Beds Are Burning: eradication and control of invasive Asian clam, Corbicula fluminea, with rapid open-flame burn treatments

Coughlan, N., Cuthbert, R., Potts, S., Cunningham, E., Crane, K., Lucy, F. E., Davis, E., & Dick, J. (2019). Beds Are Burning: eradication and control of invasive Asian clam, Corbicula fluminea, with rapid open-flame burn treatments. Management of Biological Invasions. https://doi.org/10.3391/mbi.2019.10.3.06

Published in:
Management of Biological Invasions

Document Version:
Publisher's PDF, also known as Version of record

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

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**Research Article**

**Beds Are Burning: eradication and control of invasive Asian clam, *Corbicula fluminea*, with rapid open-flame burn treatments**

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**Abstract**

Eradication and suppression strategies for established populations of invasive species require innovative but readily available techniques, which maximise efficacy whilst minimising environmental damage. The Asian clam, *Corbicula fluminea* (Müller, 1774), is a high impact freshwater invader that can dominate macroinvertebrate communities and physically alter benthic habitats. Globally, despite efforts to implement substantial population control measures, *C. fluminea* continues to invade, spread and persist within freshwater environments. Accordingly, improved eradication, population suppression and rapid reaction techniques are urgently required. As *C. fluminea* beds can often become exposed during low water conditions, the present study examines the efficacy of an open-flame heat torch, generating ~ 1000 °C, in killing exposed individuals. Direct and indirect applications of the open-flame torch were examined, for *C. fluminea* residing on top of or within the substrate, respectively. Experiments revealed that ≥ 3 seconds of direct exposure to the flame causes complete mortality of *C. fluminea*, while only low mortality rates of between 8–11% were achieved for mud-dwelling *C. fluminea* following 30 seconds of indirect exposure. However, a longer exposure time of 5 minutes can cause complete mortality of buried *C. fluminea*. Further, combined rake and burn treatments, where the substrate is disturbed between one minute flame applications, can completely kill all *C. fluminea* specimens residing within beds, following multiple applications. Overall, these results demonstrate that the application of open-flame heat treatments can be used for effective, rapid response and substantial population control of *C. fluminea* populations residing upon naturally and anthropogenically exposed river, lake and canal beds. Although promising, our laboratory results require up-scaling to field application, including examination of other substrate types, increased substrate depth, and greater bed densities of *C. fluminea*.

**Key words:** invasive alien species, biosecurity, open-flame heat torch, thermal shock, population control, population suppression

**Introduction**

Invasive alien species can severely negatively impact ecological and evolutionary dynamics, and disrupt valuable economic activities within
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Coughlan et al. (2019), Management of Biological Invasions 10(3): 486–499, https://doi.org/10.3391/mbi.2019.10.3.06

Aquatic ecosystems (Simberloff et al. 2013; Sousa et al. 2014). Currently, management options for eradication and suppression of established invader populations are often complex, resource-intensive and expensive endeavours (Caffrey et al. 2011b; Wittmann et al. 2012a, b; Piria et al. 2017; Coughlan et al. 2018b). However, even if the various challenges associated with the implementation of population management strategies can be overcome, including effective outreach and public engagement (Davis et al. 2018), the efficacy of many eradication and population suppression techniques are unknown, inadequate and can be damaging to non-target species (Wittmann et al. 2012a, b; Caffrey et al. 2014; Sousa et al. 2014). Further, substantial regulatory and legal impediments, such as access to private property, operation of control measures in protected or conservation areas, lack of responsible authorities to enforce legislation, and pollution concerns, often prevent an effective rapid response (Caffrey et al. 2014; Piria et al. 2017). Accordingly, new and innovative, yet simple and readily available methodologies, which maximise efficacy of treatment towards target species, whilst minimising broad-scale environmental damage, urgently require assessment (Coughlan et al. 2018a, b; Crane et al. 2019; Cuthbert et al. 2018, 2019).

The invasive Asian clam, Corbicula fluminea (Müller, 1774) (Bivalvia, Cyrenidae; formerly Corbiculidae), is considered a high impact freshwater invader, which can dominate macroinvertebrate communities, physically alter benthic habitats, and modify community and ecosystem dynamics through their propensity to form dense benthic beds of up to 15 cm in depth (McMahon 1982; Karatayev et al. 2007; Sousa et al. 2008, 2014). These beds can cover extensive areas (e.g. 12,000 m²), which may become exposed during low tides and low river flow conditions (Caffrey et al. 2016). In addition, macrofouling of agricultural, municipal and raw water extraction systems, increased sedimentation rates, and the disruption of ecosystem regulating services caused by C. fluminea infestations, can represent a substantial economic burden to affected agencies or the local economy, e.g. closure of sport fisheries and amenity areas (McMahon 1999; Karatayev et al. 2007). Now widespread across all major river basins in Europe and the Americas (Karatayev et al. 2007; Lucy et al. 2012; Colwell et al. 2017; Gama et al. 2017), C. fluminea has shown a remarkable capacity for human-mediated passive dispersal (McMahon 2002; Sousa et al. 2008; Belz et al. 2012; Lucy et al. 2012; Coughlan et al. 2017b). For instance, despite repeated management efforts to reduce the spread of C. fluminea, it continues to advance across hydrologically unconnected freshwater systems globally (e.g. Caffrey 2010; Caffrey et al. 2011a, 2016), likely as a consequence of zoochorous dispersal and contamination of anthropogenic vectors (Coughlan et al. 2017b). In addition, the current rate of climate change will likely increase the availability of suitable habitat within new river basins, especially at higher latitudes (Gama et al. 2017).
Although effective preventative biosecurity measures have been developed to mitigate against the spread of juvenile (Barbour et al. 2013) and adult *C. fluminea* (Coughlan et al. 2019), via cleaning and disinfection of equipment, there remains an urgent need to develop and validate a suite of tools for rapid suppression and control/eradication of emerging and existing *C. fluminea* beds (Colwell et al. 2017; Coughlan et al. 2018b). To date, although extensive population control experiments have been conducted on *C. fluminea* (Wittmann et al. 2012a, b; Sheehan et al. 2014), none have been successful in providing substantial long-term management of these populations. Recently, with a series of laboratory experiments, Coughlan et al. (2018b) demonstrated that thermal shock, caused by an application of dry ice pellets (i.e. solid CO₂ pellets at −78 °C), could be used to kill tidally exposed *C. fluminea*, potentially making this method available for effective, rapid response control and possible eradication of *C. fluminea* populations. However, although the application of a relatively extreme cold temperature has been examined, the capacity of exceptionally high temperatures to cause thermal shock has not been assessed. Yet, such thermal treatments would also likely cause substantial, if not complete mortality, of *C. fluminea* residing upon and within exposed lake, river or canal beds.

Here, using simulated *C. fluminea* beds, we examine the efficacy of rapid burn treatments to kill adult *C. fluminea* through exposure to a commercially available open-flame heat torch. We hypothesize that exposure to extreme heat will result in substantial *C. fluminea* mortality due to thermal shock. We assess several key experimental factors: direct exposure to open-flame, indirect exposure for specimens buried within simulated *C. fluminea* beds, and exposure following mechanical disruption of the structural integrity of simulated *C. fluminea* beds, i.e. rake and burn treatments.

**Materials and methods**

*Specimen collection and maintenance*

Specimens of *Corbicula fluminea* were collected from the extensive, tidally exposed *C. fluminea* beds at Poulmounty on the River Barrow in the Republic of Ireland (52°29’15.11”N; 6°55’42.20”W), and transported in source water to Queen’s Marine Laboratory (QML), Portaferry, Northern Ireland. In the laboratory, specimens were housed within a controlled temperature (CT) room (11–13 °C) on a 12:12 hour light to dark schedule. These specimens were maintained in aerated aquaria using locally sourced lake water. Specimens were allowed to acclimatise to the laboratory for at least one week prior to experimentation. Moreover, only living and feeding specimens were selected for experimental work, i.e. selected specimens that were observed opening and/or extending their muscular foot. Adult *C. fluminea* were selected based on shell height (SH), i.e. the maximum...
posterior to anterior axis, “umbo to gape”. After completion of the experiments, ≥ 1000 *C. fluminea* were maintained within the aquaria for over a three month period. Greater than 95% survival of these specimens was observed.

**Experiment 1: Direct exposure to open-flame**

*Corbicula fluminea* specimens (SH: 18–26 mm; mean ± SE: 21.9 ± 0.6) were directly exposed to open-flame (∼ 1000 °C; Sheen x300 Flame Gun) for ten different exposure times of 1–10 seconds (*n* = 3 per experimental group). Groups of ten adult specimens (160 ind. m⁻²) were selected from the aquaria and placed directly onto an outdoors patch of clean fine gravel (25 cm × 25 cm; ∼ 2.5 cm deep: 15 mm stone chips) as a single clump, to simulate exposed *C. fluminea* beds. Full personal protection gear was used by all operatives and observers, with flame retardant on standby. Control groups were allowed to air dry for the longest exposure time of 10 seconds, and theses patches were not burnt. Following flame treatment, specimens were allowed to air cool for a 15 minute period, including control groups. All groups were then immediately returned to the CT room, with replicates placed individually within 600 ml of dechlorinated tap water taken from a continuously aerated source (11–13 °C) for a 24 hr recovery period, after which mortality was assessed. Specimens were considered dead if they were gaping, or if they offered no resistance to being teased apart with tweezers and did not reclose (see Matthews and McMahon 1999).

**Experiment 2: The effectiveness of direct and indirect flame exposure**

Specimens of *C. fluminea* (SH: 18–26 mm; 22.1 ± 0.7 mm) were exposed directly or indirectly to open-flame (*n* = 3 per experimental group) in simulated *C. fluminea* beds. Groups of 50 *C. fluminea* (800 ind. m⁻²) and 100 *C. fluminea* (1600 ind. m⁻²) were simultaneously exposed, directly and indirectly, respectively. Simulated mud patches (25 cm × 25 cm; ∼ 2.5 cm deep) were constructed using ∼ 1.2 kg of earth, 500 g of clean fine gravel (15 mm stone chips) and 600 ml of tap-water. To create the indirect lower layer of specimens, 100 *C. fluminea* were placed into the mud patch and randomly mixed through the substrate. The direct layer was then formed by placing 50 *C. fluminea* randomly across the surface area of the mud patch (Figure 1A). The patches were then exposed to open-flame for either 5, 10, 15, 20, 25 or 30 seconds (Figure 1B). Control groups were likewise formed into patches and allowed to air dry for the longest exposure time, and these patches were not burnt. All patches were allowed to cool for a further 15 minute period following flame exposure (Figure 1C). All specimens were then returned to water within the CT room and left to recover for 24 hrs, after which mortality was assessed, as above.
Experiment 3: Efficacy of longer burn periods for buried C. fluminea

Given that only low levels of mortality were observed for mud-dwelling C. fluminea exposed to open-flame treatments for ≤ 30 seconds (see Results), longer flame application periods were examined. Specimens of C. fluminea (SH: 18–26 mm; 21.9 ± 0.6 mm) were indirectly exposed to open-flame
treatments for either 1, 2, 3, 4, or 5 minutes \((n = 3\) per experimental group). As before, 100 \(C.\ fluminea\) (1600 ind. \(m^2\)) were randomly mixed through substrate for the creation of mud patches \((25 \text{ cm} \times 25 \text{ cm}; \sim 2.5 \text{ cm deep})\) to simulate \(C.\ fluminea\) beds. A top layer of \(C.\ fluminea\) residing upon the surface of the mud patch was not included in this experiment. Control groups were likewise formed into patches and allowed to air dry for the longest exposure time. Control patches were not burnt. Once the prescribed 15 minute cooling period had elapsed, the specimens were immediately returned to the CT room. Specimens were then left for a recovery period of 24 hrs after which mortality was assessed, as above.

**Experiment 4: Efficacy of combined rake and burn treatments**

As encapsulation of \(C.\ fluminea\) within mud appears to limit the efficacy of open-flame treatments (see Results), the combined application of rake and burn was examined. The initial raking of the substrate was to churn-up and furrow the mud patch, in order to expose greater numbers of \(C.\ fluminea\) to the subsequent open-flame treatments. Specimens of \(C.\ fluminea\) (SH: 18–26 mm; 21.6 ± 0.8 mm) were exposed to open-flame treatments for one minute, following a 30 second period of patch raking (Fiskars soil rake). The combined application of rake and burn was examined for single, double or triplicate treatments \((n = 3\) per experimental group). As before, 100 specimens were randomly mixed into a mud layer to create simulated mud patches, which were representative of a realistic \(C.\ fluminea\) bed structure \((25 \text{ cm} \times 25 \text{ cm}; \sim 2.5 \text{ cm deep})\). A top layer of \(C.\ fluminea\) residing upon the surface of the mud patch was not included in this experiment. Control groups were likewise formed into mud patches, which were each racked for three consecutive 30 second periods and allowed to air dry for a one minute period following each raking event. Control patches were not burnt. Following a 15 minute cooling period, initiated after the final burn treatment for each patch, specimens were immediately returned to the CT room. Specimens were then left for a recovery period of 24 hrs, after which mortality was assessed.

**Statistical Analysis**

Data analyses were performed using R v3.4.4 (R Core Development Team 2018). \(Corbicula fluminea\) mortality rates were analysed using logistic regression as a function of open-flame exposure treatment in each experiment. Bias-reduced logistic regression was implemented to account for instances of complete separation, whilst quasi-Binomial error distributions were integrated where residuals were overdispersed (Firth 1993). Mortality rates towards multiple layers (i.e. Experiment 2) were analysed using a generalised linear mixed model integrating a random effects structure to account for repeated measures within each experimental unit (Bates et al. 2015). Analysis
of deviance was used to derive effect sizes between nested models, with post hoc Tukey comparisons undertaken to assess specific treatment differences (Lenth 2018).

**Results**

**Experiment 1: Direct exposure to open-flame**

There was 100% survival of control *C. fluminea* and up to 100% mortality for *C. fluminea* exposed to open-flame in this experiment (all $P < 0.05$) (Figure 2). Mortality of *C. fluminea* was significantly affected by heat torch treatment time overall ($\chi^2 = 184.55, df = 10, P < 0.001$). While some *C. fluminea* survival was noted following 1 and 2 seconds, total mortality was reliably achieved following exposures of 3 seconds or longer.

**Experiment 2: The effectiveness of direct and indirect flame exposure**

There was between 98–100%, min.-max., survival of control *C. fluminea* residing on the surface of the simulated patch, and 100% mortality of *C. fluminea* directly exposed to open-flame treatments (Figure 3A). For *C. fluminea* mixed into the mud layer, there was between 98–99% survival of control groups and between 8–11% mortality of *C. fluminea* indirectly exposed to open-flame treatments at the longest exposure time of 30 seconds (Figure 3B). Application of direct open-flame treatments significantly influenced mortality overall ($\chi^2 = 190.17, df = 6, P < 0.001$), with all flame exposures causing significantly greater mortality than controls (all $P < 0.001$). However, whilst total mortality of *C. fluminea* at the surface was caused by open-flame treatments at 5 seconds or longer, mortality rates in the mixed layer were significantly lower, with high survivability exhibited following all flame treatments ($\chi^2 = 273.25 df = 1, P < 0.001$).
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**Figure 3.** Mean mortality (± SE) of 50 adult *Corbicula fluminea* specimens (800 ind. m⁻²; A) and 100 specimens (1600 ind. m⁻²; B), 24 hrs post direct or indirect exposure to open-flame treatments, for up to 30 seconds, respectively (n = 3).

**Experiment 3: Efficacy of longer burn periods for buried *C. fluminea***

There was 98–99% survival of control *C. fluminea* and up to 100% mortality of *C. fluminea* exposed to open-flame at the longest exposure period of five minutes (Figure 4). Indirect exposure to open-flame treatments had a significant impact on *C. fluminea* mortality rates ($F_{5,12} = 38.96$, $P < 0.001$). Mortality rates of indirectly flame treated *C. fluminea* were significantly higher than that of control groups for all exposure times (all $P < 0.05$). However, mortality rates following 1 minute flame applications were significantly lower than all other exposure times (all $P < 0.05$). Mortality rates following 4 and 5 minute exposures were significantly higher than those recorded from 2 and 3 minute exposures (all $P < 0.05$). However, not all treatments achieved 100% mortality (Figure 4).

**Experiment 4: Efficacy of combined rake and burn treatments***

There was 98–99% survival of control *C. fluminea* and up to 100% mortality of *C. fluminea* exposed to the combined rake and burn treatment...
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Figure 4. Mean mortality (± SE) of 100 adult Corbicula fluminea specimens (1600 ind. m⁻²) 24 hrs post indirect exposure to open-flame treatments, for up to five minutes (n = 3).

Figure 5. Mean mortality (± SE) of 100 adult Corbicula fluminea specimens (1600 ind. m⁻²) 24 hrs post exposure to the application of combined 30 second rake and one minute burn treatments; performed as a single, double (×2) or triplicate (×3) treatment (n = 3).

conducted in triplicate (Figure 5). Mortality of C. fluminea was significantly affected by combined rake and burn treatments ($\chi^2 = 1008.90$, $df = 3$, $P < 0.001$). All applications of the combined treatments, i.e. single, double or triple, resulted in significantly higher mortality rates than control groups (all $P < 0.001$). In turn, application of the combined rake and burn treatment in triplicate was significantly more efficacious than single and double applications (both $P < 0.05$). However, a double application was significantly more effective than a single for causing C. fluminea mortality ($P < 0.001$; Figure 5). We achieved 100% C. fluminea mortality with three sessions of rake and burn (Figure 5).

Discussion

Experiment 1 has shown that application of open-flame burn treatments can cause complete C. fluminea mortality at exposure times of ≥ 3 seconds,
for directly exposed surface dwelling clams. Experiment 2 highlighted that larger groups of surface dwelling *C. fluminea* (50 ind. group⁻¹; 800 ind. m⁻²) will also be rapidly killed following ≥ 5 seconds of exposure to open-flame. Although encapsulation of *C. fluminea* within substrate can substantially reduce the efficacy of open-flame treatments on *C. fluminea* mortality, Experiment 3 has shown that longer burn times can result in up to complete mortality of buried specimens (100 ind. group⁻¹; 1600 ind. m⁻²). Importantly, Experiment 4 revealed that disturbing the sediment immediately prior to application of open-flame treatments can substantially increase *C. fluminea* mortality. In essence, raking of the sediment was visually observed to churn specimens upwards towards the surface (NEC, SP and JTAD, pers. obs.), with the associated furrowing of the substrate likely increasing overall surface area and allowing deeper penetration of the applied flame. These combined rake and burn treatments caused complete mortality of *C. fluminea* following three applications (100 ind. group⁻¹; 1600 ind. m⁻²). Accordingly, these results demonstrate that the application of open-flame burn treatments can potentially be used for effective, rapid response and substantial population control of *C. fluminea* populations residing upon exposed river, lake and canal beds. In effect, we suggest that such treatments could form part of a suite of tools available for control of this and similar invaders.

Although underwater flame torches can be obtained, deployment of such devices would likely be costly and labour-intensive. Currently, techniques such as mechanical dredging methods and the use benthic barriers (e.g. polyethylene and rubber), can achieve a short-term suppression of *C. fluminea* populations residing in deeper waters (Wittmann et al. 2012a, b; Sheehan et al. 2014). In particular, dry ice applications have been observed to be highly efficacious for *C. fluminea* that were buried within gravel or mud, due to the freezing of their surrounding substrate, even when *C. fluminea* beds are submerged by water (Coughlan et al. 2018b). Although these strategies also remain expensive and laborious, and can have detrimental impacts on native species, the overall effectiveness of management efforts may be enhanced through use of open-flame treatments on exposed banks and river beds. In particular, as Experiment 4 has shown that the disturbance of the substrate surface layer through raking provided greater efficacy of open-flame burns, multiple rake and burn treatments may improve the control of tidally accessible *C. fluminea*.

In general, although rapid exposure times to burn treatments can cause complete *C. fluminea* mortality within seconds, longer exposure times were required for mud buried *C. fluminea*. The ability of open-flame treatments to exterminate or suppress populations of other sedentary invaders, such as zebra mussels *Dreissena polymorpha* Pallas, 1771; quagga mussels *Dreissena rostriformis bugensis* Andrusov, 1897; golden mussel *Limnoperna fortunei*
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Dunker, 1857, also requires examination. Notably, open-flame treatments may be particularly effective for species which do not bury into substrate. However, consideration will need to be given to mussel clustering and layering, whereby outer layers may shield underlying mussels. Additionally, thermal shock caused by open-flame treatments may potentially result in a degree of invertebrate drift and mortality of native species (Eriksen et al. 2009; Kjerstad and Arnekleiv 2011). However, given the high levels of biological connectivity and species recolonization times associated with lotic systems (Yount and Niemi 1990; Caffrey et al. 2010; Wittmann et al. 2012a, b; Coughlan et al. 2017a), open-flame burning may be a suitable management tool that will be followed by rapid recovery. Moreover, short-term negative impacts associated with invader eradication can potentially be outweighed by the long-term positive conservation benefits gained by removing damaging invaders (Woodford et al. 2013). Despite this, the efficacy of open-flame treatments will need to be further explored under natural field conditions, with consideration for potential impact on non-target organisms inhabiting *C. fluminea* beds. Moreover, despite apparent invader control or eradication success, prediction of a long-term population response to any management strategy can be challenging. Only long-term monitoring will truly reveal the impacts of any control methodology (Wittmann et al. 2012b).

Overall, when taken together, our four experiments demonstrate that open-flame treatments can cause substantial *C. fluminea* mortality. Accordingly, open-flame treatments can potentially be used for effective, rapid response, and substantial population control of *C. fluminea* populations on exposed areas of river, lake and canal beds. Yet, may not be suitable for certain inaccessible locations, such as deep muddy bank areas. However, additional research is required to assess the effect of *in situ* factors such as different substrate types, increased substrate depth, and greater *C. fluminea* population densities. In addition, in the present study, we have only examined mortality rates 24 hrs post-exposure. Future research should also examine potential sub-lethal effects upon *C. fluminea*, other invaders and non-target organisms, which may not be killed during initial application of the treatment. Furthermore, examination of synergistic mechanisms to increase *C. fluminea* mortality should be considered. For instance, following the application of a rake and burn treatment, the target area could be further treated with dry ice (see Coughlan et al. 2018b), which may potentially increase mortality rates through additional thermal shock. Equally, multiple applications may be necessary for complete extermination to be achieved. Importantly, the proposed methods provide a means for killing *in situ* at sites where they already reside, rather than requiring the relocation of biological waste material following treatment. However, a thorough assessment of residual
treatment effects on biodiversity, such as decomposition, is required. Given the current paucity of effective, environmentally-friendly, rapid response invader eradication and control protocols, the apparent excellent potential of the novel, innovative and readily available method of open-flame burning, particularly rake and burn applications, should be further explored.

Acknowledgements

The authors gratefully acknowledge support from the Irish Environmental Protection Agency project “Prevention, control and eradication of invasive alien species” (2015-NC-MS-4). JTAD also acknowledges funding received from the Natural Environment Research Council. We particularly thank Inland Fisheries Ireland and Diarmuid McSweeney for specimen collection. We also thank Emma Gorman, Simon Exley, Dr Lawrence Eagling, Patrick Joyce, Nick Horne, Victoria Cairnduff, Amy Dunn and Stephen Younger for their helpful contributions. In addition, we thank Prof Geoff McMullan and Dr Alison Dunn for flame torch technical support. We also graciously thank Dr Calum MacNeil and two anonymous reviewers for helpful comments.

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