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Research Article

An investigation into the effectiveness of mechanical dredging to remove *Corbicula fluminea* (Müller, 1774) from test plots in an Irish river system

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Abstract

The invasive Asian clam *Corbicula fluminea* (Müller, 1774) has established a high density and self-sustaining population within the tidal reaches of the River Barrow, Ireland. A field trial was carried out to test the respective efficacy of three different mechanical dredge methods at reducing *Corbicula* clam numbers by estimating changes in abundance and biomass immediately following dredging. Quadrat samples were collected by SCUBA divers before and after dredging. A maximum pre-dredge density of 17,872 individuals/m^2 and a biomass of 43.94 kg/m^2 was recorded. Three sites which supported different population density and biomass levels within the tidal section of the River Barrow were subject to each of the dredge methods. A reduction of greater than 95% biomass and 95% density was achieved at the high density, high biomass site, while an 82% biomass and 65% density reduction was recorded at the low density, low biomass site. A 74% biomass and 92% density reduction was achieved at the high density, low biomass site. The methodology and results indicate that, while dredging can achieve a large reduction in *Corbicula* population numbers, further research is required before this can be considered as a management tool for control of Asian clams.

Key words: Asian clam, management, mechanical removal, dredge, population density, biomass, River Barrow

Introduction

A number of high profile invasive species have become established in Irish aquatic habitats in the past two decades, such as *Dreissena polymorpha* (Pallas, 1771) (McCarthy et al. 1997), *Chelicorophium curvispinum* (Sars, 1895) (Lucy et al. 2004), *Lagarosiphon major* (Ridley, 1928) (Caffrey and Acevedo 2008) and *Hemimysis anomala* (Sars, 1907) (Minchin and Holmes 2008). The Asian clam *Corbicula fluminea* (Müller, 1774) is an aquatic invasive bivalve that has invaded the island of Ireland and was first reported from the River Barrow in 2010 (Sweeney 2009). *Corbicula fluminea* has subsequently spread to the River Nore (Caffrey et al. 2011) and the Shannon River (Lucy et al. 2012; Hayden and Caffrey 2013). *Corbicula fluminea* is considered to be one of the most invasive aquatic freshwater species globally (McMahon 1999; Sousa et al. 2008b). The potential for *C. fluminea* to expand its range within the surface waters on the island of Ireland is considerable, with few water bodies not meeting its minimum biological requirements (Lucy et al. 2012). As a species possessing some of the most invasive life history strategies, e.g., r-selection (McMahon 2002), low temperature tolerance (Müller and Baur 2011) and generalist feeding (Hakenkamp and Palmer 1999), *Corbicula* has proved to be an extremely important invader in aquatic ecosystems (McMahon 1999, 2002; Sousa 2008; Lucy et al. 2012). *C. fluminea* has a lifespan of between 1 and 5 years (Sousa et al. 2008b) but more typically lives between 2 and 3 years (Mouthon and Parghentanian 2004). Extremely high fecundity levels have been estimated for this species, at over 68,000 juveniles per adult

per year (Aldridge and McMahon 1978; Williams and McMahon 1989). Reproduction can be completed sexually but is normally by asexual means through an all-male form, a process known as androgenesis (Houki et al. 2011; Pigneur et al. 2011). This allows for a single individual to found a population (Pigneur et al. 2012). The maternal DNA is extruded by the 'male' sperm with the mitrocondrium retained, leading to the 'male' pronucleus developing as the zygote (reviewed in Pigneur et al. 2011).

Corbicula fluminea has the potential to impact negatively on the biota of freshwater habitats (Hakenkamp et al. 2001; Olden 2006) by filtering a significant proportion of phytoplankton biomass from the water column (Cohen et al. 1984; Lopez et al. 2006; Descy et al. 2012) and moreover by benthic-pelagic coupling (Hakenkamp and Palmer 1999; Hakenkamp et al. 2001). In this regard, *C. fluminea* is widely recognised as an ecosystem engineer (Sousa et al. 2009; Bódis et al. 2014).

To lessen the impacts invasive species have on ecosystem functioning (Sousa et al. 2008c; Pejchar and Mooney 2009; Vilà et al. 2011) and public health (Pejchar and Mooney 2009), the importance of effective control and management of aquatic invasive species has been highlighted (Mack et al. 2000; Caffrey et al. 2010; Simberloff et al. 2013). This includes further recommendations for novel control in IAS management to research and fund emerging control methods (Caffrey et al. 2014). An evaluation of management options, benefits to be expected and gains achieved (Homans and Smith 2013), and subsequent economic benefits (Oreska and Aldridge 2011) have been presented for a range of aquatic species. Strategies currently available for controlling invasive bivalve populations are reviewed in Sousa et al. (2013). In Lake Tahoe, California, two experimental approaches demonstrated a short-term reduction in *Corbicula* abundance, namely suction dredging (Wittmann et al. 2012a) and the application of benthic gas impermeable barriers (Wittmann et al. 2012b).

The invasive bivalve *C. fluminea* was first recorded on the island of Ireland in the River Barrow, in early 2010 (Sweeney 2009). A subsequent investigation into the size and distribution of the River Barrow population detected the presence of *C. fluminea* in the connected River Nore (Caffrey et al. 2011) (Figure 1). A detailed investigation of *C. fluminea* in the Rivers Barrow and Nore revealed extensive populations, with a maximum density of 9,636 clams m^2 recorded in the St. Mullins area (Caffrey et al. 2011). This

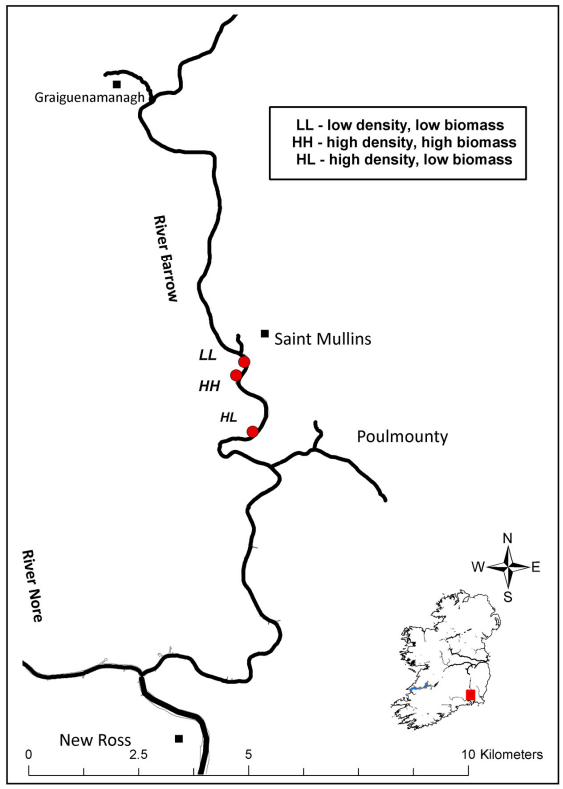

Figure 1. Location of dredge sites in the River Barrow. [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)].

infestation 'hot spot' was the driver for developing control methods to impede secondary spread of *Corbicula* from the River Barrow into other Irish waters. The aim of this paper is to report on the effectiveness of one of these approaches namely dredging, at reducing *C. fluminea* biomass and density from test plots within the River Barrow.

Study area

The River Barrow, at 192 km long, is the second longest Irish river and drains a catchment area of 2,983 km^2. It shares a common estuary with the Rivers Nore and Suir, commonly termed the Three Sisters. Subject to tidal influences over 32 km of its length, from the weir at St. Mullins to its confluence with the River Suir, 36 km downstream, the River Barrow can fluctuate up to 3 m with each tide. With an altered hydromorphology and a flow regime controlled by a series of weirs, the River Barrow allows recreational craft to navigate from the sea, into the Irish inland waterway

network (Caffrey et al. 2011). The river is tidal as far as the first weir, which is located 1 km upstream from the village of St. Mullins (52°29′15.1″N, 06°55′42.2″W), with no saline influences present in the experimental area (Figure 1).

The River Barrow is a Special Area of Conservation (SAC 002162) for smelt *Osmerus eperlanus* (Linnaeus, 1758), twaite shad *Alosa fallax* (Lacépède, 1800), sea lamprey *Petromyzon marinus* (Linnaeus, 1758), river lamprey *Lampetra fluviatilis* (Linnaeus, 1758) and brook lamprey *Lampetra planeri* (Bloch, 1784).

The dredging experiment was conducted in a section of the River Barrow immediately downstream from the village of St. Mullins (at 52°29′15.11″N, 6°55′42.20″W) (Figure 1). The selection of this site was based on a number of factors: the presence of a large and well-established population of *C. fluminea*, the presence of tidal waters which provide sufficient depth for the dredging boat to operate safely, the absence of any saline influence on the tidal waters, and the presence of a suitable substrate that is free from large rocks or obstructions. The river is between 55 and 95 metres wide at this point, with the depth ranging between 0.5 and 4 metres due to tidal range.

Methods

Sample collection

The study area was subdivided into three sampling sites (200 metres long and depending on channel width, *circa* 30–50 metres wide) based on a visual estimation of relative *C. fluminea* population density. Sites with high, medium and low densities of *C. fluminea* were identified by SCUBA divers and confirmed by camera verification from a remotely operated vehicle (ROV). The first site was located *circa* 500 metres downstream from St. Mullins; the second and third sites a further 0.5 and 1 km down river, respectively. Each sample site was divided into three control (pre-dredge) plots and three (post-dredge) test plots, corresponding to the three dredging methods utilised. Test plots were clearly marked on the water surface with large buoys. A 50 metre length section of river bed was dredged at each test plot using each of the three dredge devices. All sampling collection was completed during a two week period in April 2012.

Three dredge methods were tested at each of the three sites. Five quadrats were collected per plot for each dredge type, before dredging at all sites (control samples, N = 40) and similarly five quadrats (test samples, N = 45) were collected per plot for each dredge type after dredging. It was not technically possible to collect samples from one test plot, therefore the test sample number was 40 and not 45. SCUBA divers collected 0.25 cm^2 quadrat samples of substrate and associated *C. fluminea* to a depth of *circa* 15 cm using a hand trowel (Caffrey et al. 2011).

Samples were washed and sieved on site, using a 5 mm mesh size sieve, with all *C. fluminea* being returned to the laboratory for processing. Shell height (umbo to gape) was recorded to the nearest 0.1 mm using digital callipers and length frequency plots were generated. Abundance of individuals and biomass (blotted wet weight kg/m^2) were also estimated. A total of 2,302 individuals were measured from pooled quadrats for all test plots to produce a size distribution analysis using shell length (SL) frequency.

A substrate sample from each site was retained for granulometric analysis. Samples were oven dried at 75°C for 24 hours or until a constant weight had been reached. A 1 kg sub-sample was shaken on a mechanical sieve shaker in test sieves ranging from 62.5 µm – 64 mm mesh. Retained material on each sieve was weighed and recorded on according to the Wentworth scale (Wentworth 1922).

Dredging methods

Three different dredging devices were trialled. Each was towed behind a commercial cockle harvesting boat (Figure S1) to assess relative effectiveness in removing *C. fluminea* individuals from the river bed (see Figure 1). All three dredges are commercially available and are widely used in marine bivalve fisheries. A robust plastic mesh with an aperture size of 2 mm was fitted to each dredge to ensure the collection of juvenile *C. fluminea* sized over 2 mm.

Dredge devices

Box Dredge (Figure S2). This is a rectangular benthic dredge (1.5 m width × 0.5 m height × 2.5 m length) originally designed for commercially fishing *Cerastoderma edule* (Linnaeus, 1758), the common cockle, and *Spisula solida* (Linnaeus, 1758), the Atlantic surf clam. It is towed behind a fishing boat and captures its quarry by digging into and disturbing the top layer of substrate.

Electric Dredge (Figure S3 and S4). This dredge is approximately three times wider than the box

dredge and has a set of electrodes at its leading edge. The electrodes are powered by a generator on board the boat and pass electrical current into the sediment immediately ahead of the dredge. This drives buried clams to the surface, making them more susceptible to capture by the fishing gear. This dredge device was developed predominantly to capture *Ensis siliqua* (Linnaeus, 1758), the razor clam, and *S. solida*.

Hydraulic Dredge (Figure S5). This dredge superficially resembles the box dredge. It works on a similar principle but with the addition of water nozzles at its leading edge. The nozzles deliver high pressure water via a hose, fed from a pump on board the boat. This agitates the sediment directly ahead of the dredge and loosens the substrate, making it easier for the dredge to penetrate the top layer. This renders the clams more susceptible to capture. This style of dredge is primarily used to capture *E. siliqua* and *S. solida*.

Data analysis

A two-way analysis of variance (two-way ANOVA) was used to compare the effectiveness of each dredging device and the variation between sites. An analysis of variance (ANOVA) was used to test for a significant difference between the performances of each dredge. A value of $\alpha = 0.05$ was used to denote significance while a value of $\alpha = 0.01$ denoted a highly significant result. Data were LOG10 transformed to conform to assumptions of normality. All significance tests were conducted using Minitab16.

The power equation $Y=aX^b$ ($y=0.00037x^{3.02}$) was used to estimate individual weight from length (Smock 1980) and to calculate the % component of biomass, for two different size ranges.

Results

Shell length frequency and biomass data were used to classify the sites as follows: A – low density, low biomass (LL); B – high density, low biomass (HL); C – high density, high biomass (HH), (Table 1). The classification was based on observation by divers and on the population densities from the pre-dredge (control) quadrat data.

An analysis of sediment composition from the sites revealed that sediment in the range of 0.5 – 1 mm (coarse sand) predominated at sites LL and HH while sediment in the size range of 2 – 4 mm (very fine gravel) was predominant at site HL

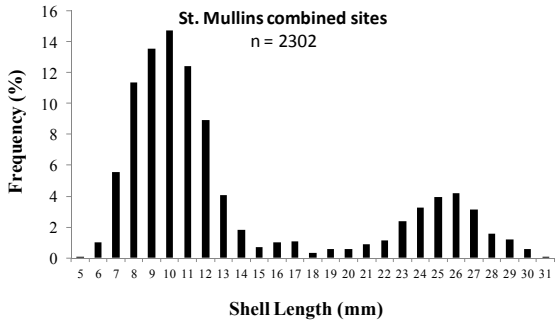

Figure 2. Size distribution for the *C. fluminea* population from the combined St. Mullins sites, River Barrow 2012.

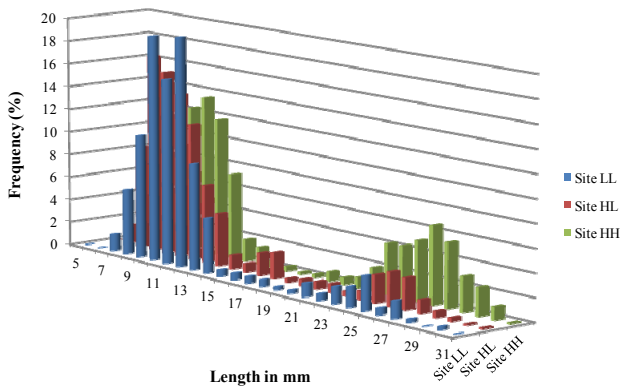

Figure 3. *Corbicula fluminea* shell length (mm) frequency histogram for each test site. [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)].

(Figure 1). Densities of *C. fluminea* within the study area fluctuated substantially, ranging between 80 and 17,760 clam/m^2. A maximum biomass of 43.94 kg/m^2 was recorded. Within each test plot, mean number and biomass varied considerably (Table 1).

Shell dimensions ranged between 5.81 and 31.27 mm. Length frequency histograms (Figures 2 and 3) are bimodal, with the first peak between 5–12 mm and the second between 20–30 mm.

A significant reduction ($P < 0.01$) in mean *C. fluminea* density and biomass from each test plot was observed after dredging, for all dredging devices when compared to control plots (Figures 4 and 5). The reduction in density was greatest at the high density test plots.

A two way ANOVA with H_0 assuming no difference in dredge type and site *versus* control plots revealed a highly significant difference in density ($P < 0.001$) and biomass ($P<0.001$) after dredging. No significant differences in *C. fluminea*

Table 1. Mean number (± SE) of *C. fluminea* individuals/m^2 and biomass (± SE) in g/m^2 for each experimental plot, pre- and post-dredging. [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)]. N/A denotes quadrats that were not collected.

Site	Dredge Type	Mean Number, Pre-dredge (m^2)	Mean Number, Post-dredge (m^2)	Mean Biomass, Pre-dredge (g/m^2)	Mean Biomass, Post-dredge (g/m^2)
LL	Box	435 ± 140	198 ± 87	947 ± 255	179 ± 68
LL	Electric	557 ± 145	243 ± 45	544 ± 99	237 ± 64
LL	Hydraulic	N/A	186 ± 83	N/A	243 ± 123
HL	Box	13667 ± 1236	586 ± 213	9664 ± 788	1818 ± 795
HL	Electric	1578 ± 463	1555 ± 636	1690 ± 488	2093 ± 817
HL	Hydraulic	2301 ± 546	1658 ± 180	6170 ± 2143	1760 ± 152
HH	Box	5696 ± 1186	326 ± 55	12390 ± 1927	806 ± 215
HH	Electric	5094 ± 1077	915 ± 170	17808 ± 5523	877 ± 228
HH	Hydraulic	6355 ± 2889	554 ± 141	15270 ± 7372	550 ± 211

Table 2. The % component of biomass for each of two size classes, as a component of total biomass for the three sites combined and for each of the three test sites individually [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)], pre- and post-dredging. The 5–17 mm class likely to correspond to the 1+ cohort and the 18–32 mm class likely to compose older cohorts. Estimated by the power equation, $Y = aX^b$.

Site	% Biomass pre- 5–17 mm	% Biomass pre- 18–32 mm	% Biomass post 5–17 mm	% Biomass post 18–32 mm
Combined	20	80	35	65
LL	44	56	44	56
HL	34	66	30	70
HH	11	89	40	60

removal capacity were observed (P >0.05) between the three dredge devices trialled, with the box dredge removing marginally more *C. fluminea* individuals than the electric and hydraulic devices (Figure 4 and 5).

A >95% biomass and >95% density reduction was achieved at the HH site. The LL site showed a 75–82% biomass and 54–65% density reduction. At the HL site, a 69–74% biomass and 78–92% density reduction was achieved (Figure 6).

A greater proportion of larger (18–32 mm) individual *C. fluminea* individuals were removed from the population by each of the dredging devices. This is evident from the combined data for percentage biomass of each size class before and after dredging (Table 2).

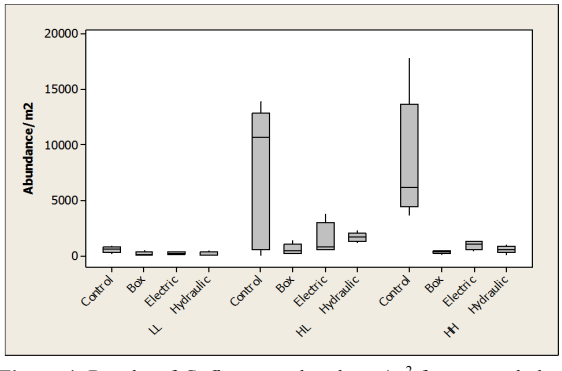

Figure 4. Boxplot of *C. fluminea* abundance/m^2 from control plots compared to each test plot (box; electric; hydraulic) after dredging, for each of the three test sites [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)].

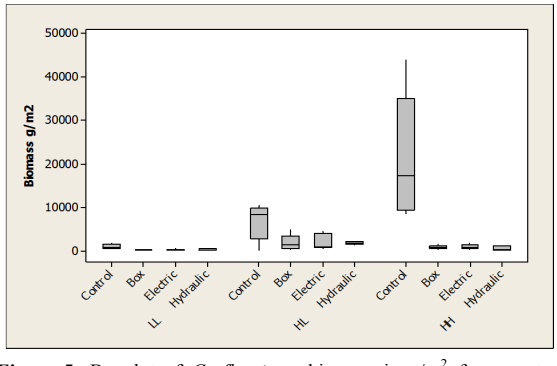

Figure 5. Boxplot of *C. fluminea* biomass in g/m^2 from control plots compared to each test plot, after dredging, for each of the three test sites [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)].

Discussion

At the sample sites on the River Barrow, abundances for *C. fluminea* were high, with a maximum of 17,872 clam/m^2. This represents a large increase on the 2010 maximum recorded density of 9,636 individuals/m^2, in the same river section (Caffrey et al. 2011). This maximum density (17,872 clam/m^2) exceeds those reported in the literature by Stites et al. (1995) (>1,000 n/m^2); Cataldo and Boltovskoy (1998) (1,722 n/m^2) and Sousa et al. (2008a) (4,185 n/m^2). Densities of up to 18,000 individuals/m^2 have been reported from natural habitats in North America (Doherty

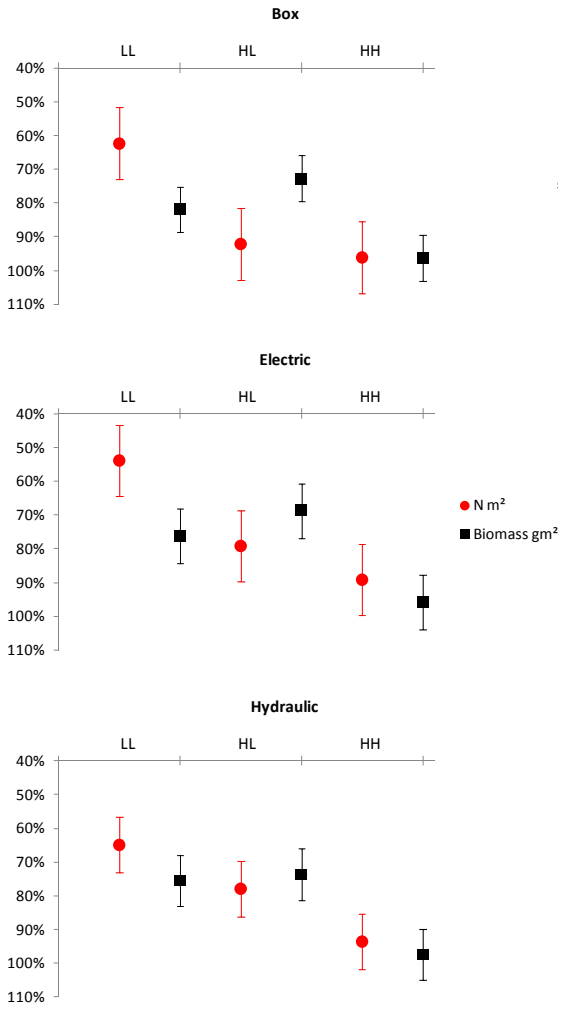

Figure 6. The percentage reduction in abundance/m^2 and biomass in g/m^2 for each site and dredge type, error bars (±SE) fitted. [Low density, low biomass (LL); high density, low biomass (HL); high density, high biomass (HH)]. Box, LL = 62% N, 82% Biomass, HL = 92% N, 73% Biomass, HH = 96% N, 96% Biomass. Electric, LL = 53% N, 76% Biomass, HL = 79% N, 69% Biomass, HH = 89% N, 96% Biomass. Hydraulic, LL = 65% N, 76% Biomass, HL = 78% N, 74% Biomass, HH = 94% N, 97% Biomass.

et al. 1987), but with such high maxima being considered exceptional. A minimum of 80 individuals/m^2 was recorded.

Length frequency histograms revealed the likely presence of a number of generational cohorts. A cohort of individuals of between 5 – 12 mm was present during the study, likely to contain 1+ individuals, and constituted the bulk of the population abundance. A second mode was present between 20–30 mm and is likely to compose 2+, 3+ and possibly older individuals. This differs from that in 2010 when the population at the St Mullins site was dominated by 2+ and 3+ cohorts (9–25 mm) (Caffrey et al. 2011), suggesting that recruitment in the intervening breeding seasons was high. A number of generational cohorts were evident from the length frequency data presented in Caffrey et al. (2011) but it was not possible to track their progress from 2012. The maximum size of an individual present in 2012 was 31.27 mm, smaller than the 32.7 mm recorded from 2010 (Caffrey et al. 2011).

Within the study area, the lowest density and biomass for *C. fluminea* was recorded at the most upstream site (site LL; Figure 1), which is immediately downstream of a major riffle. Directly downstream from this site was site HH, where the highest density and biomass was present. It is possible that individuals were displaced from the upstream site by the erosive current, particularly during high flow events (Mouthon 2003), or migrated naturally downstream from the LL to the HH site, contributing to the high density and biomass at the more down-stream site.

Mean densities and biomass of *C. fluminea* varied considerably between the three sample sites, as might be anticipated in a large natural river (Table 1), allowing for the designation of sites into LL, HL and HH. Dredge removal was most effective at the high density and high biomass site (HH), with >95% reduction achieved, suggesting that further dredging trials be focused on dense *C. fluminea* populations. This effect is likely due to the high density of individuals and subsequent higher *C. fluminea* to substrate ratio, increasing the capture efficiency of the dredge.

Each of the three dredge devices utilised achieved a significant reduction in both density and biomass. With the experimental methods reaching a >95% reduction in density and >95% biomass at the HH site, dredge removal of *C. fluminea* may be considered for further trials to assess its long-term efficiency at reducing *Corbicula* numbers from dense populations. The lower reduction achieved at the HL (78–92%) and LL (54–65%) sites indicates that dredging should be limited to dense populations. The level of reduction achieved at the HH site (>95% reduction in numbers) is comparable to the 94% reduction achieved through suction dredging by Wittmann et al. (2012a).

Efforts were made to lessen potential impacts from dredging on native fish species (e.g twaite shad *A. fallax*, lampreys *P. marinus*; *L. fluviatilis*; *L. planeri*, smelt *O. eperlanus*, Atlantic salmon *Salmo salar*, brown and sea trout *Salmo trutta*)

by carefully timing the experimental work as in (Harvey and Lisley 1998) to avoid the spawning season and the main migratory periods for anadromous and catadromous fish species (Doherty et al. 2004; Igoe et al. 2004).

Operationally, the box dredge demonstrated a number of advantages over the electric and hydraulic devices, mainly in terms of its practicality (Figure S2). It does not require either a large generator or water pump and the ancillary equipment. Therefore, associated running costs are reduced. A number of efficiencies can be gained by use of the box dredge, notably the lower training requirement for correct use, minimal service and low setup cost. Commercial fishing gear by its nature is designed to maximise capture of adult or marketable size organisms, in a cost effective manner, providing a suitable platform to test *C. fluminea* removal.

A notable effect from the dredging activity was observed by divers in that a large number of dead or gaping clams were present in and around the furrows made by each of the dredge devices in the hours and days following the operations. It is likely that a number of *C. fluminea* were crushed but not captured during the dredging process.

This trial was conducted on a section of riverbed with two similar substrate types both dominated by sands and gravel. Further assessment of dredge removal efficiency on a variety of substrate types is required along with trials to assess the long-term potential of dredging as a control tool for invasive populations of *Corbicula* (Sousa et al. 2013). Associated impacts to native biodiversity and water quality would need to be carefully considered, including potential long-scale temporal impacts to the ecosystem (Quigley and Hall 1999; Waples et al. 2008), as well the examination of short to medium term impacts to native species diversity (Van Dolah et al. 1984; Aldridge 2000; Wittmann et al. 2012a). Further measures to mitigate against impacts (Harvey and Lisley 1998; Koel and Stevenson 2002) will need to be implemented and assessed.

The present trial has demonstrated the capacity of mechanical dredging to significantly reduce *Corbicula* numbers from a test site composed of a gravel/sand dominated substrate in a natural river system. The increasing threat posed to native biodiversity by aquatic invasive species (Simberloff et al. 2013) has expedited the need for developing and testing novel control and management strategies, with mechanical dredging showing potential to fill this requirement in certain cases.

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The following supplementary material is available for this article:

Table S1. Commercial fishing boat used to conduct dredge disturbance trials with electric dredge.

Table S2. Box dredge, prior to deployment.

Table S3. Electric dredge with cable and probes highlighted.

Table S4. Close-up of probe and cable assembly on leading edge of the electric dredge.

Table S5. Hydraulic dredge in the process of being emptied after test deployment.

Supplementary material

Figure S1. Commercial fishing boat used to conduct dredge disturbance trials with electric dredge.

Figure S2. Box dredge, prior to deployment.

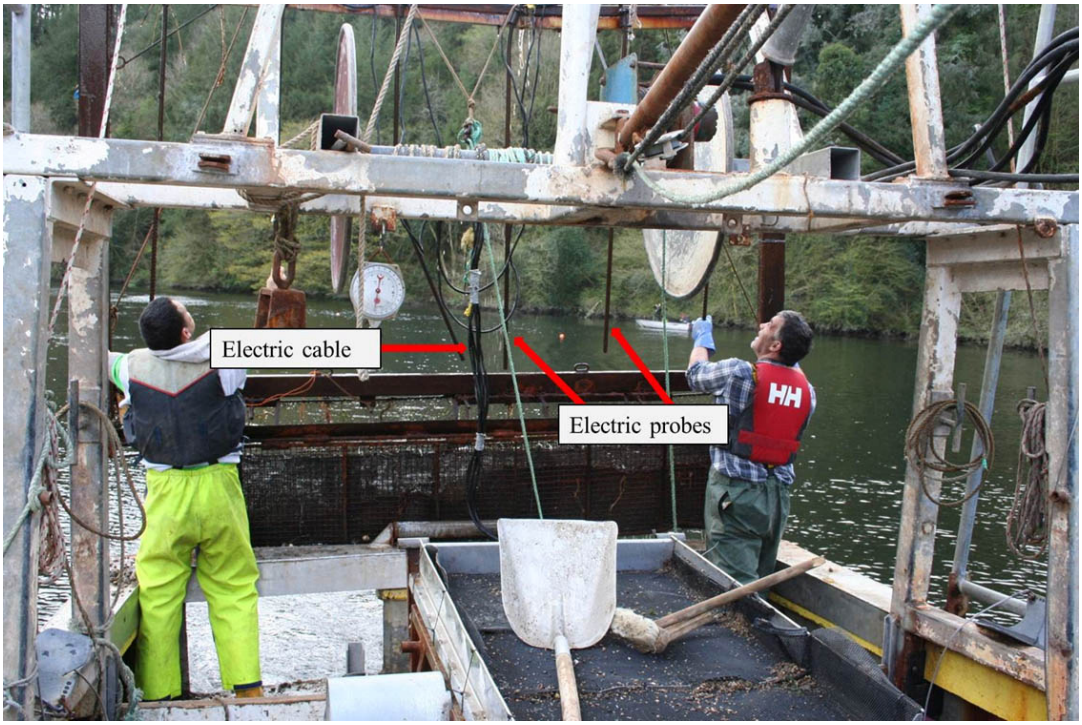

Figure S3. Electric dredge with cable and probes highlighted.

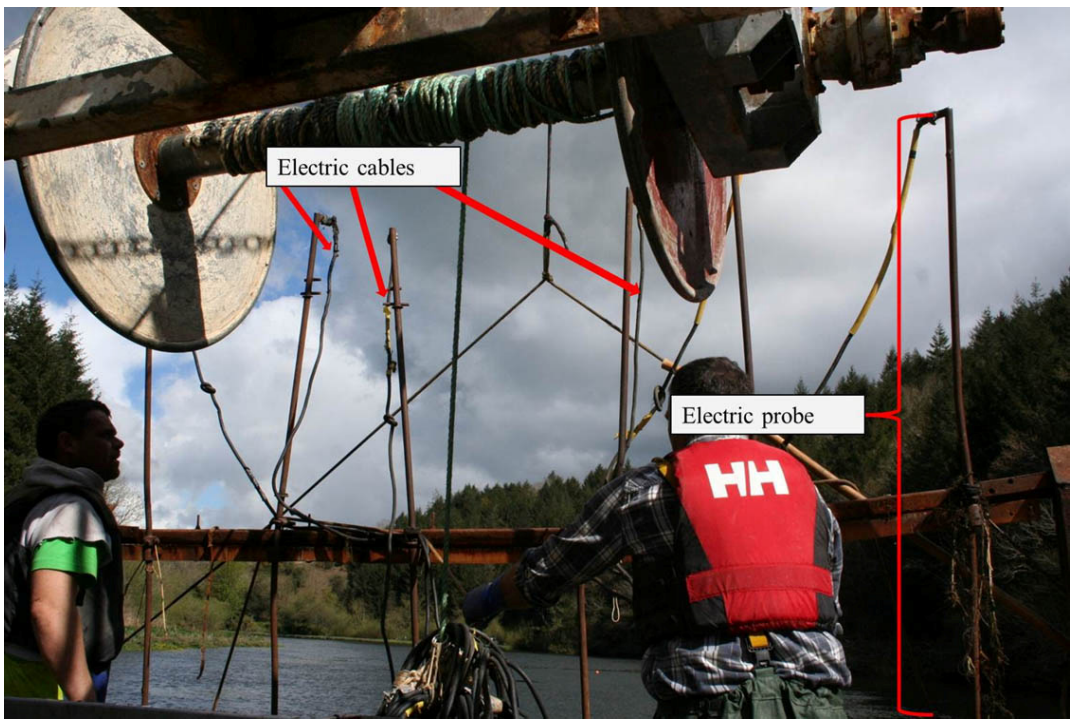

Figure S4. Close-up of probe and cable assembly on leading edge of the electric dredge. One probe and three cables highlighted.

Figure S5. Hydraulic dredge in the process of being emptied after test deployment. Water nozzles highlighted.