. (2003) and McMahon (2000) in their reviews indicated that Asian clams are intolerant of even moderate hypoxia. However, lakes with a decreased availability of oxygen in summer, when combined with low flow conditions and high levels of organic matter, can lead to heavy mortality events of a wide range of biota within the hypolimnion (Johnson and McMahon 1998; Strayer 1999; Cherry et al. 2005; Cooper et al. 2005; Sousa et al. 2007, 2008). Both Lough Ree and Lough Derg are generally polymictic lakes with a wind induced turnover, nevertheless there are periods when stratification takes place. In May and June stratification, during high atmospheric pressure periods, has taken place and will have had a surface to bottom temperature difference of ~6ºC. A prolonged high pressure period when combined with the high biomass of *Dreissena polymorpha* and known occurrence of *C. fluminea* within the hypolimnion zone could result in a demand for oxygen which could lead to a mortality event of Asian clams tipping the hypolimnion into oxygen debt. Mass mortalities according to Weitere et al. (2009) may also be due to increased metabolic rates during periods of limited food levels, which may happen at low summer flow rates. The consequences of a broad scale mortality event may deplete the mysid *Mysis salemaai* that occurs in summer in deeper lake water (Penk 2011) and the endemic *Coregonus pollan* populations (Rosell et al. 2004; Harrison et al. 2012).

Asian clams can reduce the particulate material in the water column that could lead to further increases in water transparency enabling macrophytes to extend into deeper water. While Asian clams have a preference for colonisation of rivers further increases in their density in lotic environments may be expected. A continued study of the extent and relative biomass as well as accounts of chlorophyll α and water transparency together with basic observations on the zebra mussel would be of value in a comparative study of two 'r' strategist filter feeding invaders.

Conclusions

The colonisation in the Shannon is at an early stage with a presence since at least 2007. Other populations may exist elsewhere that have not yet been found. It is unlikely that the spread of Asian clams can be curtailed due to the expanse and the disparate sites Asian clams occupy. Since the northern ends of Loughs Derg and Ree are colonised a gradual transmission down-lake is inevitable. The high densities of Asian clams in the Barrow tidal freshwater area indicate that conditions are suitable for the Asian clam and it is likely to become abundant elsewhere in Ireland. Winter temperatures would not appear to be a barrier to their existence except perhaps under exceptional conditions in canals. Should *C. fluminea* become abundant in the hypoliminion of deep lakes there is the risk of a de-oxygenation event in the late spring or summer during a prolonged period of high atmospheric pressure. A review of the most likely modes of their current spread would appear to be with angling equipment. In the future other likely vectors may distribute the species further as known populations expand.

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Supplementary material

The following supplementary material is available for this article.

Table 1S. Records of *Corbicula fluminea* in Ireland from 2011–2012.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2014/Supplements/MBI_2014_Minchin_etal_Supplement.xls