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Research Paper

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Zebra mussels in Northern Ireland

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This paper gives an introduction to the impacts and control of the zebra mussel, an invasive alien species found in water bodies across the island of Ireland. It outlines vectors and routes for further spread into un-infested waters and discusses proactive and reactive measures to limit spread and remove existing infestations. It also provides an overview of existing legislation which applies to zebra mussels in Northern Ireland, Ireland, the UK and the EU.

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Key Points

- Zebra mussels live in freshwater bodies such as lakes, canals and rivers and are present across Northern Ireland and Ireland.
- Zebra mussels change the waterbodies they invade by filtering the water and concentrating nutrients at the bottom of the lake.
- They can cause economic damage by building up large encrustations in water pipes and on other hard surfaces.
- Preventing the spread of zebra mussels relies on users of waterbodies to clean and inspect their vessels and equipment.
- Native freshwater mussel species can be wiped out from waterbodies by zebra mussels.
- Eradication of established mussels is largely not possible and currently relies on high effort manual techniques or widespread chemical application.
- Potential non-chemical control options are still in testing and involve application of targeted toxins.

Executive Summary

Zebra mussels are an invasive aquatic species with a mobile larval stage which can be carried through the water, and a sessile adult stage which attaches to hard surfaces. They have spread from the Caspian and Black sea basins across Europe, arriving in Ireland in the 1990s. Their ability to be carried naturally through water courses has meant they are now present in many waters across the island of Ireland. Both adult and larval stages can be spread further overland by human activities, namely boating. By attaching to the hulls of boats, adult zebra mussels can be transported up watercourses or carried overland between water systems. Boats also offer the opportunity for transportation in ballast or engine coolant water. Boats which are slipped less often and regularly transferred between water bodies represent the greatest risk for spread.

In order to obtain food zebra mussels filter water, reducing the number of phytoplankton and zooplankton in the water. Anything they do not recognise as food they will then secrete to the bottom of the lake. This significantly impacts the nutrient cycles present within the lake, concentrating energy to the bottom and increasing water clarity. This has knock-on effects for the fish and plankton communities in the lake. There have also been studies analysing the impact of zebra mussel presence on the relationship between nutrient input and blue-green algal blooms. By altering the nutrient cycle and selectively feeding on certain phytoplankton zebra mussels can de-couple this relationship, making it harder to predict the consequences of changing nutrient input levels.

Due to their high reproductive rate and ability to spread widely within waterbodies, full eradication of zebra mussels is generally not possible. In cases where infestation is new and localized, hand removal or oxygen deprivation can reduce numbers below a viable population size. In environments where large scale chemical treatment may not affect other species, for instance water treatment plants, numbers may be controlled, however, new individuals are likely still being introduced from the source. New control methods are currently being trialed which target zebra mussels more specifically than chemical treatments and would therefore be usable in open

water with other species present. This includes Zequanox, a biopesticide comprised of dead bacteria, and BioBullets, which encapsulate a toxic compound in a palatable coating. The strategy of both these methods is to create a treatment which the zebra mussels don't identify as harmful and will continue to feed on, unlike chemicals which cause them to close and therefore prolong treatment.

Given the economic cost and challenge of management, proactive action is key to preventing establishment of zebra mussels in new waters. Northern Ireland has produced numerous guidance resources, including codes of practice and draft pathway action plans, for water users including boaters and anglers. The Check, Clean, Dry campaign provides an annual focus point for education on biosecurity and invasive species spread within aquatic environments. Invasive species are also covered by multiple legislative instruments including EU regulation No 1143/2014 and The Wildlife (Northern Ireland) Order 1985, as amended by the Wildlife and Natural Environment Act (Northern Ireland) 2011.

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1 Introduction

1.1 Distribution

The zebra mussel (*Dreissena polymorpha*) is a species of small freshwater mussel originally from the river basins of the Caspian, Azov and Black Seas in Eastern Europe.[1] When canal networks developed throughout Europe in the 1700s the zebra mussel spread on boat hulls and in ballast water across the continent.[2] From here it was introduced to the United Kingdom (UK) on un-sawn logs from the Baltic in 1824.[3] Zebra mussels also arrived in North America in 1985-1986 after being transported in ballast water[4] and are now naturalised in the navigable waters east of the rocky mountain chain.[5]

The first official record of zebra mussels in Ireland was 1997 in Lough Derg on the Shannon River.[6] Examining the age of these individuals and later genetic testing linked these mussels to an import of second hand boats from Britain in 1993-1994.[7] The first Northern Ireland report was in Lower Lough Erne in 1996.[8]This was the result of zebra mussel fouled boats travelling along the Shannon-

[1] A Y Karatayev and L E Burlakova, 'What we know and don't know about the invasive zebra (Dreissena polymorpha) and quagga (Dreissena rostriformis bugensis) mussels' (2022) *Hydrobiologia*, p21

[2] B S Morton, 'The anatomy of Dreissena polymorpha and the evolution and success of the heteromyarian form in the Dreissenoidea'. In: T F Nalepa and D W Schloesser (eds.) *Zebra Mussels: Biology, Impacts and Control* (1993) p190

[3] J Coughlanm, 'The Origins and Status of the Zebra Mussel Dreissena polymorpha in the UK.' Abstracts of an International Workshop on Zebra Mussels, Galway, Ireland. (1998) p7

[4] As cited directly above, p9

[5] D Minchin and C Moriarty, *Zebra mussels in Ireland*, Fisheries leaflet 177, Marine Institute, Fisheries Research Centre, Dublin (1998) p3

[6] T K McCarthy, J Fitzgerald and W O'Connor, 'The Occurrence of the Zebra Mussel Dreissena polymorpha (Pallas, 1771), an Introduced Biofouling Freshwater Bivalve in Ireland', *The Irish Naturalists' Journal* (1997) Vol. 25, No. 11/12, p1

[7] B Pollux et al., 'Zebra mussels (Dreissena polymorpha) in Ireland, AFLP- fingerprinting and boat traffic both suggest an origin from Britain' (2003) *Freshwater Biology*, vol. 48, issue 6, p1

[8] R S Rosell et al., 'First Reported Settlement of Zebra Mussels Dreissena Polymorpha in the Erne System, Co. Fermanagh, Northern Ireland' (1998) *Biology and Environment: Proceedings of the Royal Irish Academy*, Vol. 98B, No. 3, p1

Erne canal. Across Ireland, zebra mussels expanded through the Shannon, Boyle, Corrib and Erne navigations, spreading outside these connected waterways to Lough Derravaragh, County Westmeath in 2002. The first record of zebra mussels in Lough Neagh, the largest lake in the UK, was in 2005 on boat hulls.[9] As of 2005, zebra mussels have spread overland and in water to at least 57 lakes in Ireland.[10] In 2009, empty shells were found in the River Barrow near Athy but there have been no confirmed records from Cork, Kerry or the south-east of Ireland to date.[11]

[9] S P McLean et al., 'Establishment of the zebra mussel Dreissena polymorpha (Pallas, 1771) In Lough Neagh, Northern Ireland', *Biology and Environment: Proceedings of the Royal Irish Academy* (2010) Vol. 110B, No. 1, p1

[10] D Minchin, F Lucy and M Sullivan, 'Ireland: A new frontier for the zebra mussel Dreissena polymorpha (Pallas)', *Oceanological and Hydrobiological Studies* (2005) Vol. 34, Supplement 1, p1

[11] National Biodiversity Data Centre, Ireland, *Dreissena (Dreissena) polymorpha | Zebra Mussel*, accessed (24/10/23)

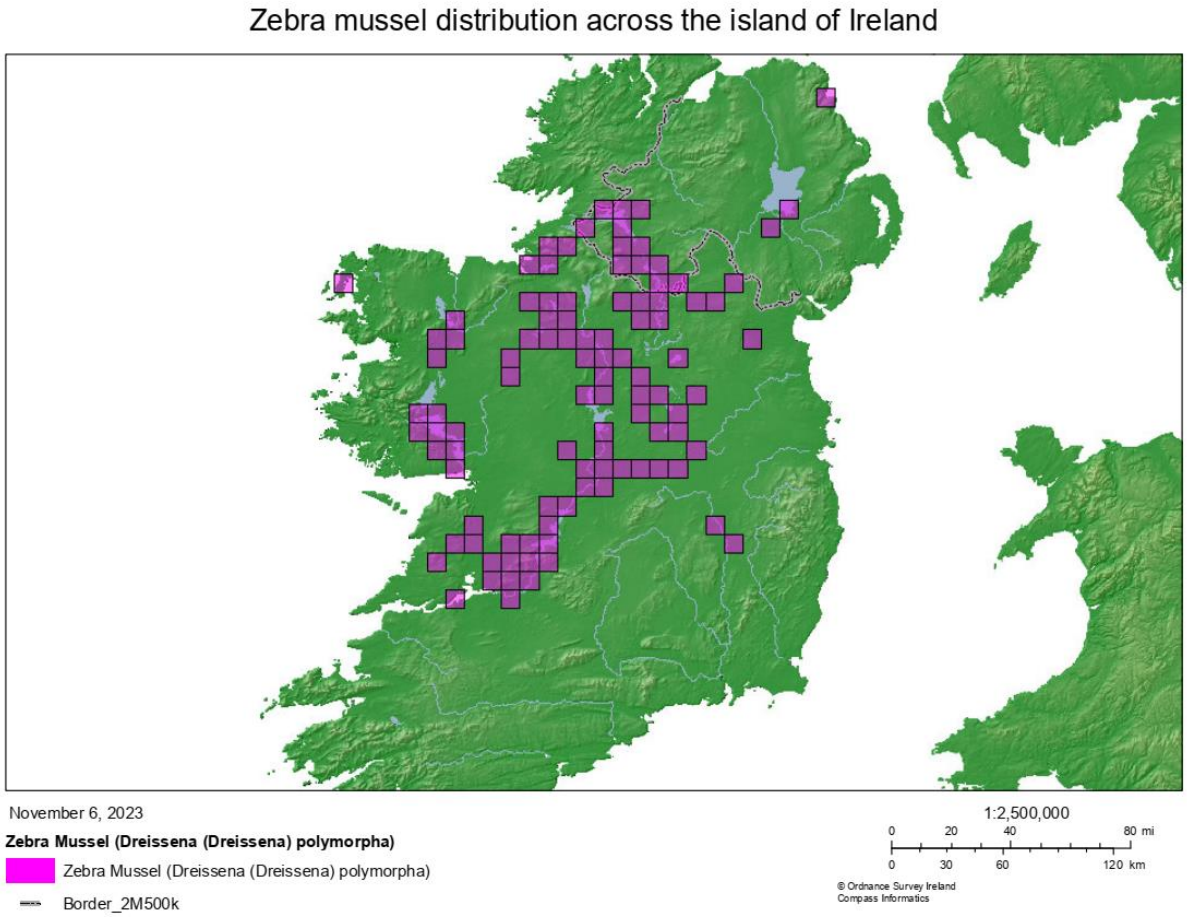

Figure 1. Distribution of zebra mussels on the island of Ireland, 10km squares. Generated from Biodiversity Maps portal of The National Biodiversity Data Centre (6/11/2023)

1.2 Biology

Zebra mussels grow to 3-4cm and generally live 2-3 years.[12] Zebra mussel growth rate is impacted by water temperature, quality, food availability and body size. Their shells have an asymmetric D shape and are identifiable from their yellow-brown colour with dark brown stripes. They live in slow-flowing freshwater such as canals, docks, lakes, reservoirs, slow rivers and water pipes. The densest aggregations are generally found in lakes.

Zebra mussels obtain food and oxygen by filtering water and secrete anything they do not identify as food as pseudofeces. They eat microscopic plants and

[12] Northern Ireland Environment Agency, Zebra mussel ID guide (accessed 07/11/2023)

animals in the water, called phytoplankton, bacteria, small zooplankton and bacterio-plankon. The result of this filtering is clearer water and lake productivity being focussed to the bottom. An individual mussel can filter up to one litre of water a day meaning the zebra mussels in Lough Erne can filter the whole lake in two weeks.[13]

Unlike the UK's other species of free-living freshwater mussels, zebra mussels attach to surfaces using hundreds of byssal threads rather than living free in the sediment. This means they can form dense aggregations on a range of surfaces, including buoys, boat hulls and water pipes. This is known as biofouling and can build up to 30cm deep (Figure 1).[14] Reports in Ireland have reached 10,000 individuals/m^2 with a biomass of ≥2kg/m^2.[15] [16]

Zebra mussels grow and reproduce quickly, meaning they can rapidly establish large populations in new sites. Their life cycle is as follows:[17]

1. adults spawn when water temperature reaches 12°C-15°C (generally May-September in Ireland)[18];
2. larvae then form from fertilised eggs and the period of larval production can last 6-52 weeks;
3. microscopic larvae (called veligers) drift for 3-4 weeks travelling up to 300km then settle on hard surfaces Summer-Autumn. In Ireland the highest abundance is in June-August[19];

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[13] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p5

[14] D Minchin and C Moriarty, *Zebra mussels in Ireland*, Fisheries leaflet 177, Marine Institute, Fisheries Research Centre, Dublin (1998) p3

[15] A Zaiko, D Minchin and S Olenin '"The day after tomorrow": anatomy of an 'r' strategist aquatic invasion', *Aquatic Invasions* (2014) Vol. 9, Issue 2, p151

[16] D Minchin, F Lucy and M Sullivan, 'Monitoring of zebra mussels in the Shannon-Boyle navigation, other navigable regions and principal Irish lakes, 2000 & 2001', *Marine Environment and Health Series* (2002) No. 5, p5

[17] As cited in footnote 13, p5

[18] As cited in footnote 16, p11

[19] F Lucy, Early life stages of Dreissena polymorpha (zebra mussel): the importance of long-term datasets in invasion ecology, *Aquatic Invasions* (2006) Vol. 1, Issue 3, p174

4. juveniles develop into adults and continue to grow.

2 Vectors

> Pathways – The route by which a species enters a new area, for instance the movement of boats between loughs
>
> Vector – The physical transfer mechanism which introduces a species, for instance ballast water or boat hulls[20]

Zebra mussels spread naturally within watercourses but vectors can introduce them into new ones. Both zebra mussel adults and larvae can survive overland transport between water bodies. Adults can survive up to a week out of water by sealing themselves shut. Often multiple introductions are required for establishment, therefore, vector risk is impacted by frequency of introductions and the life stage it introduces. Three natural vectors (birds, currents, other animals) and 20 human related ones were identified for zebra mussels and categorised by risk[21] [22]:

High risk	Medium risk
Recreational boating	Angling activities
Intentional introductions	Fisheries and aquaculture operations
Re-opening the Ulster canal	Illegal movements of eels and nets
	Accidental introduction from scientific/conservation work

[20] P Genovesi and C Shine, '*European strategy on invasive alien species*', Nature and environment, No. 137 (2004) p14

[21] L M Sykes, Developing strategies to limit the spread of the zebra mussel (Dreissena polymorpha) in Northern Ireland. MPhil thesis. The Queens University of Belfast (2003)

[22] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p10

The following sections provide further detail on the nature of each of these vectors.

2.1 Boats

Spread between disconnected water bodies is largely the result of transport on and within water vessels such as boats. Zebra mussels are able to attach to a range of solid surfaces including boat hulls, propellers, anchors and rudders.[23] They can also be carried in ballast water, engine coolant water, live wells and bait buckets. If boats are not cleaned in between leaving infested waters and entering clean waters they can introduce adults or veligers (larvae) to new sites. This is compounded by the fact that the main period of boat usage, summer, coincides with zebra mussel spawning.

Different vessels pose different risks based on the frequency of their cleaning and transport between water systems. Barges are often not removed from the water so can have large build ups of biofouling by zebra mussels.[24] They also have large surface areas and slow cruising speeds. In this way they can easily transport the mussel between connected lakes and rivers. Private boats, which are inspected and cleaned less frequently than hire boats, can also develop large encrustations[25] as biofouling can go unnoticed. Line cruisers, which are removed from the water and cleaned each year have fewer and smaller zebra mussels.[26]

Small boats such as dinghies can carry high numbers of zebra mussels and present a risk for overland spread. Angling boats in particular are moved

[23] D K Padilla, M A Chotkowski & A J Buchan Predicting the Spread of Zebra Mussels (Dreissena polymorpha) to Inland Waters using Boater Movement Patterns, *Global Ecology and Biogeography Letters* (1996) Vol. 5, No. 6

[24] D Minchin and C Moriarty, *Zebra mussels in Ireland*, Fisheries leaflet 177, Marine Institute, Fisheries Research Centre, Dublin (1998) p9

[25] As cited directly above, p9

[26] As cited in footnote 24, p9

between lakes frequently to following fishing seasons such as mayfly fishing.[27] Competitions can also mean a high number of boats new to the area are introduced to lakes, potentially carrying zebra mussels.[28]

Other water vessels such as kayaks, paddleboards, jet skis and others also have the capacity to transport zebra mussels.

2.2 Fishing

Fishing gear including nets and landing gear has the capacity to become biofouled and therefore transport zebra mussels. Bait buckets can also transport water containing veligers. Zebra mussels can be used as bait for perch and spares discarded into uncolonised lakes.[29]

2.3 Fisheries and aquaculture

Fishing equipment, cages and stocking water all have the capacity to transport zebra mussels. However, stocking water is treated with sodium chloride to counteract fish shock during transport. Low concentrations (10.0 g L^{-1}) are safe for fish but kill zebra mussel veligers.[30] Formalin used in conjunction with potassium chloride (KCl) can achieve the same thing for salmons and close relatives. However, its action on veligers is lessened by the sodium chloride.[31] Ultrafiltration is a more environmentally friendly alternative that can also prevent zebra mussel transport in water.

[27] D Minchin, C Maguire and R Rosell, 'The zebra mussel (Dreissena polmorpha Pallas) invades Ireland: Human mediated vectors and the potential for rapid intranational dispersal.' *Biology and the Environment: Proceedings of the Royal Irish Academy* (2003) vol. 103, no. 1, p28

[28] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p24

[29] As cited directly above, p14

[30] D L Waller, S W Fisher and H, 'Dabrowska, Prevention of Zebra Mussel Infestation and Dispersal during Aquaculture Operations'. *The Progressive Fish Culturist* (1996) vol. 58, issue 2, p1

[31] W J Edwards, L Babcock-Jackson and D A Culver, 'Prevention of the Spread of Zebra Mussels During Fish Hatchery and Aquaculture Activities'. *North American Journal of Aquaculture* (2011) vol. 62, issue 3, p

Eel stocking involves transporting elvers, young eels, in tanks of water between water bodies and so also poses a threat of spreading zebra mussels. However, most stocking takes place at a time of year when there are few zebra mussels in the water. Imported eels are accompanied by veterinary certificates so are not considered a risk.

2.4 Intentional introduction

There have been reports of intentional introductions from people under the mistaken impression that zebra mussels increase water quality. It is thought that zebra mussels were intentionally introduced to Lough Sheelin in County Westmeath in Ireland.[32]

2.5 Ulster canal

The Ulster canal ran for 45 miles, connecting the Erne navigation and Lough Neagh. It was originally opened in 1841 but closed in 1931. A restoration project has been underway to re-open a 13km stretch between Lough Erne in Fermanagh and Clones in Monaghan crossing the border multiple times. As Lough Erne and Lough Neagh both contain zebra mussels they will likely spread along the new waterway with the potential to biofoul new boats and connected waterbodies.

3 Impacts

Due to their ecological and economic impact zebra mussels are listed as one of the worst 100 invasive species by the International Union for Conservation of Nature (IUCN) Invasive Species Specialist Group (ISSG).[33] They are also listed

[32] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p12

[33] S Lowe, M Browne, S Boudjelas and M De Poorter, '100 of the World's Worst Invasive Alien Species A selection from the Global Invasive Species Database'. Published by The Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN) (2004) p6

as an established high risk species in Northern Ireland and Ireland[34] [35] and a moderate impacting species in other risk-assessments.[36] However, their impact varies depending on the environment they have invaded and has been suggested by some researchers to provide benefits as well as negative impacts.[37]

3.1 Ecological

Zebra mussels are ecosystem engineers which means they alter the environment around them, impacting how other species can access resources.[38] Their most impactful activity is filtering water and then excreting waste, which concentrates energy into the bottom of the lake. They also reduce the amount of zooplankton and phytoplankton in the water, altering the nutrient cycle of the lake. As a result they have profound impacts on the habitats they invade, causing increases in transparency and decreases in the levels of chlorophyll-*a*, which is an indicator of algae levels.[39] However, this does not

[34] J Kelly, C O'Flynn and C Maguire, 'Risk analysis and prioritisation for invasive and non-native species in Ireland and Northern Ireland'. A report prepared for the Northern Ireland Environment Agency and National Parks and Wildlife Service as part of Invasive Species Ireland (2013) p17

[35] C O'Flynn, J Kelly and L Lysaght, 'Ireland's invasive and non-native species – trends in introductions'. National Biodiversity Data Centre Series No. 2. Ireland (2014) p38

[36] D Minchin, 'Risk assessment of non-indigenous marine species, Ireland: including those expected in inland waters', A Report undertaken for: The Centre for Environmental Data and Recording (CEDaR), Department of Natural Sciences, National Museums, Northern Ireland (NMNI) and the Department of Arts, Heritage and the Gaeltacht, Ireland (2014) p22

[37] A Y Karatayev and L E Burlakova, 'What we know and don't know about the invasive zebra (Dreissena polymorpha) and quagga (Dreissena rostriformis bugensis) mussels' (2022) *Hydrobiologia*

[38] A R Karatayev, L E Burlakova and D Padilla, 'Impacts of zebra mussels on aquatic communities and their role as ecosystem engineers' in E Leppäkoski, S Gollasch and S Olenin (eds) *Invasive Aquatic Species of Europe: Distribution, Impacts and Spread* (2002) p434

[39] A Zaiko, D Minchin and S Olenin 'The day after tomorrow": anatomy of an 'r' strategist aquatic invasion', *Aquatic Invasions* (2014) Vol. 9, Issue 2, p149

equate to an increase in water quality as total phosphorous concentration can remain high.[40]

3.1.1 Other mussel species

Zebra mussels can colonise the shells of native mussel species such as swan and duck mussels (*Anodonta* sp.). This prevents them from opening and shutting properly, causing death by starvation. In this way zebra mussels can eradicate native mussel populations in Irish lakes. In Lough Erne the percentage of live native mussels in dredge samples was 78% in 1998 down to <1% in 2003.[41] Zebra mussels have led to the loss of *Anodonta* mussels from loughs Derg, Ree and Key.[42] At one station in Lake Erie, North America, unionid mussel populations were reduced from 53% to 0% in one year.[43] Zebra mussels can also colonise the shells of freshwater snails[44] and lead to the introduction of other associated invasive species.[45]

3.1.2 Fish

Zebra mussels fundamentally change the nutrient cycles occurring in lakes by filtering the water for food and secreting it to the bottom of water bodies. This causes increased visibility and reduced availability of certain food types, such as zooplankton and native mussel species. They can also act as a novel food

[40] M Millane, M Kelly-Quinn and T Champ, 'Impact of the zebra mussel invasion on the ecological integrity of Lough Sheelin, Ireland: distribution, population characteristics and water quality changes in the lake', *Aquatic Invasions* (2008) Vol. 3, Issue 3, p279

[41] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p8

[42] D Minchin, F Lucy and M Sullivan, 'Monitoring of zebra mussels in the Shannon-Boyle navigation, other navigable regions and principal Irish lakes, 2000 & 2001', Marine Environment and Health Series (2002) No. 5, p11

[43] D W Schloesser and T F Nalepa, 'Dramatic Decline of Unionid Bivalves in Offshore Waters of Western Lake Erie After Infestation by the Zebra Mussel, Dreissena polymorpha', *Canadian Journal of Fisheries and Aquatic Sciences* (1994) Vol. 51, number 10, p1

[44] D Minchin, F Lucy and M Sullivan, 'Ireland: a new frontier for the zebra mussel Dreissena polymorpha (Pallas)', *Oceanological and Hydrobiological Studies* (2005) Vol. 34, Supplement 1, p26

[45] F Lucy et al., 'First records of the Ponto-Caspian amphipod Chelicorophium curvispinum (Sars, 1895) in Ireland'. *The Irish Naturalists' Journal* (2004)

source themselves. As a result, it is expected that these changes will affect fish species differently, depending on which can adapt to changes in food availability. For example, Lough Erne appears to have undergone a shift from roach dominance to perch dominance as a result of zebra mussel induced changes to lake nutrient cycles.[46] Other species do not appear to show any changes in response to zebra mussels.[47] Zebra mussels can also impact fish populations by colonising their fish spawning grounds.

3.1.3 Blue-green algae

There is a misconception that the increased water clarity resulting from zebra mussel filtration equates to higher water quality. This is not the case as zebra mussels can mask the impacts of increased nutrient input and alter its impacts on lake ecology.

To date, studies investigating the link between algal blooms and zebra mussels have largely focused on North American water bodies and experimental contexts. They report a complex relationship between nutrient content, zebra mussels and algal bloom forming cyanobacteria.

By altering the nitrogen to phosphorous ratio in the water, zebra mussels can cause increases in *Microcystis* species, a type of cyanobacteria. This occurs as the result of filtering and concentrating nitrogen to the bottom of the lake and potentially also due to selective feeding.[48] These conditions created by zebra mussels may favour the growth of cyanobacteria over phytoplankton.

Varying responses of *Microcystis aeruginosa* to zebra mussels have been reported in different lakes and rivers across North America. One experiment found different impacts of zebra mussel presence on total cyanobacteria across different years, likely due to different effects on the nitrogen to phosphorous

[46] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p9

[47] AQW 7896/08

[48] O Bykova et al., 'Do zebra mussels (Dreissena polymorpha) alter lake water chemistry in a way that favours Microcystis growth?'. *Science of the Total Environment* (2006) Vol. 371, p369

ratio.[49] There may also be interactive effects between phosphorous levels and zebra mussel presence as low phosphorous (total phosphorus ~9-10 µg L^{-1}) caused zebra mussels to have a positive effect on *Microcystis* biomass and high phosphorous (total phosphorus ~40 µg L^{-1}) caused the inverse[50] [51] or no effect.[52] [53] Zebra mussels can also reduce overall algal biomass under conditions of high phosphorous.[54] Other cyanobacteria (*Aphanocapsa* and *Chroococcus*) have been shown to be affected by phosphorous fertilisation but not by zebra mussels.[55] Zebra mussels may also selectively reject blue-green algae and increase sediment-water phosphorus flux leading to algal blooms even in the absence of increased external phosphorous loadings.[56]

In summary, there are a number of factors influencing nutrient composition and balance in lakes and these factors often function on seasonal cycles. Normally, increased nutrient enrichment, such as phosphorous, would lead to increased cyanobacteria. However, the presence of zebra mussels makes it challenging to predict and control cyanobacteria blooms using monitoring and control of nutrient inputs.

[49] I Feniova et al., 'Effects of zebra mussels (Dreissena polymorpha) on phytoplankton community structure under eutrophic conditions', *Aquatic Invasions* (2020) Vol. 15, Issue 3, p443

[50] O Sarnelle et al., 'Complex interactions between the zebra mussel, Dreissena polymorpha, and the harmful phytoplankter, Microcystis aeruginosa'. *Limnology and Oceanography* (2005) Vol. 50, Issue 3, p1

[51] O Sarnelle et al., 'Phosphorus addition reverses the positive effect of zebra mussels (Dreissena polymorpha) on the toxic cyanobacterium, Microcystis aeruginosa', *Water research* (2012) Vol. 46, p3475

[52] D F Raikow et al., 'Dominance of the noxious cyanobacterium Microcystis aeruginosain low-nutrient lakes is associated with exotic zebra mussels'. *Limnology and Oceanography* (2004) Vol. 49, Issue 2, p485

[53] As cited directly above, p485

[54] A R Dzialowski and W Jessie, 'Zebra mussels negate or mask the increasing effects of nutrient enrichment on algal biomass: a preliminary mesocosm study', *Journal of Plankton research* (2009) Vol.31, number 11, p1438

[55] As cited in footnote 51, p3475

[56] V J Bierman Jr. et al., 'Modeling the Role of Zebra Mussels in the Proliferation of Blue-green Algae in Saginaw Bay, Lake Huron' Journal of Great Lakes Research (2005) vol. 31, Issue 1, p1

In Lough Erne, phytoplankton abundance is now at 10% of the peak summer maximum since zebra mussels have established. Both Erne lakes also have reduced zooplankton. Despite this, in 2003 Lower Lough Erne had an algal bloom.[57] Zebra mussels are thought to mask indicators of increased nutrient input in lakes and so algal blooms do not occur from increased nutrient loading as they usually might.

> *"Increased nutrient loading to a lake normally results in increased algal blooms. The zebra mussel de-couples the nutrient-chlorophyll relationship so this normal response does not occur"*[58]

3.1.4 Climate change

It has been noted that climate change may impact zebra mussel management and spread[59]. Increasing water temperatures may mean earlier/longer spawning periods for zebra mussels which require water temperatures of >12°C to spawn. Lower rainfall often causes mussels in shallows to freeze or dry out. However, they may become less frequent as future climate predictions are for wetter winters.[60]

3.2 Economic

The biggest economic impact of zebra mussels is biofouling. Biofouling is an accumulation of plants or animals etc. on a surface where they are not wanted and interferes with its function. Zebra mussels are capable of forming dense encrustations on a wide range of hard surfaces (Figure 2).

3.2.1 Water intake pipes

[57] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p8

[58] As directly above, p26

[59] As cited in footnote 57, p6

[60] CC West and M J Gawith (Eds.), 'Measuring progress: Preparing for climate change through the UK Climate Impacts Programme' (2005) UKCIP, p9

The inside of water intake pipes can become heavily biofouled by zebra mussel infestations. This can limit the capacity of the pipes or cause damage if colonies break off. In North America, between their discovery date in 1989 and 2004 zebra mussels cost the electricity generation and water treatment industries an estimated $267 million.[61]

Problems in screens and water intake pipes have been reported for a number of facilities in Ireland and Northern Ireland including:

- Cathleen's falls power station
- Ballyshannon and Lanesborough station
- Ardnacrusha and Parteen hydroelectric stations on the Shannon

At Lough Derg salmon fishery, water inlet pipe blockages caused 8000 salmon fry to die due to low water levels. The blockage of water intake pipes at Killyhevlin water works in Enniskillen led to costs of >£100,000 in modification.[62]

[61] N A Connelly et al., 'Economic Impacts of Zebra Mussels on Drinking Water Treatment and Electric Power Generation Facilities', *Environmental Management* (2007) vol. 40

[62] C M Maguire and L M Sykes, '*Zebra mussel management strategy for Northern Ireland 2004-2010*', Queens University Belfast (2004) p7

Figure 2. Zebra mussel-encrusted Vector Averaging Current Meter near Michigan City, IN. Lake Michigan, June 1999. NOAA, Great Lakes Environmental Research Laboratory. Image public domain, WikiMedia

3.2.2 Boats

Boats with heavily biofouled hulls can experience reduced fuel efficiency due to drag. Engine coolant pipes which have become blocked by biofouling can also

lead to engine overheating and damage.[63] Any other submerged parts of boats can also become heavily biofouled such as rudders and anchors.

3.2.3 Fishing

Limitations on boat launching to prevent the introduction of zebra mussels to uninfested lakes, especially during competitions, may impact recreational fishing. Perception of lake, and fish, quality may be impacted by zebra mussel infestation. Zebra mussels alter the nutrient balance of lakes they infest and are expected to have knock on effects for the fish populations present.

3.2.4 Recreation

Zebra mussels can cause lacerations to the feet of bathers, cut fishing lines and damage nets[64]. They can also cause unpleasant smells where water levels drop and mussels start decaying in open air.

4 Preventing spread

4.1 Physical controls

4.1.1 Bait

Anglers can prevent the transportation of zebra mussels in bait buckets by not reusing bait or bait bucket water that's been in infected waters and not using zebra mussels as bait in uninfested waters.

[63] D Minchin, F Lucy and M Sullivan, 'Zebra Mussel: Impacts and Spread'. In: E Leppäkoski, S Gollasch and S Olenin (eds) *Invasive Aquatic Species of Europe. Distribution, Impacts and Management* (2002) p145

[64] D Minchin, F Lucy and M Sullivan, 'Ireland: A new frontier for the zebra mussel Dreissena polymorpha (Pallas)', *Oceanological and Hydrobiological Studies* (2005) Vol. 34, Supplement 1, p26

4.1.2 Gear

All gear should be cleaned according to “Check, Clean, Dry” code for preventing the spread of aquatic invasive species.[65] Equipment can also be treated with hot water (>40°C) or frozen in order to kill mussels and larvae[66].

4.1.3 Boat hulls

Anti-fouling coatings on boats can help minimise spread by preventing zebra mussel attachment or easing removal. Jotun SeaLion Resilient silicone epoxy coating was the most effective hard coating out of over 100 materials tested by the U.S. Department of the Interior. It did not prevent attachment by mussels but made them easier to remove and was able to withstand abrasion better than other soft silicone foul-release coatings which fully prevented attachment.[67]

Steam cleaning boats prior to introduction into new lakes can help prevent spread. The requirement for proof of steam cleaning during competitions could reduce risk of introduction during these high-risk events. Random visual boat inspections, including outside of competitions, would help enforce this standard. From 2000-2003 the Lough Melvin Anglers Association banned all fly-fishing competitions on the lake in a bid to reduce the risk of zebra mussel introduction.[68]

4.1.4 Ballast water

Ballast water can spread aquatic invasive alien species between countries and so it is regulated by the 2004 International Convention for the Control and

[65] Invasive Species Northern Ireland, Check Clean Dry (accessed 01/11/2023)

[66] Reducing and Preventing Invasive Alien Species Dispersal, ‘Good Practice Management, Zebra mussel (Dreissena polymorpha)’, Version 1 (2018), p9

[67] A Skaja (2015) ‘Antifouling Coatings for Invasive Mussel Control Final Report ST- 2015-7095-01’ *Bureau of Reclamation Technical Service Center, Materials Engineering and Research Laboratory*, p25

[68] C M Maguire and L M Sykes, ‘*Zebra mussel management strategy for Northern Ireland 2004-2010*’, Queens University Belfast (2004) p24

Management of Ships' Ballast Water and Sediment (ratified by the UK in 2022)[69].

4.2 Education

The Northern Ireland Environment Agency (NIEA) has produced slipway signs, codes of practice for marina and slipway managers, and public awareness campaigns to empower users to take responsibility for good biosecurity measures.[70] These materials are also key to informing users which species to be aware of and require reporting.[71]

The Check, Clean, Dry (CCD) public awareness campaign has been promoted in Northern Ireland since 2012. [72]An associated border campaign has run since 2016 and CCD expanded to Ireland, Isle of Man and Channel islands in 2018.[73]

A Zebra Mussel Control Group was established by NIEA after the initial 1997 report in the Shannon-Erne system as a means to coordinate with other departments and maintain awareness of emerging best management practices.[74]

4.3 Monitoring

Early warning systems include sampling veligers from the shore or using spat collectors. Rapid response plans for the detection of a new species can ensure the right agencies are able to undertake further assessments and control measures in a timely manner.

[69] United Kingdom, *The Merchant Shipping (Control and Management of Ships' Ballast Water and Sediments) Regulations 2022* 2022

[70] AQW 3775/11-15

[71] Invasive Species Northern Ireland, Check Clean Dry (accessed 06/11/2023)

[72] Department of the Environment, *An Invasive Alien Species Strategy for Northern Ireland* (2013) p29

[73] R Muir 'Northern Ireland Non-Native Species Pathway Action Plan: Angling' (2019) p1 (Pre-consultation draft)

[74] AQW 3775/11-15

5 Controlling existing infestations

When designing a plan of control measures it is important to determine if the goal is eradication or control. Eradication is often only possible for newly established and not widely distributed populations. Even then eradication is considered nearly impossible.[75] However, control measures can still be valuable in limiting negative economic and ecological consequences and preventing further spread. A 2023 synthesis of 33 dreissenid mussel control projects summarised that defining the control project goals, objectives and thresholds for acceptable effects to non-target organisms was key to project success and utilising resources efficiently.[76] This includes identifying suitable pre- and post-treatment surveying techniques. They also highlighted the need to define the treatment area, depending on the management goals, accounting for uncertainty in dreissenid mussel detection methods. This was because many partial lake approaches discovered mussels outside their treatment area during or after treatment.

5.1 Non-chemical

5.1.1 Hand-removal

Where zebra mussel infestation is concentrated in a small area, mechanical removal can be used to reduce the population to below a self-sustaining size. Divers can use paint scrapers, chisels, screwdrivers and dull knives to remove and collect mussels. This can potentially cause damage to surfaces during removal. An underwater suction device can be used to aid collection after removal.[77] Venture dredges can be used to remove mussels in shallow water.[78] It is important that mussels are not discarded in the water as they will likely

[75] A D Dahlberg et al., 'Open water dreissenid mussel control projects: lessons learned from a retrospective analysis' (2023) *Scientific Reports*, Vol. 13, Article number 1041, p1

[76] As cited directly above, p9

[77] C Culver et al., 'Quagga and zebra mussel eradication and control tactics.' *California Sea Grant Report No. T-076/UCCE-SD Technical Report No. 2013-1*. (2013) p9

[78] As cited immediately above, p9

survive. Collected mussels can then be euthanised by either freezing for 24 hours, exposure to 40°C heat or drying out in a controlled environment.

This approach has been applied successfully in North America where zebra mussels were removed from Lake George, New York to the point where the population was no longer self-sustaining.[79] It is worth noting that this lake already had marginal chemical properties for zebra mussel survival. Manual removal is most useful when the mussels are concentrated in one area and new larvae/juveniles are not being produced or introduced.

5.1.2 Hydroblasting: High-pressure water guns

In deep lakes, high pressure hoses can be used to remove zebra mussels and allow them to fall to the bottom of lakes. Zebra mussels can survive without oxygen for one month, therefore the lake must be deep enough that the bottom consistently has a dissolved oxygen content of <2mg/L. However, repeatedly doing this can lead to a build-up of decomposing mussels, affecting water quality.[80] These hoses can also seriously injure users so require training to work with. Pressure washers can also be used in industrial contexts where infestations are accessible, however they often require shutdown of facilities.

5.2 Environmental

5.2.1 Oxygen deprivation

Zebra mussels can be killed by reducing available oxygen for at least one month. To do this, divers cover mussels with tarpaulins or benthic mats weighed down with sandbags or rebar. Adding potassium chloride (KCL), chlorine or wood shavings[81] under the mats can reduce the time needed but requires extra

[79] J Wimbush et al., 'Eradication of colonizing populations of zebra mussels (Dreissena polymorpha) by early detection and SCUBA removal: Lake George, NY.' *Aquatic Conservation: Marine and Freshwater Ecosystems* (2009) Vol 19 p711

[80] C Culver et al. 'Quagga and zebra mussel eradication and control tactics.' *California Sea Grant Report No. T-076/UCCE-SD Technical Report No. 2013-1*. (2013) p10

[81] M Wittmann et al., 'The Control of an Invasive Bivalve, Corbicula fluminea, Using Gas Impermeable Benthic Barriers in a Large Natural Lake', *Environmental Management* (2012) vol. 49, p1

environmental considerations.[82] This intervention can necessitate reduced usage of the lake to prevent the mats being moved or damaged.[83] It also leads to the dead mussels being left in the water.

This technique is most useful when sessile stages (juveniles and adults) are being targeted and the infestation is site-specific, low-moderate in size or mussels are in hard to reach places.

5.3 Chemical

Chemical control is popular and widely used as it can be used to treat entire waterbodies with large infestations or hard to reach mussels. Chemical approaches include chlorine, ozone, bromine, potassium permanganate and molluscicides.[84] However, they can negatively impact other species and the environment, therefore their application in open water requires consideration.

5.3.1 Potassium chloride (KCl)

KCl kills zebra mussels by destroying their gill membranes so they cannot filter oxygen from the water.[85] Achieving a consistent concentration can require repeatedly applying the chemical at multiple depths. This is done by using a small vessel with a diffuser system attached. The length of treatment time needed is impacted by water temperature and life cycle stage. Therefore constant monitoring and reapplication is required to ensure the desired

[82] C Culver et al., 'Quagga and zebra mussel eradication and control tactics.' *California Sea Grant Report No. T-076/UCCE-SD Technical Report No. 2013-1*. (2013) p14

[83] As cited directly above, p15

[84] C M Maguire and L M Sykes, 'Zebra mussel management strategy for Northern Ireland 2004-2010', Queens University Belfast (2004) p9

[85] S W Fisher et al., 'Molluscicidal activity of potassium to the zebra mussel, Dreissena polymorphia: toxicity and mode of action', Aquatic Toxicology (1991), vol. 20, issue 4, p1

concentration is being maintained for at least 2-4 weeks.[86] A minimum of 30mg/L at a temperature of 17°C is required to kill zebra mussels.[87]

KCl is effective against zebra mussel adults and has reduced toxicity against fish species and the unionid mussel (threehorn wartyback, *Obliquaria reflexa*) compared to other potential chemical controls.[88]

This technique has been used in North America where 174,000 gallons of KCl (100mg/L[89]) was added to Milbrook Quarry, Virginia over the course of three weeks. There was little reported effect on non-target species. However, the quarry did not contain the biodiversity present in other waterbodies.[90]

This technique is most useful when the goal is to eradicate a dense and widespread infestation, as prolonged exposure will result in negative environmental impacts. It is most effective when there is little through flow in the lake.[91]

5.3.2 Copper based treatments

Copper based treatments which are established for use as algaecides and bactericides can be effective at killing zebra mussels.[92] [93] However, when

[86] C Culver et al., 'Quagga and zebra mussel eradication and control tactics.' *California Sea Grant Report No. T-076/UCCE-SD Technical Report No. 2013-1*. (2013) p21

[87] D L Waller et al., 'Toxicity of Candidate Molluscicides to Zebra Mussels (Dreissena polymorpha) and Selected Nontarget Organisms', Journal of Great Lakes Research (1993), vol. 19, issue 4, p698

[88] As cited directly above, p698

[89] R T Fernald and B T Watson, 'Chapter 13: Eradication of zebra mussels (Dreissena polymorpha) from Millbrook Quarry, Virginia: rapid response in the real world.' In T F Nelepa and D W Schloesser, (Eds), Quagga and Zebra Mussels: Biology, Impacts, and Control. CRC Press (2014) p202

[90] As cited directly above, p208

[91] As cited in footnote 84, p20

[92] K Lund et al., 'Zebra mussel (Dreissena polymorpha) eradication efforts in Christmas Lake, Minnesota' (2018) *Lake and Reservoir Management*, Vol. 34, Issue 1

[93] D Hammond and G Ferris, 'Low doses of EarthTec QZ ionic copper used in effort to eradicate quagga mussels from an entire Pennsylvania lake' (2019) *Management of Biological Invasions,* Vol. 10, Issue 3

tested, copper products had differing toxicity depending on their formula and appeared to be more effective against quagga mussels than zebra mussels.[94]

5.4 Biological

Biological control involves the usage of other species, whether predators, parasites or diseases to control an invasive population. Currently, this technique is unlikely to eradicate populations of zebra mussels as they reproduce quickly and in high number.[95] Diving ducks will eat high numbers of zebra mussels in winter in Europe and fish such as *Ruilus rutilus* are also known to feed on adults and juvenile zebra mussels but need to be a certain size to do so.[96] Other potential fish predators of adult and juvenile zebra mussels such as the redear sunfish (*Lepomis microlophus*), common carp (*Cyprinus carpio*) and pumpkinseed (*Lepomis gibbosus*), are all non-native to the UK[97]. Fish which eat the planktonic larval stage of zebra mussels include the threadfin shad (*Dorosoma petenense*) and small (<90 mm, <3.5 inch) bluegill (*Lepomis macrochirus*). In theory, usage of these fish could be used in high-density cages during periods of high mussel settlement, using a combination of species to target all life stages.[98]

[94] RNT Consulting Inc., Efficacy of Copper Based Algaecides for Control of Quagga and Zebra Mussels (2014)

[95] D D Magoulick and L C Lewis, 'Predation on exotic zebra mussels by native fishes: effects on predator and prey'. *Freshwater Biology* (2002) Vol. 47, Issue 10

[96] A Prejs, K Lewandowski and A Stańczykowska-Piotrowska, 'Size selective predation by roach (Rutilus rutilus) on zebra mussel (Dreissena polymorpha): field studies'. *Oecologia* (1990) Vol. 83, p1

[97] Reducing and Preventing Invasive Alien Species Dispersal, 'Good Practice Management, Zebra mussel (Dreissena polymorpha)', Version 1 (2018) p7

[98] C Culver et al., 'Quagga and zebra mussel eradication and control tactics.' *California Sea Grant Report No. T-076/UCCE-SD Technical Report No. 2013-1*. (2013) p27

5.5 Other

5.5.1 Zequanox and biobullets

Zequanox © is a biopesticide made from dead bacteria developed in the US by Marrone Bio Innovations.[99] It is lethal to zebra and quagga mussels[100] but not harmful to other aquatic species.[101] As of 2019 it is currently only permitted for usage in the US where it is used in water facility pipes or other enclosed/semi-enclosed systems with an inlet and outlet. However the company was looking to expand the product into Europe at this time.[102]

When tested at concentrations lethal to zebra mussels, Zequanox was found not to be toxic to Irish freshwater species (native *Anodonta* mussels, a non-biting midge species and white-clawed crayfish).[103] It has also successfully been applied in an experimental context in a canal in Ireland, controlling up to 75% of zebra mussels.[104] In comparison to chlorine which is typically used to control zebra mussels in water treatment facilities[105] [106], Zequanox achieved similar mortality, but with a longer timeframe.[107] Unlike chlorine, however,

[99] ProFarm, Marrone Bio – Zequanox, accessed (30/10/23)

[100] D P Molloy et al., 'Pseudomonas fluorescens strain CL145A – A biopesticide for the control of zebra and quagga mussels (Bivalvia: Dreissenidae)', *Journal of Invertebrate Pathology* (2013) Vol. 113, p1

[101] D P Molloy et al., 'Non-target trials with Pseudomonas fluorescens strain CL145A, a lethal control agent of dreissenid mussels (Bivalvia: Dreissenidae)', *Management of Biological Invasions* (2013) Vol. 4, Issue 1, p77

[102] J A Luoma et al., 'Assessment of uncontained Zequanox applications for zebra mussel control in a Midwestern lake', *U.S. Geological Survey*, Open-File Report 2019–1126, p2

[103] S Meehan et al., 'Ecotoxicological impact of Zequanoxs, a novel biocide, on selected non-target Irish aquatic species', *Ecotoxicology and Environmental Safety* (2014) Vol. 107, p148

[104] S Meehan, B Gruber and F E Lucy, 'Zebra mussel control using Zequanox® in an Irish waterway', *Management of Biological Invasions* (2014) Vol. 5, Issue 3, p285

[105] Manitoba Hydro, Zebra mussels (accessed 03/11/2023)

[106] J E Van Benschoten, 'Zebra mussel mortality with chlorine', *Journal AWWA* (1995) Vol. 87, Issue 5, p1

[107] S Meehan, F E Lucy, B Gruber and S Rackl, 'Comparing a microbial biocide and chlorine as zebra mussel control strategies in an Irish drinking water treatment plant', *Management of Biological Invasions* (2013) Vol. 4, Issue 2, p20

Zequanox is not recognized as toxic by the mussels and so they remain open and feeding, enabling a shorter treatment time.

Biobullets are a capsule surrounding an active ingredient, KCl, poisonous to the target mussel. Unlike bulk applying chemicals to the water which causes the mussels to close, prolonging the necessary period of treatment, Biobullets are not recognised as toxic by the mussels so taken up by filter feeding.[108] The bullets break up naturally in the water after a few hours and so pose no risk to drinking water or other species.[109]

5.5.2 Pressure pulses

Seismic guns have been used to control invasive fish species and there is potential in using UV and seismic technology as non-toxic control alternatives.[110] Sparker pressure pulses have successfully been used to control adult zebra mussels and prevent larval settlement in a water intake pipe.[111] Plasma sparkers are currently used in utilities and industries in Canada and the US to kill adult zebra mussels and prevent settlement of new individuals.[112] Electrified fields, created by inserting electrodes into the water and running a current between them, can also kill adult zebra mussels in the electric current.[113]

[108] BioBullets (accessed 26/10/23)

[109] D C Aldridge, P Elliott, and G D Moggridge, 'Microencapsulated BioBullets for the Control of Biofouling Zebra Mussels', Environmental Science and Technology (2006) Vol. 40, Issue 3, p1

[110] J Gross, 'UV light and seismic technology as potential control strategies for dreissenid mussel invasion' presented as part of Quagga and Zebra Mussel Eradication and Control Workshop, California Sea Grant Extension and University of California Cooperative Extension (2012) p23

[111] R Schaefer, R Claudi and M Grapperhaus, 'Control of zebra mussels using sparker pressure pulses'. *Journal of the American Water Works Association* (2010) Vol. 102, Issue 4, p1

[112] G L Mackie, P Lowery and C Cooper, 'Plasma pulse technology to control zebra mussel biofouling', Zebra Mussel Technical Notes Collection (ERDC TN-ZMR-2-22), U.S. Army Engineer Research and Development Center (2000) p1

[113] J A Louma et al., 'Use of alternating and pulsed direct current electrified fields for zebra mussel control', *Management of Biological Invasions* (2017) vol. 8, issue 3, p314

5.5.3 pH

The pH tolerance of zebra mussels is 7.5-9.3.[114] A more acidic environment, pH 7.1-6.9, created using phosphoric acid, can prevent settlement and cause mortality through erosion of shells.[115] Greater reductions, pH3 for 48 hours, can cause 100% mortality.[116] Lake conditions such as conductivity and calcium levels can affect the impact of pH depression.[117] Increased pH (≥9.6) using sodium hydroxide can also prevent settlement. However this is similarly affected by lake conditions and significant increases in pH can be impeded by the formation of unmanageable solid precipitate.[118] Very high pH (pH10-12) can lead to significant mortalities.[119]

6 Legislation

The introduction of zebra mussels represents an economic and ecological threat to waterbodies and as such is regulated by a number of national and international instruments. A full list of legislation relating to invasive species is outlined in the 2013 Invasive Alien Species Strategy for Northern Ireland.[120] Below, legislation relevant to zebra mussels is discussed further.

6.1 EU

EU regulation 1143/2014, which came into force 1 January 2015, sets out "*rules to prevent, minimise and mitigate the adverse impact on biodiversity of the*

[114] R Claudi et al., 'Impact of pH on survival and settlement of dreissenid mussels' *Aquatic Invasions* (2012) vol. 7, issue 1, p22

[115] R Claudi et al., 'Impact of pH on survival and settlement of dreissenid mussels' *Aquatic Invasions* (2012) vol. 7, issue 1, p28

[116] R Claudi et al., 'Evaluating Low pH for Control of Zebra Mussels', RNT Consulting Inc (2012) p2

[117] As cited immediately above, p25

[118] R Claudi et al., 'Evaluating High pH for Control of Dreissenid Mussels', RNT Consulting Inc (2012) p2

[119] As cited immediately above, p3

[120] Department of the Environment, *An Invasive Alien Species Strategy for Northern Ireland* (2013) p7

introduction and spread within the Union, both intentional and unintentional, of invasive alien species".[121] This restricts any species listed as being of Union concern from being:

- brought into the territory of the Union, including transit under customs supervision;
- kept, including in contained holding;
- bred, including in contained holding;
- transported to, from or within the Union, except for the transportation of species to facilities in the context of eradication;
- placed on the market;
- used or exchanged;
- permitted to reproduce, grown or cultivated, including in contained holding;
- released into the environment.[122]

It tasks Member States with managing species already widely spread in their territory, taking measures for early detection and rapid eradication and taking preventative action on pathways of unintentional introduction. There are currently 88 species, including 47 animals, listed as being of Union concern.[123] The list does not include zebra mussels.

In response to the EU invasive alien species regulation, Northern Ireland has produced draft Invasive Non-Native Species (INNS): Recreational Boating[124]

[121] European Union, *EU Regulation No 1143/2014 on the prevention and management of the introduction and spread of invasive alien species* 2014, Chapter 1, Article 1

[122] European Union, *EU Regulation No 1143/2014 on the prevention and management of the introduction and spread of invasive alien species* 2014, Chapter 2, Article 7, paragraphs 1 & 2

[123] European Union, *Commission implementing regulation (EU) 2016/1141, adopting a list of invasive alien species of Union concern pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council* 2016, Annex

[124] Invasive Species Northern Ireland, '*Northern Ireland (NI) Invasive Non-Native Species (INNS): Recreational Boating Pathway Action Plan (PAP)*' (2020) (Pre-consultation draft)

and Angling[125] Pathway Action Plans (PAPs) which outline actions to increase biosecurity and reduce the risk of spread by boats and angling.

Article 22 paragraph (b) of the EU Habitats Directive also requires that the deliberate introduction of any non-native wild species is regulated or prohibited to preserve the natural habitats present.[126] The European Marine Strategy Framework Directive (MSFD) includes a set of qualitative descriptors for determining 'good environmental status' for Member States' marine waters. This includes "Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems". [127] [128]

6.2 UK

The EU regulation 1143/2014[129] was retained under the European Union (Withdrawal) Act 2018[130] and amended using statutory instruments for application in Great Britain. For Northern Ireland, EU regulation 1143/2014 is listed in Annex 2 of the Ireland/Northern Ireland Protocol[131] and therefore remains in force under the Windsor Framework[132]. In 2022 the International Convention for the Control and Management of Ships' Ballast Water and Sediments (2004) came into force in the UK. This convention takes steps to

[125] Invasive Species Northern Ireland, *'Northern Ireland Non-Native Species Pathway Action Plan: Angling'* (2019) (Pre-consultation draft)

[126] European Union, *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora* 1992, Article 22 paragraph (b)

[127] European Union, *Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (Text with EEA relevance)* 2008, Annex I, descriptor (2)

[128] United Kingdom, *Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (Text with EEA relevance)* 2008

[129] UK legislation, *EU Regulation No 1143/2014* 2014

[130] UK legislation, *European Union (Withdrawal) Act 2018* 2018

[131] Protocol on Ireland/Northern Ireland.

[132] The Windsor Framework.

prevent the spread of invasive alien species through ballast water by ensuring ballast water or sediment is not discharged without proper management.[133]

Zebra mussels are listed in 35 invasive species country checklists, including the UK[134] and Ireland[135], compiled by the Global Register of Introduced and Invasive Species. However, zebra mussels are not a species of special concern in Great Britain.[136]

6.2.1 England and Wales

In England and Wales 30 animals are of concern due to their invasiveness and the problems they cause for native species. Zebra mussels are not on this list.[137]

The Wildlife and Countryside Act 1981 (WCA) section 14[138] bans the release into the wild of any animal that is:

- not a resident;
- a regular visitor in the wild in Great Britain;
- listed in Schedule 9 of the WCA.[139] This includes already established non-native species which continue to pose a conservation threat and native species whose releases should be closely monitored (usually as part of re-introduction programmes).

[133] UK legislation, *The Merchant Shipping (Control and Management of Ships' Ballast Water and Sediments) Regulations 2022* 2022

[134] Global Register of Introduced and Invasive Species, United Kingdom checklist, (accessed 30/10/2023)

[135] Global Register of Introduced and Invasive Species, Ireland checklist, (accessed 30/10/2023)

[136] Non-native Species Secretariat, Non-native species information portal, Species of Special Concern (accessed 30/10/2023)

[137] UK Government, Guidance: Invasive non-native (alien) animal species: rules in England and Wales, Last updated 20 September 2022 (accessed 30/10/2023)

[138] UK legislation, *Wildlife and Countryside Act 1981* 1981, Section 14 England & Wales, subsection 1

[139] As cited immediately above, Schedule 9, Part 1

Penalties range from receiving a warning to two years in prison for an indictable offence.

6.2.2 Scotland

The Wildlife and Countryside Act 1981, as amended by the Wildlife and Natural Environment (Scotland) Act 2011[140] and 2012[141], prevents the release of animals outside their native range. This is laid out in the Scottish Government's Code of Practice on Non-Native Species, created under section 14C of the Wildlife and Countryside Act 1981.[142]

6.2.3 Northern Ireland

The Invasive Alien Species (Enforcement and Permitting) Order (Northern Ireland) 2019 enforces the requirements of the EU Regulation 1143/2014 through criminal offences. The Order came into operation on 1 December 2019. Zebra mussels are included in Schedule 9 Part 1 of The Wildlife (Northern Ireland) Order 1985, as amended by the Wildlife and Natural Environment Act (Northern Ireland) 2011,[143] making it an offence to release them into the wild.[144]

The Northern Ireland Invasive species strategy was published in 2013[145] and a revised plan issued in 2018.[146] In Northern Ireland reporting invasive species is

[140] Scotland, *Wildlife and Natural Environment (Scotland) Act 2011* 2011, Part 2, Section 14

[141] Scotland, *The Wildlife and Countryside Act 1981 (Keeping and Release and Notification Requirements) (Scotland) Order 2012* 2012, Schedule 1, Part 1

[142] The Scottish Government, *Code of Practice on Non-Native Species* (2012) p8

[143] Northern Ireland, *Wildlife and Natural Environment Act (Northern Ireland) 2011* 2011, Schedule 1, Paragraph 9

[144] Northern Ireland, *The Wildlife (Northern Ireland) Order 1985* 1985, Schedule 9, Part 1

[145] Department of the Environment, *An Invasive Alien Species Strategy for Northern Ireland* (2013)

[146] Department of the Environment, *Northern Ireland Invasive Alien Species Implementation Plan (Revised 2018)* (2018)

done through CEDaR (Centre for Environmental Data and Recording) online recording.[147]

There are many other legislative and regulatory measures in place which impact the fishing industry in Northern Ireland and its potential to spread invasive species:[148]

- The Fisheries Act (Northern Ireland) 1996 as amended
- The Aquatic Animal Health Regulations (Northern Ireland) 2009
- Molluscan Shellfish (Control of Deposit) Order (Northern Ireland) 1972 Order
- Lobsters (Prohibition of Introduction) Order (Northern Ireland) 1982
- Commission Regulation (EC) No 1251/2008 implementing Council Directive 2006/88/EC – conditions and certification requirements for the placing on the market and the import into the Community of aquaculture animals and products thereof and laying down a list of vector species.
- The EU fish health regime under Directive 2006/88/EC
- All movements of fish or shellfish into Northern Ireland must be notified on Trade Control and Expert System (TRACES) [149]
- European Code of Practice for Angling

The 2019 draft angling pathway action plan for Northern Ireland would task the DAERA Invasive Non Native Species Team with maintaining a database of waterbodies which contain critical invasive non-native species which are a priority for management and where angling takes place.[150] Zebra mussels are not on this list of critical invasive non-native species.

[147] CEDaR Online Recording, Submit record of invasive non-native species in Northern Ireland (accessed 01/11/2023)

[148] R Muir, 'Northern Ireland Non-Native Species Pathway Action Plan: Angling' (2019) p2 (Pre-consultation draft)

[149] European Commission, Trade Control and Expert System (accessed 21/11/23)

[150] R Muir, 'Northern Ireland Non-Native Species Pathway Action Plan: Angling' (2019) p4 (Pre-consultation draft)

6.3 Republic of Ireland

Zebra mussels are included in regulations 49 and 50 of the European Communities (Birds and Natural Habitats) Regulations 2011 enacted in Irish law[151] which transposes the EU Habitats Directive and the EU Birds Directive.

Reporting invasive species in the Republic of Ireland is through the National Biodiversity Data Centre.[152] Invasive Alien Species are addressed in the current River Basin Management Plan for Ireland (2022-2027) which highlights the need to create priority pathway action plans for priority invasive species.[153]

7 Quagga mussels

The quagga mussel (*Dreissena rostriformis bugensis*) is a close relative of the zebra mussel which is present in Great Britain and recently reported in Ireland (2021 in Lough Ree and Lough Derg and the connecting section of the Shannon River).[154] Quagga mussels are known to displace zebra mussels and are capable of tolerating a wider range of environmental conditions, meaning they have the potential to spread further.[155] As a result, quagga mussels are listed as an Alarm species for Ireland by the water framework directive UK

[151] Ireland, *S.I. No. 477/2011 - European Communities (Birds and Natural Habitats) Regulations 2011* 2011, Third schedule, Part 2: A

[152] National Biodiversity Data Centre, Invasive Species reporting (accessed 01/11/2023)

[153] Government of Ireland, Department of Housing, Local Government and Heritage, *Draft River Basin Management Plan for Ireland 2022 - 2027* (2021)

[154] Invasive Species in Ireland, Invasive Species Alert: Quagga mussel (accessed 06/11/2023)

[155] J L Ram et al., 'Invading the invaders: reproductive and other mechanisms mediating the displacement of zebra mussels by quagga mussels', *Invertebrate Reproduction & Development* (2012) Vol. 56, Issue 1, p1

technical Advisory Group [156] and have a species alert in Northern Ireland.[157] They were also identified as one of the top ten predicted invasive alien species for Ireland in a 2017 horizon scanning exercise.[158]

8 Considerations

The research presented in this paper prompts a number of potential considerations for policy. These include the following points:

- Can we expect quagga mussels to spread across Ireland in a similar way to that of zebra mussels? Further to this, are there lessons which can be learned from zebra mussel prevention and management to slow spread?
- Are there any water bodies where eradication is a possibility, if not what management techniques should be used in different water bodies and industries to control zebra mussel populations?
- What will the long term effect of increasing zebra mussel invasion be on fish populations in Northern Ireland?
- Given the interaction between zebra mussel invasion, nutrient inputs and algal blooms, should nutrient inputs be monitored or reported differently if zebra mussels are present in the water body?

[156] Water Framework Directive UK Technical Advisory Group, Alien Species Alarm List (2015) p2

[157] Invasive Species Northern Ireland, Quagga mussel Invasive Species Alert (accessed 30/11/2023)

[158] E Davis et al., 'Horizon scanning for invasive alien species on the island of Ireland' (2017) p15