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Prevention, Control and Eradication of Invasive Alien Species

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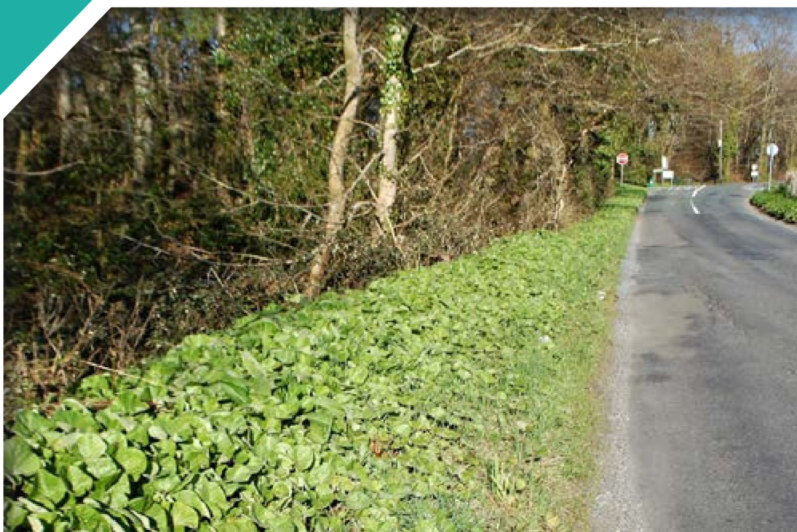

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

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Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

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- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

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The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2021–2030

Prevention, Control and Eradication of Invasive Alien Species

(2015-NC-MS-4)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Institute of Technology Sligo, Queen's University Belfast and INVAS Biosecurity Ltd

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Ireland, being an island situated on Europe's western seaboard, has fewer native species than most Member States on the European Union mainland. Increased numbers of vectors and pathways have reduced the island's biotic isolation, increasing the risk of new introductions and their associated impacts on native biodiversity. Protecting biodiversity is a key research priority of the Environmental Protection Agency. There is a worldwide recognition of the pressures that invasive alien species (IAS) can impose on ecosystems, and targets for IAS management developed by the Convention on Biodiversity[1] are central to both the National Biodiversity Action Plan for Ireland (2017–2021) and the Biodiversity Strategy for Northern Ireland (2015–2020). Relevant legal frameworks are also in place at both jurisdictional and European levels. The overarching aim of this project was to increase the efficacy of prevention, control and eradication of IAS on the island of Ireland by providing research outputs to determine pressures, inform policy and provide management solutions.

A horizon-scanning approach was used to identify the top 40 IAS with the potential to impact biodiversity that are most likely to arrive on the island of Ireland within the next decade. The IAS list included 18 freshwater species, 15 terrestrial and seven marine species. Freshwater species dominated the top 10 IAS (seven species out of 10), with the signal crayfish (*Pacifastacus leniusculus*) the most likely species to arrive and establish. This evidence-based list provides important information to the relevant jurisdictional statutory agencies to prioritise prevention methods.

Laboratory experiments on a range of aquatic invasive plants and invertebrates showed that several proprietary aquatic disinfectants can be used in "check, clean, disinfect, dry" biosecurity measures for water-based recreation events. Best biosecurity practice guidelines were produced for Asian clam.

Surveying attendees at the Irish National Ploughing Championships indicated a need for more outreach and education focused towards the farming community. The project team considers that controlling entry at ports and airports is imperative for effective biosecurity, i.e. reducing the probability of introductions of IAS to this island. However, for this project, it was not possible to engage in research with the relevant competent authorities.

During this project, IAS control experiments focused on two species – winter heliotrope, a common and easily spread plant, and Asian clam, a freshwater bivalve shellfish. Distribution and vegetative extent of winter heliotrope can be quantified using open-source image processing software and is a promising technique for monitoring the management of IAS plant species. Year-long field trials analysed the optimum treatment of winter heliotrope with herbicides and indicated that the most effective control product was Synero. Laboratory experiments using thermal shock treatment (dry ice, heat torch) on Asian clam show promise for use in special areas of conservation, to mitigate impacts on protected species and habitats. Best practice guidelines were developed for both winter heliotrope and Asian clam, such that practitioners have a "tool box" to carry out *in situ* control and also reduce spread.

A range of communication projects utilising diverse channels were implemented over the course of the project, including a citizen science recording initiative, the Winter Heliotrope Challenge, 11 peer-reviewed publications, a successful Twitter account, and TV and radio appearances.

This project has provided management tools for IAS prevention and control. However, global evidence indicates that the number of introductions of IAS to this island will increase with burgeoning international trade and travel, and climate change. More research and policy implementation is needed in order to protect Ireland's biodiversity and ensure regulatory compliance. Targeted biosecurity in both jurisdictions is urgently required in order to manage the arrival pathways, and is vital to maintaining native biodiversity on the island of Ireland.

1 https://www.cbd.int/doc/strategic-plan/targets/T9-quick-guide-en.pdf

1 Introduction

1.1 Objectives

The overarching objective of this project was to increase the efficacy of prevention, control and eradication of invasive alien species (IAS) on the island of Ireland by identifying pressures, informing policy and developing solutions. The research was designed to focus on these three key elements using a combination of methods including workshops, surveys, rigorous experiments (focused on IAS control measures) and the subsequent production of multiple research papers, media outputs, IAS outreach and best practice guidelines. The aim was to increase awareness of IAS among the public, stakeholders and the legislature. The deliverables focus on providing information on IAS issues for relevant government departments and agencies, relevant stakeholder groups, researchers and the general public. The outcomes can inform policy and best practice, as well as provide IAS information that is valuable both nationally and internationally.

1.2 Context and Approach

Globally, IAS are considered to be one of the major threats to native biodiversity and the environment (Ricciardi *et al.,* 2013; Dick *et al.,* 2017a). IAS threaten the ecological stability of invaded habitats and native species, and threaten essential ecosystem functions and services (Simberloff *et al.,* 2013; IPBES, 2019a). It is estimated that 11% of the *c.*12,000 alien species in Europe are invasive, causing significant environmental, economic and social damage (EU, 2014). Further, and worryingly, recent analyses concur that there will be no abatement in the rate of biological invasions in the near future (Seebens *et al.,* 2017, 2018, 2019).

In Europe, the approach to IAS has been fragmented and uncoordinated (Caffrey *et al.,* 2014; Piria *et al.,* 2017). As a consequence, the rate of IAS intrusions, introductions and spread has increased significantly in most European countries, including Ireland, in recent decades (O'Flynn *et al.,* 2014; Lucy *et al.,* 2020). The increased occurrence of IAS has resulted in significant adverse impacts on native biodiversity, natural capital, ecosystem services, local and national economies and human health in many affected countries and localities.

As an island on the western edge of Europe, Ireland is fortunate to possess a relative paucity of non-native species that can be deemed to be truly invasive. However, those introduced species that are established and invasive clearly pose considerable problems for our unique ecosystems, human health, ecosystem services and the Irish/UK economy. A number of high-profile invasive species have become established in Irish freshwater, marine and terrestrial habitats during the past two decades (Lucy *et al.,* 2004*,* 2005, 2012; Minchin and Sides, 2006; Caffrey *et al.,* 2008, 2011a,b, 2018; Sweeney, 2009; Dick *et al*., 2013; Hayden and Caffrey, 2013). Worryingly, recent horizon scanning exercises have identified a potential new set of aquatic invaders that could soon reach Great Britain (Gallardo and Aldridge, 2013; Roy *et al.,* 2014a) and the island of Ireland (this project; Lucy *et al.,* 2020).

The prevention aspects of the current project focused on a literature review of IAS issues in Ireland and a horizon scan of terrestrial, marine and freshwater species likely to arrive on the island in the next 10 years. Horizon scans have been highly successful in focusing IAS issues for academia, government and stakeholders (Caffrey *et al.,* 2014, 2015), and horizon scanning is recognised as an essential component in IAS management (Roy *et al.,* 2014b, 2019). The horizon scan in this project involved the commitment of 23 scientific experts to provide a list of 40 of the most likely terrestrial, freshwater and marine IAS to arrive on the island of Ireland within the decade to 2027. This list can be used to inform policy on prevention and early detection so that governmental and other resources can be utilised in the most efficient way (Caffrey *et al.,* 2014, 2015). Scientists and citizen scientists can also be educated in the awareness and identification of these species. Both a research paper (Lucy *et al.,*

2020) and an "easy-to-read" layman's pictorial report[2] were produced as project deliverables.

Biosecurity is the key element in preventing the introduction and subsequent spread of IAS. This project researched current knowledge and attitudes of various stakeholders in order to effectively inform biosecurity policy. Although it was beyond the scope of the project, the outcomes revealed that, currently, only a small proportion of IAS stakeholders working, managing or taking recreation in terrestrial, marine and freshwater systems are educated in or actively implement existing biosecurity practices or protocols. The implementation of best biosecurity practice is vital if the introduction and spread of IAS are to be prevented. The results on the awareness of IAS in the Irish agricultural community can be utilised for developing policy and best practice for farmers in Ireland and, also, more widely on a European scale, by informing biodiversity aspects of the Common Agricultural Policy. Rigorous biosecurity experiments were also carried out on a range of IAS, including species already present in Ireland (Asian clam, zebra mussel and aquatic plants) and some "door-knocker" species present in Great Britain (e.g. killer shrimp and quagga mussel). These laboratory studies are summarised in this report and are also available as individual scientific publications.

Control, and perhaps eradication, of already established species using methods and products that are acceptable to conservationists and within European Union (EU) legislation is always challenging. This project worked on control experiments for two very different species, the freshwater Asian clam and the terrestrial plant winter heliotrope, resulting in a number of publications detailing new research into novel control methods that show great promise for control and eradication across multiple IAS. Best practice guidelines for biosecurity and control of these two focal species were also produced for this project.

Communications for the Environmental Protection Agency (EPA) project Prevention, Control and Eradication of Invasive Alien Species were considered in all work elements of this project. During the course of the project, the team contributed to three television programmes – *10 Things You Should Know About Aliens*, *Ear to the Ground* and *Eco Eye* (RTÉ television) – and two national radio programmes – *Drivetime* and *Mooney Goes Wild* (RTÉ radio). The project also has a Twitter following of 1638 via the account @InvasiveAliens. Communications also formed a discrete element of the research. Throughout the EU, a number of databases are used by governments, agencies, academics, students and citizens. This research element of the project investigated the information harmonisation and educational value among international databases for IAS designated as of "Union concern". A further study was carried out on communications, outreach and citizen science: spreading the word about IAS (Davis *et al*., 2018). This analysed all the various communications outputs of the project, including a national citizen winter heliotrope survey carried out using the National Biodiversity Data Centre (NBDC) recording app. Both the database study and the outreach research are available as research publications.

With increased globalisation and climate change, it is assured that the number of IAS on the island of Ireland will increase further, with consequent adverse impacts on native biodiversity, economy and ecosystem services. This EPA report provides a range of communications for the prevention, control and eradication of IAS. These can be used in the development of biosecurity policy, tools for early detection, control methods, citizen science and broad-based education and outreach on the island of Ireland.

2 https://tinyurl.com/y83s8c3v

2 Literature Review of Invasive Alien Species Issues in Ireland

2.1 Current and Future Threats to Irish Biodiversity and Natural Capital

A healthy human population is reliant on the quality of biodiversity and natural capital available to underpin critical ecosystem services, which are freely and naturally provided in a healthy, functioning environment (Mace *et al.*, 2015). Anything that damages biodiversity or natural capital is, therefore, an environmental threat (CBD, 2014) and, by implication, an economic problem. IAS are recognised as one of the most serious threats to global biodiversity (Seebens *et al.,* 2017).

Ireland has enjoyed the natural protection of its island status as a barrier to invasion by IAS. Additionally, Ireland's maritime temperate climate remains a suboptimal environment for the successful establishment of many would-be colonisers (Stokes *et al.*, 2004; Harrison, 2014). This protection can no longer be taken for granted, however, as new invasions to the country have increased in the last two decades in line with increased international trade, transport and tourism (Hulme, 2009; Melly and Hanrahan, 2020). Furthermore, islands can be particularly prone to high levels of damage from invasive species (Courchamp *et al.,* 2007).

Invasive alien species represent a serious threat to natural capital "provisioning services" (e.g. food security, fresh water, fuelwood, fibre) and fundamental ecosystem "regulating services" (e.g. water regulation, pollination, pest control, climate mitigation), upon which fisheries, forestry and agricultural crop yields depend (Lovell *et al.*, 2006; Pejchar and Mooney, 2009). One of the primary ecosystem services that underpins our food security is pollination. With 35% of global crop production reliant to some degree on pollination (Klein *et al.,* 2007), any reduction in pollinator populations will put pressure on agricultural production (Oldroyd, 1999; Fürst *et al.*, 2014).

Habitat loss, alteration and fragmentation have been extensively documented as leading mechanisms of biodiversity decline, extinction events and depletion of ecosystem functioning (Naeem *et al.*, 2012; Isbell *et al.*, 2015; Joppa *et al.*, 2016; Segan *et al.*, 2016). IAS play an important role in such adverse habitat impacts and it is acknowledged that many IAS alter habitats via physical and/or chemical means to promote their own survival (Roy *et al.*, 2014b). In Ireland, for example, the freshwater invader Asian clam (*Corbicula fluminea*) has the potential to disrupt community structure across various tropic levels and exert considerable pressure on native biodiversity (Caffrey *et al.*, 2011a).

Exotic species traded as pets, and recreational equipment such as boats and angling gear, can harbour invasive "hitchhikers", parasites and pathogens. While these may not be detrimental to the host species, they can have significant detrimental impacts on native species in introduced areas. Between 2015 and 2019, Ireland's native and protected white-clawed crayfish (*Austropotamobius pallipes*) population was decimated in infested river catchments by the inadvertent introduction of crayfish plague (*Aphanomyces astaci*), which can result in 100% mortality of native crayfish in affected waters. It is probable that *A. astaci* spores were introduced on angling equipment from contaminated waters in the UK or continental Europe. Without a decisive change in environmental management practice and concerted efforts to stop the introduction and spread of IAS, Ireland will face increased biodiversity loss and localised extinctions (Isbell *et al.*, 2015).

2.2 Cross-jurisdictional Policy and Legislation

Globalisation and increased levels of trade have led to an escalation in species translocations and biological invasions (Ricciardi, 2007). Although the transboundary nature of IAS risk assessment has received relatively insufficient attention (Hulme *et al.*, 2016), several international conventions currently address issues relating to IAS. The Convention on the Conservation of European Wildlife and Natural Habitats (Council of Europe, 1979 – the Bern

Convention) and the United Nations Convention on Biological Diversity (CBD) (CBD, 2002, 2014), of which the European Commission, the UK and Ireland are signatories, are among the primary international agreements. The principles enshrined in these Conventions are reflected in parallel targets under the EU Biodiversity Strategy. Aichi Target 9 of the CBD Strategic Plan 2011–2020 requires that "by 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment" (CBD, 2014).

Currently, there is no overall guiding policy on IAS management for the island of Ireland. Furthermore, given the transboundary nature of biological invasions, the island of Ireland is susceptible to the introduction of IAS in either jurisdiction. Legislation in Ireland – principally Article 49 of the European Communities (Birds and Natural Habitats) Regulations 2011 – and in Northern Ireland (NI) – the Wildlife Order (NI) 1985 and Wildlife and Natural Environment Act (NI) 2011 – prohibit the introduction and dispersal of introduced species in their own jurisdictions. Given that the island of Ireland is a single biogeographical entity (Ecoregion 17 within the Water Framework Directive), there is a clear need for greater cross-jurisdictional cooperation in relation to IAS management strategies (Caffrey *et al.*, 2014). Fortunately, legislation operating in both territories that governs animal, plant and fish health places a coherent emphasis on the precautionary principle, with robust measures enabling the banning of certain introductions at the point of entry (Turner, 2008; Caffrey *et al.*, 2014). There now exists strong EU legislation to enable both jurisdictions on the island of Ireland to align their approach to IAS management, although further negotiations may be required between the UK, Ireland and the EU, particularly in the light of Brexit.

Despite the goals of the CBD, the approach to IAS throughout the Member States (MSs) of the EU has been fragmented and inconsistent. To address this, the EU Regulation on Invasive Alien Species (EU, 2014) was introduced in 2015. This obliges all MSs to prevent and manage the introduction and spread of IAS. In particular, the Regulation imposes restrictions on a list of species known as IAS of Union concern, i.e. species whose potential adverse impacts across the EU are such that concerted action across all MSs is required. As of June 2020, the list comprised 66 species. Following agreement on Brexit, NI has introduced new legislation on IAS. The Invasive Alien Species (Enforcement and Permitting) Order (NI) 2019, which acts in parallel with EU Regulation No 1143/2014, includes current and updated lists of species of EU concern, as specified by the Regulation.

While the EU Regulation is a groundbreaking attempt to set a common standard for combating IAS across the multinational political jurisdictions of the EU, several major concerns surround the effective implementation of this legislation. Among these is the fact that already widespread and highly detrimental IAS (e.g. Japanese knotweed) are not included as species of Union concern because the prevention or control of adverse impacts will be considered unfeasible and not cost-effective by some MSs (Tollington *et al.*, 2015). The lack of a dedicated funding mechanism is another serious cause for concern (Caffrey *et al.*, 2014; Beninde *et al.*, 2015; Genovesi *et al.*, 2015). Currently, there is no dedicated funding in relation to most aspects of the new legislation provided within the programming period, 2014 to 2020.

2.3 International and Cross-jurisdictional Pathways and Vectors

A pathway of biological invasion includes both the vector (e.g. ship), which carries the IAS, and the route along which it travels (Carlton and Ruiz, 2005; Essl *et al.,* 2015). While primary introductions are most likely to occur via anthropogenic means, secondary spread of IAS from an initial place of establishment can be facilitated by a wide range of dispersal vectors (Stokes *et al.,* 2004). Increasing transport networks and demand for commodities have led to pathway risk assessments becoming the frontline in the prevention of biological invasions (Hulme *et al.,* 2016). In compliance with the EU Regulation, each MS must prioritise pathways used by IAS of Union concern and implement action plans to address these priority pathways.

The international trade in living organisms represents a major pathway for both deliberate and accidental IAS introductions (Westphal *et al.*, 2008; Verbrugge *et al.*, 2014). The growing demand globally for ornamental and exotic pet species has resulted in a dramatic escalation of deliberate importation of non-native species. In an effort to manage priority pathways, hotspots of invasion and source areas of the most damaging IAS located both within and outside EU borders will need to be thoroughly risk assessed. For example, Asian, American, and Ponto-Caspian species are often transported into EU territories through international shipping. Once established, these IAS can spread through EU territories via natural means and infrastructural corridors such as canals, roads and waterways (Laverty *et al.*, 2015). Equally, a large proportion of the freshwater IAS found across Europe are native to some regions within European territories and can similarly spread along dispersal corridors (Nunes *et al.*, 2015).

Freshwater systems are acknowledged to be at particularly high risk from biological invasions. The development of major connected European waterways, such as the Rhine–Maine–Danube Canal that connects the North Sea and Atlantic Ocean with the Black Sea, have facilitated the spread of many Ponto-Caspian species into Western Europe, and further afield to Great Britain and the island of Ireland (Bij de Vaate, 2002; Minchin *et al*., 2002; Panov *et al*., 2009).

Disruption of IAS dispersal pathways is a fundamental aspect of any biosecurity plan. Practical efforts to control pathways will need to prioritise the management of human-operated pathways of primary introductions (i.e. release, escape, contamination, stowaway and corridors) over unaided pathways for the secondary spread of already established IAS (Solarz *et al*., 2016). Focusing on prevention of IAS incursion at ports and airports, followed by applying control and eradication measures to extant IAS populations, is the prioritisation that best conforms to the three-stage hierarchical approach proposed within the CBD Guiding Principles (CBD, 2002). Additionally, survey and modelling techniques can be combined to predict likely dispersal networks (i.e. determine human-mediated pathways and associated vectors) and, accordingly, identify potential invasion hubs, i.e. sites at risk of invasion, which in turn would act as new IAS source areas (Muirhead and MacIsaac, 2005).

2.4 Risk Management Associated with Specific Pathways

Risk management is the process of evaluating and implementing management options in order to reduce the risks posed by invasive non-native species.[3] Below, risk management relating to the pet trade, horticulture and aquaculture, and fisheries, angling and water-based recreation pathways are examined.

2.4.1 Pet trade

Most IAS of Union concern (and many other IAS species) have been introduced into the EU through escapes from confinement (botanical gardens, zoos, aquaria) and escapes linked with the ornamental trade (Tsiamis *et al.*, 2017). The trade in ornamental animals and plants represents a global multibillion dollar industry responsible for the cross-border movement of multiple taxa, including the unintended introduction of non-target organisms such as pathogens (e.g. crayfish plague in many MSs). In order to prevent the transmission of emerging diseases to wildlife, effective IAS risk management practices should include examination of exotic species for pathogens likely to be harboured within the pet trade. Imported animals should undergo strict quarantine protocols. Where a species poses a high risk for invasion, an outright ban on its trade, transport or advertisement for sale is an appropriate measure. Relevant legislation to tackle this has been drafted in both Ireland and NI, but has yet to be enacted. The internet facilitates the globalisation of live animal sales and circulation of exotic species (Kikillus *et al.,* 2012). As a result, the online trade of ornamental species has become a major and consistent source of IAS, and is a significant threat to biosecurity worldwide (Kikillus *et al.,* 2012; Chucholl, 2014). The collection and analysis of data related to the online trade of exotic species can be used to inform biosecurity in terms of IAS horizon scanning and pathway risk assessment. Ironically, however, the banning of the keeping of certain species is anecdotally resulting in releases into the wild (e.g. *Trachemys* turtles in the UK and Ireland).

3 http://www.nonnativespecies.org

2.4.2 Horticultural centres

Horticultural centres (including botanic gardens, arboreta, garden centres, private collections and plant nurseries) are increasingly recognised for their role in both the deliberate and accidental introduction of invasive alien plants (Kiritani, 2006; Heywood, 2011; Hulme, 2011). The intentional introduction of IAS is thought to favour the success of establishment, as intentionally introduced species are often released in larger numbers and are afforded greater care in captivity than unintentional stowaway species (Hänggi and Straub, 2016; Kopeckỳ *et al*., 2016). Species that are released/escape can cause severe ecological and economic impacts in the recipient area (Caffrey *et al*., 2011b; Verbrugge *et al*., 2014). Aquatic and semi-aquatic plants have a higher probability of becoming invasive than do terrestrial plant species (Daehler, 1998), and thus form a significant proportion of potential invasive species (Andreu and Vilá, 2010). The disposal of unwanted plants, garden waste and soil are common routes of unintentional IAS spread. These activities are primarily responsible for the spread of Japanese knotweed and other damaging IAS in MSs throughout the EU and must be widely regulated for (as they are in Ireland and the UK). Like the pet trade, the collection and analysis of data related to the online trade of exotic plant species can be used to inform biosecurity in terms of IAS horizon scanning and pathway risk assessment.

2.4.3 Aquaculture, fisheries, angling and water-based recreation

Many non-native species have been deliberately introduced, both legally and illegally, by aquaculture enthusiasts and anglers to improve or diversify resident fish stocks. The potential impacts of such stockings include predation, hybridisation, competition, disease, habitat and food web alteration (Savini *et al*., 2010). Such stockings have also contributed to the accidental introduction of other invasive aquatic organisms and pathogens. The removal of introduced fishes or fish populations that become or are potentially invasive is extremely difficult and costly (Caffrey *et al*., 2018). Lack of biosecurity awareness and appropriate protocols have resulted in the introduction and spread of many freshwater IAS. The main barriers to effective biosecurity compliance have been cited as cost and time (Foster *et al*., 2016). However, biosecurity campaigns such as New Zealand and Britain's Check, Clean, Dry programme have successfully increased biosecurity awareness and practice, particularly among anglers and recreational water users. Additionally, best biosecurity practice may require the quarantine of invaded sites, thus excluding water users from infested areas, as occurred in Ireland in 2018 and 2019 as a response to the outbreak of crayfish plague.

2.5 Existing and Emerging Early-warning and Rapid Response Mechanisms

Early-warning and rapid reaction mechanisms are widely acknowledged as being critical tools in any IAS management protocol that is implemented, and are crucial to mitigating the impact of IAS (Genovesi, 2005). Here, rapid response includes a suite of management options that includes surveillance of spread, education and outreach, citizen science initiatives, and real-time management of specific IAS issues.

2.5.1 Early warning, early detection and surveillance monitoring

An early-warning protocol is a framework designed to respond to biological invasions through a coordinated system of surveillance and monitoring activities, to identify invading species, and circulate information, including reporting to competent authorities (O'Flynn, 2014). The National Parks and Wildlife Service (NPWS) in Ireland and the Northern Ireland Environment Agency (NIEA)/Department of Agriculture, Environment and Rural Affairs (DAERA) in NI are the competent authorities for IAS management. In Ireland, the NBDC provides a central recording database for verified IAS incursions in Ireland and generates Species Alerts when there is a new verified IAS or an increased risk level of incursion for Ireland (Lysaght *et al*., 2016). The Centre for Environmental Data and Recording (CEDaR) serves the same function in NI, and the agencies liaise closely regarding IAS issues. The European Alien Species Information Network (EASIN) is the dedicated information exchange mechanism supporting MSs in the implementation of the Regulation and is tasked with developing early-warning and rapid reaction measures. The Regulation obliges all MSs to establish a robust and dynamic surveillance system for IAS of Union concern "within 18 months of the adoption of the Union list" that will collect, record and disseminate data relating to these species (EU, 2014). A key aspect of early detection and rapid response is that the competent authority within each MS must notify, in writing and without delay, the European Commission of the detection of an IAS of Union concern that was previously unrecorded there and inform other MSs.

In order to protect Irish biodiversity and comply with the Regulation, comprehensive monitoring of introduction (and spread) pathways for species of Union concern, linked with rapid response, must be put in place at the national level. This includes the development of contingency plans, implementation of surveillance systems focused on high-risk entry points, undertaking prompt actions after detection of an incursion, with complete eradication as the preferred outcome, and post-eradication monitoring (Solarz *et al.,* 2016). This will require port/airport custom staff training in IAS identification, sustained communication and education programmes, dedicated staff and sustainable funding streams.

2.5.2 Rapid response and other management strategies

Rapid response is the most realistic and cost-effective method for tackling invasions, as a species, once established, is almost impossible to eradicate (Roy *et al.*, 2014a). The Regulation obliges MSs, within 3 months of notification regarding the early detection of an IAS of Union concern, to apply eradication measures, the effectiveness of which must be reported to the European Commission within 18 months and again after 3 years. As a consequence of early detection and rapid, coordinated response events in Ireland, a small number of IAS have been successfully eradicated or had their populations reduced to very low and probably unsustainable levels [e.g. the mammals muskrat (*Ondatra zibethicus*) and feral pig/ wild boar hybrids (*Sus scrofa*), the freshwater fish chub (*Leuciscus cephalus*) (Caffrey *et al.*, 2018) and the macrophyte water primrose (*Ludwigia grandiflora*) (J. Caffrey, INVAS Biosecurity Ltd, personal communication)]. However, for many IAS there are simply no successful control or eradication methods or "tool boxes" available or deemed acceptable on economic, environmental or other bases (e.g. welfare).

2.6 The Future

On the island of Ireland, we are uncertain of how the two jurisdictions will coordinate activities with regard to IAS issues, particularly with Brexit on the horizon. Post Brexit, the British–Irish Council will probably continue to provide a good working framework for the ongoing sharing of information and encouraging collaboration between Ireland, NI and the rest of UK. For the island of Ireland, the return of an all-Ireland forum, such as Invasive Species Ireland, would go a long way to ensuring open communication and active cooperation between the two jurisdictions in an effort to effectively tackle IAS. It is important that applied research projects aimed at developing new and novel control methods for existing and horizon scanned IAS in Ireland will be funded and resourced. The novel IAS control research conducted as part of the current project could provide a useful platform on which to commence and operationalise such research.

3 Horizon Scan of Invasive Alien Species in Ireland

Ireland, being an island situated on Europe's western seaboard, has fewer native species than mainland EU MSs. Increased numbers of vectors and pathways have reduced the island's biotic isolation, increasing the risk of new introductions and their associated impacts on native biodiversity. It is likely that these risks are greater here than in continental MSs, where the native biodiversity is richer. A horizon-scanning approach was used to identify the most likely IAS (with the potential to impact biodiversity) to arrive on the island of Ireland within the next 10 years, to 2027. To achieve this, we used a consensus-based approach, whereby 23 scientists engaged in a process of expert opinion (prior to a workshop) and discussion groups (during a workshop) to establish and rank a list of 40 of the most likely terrestrial, freshwater and marine IAS to arrive on the island of Ireland within the decade 2017–2027. The list of 40 included 18 freshwater invaders, 15 terrestrial IAS and seven marine species. Crustacean species (freshwater and marine) were taxonomically dominant (11 out of 40); this reflects their multiple pathways of introduction, their ability to act as ecosystem engineers and their resulting high impacts on biodiversity. Freshwater species dominated the top 10 IAS (seven species out of 10), with the signal crayfish (*Pacifastacus leniusculus*) highlighted as the most likely species to arrive and establish in freshwaters, while roe deer (*Capreolus capreolus*) (second) and the warm-water barnacle (*Hesperibalanus fallax*) (fifth) were the most likely terrestrial and marine invaders, respectively. This evidence-based list provides important information to the relevant statutory agencies in both jurisdictions in Ireland to prioritise the prevention of the most likely invaders and aid in compliance with legislation, in particular the EU Regulation on Invasive Alien Species (EU, 2014). Targeted biosecurity in both jurisdictions is urgently required in order to manage the pathways and vectors of arrival, and is vital to maintaining native biodiversity on the island of Ireland.[4]

3.1 Top 10 Species Emerging from the Horizon Scan for Ireland

Species were scored from 1 to 5 according to their likelihood of arrival (A), their likelihood of establishing in the wild (B) and their impact on biodiversity (C) (Table 3.1). They were ranked according to the product of those scores, taking uncertainty into consideration. Prioritisation of species was based on the highest score paired with the highest uncertainty.[5]

4 The research paper is available at https://www.reabic.net/journals/mbi/2020/Issue2.aspx

5 For a full list of pathway codes, see https://www.reabic.net/journals/mbi/2020/Issue2.aspx

Table 3.1. Top 10 species emerging from horizon scan for Ireland

Rank	Species	Common name	Taxonomic group	Functional group	Environment	Native range	A	B	C	Product	Uncertainty
1	*Pacifastacus leniusculus*	Signal crayfish	Crustacean	Omnivore	Freshwater	North America	5	5	5	125	Low
2	*Capreolus capreolus*	Roe deer	Mammal	Herbivore	Terrestrial	Europe, Middle East	5	4	5	100	Low
3	*Dikerogammarus villosus*	Killer shrimp	Crustacean	Predator	Freshwater	Ponto-Caspian	5	4	5	100	Low
4	*Gyrodactylus salaris*	Salmon fluke	Monogenean	Parasite	Freshwater	Baltic Sea	4	5	5	100	Low
5	*Hesperibalanus fallax*	Warm-water barnacle	Crustacean	Filter feeder	Marine	Atlantic coast of tropical Africa	5	5	4	100	Medium
6	*Hydrocotyle ranunculoides*	Floating pennywort	Plant	Primary producer	Freshwater	North and South America, Africa	5	5	4	100	High
7	*Dreissena rostriformis bugensis*	Quagga mussel	Mollusc	Filter feeder	Freshwater	Ponto-Caspian	4	4	5	80	Low
8	*Caulacanthus okamurae*	Pom-pom weed	Alga	Primary producer	Marine	Japan, Northwest Pacific	5	5	3	75	Low
9	*Eriocheir sinensis*	Chinese mitten crab	Crustacean	Predator	Freshwater	Eastern Asia	5	3	5	75	Low
10	*Pseudorasbora parva*	Topmouth gudgeon; stone moroko	Crustacean	Predator	Freshwater	Northwest Pacific	3	5	5	75	Medium

4 Biosecurity for Invasive Alien Species on the Island of Ireland

4.1 Awareness of Invasive Alien Species and Biosecurity in the Farming Community

4.1.1 Introduction

Invasive alien species are recognised as a major threat to global biodiversity (IPBES, 2019a,b). Traditional farming landscapes are an important preserve of biodiversity, of which farmers are the custodians (de Snoo *et al.*, 2012). In particular, the high nature value farmlands of traditional Irish agriculture are essential to the delivery of ecosystem services and biodiversity conservation (Fischer *et al.*, 2012; Lomba *et al.*, 2019), which can be severely impacted by IAS (Caffrey *et al.*, 2014).

As part of this project, Eithne Davis from the Institute of Technology Sligo initiated a public survey, the goal of which was to assess general awareness of IAS and biosecurity, and gather insight into the perceived importance of these issues among the rural Irish public, in particular the farming community. The Irish National Ploughing Championships is a significant annual event in the public calendar that attracted an attendance of 290,000 in 2017 and 240,000 in 2018. Interacting with respondents face to face gave an opportunity to gauge their receptiveness to finding out more about IAS and how best to go about delivering that information (Schüttler *et al.*, 2010). Raising awareness and instigating a potential "ripple effect" through mindful public interaction is a necessary precursor to the proactive stage of instigating preventative measures against the spread of IAS (Bremner and Park, 2007; Eiswerth *et al.*, 2011; Davis *et al.*, 2018).

4.1.2 Methodology

The survey was repeated over 2 years at the National Ploughing Championships. Designed by researchers at the Institute of Technology Sligo, the aim of the survey was to establish the levels of understanding existing within the rural Irish community around IAS and biosecurity, and whether or not there is a willingness to learn more about these subjects and alter behaviour. The survey was piloted among students and members of the local agricultural community. As a result, several questions were altered or eliminated to avoid unintentionally leading the respondents and improve clarity. No identifying information was recorded.

The first round of the survey was carried out over 3 days in 2017, and the second (identical) round over 2 days in 2018. A further day of surveys was planned in 2018, but the event was cancelled owing to adverse weather conditions. Surveyors approached members of the public with a written questionnaire and offered to either read out and write down answers on behalf of the respondent, or allow them to self-report. This gave the surveyors an element of control over the standard to which the survey was completed, and allowed an opportunity to interact with individuals once the survey was completed. Interaction and answering questions after the survey was completed were an important element of the outreach remit of the project (Davis *et al.,* 2018).

Eight questions were asked in the survey (plus two questions about age and agricultural activity, to give context), focusing on two areas:

Three questions asked about perception of risk around IAS and the importance of biosecurity:

1. Are IAS a threat to farming?
2. Do you take biosecurity measures to prevent the spread of IAS?
3. Do you think biosecurity is worth investing in?

The remaining five questions aimed to gauge respondents' familiarity with IAS and their willingness to get further knowledge:

4. I have been involved in managing IAS – Y/N
5. Are IAS different from noxious weeds?
6. Do you need more information on identifying IAS?

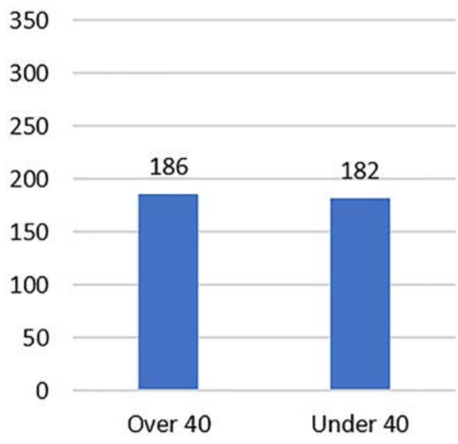


Figure 4.1. Survey respondents per age group.

7. Identify the following five IAS present in Ireland from the 12 images provided (Japanese knotweed, New Zealand flatworm, giant hogweed, coypu, muntjac).
8. Which three of the following would you go to for information: local co-op/supplies store, Teagasc, Department of Agriculture, farm advisor, County Council, Irish Farmers' Association website, *Irish Farmers Journal,* other?

The order of the questions was randomised to avoid leading the responses.

4.1.3 Results

The responses were considered under two broad age groupings: the over-40s and under-40s. There was no significant difference in the number of responses from each cohort; of the 368 respondents, 186 were aged over 40 and 182 were under 40 (Figure 4.1).

4.1.4 Responses

Not all respondents answered all the questions. One did not answer "Are IAS a threat to farming?", two did not answer "Do you take biosecurity measures to prevent the spread of IAS?", one did not answer "Do you need more information on identifying IAS?", three did not answer "Do you think biosecurity is worth investing in?", and eight did not answer "I have been involved in managing invasive alien species". The average response rate per question was 99.76%.

Question 1. Are IAS a threat to farming?

Eleven per cent (41 people) stated that IAS are not a concern to farming, 6% (22) said they are a low risk, 29% (105) said they are a medium risk, 25% (93) said they are a high risk and 29% (106) said they are a major risk (Figure 4.2). There was a tendency for IAS to be viewed as more of a risk among the over-40s than in the under-40s age group (Figure 4.3).

Question 2. Do you take biosecurity measures to prevent the spread of IAS?

Only 38% of respondents stated that they take biosecurity measures to prevent the spread of IAS (Figure 4.4). The proportion who reported taking biosecurity measures was considerably higher in the over-40s cohort (46%) than in the under-40s cohort (29%) (Figure 4.5).

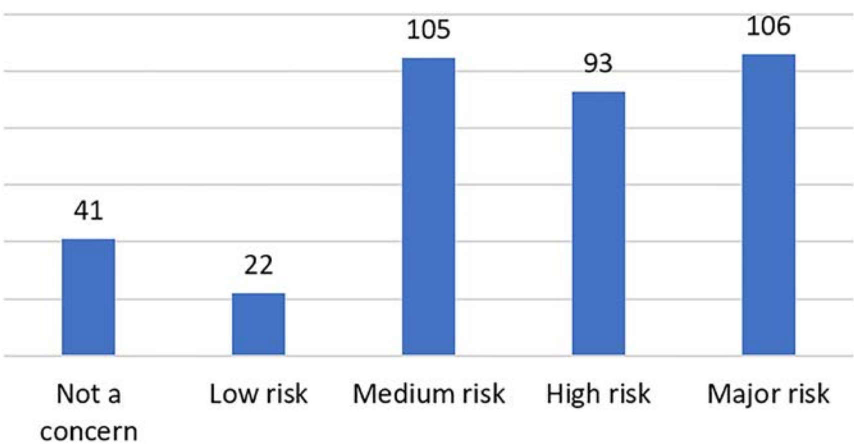


Figure 4.2. Ratings of the perceived level of threat to farming from IAS.

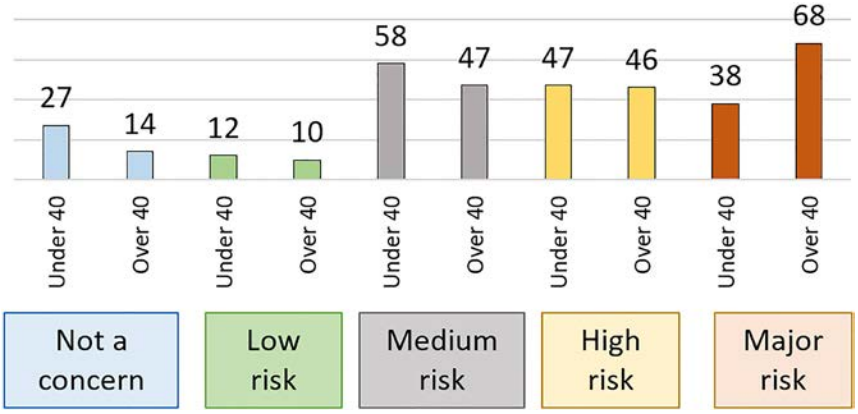


Figure 4.3. Number of participants in each age group who perceived IAS to be a threat to farming.

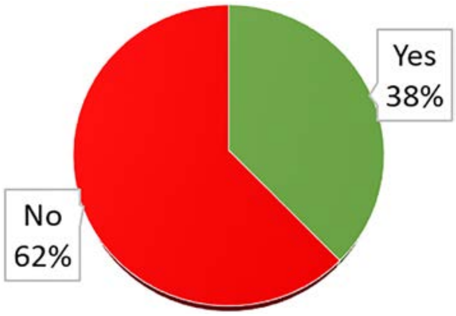


Figure 4.4. Overall percentage of respondents who take biosecurity measures.

Question 3. Do you think biosecurity is worth investing in?

Only 4% (13) of respondents stated that biosecurity to prevent IAS is not worth investing in. Five per cent (19) felt that it is a low priority, 28% (104) considered it a medium priority and 28% (102) regarded it as important, while 35% (127) stated that investing in biosecurity to prevent the spread of IAS is a high priority (Figure 4.6).

Question 4. I have been involved in the management of IAS (Y/N)

Of the 360 respondents who answered, 43 (11.9%) stated that they had been involved in the management of IAS.

Question 5. Are IAS different from noxious weeds?

Many respondents were unaware of the difference between IAS and noxious weeds. A total of 144% (63 people) stated that IAS were not different from noxious weeds. The over-40s cohort was clearer about the distinction between the two than the under-40s cohort (Figure 4.7).

Question 6. Do you need more information on identifying IAS?

A total of 239 (65%) people responded that they need more information on identifying IAS. The remaining 128 (35%) did not feel they need more information on identifying IAS. There was a slight difference between the age cohorts, with a higher number of the over-40s willing to learn more (Figure 4.8).

Question 7. Identify the following five IAS present in Ireland from the 12 images provided (Japanese knotweed, New Zealand flatworm, giant hogweed, coypu, muntjac)

The 12 images presented (a mixture of IAS and native species) were New Zealand flatworm (*Arthurdendyus triangulatus*), giant hogweed (*Heracleum mantegazzianum*), hedge bindweed (*Calystegia sepium*), Japanese knotweed (*Fallopia japonica*), Chinese muntjac (*Muntiacus reevesi*), gunnera (*Gunnera tinctoria*), brown rat (*Rattus norvegicus*), sika deer (*Cervus nippon nippon*), otter (*Lutra lutra*), coypu (*Myocastor coypus*), marine flatworm (*Prostheceraeus giesbrechtii*) and rhododendron (*Rhododendron ponticum*).

When asked to identify five IAS currently present in Ireland, only 20 respondents (5%) were able to identify all five. Thirty-eight (10%) correctly identified four out of five, 91 (25%) correctly identified three out of five, 81 (22%) correctly identified two out of five, 82 (22%) identified one out of five and 42 (11%) were unable to identify any of the five IAS (Figure 4.9).

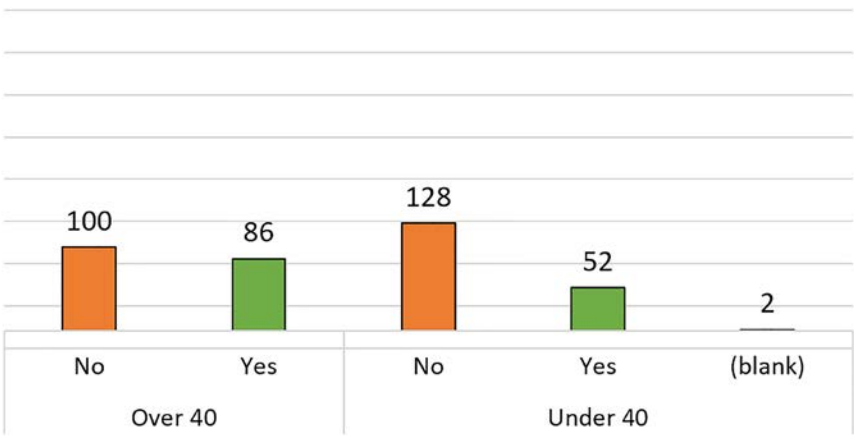


Figure 4.5. Biosecurity measures further broken down by age group.

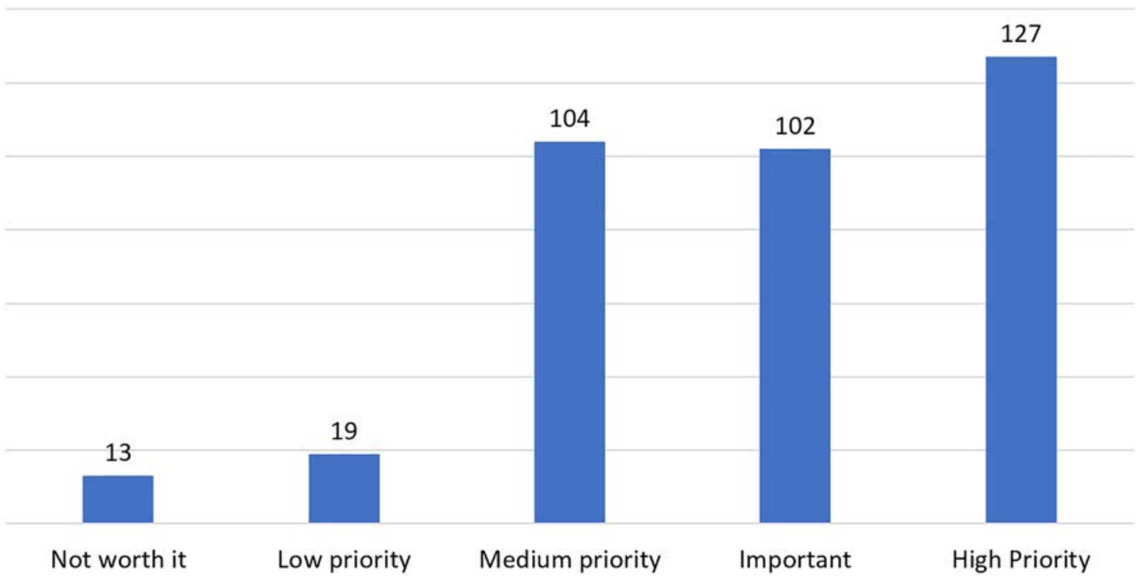


Figure 4.6. Perceived importance of investment in biosecurity to prevent the spread of IAS.

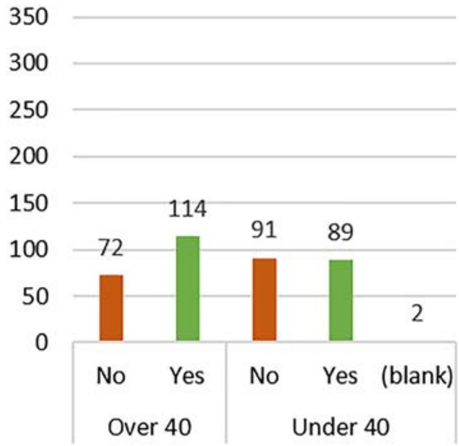


Figure 4.7. Understanding of the difference between IAS and noxious weeds, broken down by age group.

Looking more closely at familiarity with particular species, Japanese knotweed was correctly identified by 57% of respondents, New Zealand flatworm by 71%, giant hogweed by 32%, coypu by 27% and muntjac by 29% of respondents (Figure 4.10).

Question 8. Which three of the following would you go to for information: local co-op/supplies store, Teagasc, Department of Agriculture, farm advisor, County Council, Irish Farmers' Association website, Irish Farmers Journal*, other?*

Respondents were asked to select the three most likely places they would go for information around IAS from a given list. Not all respondents filled three boxes. Of the 998 answers given, the Department of

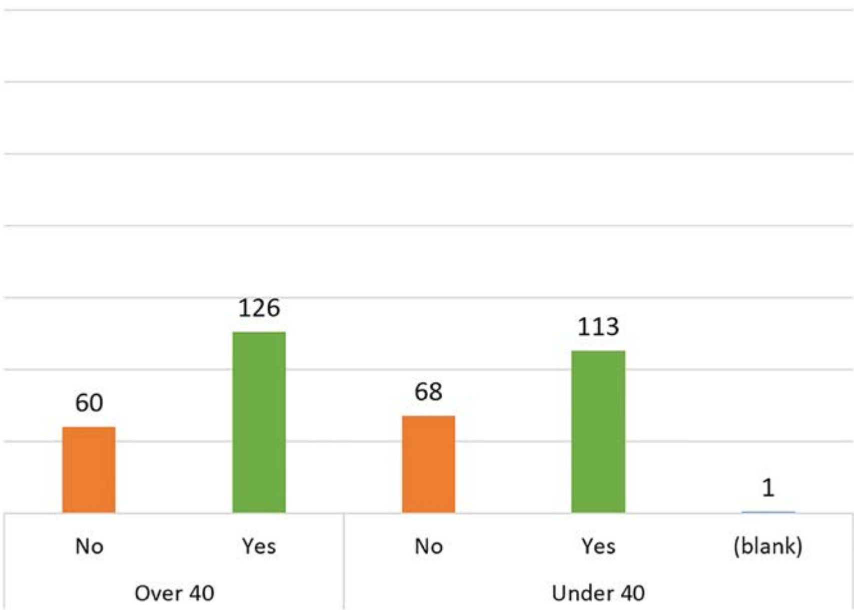


Figure 4.8. Respondents' recognition of the need for further information on IAS identification, broken down by age group.

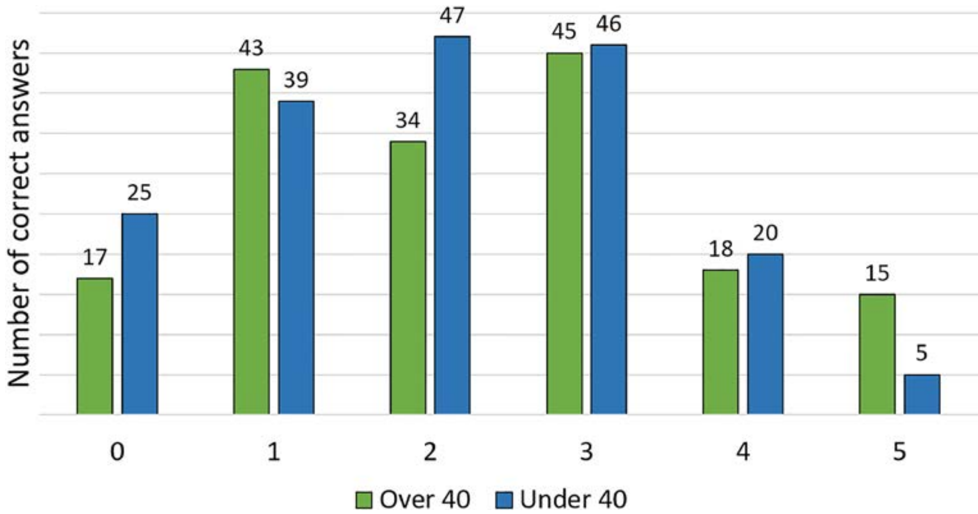


Figure 4.9. Number of species correctly identified, broken down by age group.

Agriculture, at 230 (24%), and Teagasc, at 227 (23%), scored highest. The over-40s cohort was slightly more likely to consider Teagasc than the under-40s group. One hundred and nine (11%) respondents would go to their farm advisor for information, with the over-40s cohort giving this option a higher score. The *Irish Farmers Journal* was preferred by the under-40s, but, overall, 104 (10%) would consult it for information. The County Council received 98 (10%) positive responses, the Irish Farmers' Association 94 (9%) and the local co-op or farm supplies store 87 (9%). "Other" was declared by 29 (2%) of respondents, all of whom said they would look for information online themselves (Figure 4.11).

4.1.5 Discussion

The findings from this survey suggest that people are not consistently confident in their understanding of IAS. While 82% perceived IAS as either a medium, high or major threat to farming, only 38% said that they take any biosecurity measures, while 91% scored investment in biosecurity as either medium priority, important or a high priority. There appears to be disconnect

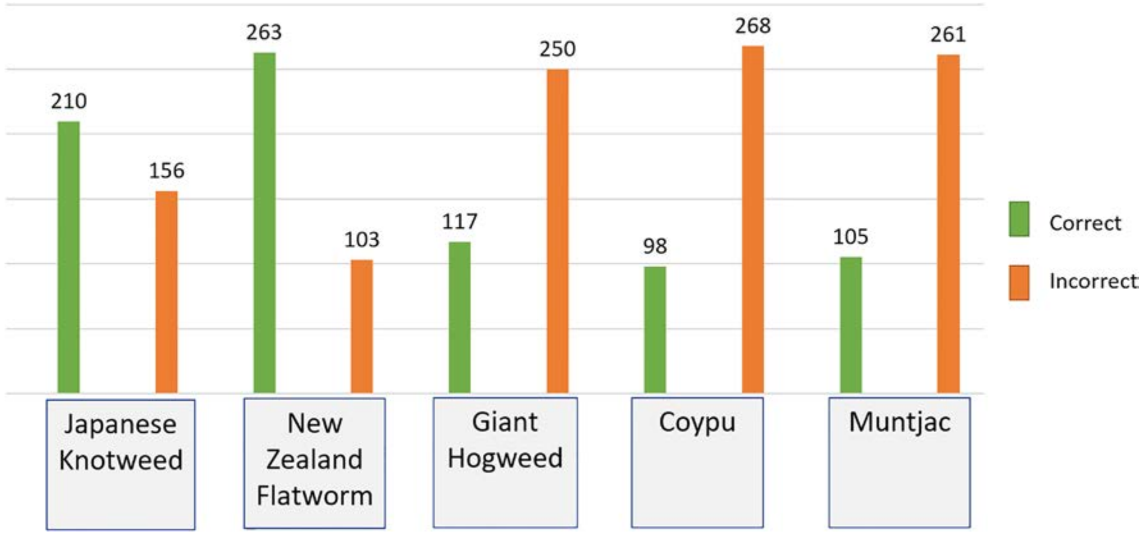


Figure 4.10. Breakdown of respondents' overall ability to identify species present in Ireland from a selection of images.

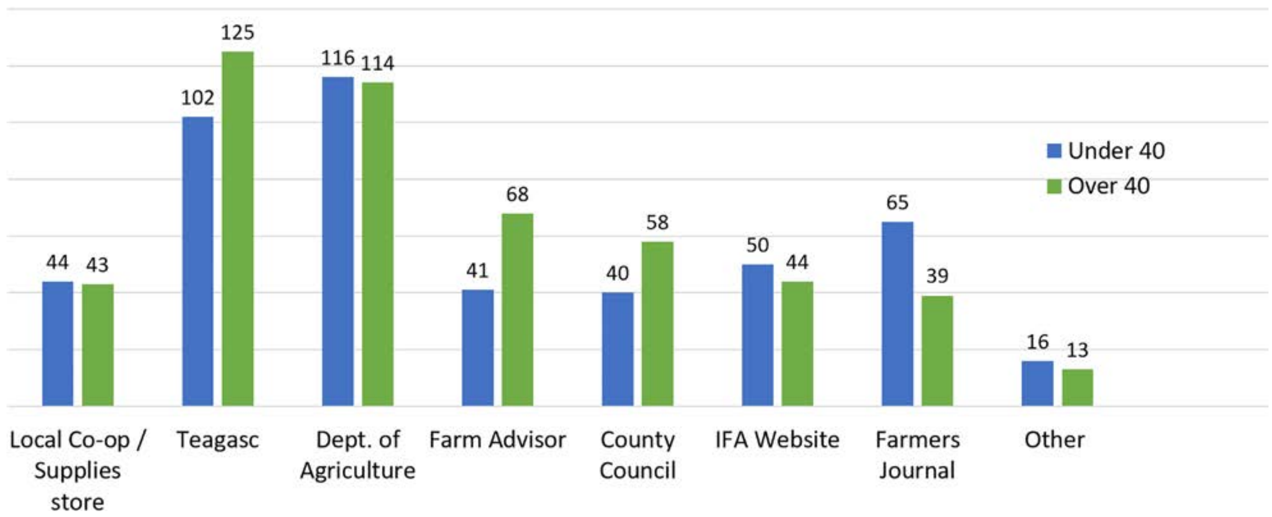


Figure 4.11. Preferences indicated by respondents for sources of information around IAS. IFA, Irish Farmers' Association.

between good intention with willingness to act and an understanding of what measures need to be taken. Many respondents were unaware of the difference between IAS and noxious weeds, and respondents were not accurate in their visual identification of particular species, even commonly occurring plants such as Japanese knotweed and giant hogweed. A false level of accuracy in identifying the New Zealand flatworm may have occurred owing to a flaw in the survey design. The selection of images shown to respondents contained only two worms, one of which was a highly colourful marine species. This flaw was recognised early in the interactions with the public, but was retained throughout to maintain consistency.

For many years now, it has been increasingly difficult for farmers to fulfil their responsibilities in maintaining economically viable farms in a changing cultural landscape (Ní Loaire, 2005; Burton *et al.,* 2008; Brandth and Haugen, 2011). Farmers play a significant role in conservation. They have a vested interest in protecting ecosystem services and need to be supported through knowledge and understanding of the issues in order to motivate them in acting to control and manage IAS (Bremner and Park, 2007). Targeting this community with awareness programmes is likely to be effective, given that they are actively engaged and knowledgeable, and motivated to maximise the quality of the land for productivity and environmental quality (Pretty *et al.,* 2010; Eisworth *et al.,* 2011; Paini *et al.,* 2016). The findings of this survey support the evidence of the willingness of farmers, as experts and professionals, to improve their understanding. As climate change continues to drive loss of biodiversity and facilitate the spread of IAS, agricultural biodiversity has an increasingly important role in ecosystem resilience through conservation and IAS prevention (Godfray, 2010; Mijatović *et al.,* 2013).

The sense from this survey is that the over-40s cohort is more concerned about IAS and practising good biosecurity, and the lack of biosecurity measures being undertaken by the under-40s cohort is concerning. This echoes findings of previous studies into the level of support for control and eradication programmes (Bremner and Park, 2007). Overall, the survey results suggested a need for more information to help respondents identify IAS. The Department of Agriculture, Teagasc and individual farm advisers emerged as potentially useful conduits for information, and it would be worthwhile focusing future dissemination efforts via these bodies. The *Irish Farmers Journal*, and particularly its website (E. Davis, Institute of Technology Sligo, February 2020, personal communication), is a medium that appears to appeal to the under-40s group as a good source of information.

In expecting farmers to act as stewards of a high-quality landscape and its associated benefits, we must recognise their need to preserve their professional identities and way of life alongside a sense of the value of their contribution to society as a whole (Burton *et al*., 2008). If we wish to include them as key players in the control of IAS through policy, we need to value their environmental work and recognise the increasing pressures that they face (Brandth *et al*., 2011). It is important to consider what we can expect from farmers and what we need to deliver to support their inclusion in IAS control (Sutherland *et al*., 2015).

4.1.6 Conclusion

The results of this survey indicate that there is a low level of engagement around IAS issues among farming and rural communities. There is a need to address high levels of confusion about what constitutes an invasive species and what management measures can be put in place. Before any engagement can be expected, awareness levels around IAS must be increased. The willingness to engage and learn more about species identification, together with the recognition that investment in biosecurity to mitigate against the threat of IAS to farming, is encouraging. This survey indicated that relevant, focused information delivered through some trusted sources will reach a receptive audience, but further engagement specific to the needs of this group is required to address the current low levels of awareness around IAS.

4.2 Biosecurity Experiments

Invasive freshwater plant (macrophytes) and invertebrate species have a remarkable capacity for overland transport by anthropogenic vectors such as boats, fishing equipment and vehicles (Coughlan *et al*., 2017, 2018). Accordingly, prevention of initial introduction and secondary spread of IAS is the first line of defence, and biosecurity protocols designed to prevent invader spread have become a key aspect of management strategies (Crane *et al*., 2019). However, there often exists only a limited understanding of the relative efficacies of proposed spread-prevention procedures (Barbour *et al*., 2013; Piria *et al*., 2017; Crane *et al*., 2019). Therefore, to curtail IAS, there is an urgent need for simple prevention protocols that minimise risk of spread, yet remain user- and environmentally friendly (Crane *et al*., 2019).

4.2.1 Invasive macrophytes

Aim of the study

As aquatic disinfectants are already commonly used to decontaminate equipment, the efficacy of selected disinfectants to reduce growth rates, induce plant tissue biodegradation and limit new shoot and root growth of apical fragmentary propagules was examined for four invasive macrophytes: *Crassula helmsii*, *Egeria densa*, *Elodea canadensis* and *Lagarosiphon major*.

Materials and methods

The efficacy of Virkon Aquatic (Antec Int. DuPont) and Virasure Aquatic (Fish Vet Group) was examined using 2% ($20\,g\,L^{-1}$) and 4% ($40\,g\,L^{-1}$) disinfectant solutions, and a 0% ($0\,g\,L^{-1}$) control. In all cases, apical fragments were harvested from mature plants and cut from unbranched sections of stem. Fragmentary propagules of each species were then independently submerged in 2% and 4% solutions of Virkon Aquatic or Virasure Aquatic for a period of 5, 15 or 30 minutes. All treatment combinations were replicated in triplicate, i.e. $n = 3$. All solutions were made using dechlorinated tap water. Control groups were likewise submerged in dechlorinated tap water (i.e. a 0% solution) for the same exposure times. Post exposure, all samples were submerged in dechlorinated water and gently washed clean for 2 minutes; this was repeated twice. All fragments were then immediately placed within individual plastic Magenta vessels containing 300 mL of locally sourced pond water. The fragmentary propagules were then housed under standard growth conditions of 18°C, with a 16:8 hours light–dark regime. Water lost due to evaporation was replenished as required. Retention of viability, as evidenced by the presence of new shoot growth, was assessed at 28 days following exposure to disinfectants. Viability of plants in relation to the length of new shoot growth was analysed using beta regression. All statistical analyses were performed using R software.

Results

New shoot relative growth rate (RGR) was significantly reduced by treatment ($F_{4,119} = 9.74$, $p < 0.001$; Figure 4.12), reflecting lower regrowth across all disinfectant-treated plant species relative to the controls (all $p < 0.001$). However, there were no significant differences in shoot RGR among disinfectant treatments, regardless of concentration (all $p > 0.05$). Relative growth rates also differed significantly between species overall ($F_{3,119} = 22.58$, $p < 0.001$), with *C. helmsii* displaying significantly lower RGR of new shoots than all other species (all $p < 0.001$), and *L. major* exhibiting greater regrowth than *E. canadensis* or *E. densa* (both $p < 0.01$). RGRs of new shoots were not significantly affected by exposure time ($F_{3,119} = 2.16$, $p > 0.05$).

Discussion

Although 2% and 4% solutions of both aquatic disinfectants induced substantial degradation of the original fragmentary propagule, all species retained viability in relation to shoot regrowth, even following submergence in 4% solutions for exposure times of 30 minutes. Accordingly, the present study indicates that the examined broad-spectrum aquatic disinfectants will not be capable of curtailing the regrowth for invasive macrophytes. See Crane *et al.* (2020) for further in-depth discussion.

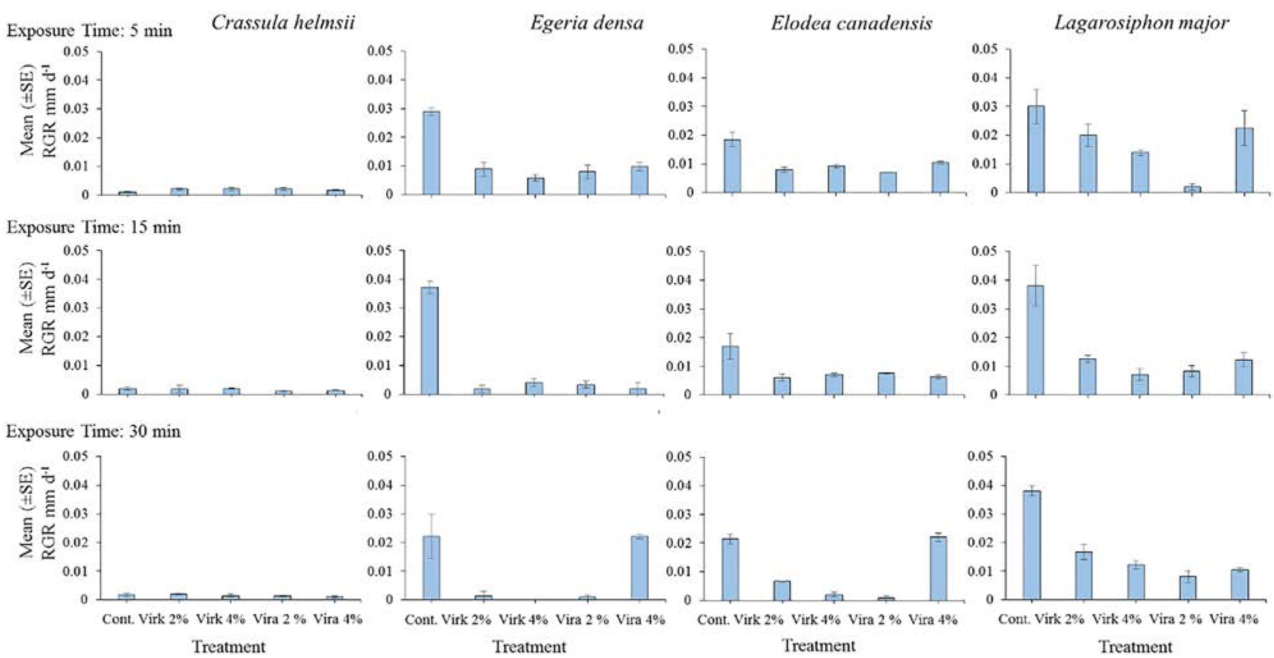


Figure 4.12. Relative growth rate (mean ± SE) of new shoots produced by macrophyte fragmentary propagules at 28 days post exposure to aquatic disinfectants, for 0% (0 g L^{-1}), 2% (20 g L^{-1}) and 4% (40 g L^{-1}) solutions of selected aquatic disinfectants. Fragments were submerged for 5, 15 or 30 minutes ($n = 3$ per treatment). Cont., control; Virk, Virkon Aquatic; Vira, Virasure Aquatic. SE, standard error.

4.2.2 *Killer shrimp (*Dikerogammarus villosus*)*

Aim of the study

Although *Dikerogammarus villosus* is not yet present on the island of Ireland, there is an urgent need to prevent the introduction of this highly invasive and damaging amphipod crustacean. While broad-spectrum aquatic disinfectants are frequently suggested as a means to kill *D. villosus*, data concerning their effectiveness are unclear. Here, the effectiveness of disinfectant soaking and mist spray treatments, as well as novel steam spray applications, in killing *D. villosus* is assessed.

Materials and methods

D. villosus specimens were collected at two sites in Great Britain and transported to the University of Leeds, where these specific experiments were hosted. The efficacy of Virasure Aquatic, Virkon Aquatic and Virkon S (Antec Int. DuPont) was examined using 1% ($10\,g\,L^{-1}$), 2% ($20\,g\,L^{-1}$) or 4% ($40\,g\,L^{-1}$) disinfectant solutions, and a 0% ($0\,g\,L^{-1}$) control. Virkon S is not recommended for use near aquatic environments but can be used elsewhere, such as at depots. Initially, immersion of specimens in 1% disinfectant solutions was assessed for four exposure times: 30, 60, 120 and 300 seconds ($n=3$ per experimental group). Following this procedure, new specimen groups were submerged in 2% or 4% solutions for five exposure times: 5, 15, 30, 60 and 300 seconds ($n=3$ per experimental group). Each experimental group consisted of 10 *D. villosus* specimens, which were immersed in disinfectant solutions for the allotted treatment period. Control groups were likewise immersed in dechlorinated tap water (i.e. 0% solution) for the same exposure times. Following experimental exposure, the *D. villosus* specimens were re-immersed in dechlorinated tap water for a 2-minute period to remove excess disinfectant. This washing process was repeated twice.

Mist spray applications for all three disinfectants were examined using 1%, 2% or 4% solutions and a 0% control. Groups of five *D. villosus* specimens were exposed to disinfectant mist spray for 2, 5 or 10 spray applications ($n=3$ per experimental group). Spray treatments were directly applied at a distance of 6–8 cm from the exit point of the spray bottle. Specimens were then left air exposed for a 5-minute period (at 20°C), before being re-immersed in dechlorinated tap water for a period of 2 minutes to removed excess disinfectant. This washing process was repeated twice. In addition, groups of 10 *D. villosus* specimens were directly exposed to a continuous jet of steam for 5, 10, 30, 60 or 120 seconds (≥100°C; Kärcher SC3 Steam Cleaner) ($n=3$ per experimental group).

Steam was directly applied at a distance of 6–8 cm from the exit point of the lance. Groups were then air exposed for a 10-minute period (at 20°C) to allow gradual cooling before being re-immersed in dechlorinated tap water. Control groups were air exposed for 12 minutes.

In all cases, following the removal of excess disinfectant for both soaking and mist spray experiments or cooling periods, specimen groups were immediately returned to 200 mL of aerated, dechlorinated tap water in their original containers for a 24-hour recovery period (14°C; 12:12 hours light–dark), after which mortality was assessed. Specimens were considered dead if they did not respond to stimuli and did not hold their pereopods under their body. Mortality of *D. villosus* was analysed using generalised linear models (GLMs) assuming a binomial error distribution. Statistical analyses were performed using R software.

Results

Immersion in 1% disinfectant caused significant mortality of *D. villosus* [$\chi^2=432.32$, degrees of freedom (df) $=3$, $p<0.001$]. Total mortality was evidenced following immersion in 1% of all three disinfectant solutions for ≥120 seconds (Table 4.1). Furthermore, at a concentration of 1%, Virasure Aquatic caused significantly higher mortality than either Virkon Aquatic or Virkon S (both $p<0.05$). Following immersion treatments in 2% and 4% disinfectant solutions, total *D. villosus* mortality was observed for all disinfectant treatments at exposure durations of ≥60 seconds (Table 4.1). Overall, treatment had a significant effect on *D. villosus* mortality ($\chi^2=712.59$, df $=6$, $p<0.001$). Treatment with 2% Virasure Aquatic was significantly more effective than either 2% Virkon Aquatic or Virkon S (both $p<0.001$). Furthermore, immersions in all 4% disinfectant solutions were significantly more efficacious than 2% disinfection in Virkon Aquatic or Virkon S (all $p<0.001$).

Table 4.1. Raw percentage mortality (mean ± SE) of *D. villosus* at 24 hours following exposure to disinfectant treatments for various exposure times

Treatment	Concentration (%)	Exposure time (seconds) 5	15	30	60	120	300
Immersion in 1% disinfectants							
Control	0	–	–	0	0	0	0
Virasure Aquatic	1	–	–	83.3±12	100	100	100
Virkon Aquatic	1	–	–	46.6±3.3	96.3±3.3	100	100
Virkon S	1	–	–	40±5.7	86.6±3.3	100	100
Immersion in 2% and 4% disinfectants							
Control	0	0	0	3.3±3.3	3.3±3.3	–	0
Virasure Aquatic	2	23.3±8.8	100	100	100	–	100
	4	46.6±8.8	100	100	100	–	100
Virkon Aquatic	2	3.3±3.3	56.7±12	100	100	–	100
	4	23.3±8.8	100	100	100	–	100
Virkon S	2	3.3±3.3	56.7±26	86.6±3.3	100	–	100
	4	80±15.3	100	100	100	–	100

Note: all treatments were replicated three times.
SE, standard error.

Disinfectant spray treatments caused significant mortality of *D. villosus* ($\chi^2 = 247.43$, df = 9, $p < 0.001$). Total *D. villosus* mortality was observed following treatments of 2% and 4% solutions of all three disinfectants after five sprays (Table 4.2). Five spray treatments of 1% solutions resulted in high, but not complete, mortality. The maximum number of sprays tested here – 10 – resulted in a mean mortality of 86.6% for 1% Virkon Aquatic and Virkon S and 100% mortality for 1% Virasure Aquatic. Mortality following treatment with 1% Virasure Aquatic was significantly greater than that achieved with either 1% Virkon Aquatic or 1% Virkon S (both $p < 0.05$), but the effectiveness of the two Virkon products was more similar ($p > 0.05$). All 4% disinfectant treatments caused significantly greater mortality than 1% Virkon Aquatic and Virkon S solutions (all $p < 0.01$), but the differences in effectiveness compared with 1% Virasure Aquatic

Table 4.2. Raw percentage mortality (mean ± SE) of *D. villosus* at 24 hours following exposure to different numbers of disinfectant treatments

Treatment	Concentration (%)	Number of sprays 2	5	10
Control	0	0	0	6.6±6.6
Virasure Aquatic	1	66.6±24	80±20	100
	2	20±11.5	100	100
	4	100	100	100
Virkon Aquatic	1	20±11.5	66.6±13.3	86.6±13.3
	2	13.3±13.3	100	100
	4	80±20	100	100
Virkon S	1	6.6±6.6	73.3±13.3	86.6±6.6
	2	33.3±13.3	100	100
	4	100	100	100

Note: all treatments were replicated three times.
SE, standard error.

were less marked (all $p > 0.05$). Treatments with 2% disinfectants were similar among products (all $p > 0.05$). Number of sprays also significantly influenced mortality ($\chi^2 = 140.99$, df = 2, $p < 0.001$), with mortality following two sprays significantly lower than treatment with five or 10 sprays, at all concentrations (all $p < 0.001$).

Total *D. villosus* mortality was caused by direct steam exposures of ≥ 10 seconds, while exposure for 5 seconds resulted in a mean mortality of 70%. Steam treatments had a significant effect on mortality of *D. villosus* ($\chi^2 = 148.13$, df = 5, $p < 0.001$). There were no significant differences in mortality between steam application durations (all $p > 0.05$).

Discussion

Immersion of specimens in disinfectant solutions was shown to be a suitable biosecurity treatment, with complete *D. villosus* mortality. Mortality was greater at higher concentrations of disinfectant and for longer immersion durations. For all three disinfectants tested, total mortality of *D. villosus* was achieved following immersion times of ≥ 120, 60 and 15 seconds for 1%, 2% and 4% solutions, respectively. Disinfectant spray treatments were also highly effective. Total *D. villosus* mortality was observed for all disinfectants at 2% and 4% solutions following five spray treatments. High mortality (> 85%) was recorded following 10 spray treatments of 1% solutions. Overall, for shorter immersion times and reduced spray exposure, Virasure Aquatic solutions appeared to be marginally more effective. On the other hand, steam exposure was highly efficacious, with complete mortality occurring at exposure durations of ≥ 10 seconds. See Bradbeer *et al*. (2020) for further in-depth discussion.

*4.2.3 Quagga mussel (***Dreissena bugensis***) and zebra mussel (***Dreissena polymorpha***)*

Aim of the study

Invasive bivalve species such as quagga mussels (*Dreissena bugensis*) and zebra mussels (*Dreissena polymorpha*) are considered a major threat to the function and biodiversity of freshwater ecosystems worldwide (Sousa *et al*., 2014). However, the effectiveness of suggested biosecurity treatments is frequently unclear or unknown. Here, therefore, the effectiveness of two commonly used broad-spectrum aquatic disinfectants and various thermal treatments were assessed.

Materials and methods

For the assessment of disinfectant solutions and steam treatments, *D. bugensis* and *D. polymorpha* specimens were collected from two sites in Great Britain and transported to the University of Leeds. Only actively filtering individuals that responded to mechanical stimuli were selected for experimentation. The efficacy of aquatic disinfectants Virasure Aquatic and Virkon Aquatic was examined using 2% (20 g L^{-1}) or 4% (40 g L^{-1}) disinfectant solutions, and a 0% (0 g L^{-1}) control. All solutions were made using dechlorinated tap water. Disinfectant solutions were assessed for four exposure times: 15, 30, 60 and 90 minutes. In all cases, experimental groups consisted of 10 specimens. Each species was examined separately. Treatment groups were submerged in disinfectant solutions for the allotted treatment period. Control groups were likewise immersed in dechlorinated tap water (i.e. 0% solution) for the same exposure times. Following experimental exposure, the groups were immediately extracted and re-submerged in dechlorinated water for a 2-minute period to aid the removal of excess disinfectant; this washing process was repeated twice. All disinfectant treatments were replicated three times per concentration, species and exposure time (i.e. $n = 3$).

To examine the efficacy of steam treatments in killing *D. bugensis* and *D. polymorpha* specimens, experimental groups of 10 specimens were directly exposed to a continuous jet of steam (≥ 100°C; 350 kPa: Kärcher SC3 Steam Cleaner), at a distance of 2–3 cm from the spout of the lance for 5, 10, 30, 60 or 120 seconds ($n = 3$ per experimental group). Each species was examined separately, and all treatments were replicated three times per species. Control specimens were allowed to air dry for a 15-minute period. After exposure, all specimens were cooled for a 5-minute period.

In all cases, upon cessation of an experiment, specimen groups were returned to 250 mL of dechlorinated bubbled water (13–14°C; 12:12 hours light–dark) for a 24-hour 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. Binomial GLMs with logit links were used to examine bivalve mortality rates separately in each experiment. Estimated marginal means were used post hoc for pairwise Tukey comparisons of significant predictors. All statistical analyses were performed using R software.

Results

Total mortality was consistently observed in *D. polymorpha* following all 90-minute disinfectant exposures, and following 15-minute exposures to 2% Virkon Aquatic. Conversely, a maximum average of 80% mortality was observed in *D. bugensis* following disinfectant treatments. Controls for both species exhibited high survivability (Table 4.3). A significant "treatment × species" term (GLM, $\chi^2 = 20.36$, df = 4, $p < 0.001$) reflected significantly greater mortality of *D. polymorpha* compared with *D. bugensis* following all disinfectant treatments (all $p < 0.05$), while interspecific mortality rates were more similar in controls ($p = 0.14$). The "exposure × species: interaction was also significant (GLM, $\chi^2 = 31.90$, df = 3, $p < 0.001$), with mortality rates of *D. polymorpha* significantly higher than *D. bugensis* following 90 minutes of exposure ($p < 0.001$). For both species, total mortality was observed following steam exposures at or exceeding 30 seconds. Steam treatment caused significant mortality in bivalves (GLM, $\chi^2 = 334.11$, df = 5, $p < 0.001$), with exposures for 10 seconds or longer causing significantly greater mortality than in the control or 5-second groups (all $p < 0.001$). Differences between 5-second exposures and control groups were not statistically clear ($p = 0.05$). Mortality rates of *D. polymorpha* were significantly higher than *D. bugensis* overall (GLM, $\chi^2 = 9.56$, df = 1, $p = 0.002$).

Discussion

Immersion in 2% and 4% solutions of Virasure Aquatic or Virkon Aquatic did not reliably kill adult *Dreissena* bivalves. For both species, although high, if not complete, mortality was observed for almost all treatments, these findings lack a clear consistency. High levels of bivalve survival following exposure to chemical disinfectants is unsurprising, and probably reflects a deliberate behavioural strategy whereby bivalves close their valves and isolate themselves from unfavourable environmental conditions. However, for both *Dreissena* species, complete mortality was reliably achieved following steam exposure of ≥30 seconds. This result is consistent with the high levels of efficacy reported for steam spray treatments by a number of other studies concerning bivalves.

Table 4.3. Raw percentage mortality (mean ± SE) of *D. bugensis* and *D. polymorpha* at 24 hours following immersion in 2% (20 g L^{-1}) or 4% (40 g L^{-1}) disinfectant solutions, and a 0% (0 g L^{-1}) control, for various exposure times

		Exposure time (min)			
Treatment	**Concentration (%)**	**15**	**30**	**60**	**9**
D. bugensis					
Control	0	0	0	3.3 ± 3.3	0
Virasure Aquatic	2	66.7 ± 8.8	56.7 ± 3.3	63.3 ± 6.7	70 ± 5.8
Virasure Aquatic	4	46.7 ± 3.3	76.7 ± 3.3	73.3 ± 8.8	66.7 ± 6.7
Virkon Aquatic	2	73.3 ± 3.3	73.3 ± 3.3	80 ± 5.8	73.3 ± 3.3
Virkon Aquatic	4	46.7 ± 3.3	80 ± 10	46.7 ± 6.7	56.7 ± 8.8
D. polymorpha					
Control	0	0	0	0	0
Virasure Aquatic	2	76.7 ± 3.3	96.7 ± 3.3	80 ± 5.8	100
Virasure Aquatic	4	56.7 ± 14.5	86.7 ± 3.3	53.3 ± 6.7	100
Virkon Aquatic	2	100	96.7 ± 3.3	90	100
Virkon Aquatic	4	83.3 ± 6.7	70 ± 5.7	86.7 ± 6.7	100

Note: all treatments were replicated three times.
SE, standard error.

Overall, although exposure to broad-spectrum aquatic disinfectants did not reliably cause mortality, it appears that relatively brief exposure to steam could be used as part of effective and efficient biosecurity protocols to prevent further spread of the *Dreissena* bivalves. See Coughlan *et al.* (2020) for further in-depth discussion.

*4.2.4 Asian clam (***Corbicula fluminea***)*

Aim of the study

The Asian clam (*C. fluminea*) is a high-impact invader that can dominate macroinvertebrate communities, physically alter benthic habitats and disrupt ecosystem-regulating services (Sousa *et al.*, 2014). Once established, populations of *C. fluminea* are notoriously difficult to eradicate or control (Caffrey *et al.,* 2011b; Sheehan *et al.,* 2014). Although effective biosecurity measures exist for spread prevention of juvenile *C. fluminea* [shell height (SH) ≤10 mm; Barbour *et al.,* 2013], the efficacy of these biosecurity measures on larger adult specimens is currently unknown. Here, the effectiveness of a variety of potential biosecurity measures is examined: aquatic disinfectants, hot water and steam applications.

Materials and methods

Adult *C. fluminea* specimens were collected from the River Barrow in Ireland and transported in source water to Queen's University Marine Laboratory (QML), Portaferry, NI. Only specimens that were obviously alive and feeding were selected for experimental work. The efficacy of Virasure Aquatic and Virkon Aquatic was examined using 2% (20 g L^{-1}) and 4% (40 g L^{-1}) concentrations. A pilot study indicated that 1% (10 g L^{-1}) solutions would be ineffective. Groups of 10 medium (SH = 15–20.9 mm) and large (21–36 mm) specimens were immersed in solutions (dechlorinated tap water) of either chemical for 10, 20, 40 and 80 minutes ($n = 5$ replicates). Control groups were submersed in dechlorinated tap water for the same time periods to act as a procedural control. Immediately after submersion for the defined periods, specimens were washed with tap water for 2 minutes to remove excess disinfectant. Control groups were likewise washed. To investigate the effectiveness of hot water treatments, groups of 10 medium and large specimens were immersed in water at 35, 40 and 45°C for 5, 10 and 20 minutes ($n = 5$ replicates). Constant water temperature was maintained using water baths. Control groups were submersed in dechlorinated tap water at 12°C. For assessing efficacy of steam spray, groups of 10 specimens (SH = 15–26 mm) were directly exposed to a continuous jet of steam (≥100°C; Bissell SteamShot Handheld Steam Cleaner) at a distance of 2–3 cm from the source for 10 seconds, 30 seconds or 1, 2, 5 or 10 minutes ($n = 5$ replicates). Control groups were taken out of water and allowed to air dry for the same time periods. Following each experiment, all specimens were returned to 600 mL of dechlorinated bubbled water at 12°C for a 24-hour recovery period, after which mortality was assessed. Specimens were considered dead if they were gaping, or if they did not offer any resistance to being teased apart with tweezers and did not reclose. Beta regression was used to analyse mortality rates in each experiment. Analysis of deviance was then applied to derive appropriate models, with the chi-squared test (χ^2) used to report the relevance of effects to the dependent variable. Tukey's honest significant difference method was used for specific pairwise comparisons where required. All analysis was conducted using R software.

Results

The mortality of medium and large clams exposed to aquatic disinfectants was up to 31% and 58%, respectively. Significantly higher clam mortality was observed at greater disinfectant concentrations ($\chi^2 = 133.4$, df = 4; $p < 0.001$), for larger clams ($\chi^2 = 17.5$, df = 1; $p < 0.001$) and at longer exposure times ($\chi^2 = 40.2$, df = 3; $p < 0.001$). Mortality levels for clams submersed in aquatic disinfectants were significantly higher than in control treatments, across all concentrations (all $p < 0.001$). However, no significant differences between the efficacy of the different concentrations of Virasure and Virkon solutions were observed (all $p > 0.05$). Furthermore, there were no significant differences between 10- and 20-minute exposures, nor between 20- and 40-minute exposures (all $p > 0.05$). There was up to 100% mortality of hot water-treated clams across both size classes. Overall, there was significantly greater clam mortality with increasing water temperature ($\chi^2 = 1156.9$, df = 3; $p < 0.001$). However, there was no significant difference between the control and the 35°C treatment ($p > 0.05$). Mortality was not significantly affected by either clam size or exposure time, and there were no interactions between the treatment, clam size and exposure time effects (all $p > 0.05$; Figure 4.13). Furthermore, up to 100% mortality was recorded for steam-treated clams. The exposure to direct steam applications significantly increased clam mortality ($\chi^2 = 1684.4$, df = 6; $p < 0.001$), wherein maximum mortality was caused at, and beyond, an exposure time of 30 seconds.

Discussion

Overall, the aquatic disinfectants examined did not cause substantive mortality of adult *C. fluminea*. When compared with the disinfectant treatment efficacies reported by Barbour *et al.* (2013), these data suggest that adult *C. fluminea* are less susceptible than juveniles to previously proposed chemical biosecurity protocols. However, hot water (45°C) can efficaciously cause 100% mortality of *C. fluminea* specimens at a 5-minute exposure. Furthermore, direct steam applications have been shown to cause 100% mortality of adult *C. fluminea* specimens at a 30-second exposure. See Coughlan *et al.* (2019a) for further in-depth discussion.

4.3 Biosecurity Best Practice Guidelines

3.3.1 Overarching principles

The steps of "check, clean, disinfect and dry" are essential for robust prevention of the spread of invasive species in aquatic environments.

Check

Upon exiting an aquatic site, all equipment, clothing and footwear should be visually checked for the presence of adhering material – biological or otherwise. Particular attention should be given to areas that are damp or difficult to inspect. A systematic checklist for larger, more complex items is recommended.

Clean

All material found adhering should be removed, including mud. This may be achieved through physical removal by hand, or by scrubbing, brushing or wiping down surfaces. Living organisms should be returned to the aquatic environment they came from. Never transfer living or dead organisms away from the site unless instructed otherwise. Inorganic material, such as plastic and other waste, should be correctly disposed of in an appropriate refuse receptacle. Equipment must also be washed or decontaminated. To wash small and delicate equipment (e.g. wetsuits), items can be submerged in a hot water bath. Larger, more structurally robust equipment (e.g. boats, vehicles) can be power washed or decontaminated with steam spray.

Disinfect

Once equipment has been cleaned, disinfection should occur. Small equipment items should be submerged in a disinfection bath, while larger items should be mist

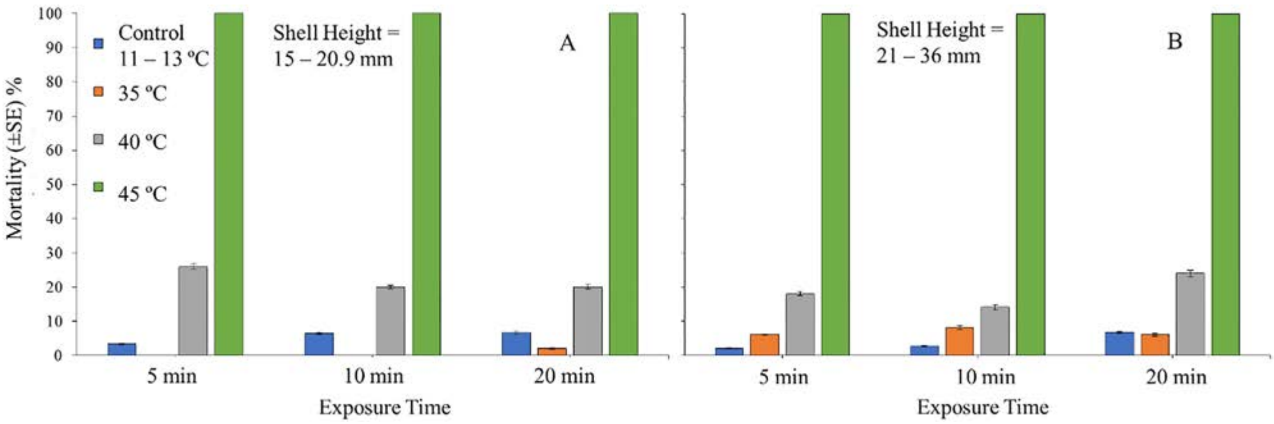


Figure 4.13. Mortality (mean ± SE) among groups of (A) 10 medium and (B) 10 large adult *C. fluminea* specimens 24 hours following exposure to hot water temperatures of 35°C, 40°C or 45°C for 5, 10 or 20 minutes ($n = 5$). SE, standard error.

sprayed. In addition, internal structures of equipment (e.g. water intake systems, designed to aid cooling of outboard motors) should be flushed with disinfectant solutions. Disinfection is particularly important to eliminate aquatic pathogens, parasites and other organisms that are difficult to detect visually (e.g. killer shrimp, crayfish plague).

Dry

Finally, all equipment and clothing should be allowed to dry before reuse. Ideally, drying periods should last 24 hours or longer. Make sure you do not transfer water elsewhere. Drain or wipe dry any areas that retain water (e.g. bilge or baitwells).

4.3.2 Health and safety considerations

User health and safety will also need to be considered in any proposed IAS spread prevention techniques, relevant to the jurisdiction in which they are to be performed. Therefore, the availability of any necessary personal protective equipment (PPE) (e.g. clothing, boots, face visor and other equipment) required for safe use should be confirmed prior to any endorsement of the suggested techniques. However, although the soaking of small equipment items in 1% or 2% solutions of aquatic disinfectants is considered a safe and practical cleaning protocol for recreational water users, the use of thermal treatments could result in user harm (e.g. water at >60°C or steam).

5 Practical Control and Best Practice Guidelines

5.1 Winter Heliotrope (*Petasites pyrenaicus*)

5.1.1 Growth habits of winter heliotrope

Winter heliotrope [*Petasites pyrenaicus* (L.) G. López, formerly known as *P. fragrans* (Vill.) C. Presl] is a low-growing and shade-tolerant plant native to the Mediterranean region of Europe. It was introduced to Ireland in the early 19th century (Hackney, 1992), where it has become invasive (Preston *et al.*, 2002; Reynolds, 2002; Booy *et al.*, 2015; Stace, 2019). Outside its native range, *P. pyrenaicus* grows vigorously along roadside verges and disturbed ground, where it successfully outcompetes native species. It has proved to be particularly problematic in the areas in which it was initially introduced, such as graveyards and landed estates. Here, it has extensively infested the understorey of ancient woodlands, to the detriment of native species. It is an extremely difficult plant to control (Reynolds, 2002; Devlin, 2008; Stace, 2019).

Aim of the study

The aim of this study was to understand the growth pattern of *P. pyrenaicus* in open and shaded habitats, its impact on light reaching the soil, and the nature of its asexual reproduction through vegetative propagation.

Materials and methods

Three separate experiments were completed.

1. Growth patterns: observations of *P. pyrenaicus* growth patterns were recorded (in percentage cover) over a 12-month period, on a suite of 1 m × 1 m plots.
2. Shading effect: the light level above and below the *P. pyrenaicus* canopy was recorded in six open and six shaded sites, and compared with the percentage cover.
3. Vegetative reproductive capacity: laboratory experiments in a growth chamber assessed the viability of a range of vegetative cuttings to propagate (leaf, leaf and petiole, rhizome and crown).

Results

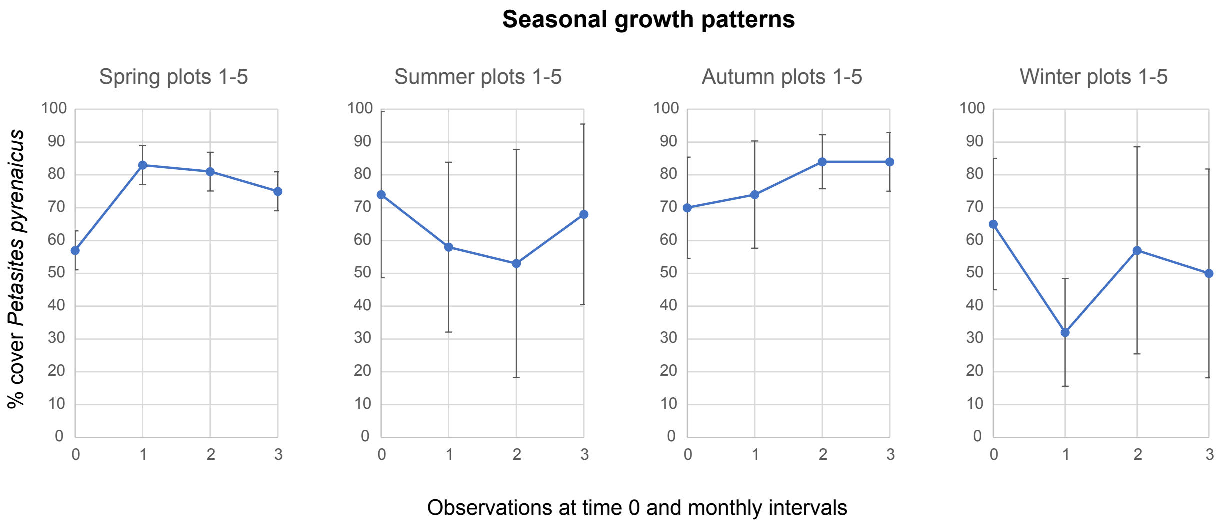
Growth patterns. One of the principal reasons for the original introduction of *P. pyrenaicus* as groundcover was its year-round vegetation. It is not an evergreen plant but grows continuously throughout the seasons (Figure 5.1). Our studies indicated that, during the annual growing cycle for 2017/2018, the plant grew most vigorously in early spring and late autumn, and its vigour and vegetative expression decreasing during the summer and winter months. Leaf cover was least in early winter, coinciding with the flowering period of the plant.

Shading effect of canopy vegetation. Our experimental results indicate that *P. pyrenaicus*, while often described as a shade-loving plant, exhibits a greater vegetation growth rate in open sites than in shaded situations. Where roadside verges and waste ground are infested with *P. pyrenaicus*, leaf cover is greater and soil conditions may more closely resemble those of a shaded (e.g. forest floor) habitat (Figure 5.2). This limits the abundance and variety of native species present and reduces the opportunity for disturbed ground to regenerate via the normal succession.

Vegetative reproductive capacity. Experiments carried out under controlled laboratory conditions at the Institute of Technology Sligo showed the ability of *P. pyrenaicus* to propagate from a variety of vegetative cuttings, without requiring an attached rhizome (Figure 5.3). This implies that cutting the plant, as is done routinely during maintenance by road crews, has the potential to spread and further distribute the plant.

Discussion

These observations give us an insight into the behaviour of *P. pyrenaicus*, which was not available to us in the literature. Understanding its methods of growth and reproduction, and its impact on infested habitats, will inform its prioritisation for future management.



Each graph shows the average % cover on five discrete plots, measured at time 0 and three distinct monthly intervals thereafter. New plots were marked out in spring, summer, autumn and winter, a total of ten plots per season. Seasons relate to visual growth indicators, rather than calendar months. The graphs show a general growth trend for *P. pyrenaicus*, with a peak in early spring and mid-autumn. Cover of leaves is least in early winter.

Figure 5.1. Observations of percentage cover of *P. pyrenaicus* according to season.

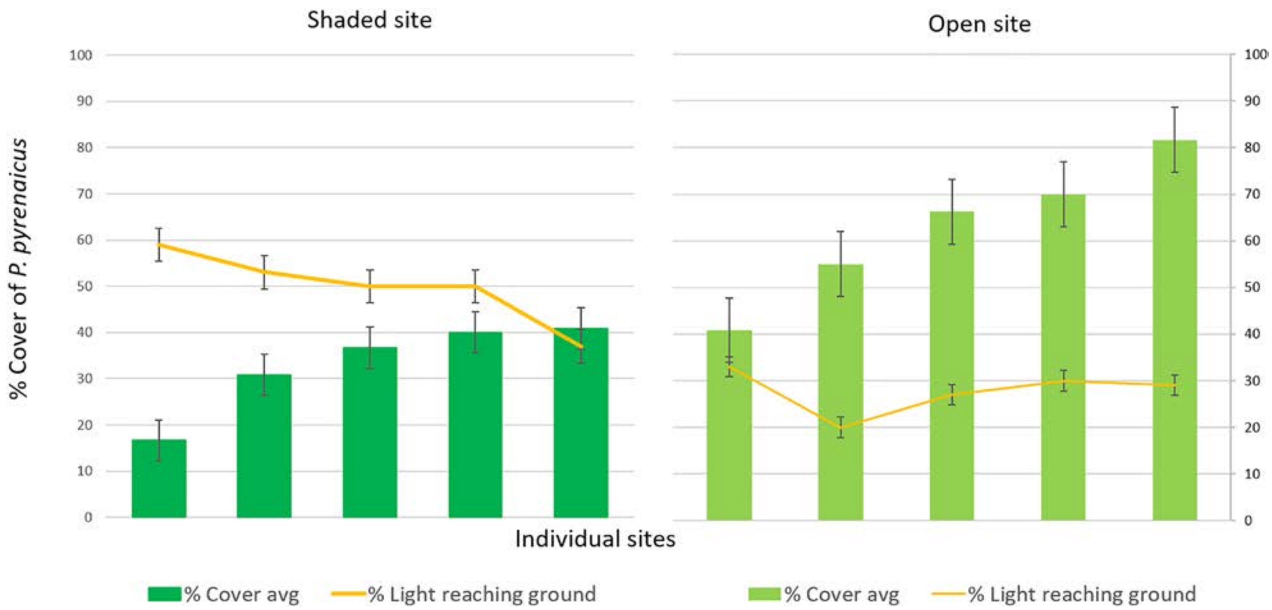


Figure 5.2. Impact of *P. pyrenaicus* cover on light levels below. Avg, average.

The detailed results of these experiments will be made available through the outputs of this project.

5.1.2 The impact of different chemical treatments and the timing of their application on the control of winter heliotrope

The control and eradication (where possible) of IAS is required under EU legislation. Control measures must be appropriate and effective both for the species being treated and for the site in which the IAS are resident. Effective use of herbicides is an important element of IAS management and the most effective application will give the greatest impact at the lowest environmental and economic cost. *P. pyrenaicus* has overgrown many of the areas where it was originally introduced and its eradication from these sites may now be technically and practicably impossible. Its increasing spread along roadsides and waste ground, however, must be managed.

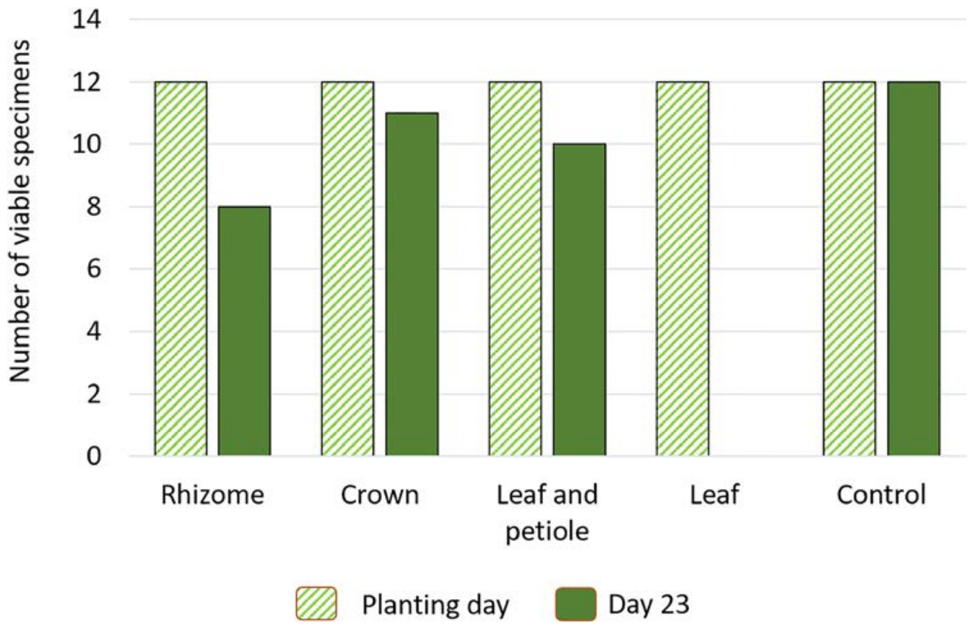


Figure 5.3. Results of growth chamber experiments with *P. pyrenaicus*.

Aim of the study

The aim of this study was to identify the most effective herbicidal treatment to control *P. pyrenaicus*, and the most effective timing of application to optimise results. The experiments took place at Lissadell House and Gardens, County Sligo, between 2016 and 2018.

Materials and methods

The treatments used were Synero (a selective herbicide containing aminopyralid and fluroxypyr) and Roundup Biactive (a systemic, broad-spectrum herbicide containing glyphosate that is cleared for use near aquatic situations), and these two herbicides each combined with Topfilm (an adjuvant designed to improve the performance of herbicides, particularly in water). Treatments to a suite of 1 m × 1 m plots were delivered in four seasonal applications and monitored for a further 4 months for their impact on vegetation and regrowth.

Results

Synero showed an immediate and comprehensive impact on the growth of *P. pyrenaicus*, regardless of the season of application. Some regrowth was observed 4 months after the summer application. Roundup Biactive significantly reduced leaf cover of *P. pyrenaicus* 1 month post treatment. This reduction was retained after 2 months with both the spring and summer applications. Autumn- and winter-treated plots showed substantial regrowth 2 months post treatment. By month 4, all plots treated with Roundup Biactive were showing strong regrowth. There was no significant impact on growth retardation from the addition of Topfilm in this series of experiments.

Conclusion

Synero gave the most consistently successful results in these experiments. In locations where the use of Synero is not permitted, such as under the dripline of trees, repeated applications of Roundup Biactive may be used to suppress growth.

5.1.3 Using open-source software and digital imagery to efficiently and objectively quantify cover density of an invasive alien plant species

Introduction

Reducing errors in monitoring IAS positively influences the efficacy of management and eradication protocols (Piria *et al.,* 2017), as well as improving our understanding of the effects of climate change and increasing anthropological disturbances (Davis *et al.*, 2018). The development of accurate and repeatable vegetation monitoring techniques that require minimal resources is urgently required for the study and long-term monitoring and modelling of invasive plant species and their pathways of introduction (Caffrey *et al.*, 2014; Dick *et al.*, 2014, 2017a,b; Essl *et al.*, 2015; Piria *et al.*, 2017). The most commonly used method for measuring vegetation cover is visual estimation, which is highly subjective, potentially leading to measurement errors. Our novel application of morphological image analysis provides an objective method for detection and accurate cover assessment of an invasive alien plant species, giving reduced measurement errors when compared with visual estimation. Importantly, this method is entirely based on free software. GuidosToolbox is a collection of generic raster image-processing routines, including morphological spatial pattern analysis (MSPA) – a cost-effective, accurate, objective and repeatable method that classifies and quantifies features according to shape. MSPA was employed in this study to detect and quantify cover of invasive winter heliotrope, *P. pyrenaicus*. Its efficacy was compared with that of two other methods – geographical information system (GIS) digitisation (used as an accurate baseline) and visual estimation (standard method) (see Figure 5.1). We tested the limit of MSPA usability on images of varying complexity, i.e. “simple”, “intermediate” or “complex”, depending on the presence/absence of other vascular plant species and the species richness of the plot.

Morphological spatial pattern analysis consistently provides higher accuracy and precision for *P. pyrenaicus* cover measurement than the standard visual estimation method. Our methodology is applicable to a range of focal vegetation species and can be applied where other methods are limited, and where there are extremes of light and shade or distortion of colour such as occurs with understorey vegetation.

Aim of the study

The study hypothesises that MSPA (1) is a suitable image-processing routine for the quantification of *P. pyrenaicus* ground cover from digital imagery and (2) provides an objective, accurate and repeatable approach to quantifying *P. pyrenaicus* ground cover, complementary to expert visual estimation.

Materials and methods

Images were obtained from an experimental field study researching a variety of treatment options for the control of *P. pyrenaicus*. Each image captured a 1-m^2 quadrat of *P. pyrenaicus*-infested ground cover. The methodology followed a three-step process (Figure 5.4): (1) MSPA was used to determine percentage leaf cover based on morphological components of the image features; (2) GIS digitisation of *P. pyrenaicus* leaf images were generated, determining a precise percentage leaf cover within each image; and (3) field ecologists visually estimated *P. pyrenaicus* leaf cover from the 1-m^2 quadrat images.

Data from each step were statistically analysed using five separate methods for precision and accuracy in order to quantify the level of agreement between MSPA, GIS digitisation and visual estimation (Table 5.1). Cover values obtained for each method were also transformed into the ordinal DAFOR (dominant, abundant, frequent, occasional, rare) scale, which was subsequently analysed to explore the effectiveness of the methods within the context of a cover scale in addition to percentage cover.

Image complexity levels. From a bank of 480 images (all taken with a Nikon D-40 SLR camera), 30 were assigned to each level of complexity and, from these, 10 images were randomly selected within each complexity level.

Three levels of complexity were used: (1) simple – images containing *P. pyrenaicus* only, (2) intermediate – images containing *P. pyrenaicus* and one additional plant species (typically *Poaceae* spp.), and (3) complex – images containing *P. pyrenaicus* and multiple plant species (typically *Poaceae* spp., *Ranunculus* spp., *Equisetum* spp., etc.).

Statistical analyses. “Agreement” is a broad term that incorporates the concepts of precision and accuracy, to measure “closeness” between values obtained by different methods (Barnhart *et al*., 2002). The statistical approaches applied were: (1) Bland–Altman plots, (2) the concordance correlation coefficient, (3) Fleiss’s kappa, (4) one-way analysis of variance (ANOVA) and (5) the two-samples Wilcoxon test.

Results

Table 5.2 summarises the results of the statistical analysis. MSPA gave the best agreement, i.e. the most

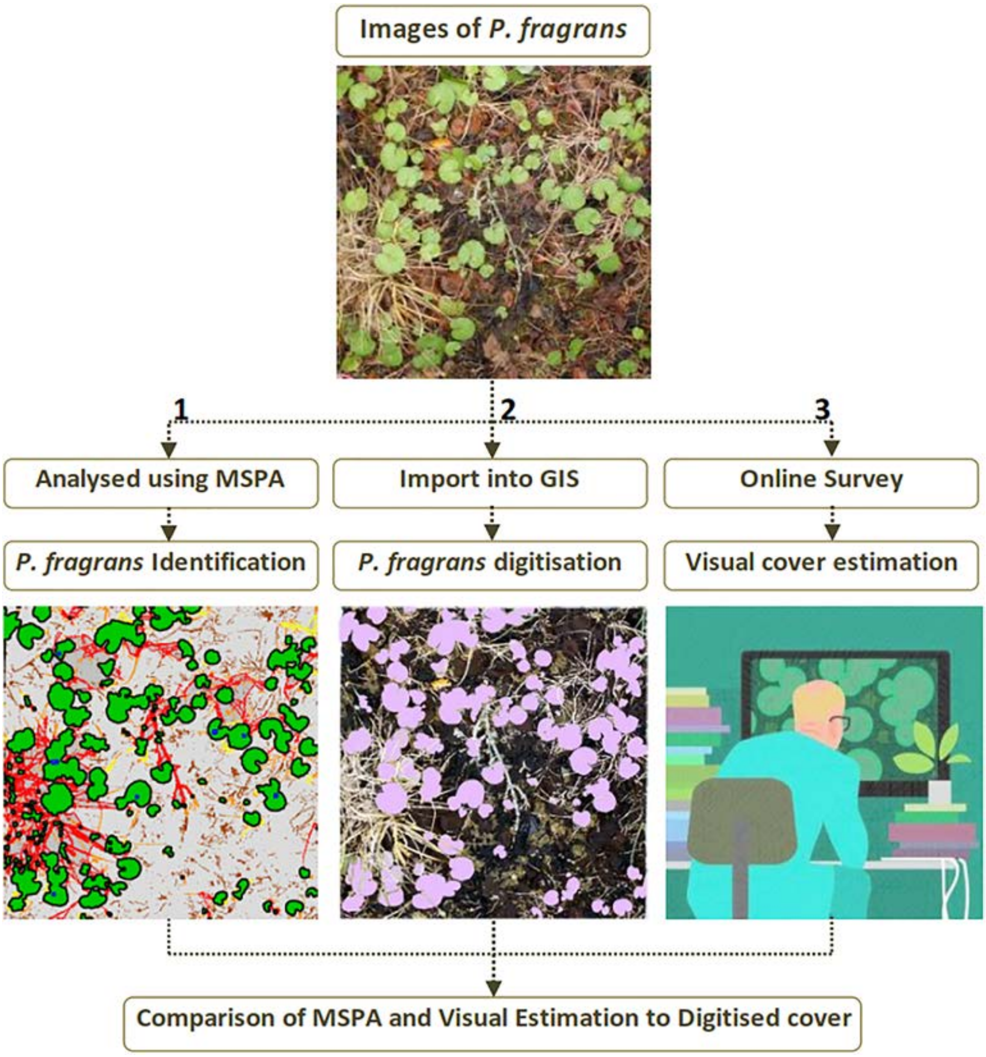


Figure 5.4. Schematic of the main steps taken to quantify *P. pyrenaicus* leaf cover.

Table 5.1. Summary explanation of methods used to assess percentage cover of *P. pyrenaicus* in images

MSPA	Detects pixel patterns within binary imagery of foreground (interest) and background (non-interest), describing the geometry and connectivity of the image components
GIS digitisation of images	Provides a pseudo-control to accurately quantify living (green) *P. pyrenaicus* leaf cover and to validate the accuracy of MSPA and visual estimation
Visual estimation	Eleven experienced field ecologists in Ireland, the UK and Belgium completed visual estimation of the percentage *P. pyrenaicus* cover in all 30 normalised images via an anonymous online survey. For each image, the mode of all participants' abundance estimations was considered for the statistical analyses

accurate and precise results. Visual estimation was precise, but less accurate.

Discussion

This study examined the overall agreement, precision and accuracy of three methods to quantify invasive winter heliotrope (*P. pyrenaicus*) leaf cover from a range of digital images taken during field monitoring of experimental treatment quadrats. Overall, there was good agreement between all the methods used. The comparison of precision shows that all methods produce similar results, and that agreement differences observed are related to accuracy. The results are consistent regardless of whether continuous or ordinal data (DAFOR scale) are used (see Table 5.2). The use of MSPA to discriminate leaf shape and assess

Table 5.2. Summary of statistical processes completed

Technique	GIS digitisation/MSPA	GIS digitisation/visual estimation	MSPA/visual estimation
Bland–Altman plots	Strong agreement	Weaker agreement	Weaker agreement
	MSPA gives the best combination of accuracy and precision when compared with the control (GIS digitisation)		
Concordance correlation coefficient (CCC)	Strong agreement	Weaker agreement	Weaker agreement
	The CCC allows us to differentiate between comparisons at different levels of complexity. All levels of complexity showed stronger agreement using MSPA		
Fleiss's kappa (DAFOR scale)	Strong agreement	Weaker agreement	Weaker agreement
	When substituting the DAFOR scale for percentage cover, we can still see that MSPA gives the best combination of accuracy and precision when compared with the control (GIS digitisation)		
One-way ANOVA	No significant difference between the means. This implies that any differences in results are not because of precision		
Two-samples Wilcoxon text	Significant difference in the means. MSPA gave results closer to GIS digitisation than visual estimation did. This implies that any differences are differences in accuracy		

cover in digital imagery is a novel and innovative approach that can provide an accurate and objective alternative to traditional visual estimation. The method presented has potential for further application where rapid and accurate assessment of low vegetation structure complexities is required. Examples could include determining the percentage cover of *Trifolium* spp. in crop research (Figure 5.5) (e.g. Buchanan *et al.*, 2016; Rosario-Lebron *et al.*, 2019), *Lemnoideae* spp. encroachment in ponds (e.g. Smith, 2014) and *Gunnera tinctoria* infestation (e.g. Costa *et al.*, 2015), at a range of spatial scales.

As morphological analysis of vegetation approaches performances comparable to (and exceeding) that of visual estimation, it will present distinct advantages. The present method is applicable to temporal monitoring, particularly using fixed-point photography for change analyses. MSPA can be applied to accurately detect small changes, while mitigating the disadvantages associated with plant cover visual estimation uncertainty (Kennedy and Addison, 1987).

Morphological spatial pattern analysis performed better for images in the simple and complex categories, with results closest to those of digitisation.

Figure 5.5. Example of the use of MSPA to quantify *Trifolium* spp. within grassland sward.

The average difference between digitisation (used in this study as a pseudo-control) and MSPA is always smaller than the difference between digitisation and visual estimation for all the levels of complexity, despite not being significant throughout. MSPA consistently discriminated between linear and more ovate vegetation, including complex linear whorls of branches of *Equisetum* spp. Dead leaves from surrounding vegetation and other living green vegetation may have led to over-interpretation of *P. pyrenaicus*. Young, emerging *P. pyrenaicus* growth may also lead to under-interpretation depending on MSPA "edge" parameter settings. This effect may also be observed for severely damaged or distorted mature leaves. MSPA accuracy may decrease with extremely heterogeneous vegetation structures. Non-target species with similar leaf morphologies (e.g. *Rumex obtusifolius*) could lead to gross over-interpretation. However, improved digital image capture and survey methodologies could help increase the quality of results.

This study presents opportunities for further research and applications. The method developed is cost-effective, not limited to the management of IAS, and has the potential to be up-scaled to process large image datasets. In the context of the continued expansion of IAS globally, and our moral and legal obligations to address this problem, powerful image-processing tools can underpin improved management methods which are both intelligent and strategic. GuidosToolbox has far-reaching potential in field ecology which has yet to be harnessed, and is a potentially valuable element in an IAS management toolkit.

5.1.4 Best practice for control of winter heliotrope (Petasites pyrenaicus)

Scope

This best practice document provides guidance to stakeholders and government agencies on effective measures to manage and control winter heliotrope, an invasive terrestrial plant in Ireland. These measures are based on an assessment of the current recommended methods used worldwide and on studies carried out by the Institute of Technology Sligo, INVAS Biosecurity Ltd and Queen's University Belfast under the EPA project Prevention, Control and Eradication of Invasive Alien Species.

Identification

Winter heliotrope is a rhizomatous perennial herb that is invasive outside its native range in North Africa and the Mediterranean (GBIF, 2020; NBDC, 2020). It is equally successful in open and shaded sites, and in damp and well-drained soils. It was introduced to Ireland in the early 19th century as ground cover (Figure 5.6) in large demesnes and churchyards (Devlin, 2008). In 2017, this plant was recorded in 28 counties in Ireland during a citizen science project run by this project, in conjunction with the NBDC, entitled the Winter Heliotrope Challenge. It is considered "established – widespread and common" (NBDC, 2020), occurring frequently on rough ground, roadside verges and riverbank sides, where it commonly forms large, often continuous stands of relatively low-growing vegetation that flowers from November to March. The flowers are pale, pinkish mauve, scented, borne on spikes approximately 25 cm high and visible above the leaves (Figure 5.7). The kidney-shaped leaves are green, shiny and hairless on the upper surface, with a greyish, hairy underside. Female plants of this species do not exist in Ireland; all plants are male clones. Therefore, it does not reproduce by seed, and spreads only by vegetative propagation (Hackney, 1992; Reynolds, 2002; Devlin, 2008; Booy *et al*., 2015; Stace, 2019). Winter heliotrope remains green throughout the winter.

Impacts

Winter heliotrope is a persistent perennial with an extensive rhizome structure. It forms dense colonies and acts as an ecosystem engineer, outcompeting native species through shading and monopolising below-ground space and resources (Valldares *et al*., 2016). It creates a level of shade that is not normally present in uninfested habitats throughout the year, displaying strong growth in late winter and early spring, which inhibits the emergence of native species in spring, resulting in reduced biodiversity at invaded sites.

Pre-control assessment

Surveying for the presence of winter heliotrope should ideally take place during the winter months, when the

Figure 5.6. Winter heliotrope invading woodland habitat.

Figure 5.7. Winter heliotrope flower (left) and close-up of leaves (right).

plant is in flower, and it is difficult to confuse it with any of the native species that look somewhat similar, in particular butterbur (*Petasites hybridus*) and coltsfoot (*Tussilago farfara*). If this is not feasible, then the surveyor must be competent in its identification. Health and safety protocols must be followed, particularly in assessing roadside verges, and all relevant legislation must be adhered to. It is not appropriate to complete this survey from a moving vehicle, as this could result in recording errors. All information should be recorded on data recording sheets, noting the exact location [global positioning system (GPS) coordinates] and extent of the infestation, proximity to water and infrastructure, and access to the site. The presence and abundance of other species should also be noted. This information will dictate which site-specific management options are practical and appropriate. It is important to photograph the site, as this can be helpful in mapping the habitat and monitoring species control progress.

Before any treatment is implemented, a management plan should be drawn up describing the manner and timing of the planned control measures, any health and safety precautions that must be considered, and contact details for those responsible for the development and execution of the management plan.

It is good practice to report all infestation of winter heliotrope to the NBDC for inclusion in records of the Global Biodiversity Information Facility (GBIF).

Spread prevention

Effective biosecurity is essential in any invasive species management plan to avoid unintentional spread and maximise the effectiveness of any measures undertaken. As winter heliotrope does not produce viable seeds, surveying does not carry the same biosecurity risk as with some other species. However, both rhizomes and aerial plant parts have the potential to generate new individuals and populations, so particular care should be taken to avoid transport of soil or vegetation off site. Any risk assessment should include biosecurity concerns and advise on appropriate measures to put in place, including the necessary equipment for washing the wheels and undercarriage of vehicles and the PPE of surveyors. All living plant material must be left on site. The risk of spread can be reduced by parking vehicles away from the infested site.

Control measures

Winter heliotrope is notoriously resistant to traditional control methods. Established stands, particularly in woodland habitats, are pervasive and pernicious, and gardeners and land managers have acknowledged the difficulty in controlling and eradicating this plant. Site-specific details will dictate appropriate control measures. The following recommendations have been informed by a study of the available literature and by scientific experiments completed during the current EPA project, under both field and laboratory conditions. Detailed results from these studies are available from Eithne Davis at the Institute of Technology Sligo.

Mechanical removal. Mechanical removal of all plant material, including rhizomes and contaminated soil, is an effective control and eradication technique in specific circumstances (e.g. where the rhizomes have not entangled with other underground root systems and where adequate biosecurity and spoil disposal methods have been put in place). If eradication is to be achieved at a site, soil to a depth of 500 mm beneath the invasive plant stand must be removed and disposed of at a licensed landfill facility. New individual plants can regenerate from small rhizome fragments that remain in the soil or are dispersed during excavation. Winter heliotrope excavation operations should be supervised by an invasive species specialist, and good biosecurity practice is paramount.

Cultivation. The use of soil cultivation by repeated digging to expose and weaken rhizomes is recommended as a control method by the Royal Horticultural Society (RHS, 2008). There is no empirical evidence available to prove that this is successful, and the method carries a high risk of spread. We do not recommend cultivation as a management technique, unless carefully undertaken over a period of many years.

Cutting. The cutting of winter heliotrope by strimming or other mechanical methods is to be discouraged, as it actively spreads aerial parts of the plant, which can develop into new individuals and populations.

Mulching. The use of membrane barriers is not proven to be a successful control method for winter heliotrope. Even young plants with no significant rhizome network have been shown to survive for extended periods of time when deprived of light during experiments at the Institute of Technology Sligo. Mulching is appropriate only as a temporary biosecurity measure to prevent the accidental dispersal of vegetation during treatment works.

Herbicidal treatments

Synero (active ingredients: aminopyralid and fluroxypyr). Synero is a selective herbicide for weed control on amenity grasslands and roadside verges, and has the added advantage of leaving grasses unharmed (Dow AgroScience Ltd, 2014). Results from short-term experiments completed as part of the current EPA project demonstrated that a single application of Synero was highly effective at controlling even large stands of winter heliotrope, no matter which season the herbicide was applied in (Figure 5.8). In addition, there was no significant regrowth of the treated plants over the following 4-month period. No long-term trials have yet been carried out following on from this research, and repeat treatments may be required if subsequent monitoring shows regrowth.

According to the manufacturer's recommendations, this product cannot be used under existing tree lines owing to risk of damage to established trees, or in areas where grazing will take place, as it affects the gastrointestinal tracts of grazing animals. Nor can grass cuttings from previously treated sites be composted or used as mulch owing to the impact of residues on other plants (Dow AgroScience Ltd, 2014). These factors will limit the sites where this treatment is appropriate. Suitable sites for the use of this product include motorway and railway embankments, roadsides, grassland of little agricultural importance and industrial areas. Where the use of Synero is considered appropriate, winter treatment to minimise impact on non-target annual species, followed by the addition of fresh, inert topsoil in spring and hydroseeding with native species can facilitate the speedy remediation of an infested site.

Roundup Biactive (active ingredient: glyphosate). Roundup Biactive is a systemic, broad-spectrum herbicide (Monsanto, 2014). It has been proven to have limited impact on winter heliotrope in field experiments conducted at the Institute of Technology Sligo during the current project. Treatment in early summer gives the greatest suppression, with < 10% ground cover of vegetation observed 4 months after treatment. Spring treatment resulted in *c.*15% cover of vegetation remaining after 4 months (Figure 5.9). Autumn (> 50% cover observed 4 months after treatment) and winter applications (> 30% cover observed 4 months after treatment) do not offer even moderate control of winter heliotrope, and are not recommended. As regrowth was observed after all seasonal applications of this herbicidal product, repeated application will be required if an acceptable level of control is to be achieved. No long-term trials have yet been carried out following on from this research.

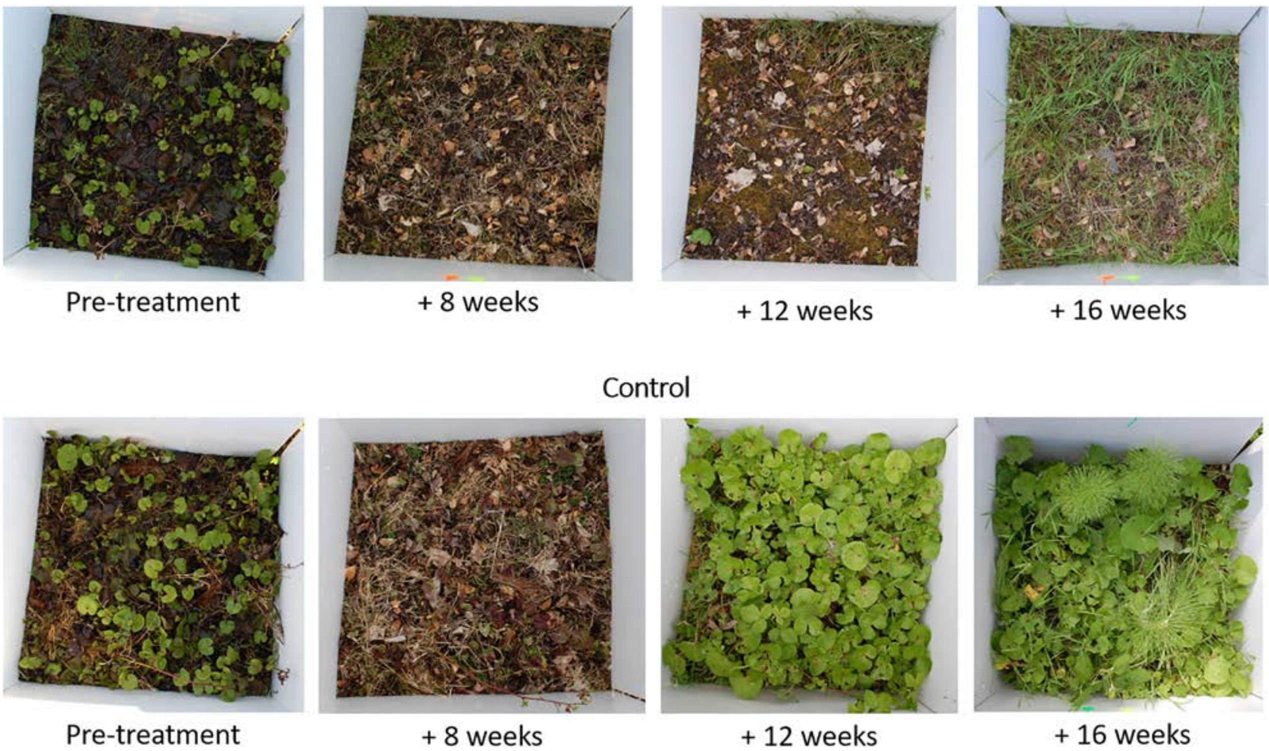


Figure 5.8. Impact of Synero applied to winter heliotrope in winter.

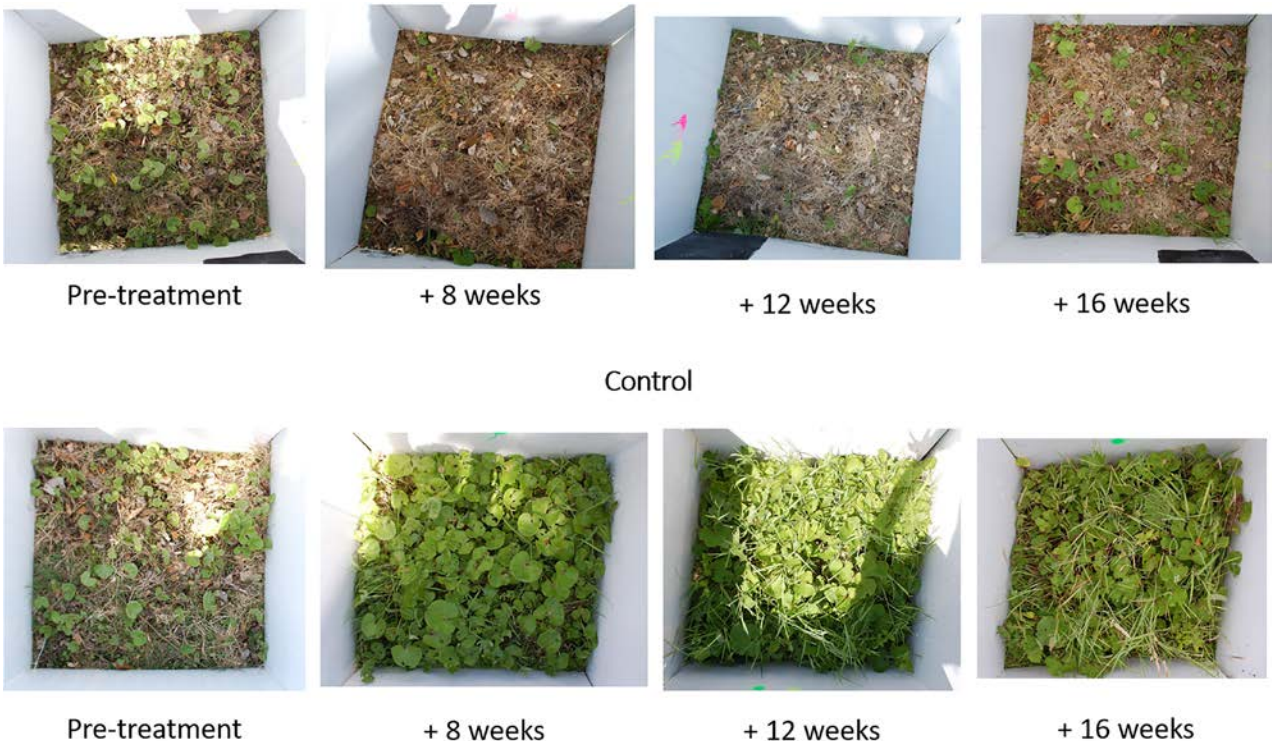


Figure 5.9. Impact of Roundup Biactive applied to winter heliotrope in spring.

Post-control monitoring

Because of the acknowledged capacity of winter heliotrope to regrow from plant fragments, post-treatment monitoring is essential. Such monitoring should be conducted at 1 month and again at 4 months after any treatment, and treatment reapplied as necessary. Follow-up assessments should be conducted on an annual basis to ensure early detection of regrowth. A minimum of two annual surveys where no regrowth of winter heliotrope is recorded should be completed before significant control is confirmed. Using the same protocol for both initial (pre-treatment) surveys and all post-treatment monitoring will allow for robust evaluation of the management measures undertaken.

Post-treatment remediation of sites is recommended once the invasive species has been significantly controlled. Hydroseeding with a selection of native wildflower mixes can produce rapid and effective results.

Additional considerations

An appropriate risk assessment, which includes health and safety considerations, should be carried out before any control or survey work is undertaken. If required, permission or licences (from the NPWS in Ireland or DAERA in NI) to carry out invasive species control work must be procured. Special consideration of site-specific sensitivities and positive stakeholder engagement will need to be accommodated in Natural Heritage Areas, Special Areas of Conservation, Special Protection Areas and waterways.

All of the experiments that inform this document were completed at Lissadell House and Gardens and the Centre for Environmental Research, Innovation and Sustainability (CERIS) by researchers at the Institute of Technology Sligo, in conjunction with INVAS Biosecurity, Dublin.

Further information on winter heliotrope is available from the NBDC,[6] to which sightings can also be reported.[7]

6 https://maps.biodiversityireland.ie/Species/43895

7 https://records.biodiversityireland.ie/record/invasives#7/53.455/-8.016

5.2 Asian Clam (*Corbicula fluminea*)

As described in section 4.2.4, the Asian clam (*C. fluminea*) is a high-impact invader that can dominate macroinvertebrate communities and disrupt ecosystem regulating services. Although extensive eradication and control experiments have been conducted on *C. fluminea* globally, none have been successful in providing substantial long-term management of *C. fluminea* populations (Sheehan *et al.*, 2014). However, thermal shock treatments, which can be considered as the sudden or gradual exposure of organisms to cold or hot thermal regimes beyond their physiological tolerance, could prove an effective method for control and eradication.

5.2.1 *Pelleted dry ice for control and eradication*

Aim of the study

Here, using laboratory-based experiments and simulated clam patches, the efficacy of commercially available dry ice (DI) pellets (i.e. solid CO_2 pellets at –78°C) to kill *C. fluminea* was examined. Overall, it is hypothesised that the extreme cold will induce thermal shock, resulting in substantial clam mortality (e.g. Figure 5.10a,b).

Materials and methods

Adult *C. fluminea* specimens were collected from the River Barrow in Ireland and transported in source water to QML, Portaferry, NI. Only specimens that were obviously alive and feeding were selected for experimental work. Adult specimens (SH 15–26 mm) were exposed to 400 or 600 g of 9-mm DI pellets within cylindrical plastic containers of the dimensions 234 mm (height) × 180 mm (diameter). All specimens were positioned upon a layer of gravel and were either left uncovered, were partially covered by a second layer of gravel or were fully covered by the addition of a third layer of gravel. A density of 30 specimens (1179 ind. m^{-2}) was examined. *C. fluminea* were exposed to DI for either 15 or 30 minutes, for both direct and indirect (2.5 L) applications ($n = 3$ replicates). A 350-g layer of clean fine gravel (15 mm stone chips) was evenly spread to cover the base of the experimental containers to create the substrate layer. Living specimens were placed directly on top of this gravel layer to represent surface-residing clams. A second layer of gravel (350 g) was then added to the required containers, and evenly spread to leave all specimens partially covered. A third layer of gravel (350 g) was added to the appropriate containers, and evenly spread to fully cover all specimens to create fully covered experimental groups. After the prescribed DI exposure time, specimens were immediately

Figure 5.10. (a) Tidally exposed bed of *C. fluminea* on the River Barrow, St Mullins, Ireland. (b) View of *C. fluminea* specimens during a direct application of DI. (c) View of *C. fluminea* specimens immediately post exposure to DI. (d) View of *C. fluminea* specimens during open-flame burn applications. Photo credits: Stephen Potts and Daniel Walsh.

removed from the experimental containers. All specimens were returned to 600 mL of dechlorinated bubbled water (11–13°C) for a 24-hour 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 (e.g. Figure 5.10c). All data were analysed in R software environment using GLMs. As residual deviance was greater than the degrees of freedom, quasi-Poisson error distributions were used to account for overdispersion of residuals and to analyse the numbers of dead *C. fluminea* in each experiment with respect to each treatment term and associated interactions.

Results

Mortality of DI-exposed specimens varied between 31% and 100% (Figure 5.11). There was no overall significant difference in clam mortality with respect to gravel coverage, although interaction terms suggest some reduction of DI efficacy due to gravel, and higher efficacy with the larger mass of DI when the specimens were covered by water (Figure 5.11). There was significantly higher mortality with the greater quantity of DI, and with direct application (both $p < 0.001$).

Discussion

Overall, the application of 9-mm DI pellets was highly effective for causing *C. fluminea* mortality, even for those that were buried in gravel substrate. Crucially, DI tended to create a layer of frozen substrate around the specimens, particularly during indirect applications. This enhanced encapsulation of *C. fluminea* by frozen substrate appears to have increased the efficacy of DI, rather than provide a buffering effect against thermal shock. As DI will rapidly dissipate into gaseous CO_2 once exposed to ambient air and water temperatures, DI applications may be preferable to other more destructive control methods that can result in habitat alteration. However, only long-term field monitoring will truly reveal the impacts of any control methodology. Future research should examine potential sub-lethal effects upon *C. fluminea*, other invaders and non-target organisms (e.g. reduced growth or reproductive output, acute or chronic morbidity) that may possibly be induced by DI application alone, or when combined with other control and eradication actions. See Coughlan *et al.* (2018) for further in-depth discussion.

5.2.2 Steam and flame for control and eradication

Aim of the study

Using simulated clam beds, the efficacy of hot thermal shock treatments in killing adult *C. fluminea* was examined. It is hypothesised that exposure to the extreme heat of steam spray or open flame could result in substantial, if not complete, mortality of *C. fluminea*.

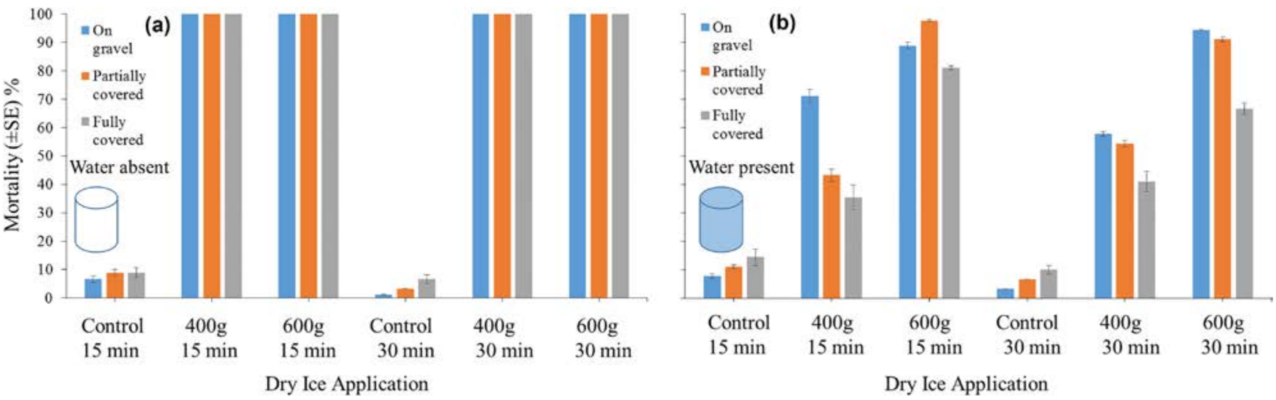


Figure 5.11. Mortality (mean ± SE) of 30 adult *C. fluminea* specimens (1179 ind. m^{-2}) 24 hours post varied exposure times to either 400 or 600 g of 9-mm DI pellets ($n = 3$). Specimens were placed directly upon a gravel layer or partially covered or fully covered by additional gravel layers prior to DI application. Left: 0 L of water at a height of 0 mm (i.e. direct DI application). Right: 2.55 L of water at a height of 100 mm (i.e. indirect DI application). SE, standard error.

Materials and methods

As before, adult *C. fluminea* specimens were collected from the River Barrow in Ireland and transported to QML, NI. Only living specimens were selected for experimental work. *C. fluminea* specimens (SH 18–20 mm) were exposed directly or indirectly to steam spray for 1, 2, 3 or 5 minutes ($n = 3$ per experimental group). Groups of 30 *C. fluminea* (1179 ind. m^{-2}) were placed randomly within the cylindrical experimental containers (as before) upon a 6-cm-deep bed of dry sand. Specimens were gently pressed into the sand until half of each individual was exposed. For indirect exposure groups, an additional 3 cm of dry sand was used to cover the specimens entirely. Control groups were likewise placed into containers and covered with sand, as required by the experimental design. All control groups were allowed to air dry for the longest exposure time of minutes, and these specimens were not exposed to steam. As before, following steam exposure, specimen groups were allowed to air-cool for 15 minutes, including control groups. All groups were then immediately returned to the computerised tomography (CT) room and individually placed in 600 mL of aerated dechlorinated tap water for a 24-hour recovery period, after which mortality was assessed (as before).

Specimens of *C. fluminea* (SH 18–26 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}) specimens 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* specimens were placed into the mud patch and randomly mixed through the substrate. The direct layer was then formed by placing 50 *C. fluminea* specimens haphazardly across the surface area of the mud patch. The patches were then exposed to open flame for either 5, 10, 15, 20, 25 or 30 seconds. Control groups were likewise formed into patches and allowed to air dry for the longest exposure time, and these patches were not burned. All patches were allowed to cool for a further 15-minute period following flame exposure. All specimens were then returned to water within the CT room and left to recover for 24 hours, and then mortality was assessed (as before). All data were analysed in the R software environment using binomial GLMs with logit links to examine bivalve mortality rates with respect to experimental treatment for each experiment separately. Estimated marginal means with Tukey adjustments were used for post-hoc treatment level contrasts where an effect was significant.

Results

Direct steam exposures lasting 1 minute or longer always caused 100% mortality of *C. fluminea* (Figure 5.12A), while mortality rates of between 30.7% and 100% were observed following indirect

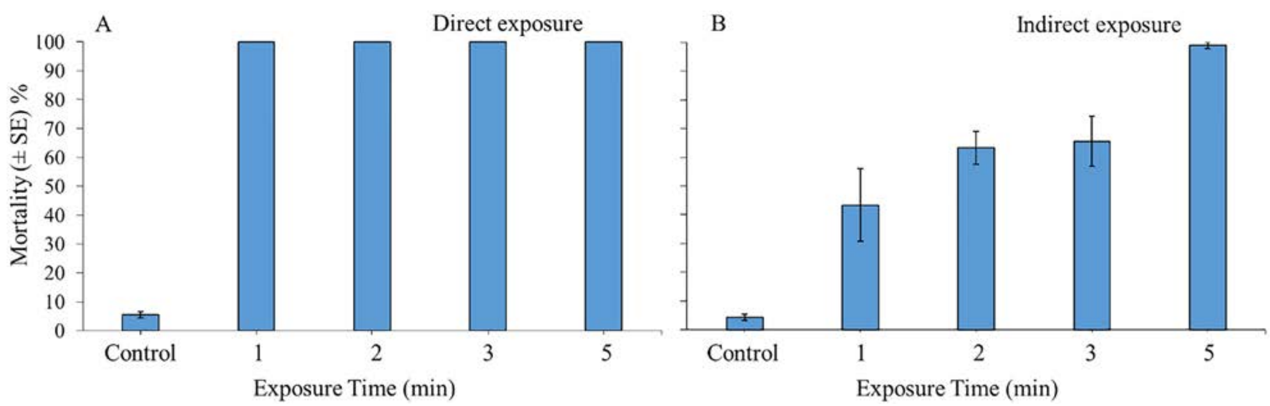


Figure 5.12. Mortality (mean ± SE) of 30 adult *C. fluminea* specimens (1179 ind. m^{-2}) 24 hours after (A) direct exposure (partially buried, i.e. half of each specimen was buried by dry sand substrate) and (B) indirect exposure (fully buried below 3 cm of dry sand) to steam spray treatments for up to 5 minutes ($n = 3$ replicates). SE, standard error.

exposures, with increased exposure times resulting in greater mortality (Figure 5.12B). The steam treatment effect thus interacted significantly with the level of cover ($\chi^2 = 22.95$, df = 4, $p < 0.001$), reflecting greater differences among steam exposures following indirect treatments. In particular, indirect 5-minute exposures were more efficacious than all other durations (all $p < 0.001$), while 3-minute indirect exposures drove significant mortality compared with 1-minute durations ($p = 0.03$). Differences between 1- and 2-minute indirect exposures, and between 2- and 3-minute indirect exposures, were not statistically significant (both $p > 0.05$). Nevertheless, both direct and indirect steam treatments always induced significant mortality compared with control treatments (all $p < 0.001$).

Mortality among *C. fluminea* directly exposed to open-flame treatments was 100% (Figure 5.13A) whereas following indirect exposure (i.e. when *C. fluminea* was mixed into the mud layer) between 98% and 99% of control groups survived and mortality ranged from 8% to 11% at the longest exposure time of 30 seconds (Figure 5.13B). Application of direct open-flame treatments significantly influenced mortality overall ($\chi^2 = 190.17$, df = 6, $p < 0.001$), with mortality at all flame exposures significantly greater than among controls (all $p < 0.001$). However, although exposure of *C. fluminea* at the surface to open-flame treatments for 5 seconds or longer resulted in 100% mortality, mortality rates in the mixed layer were significantly lower, with high survivability exhibited at all durations of flame treatment ($\chi^2 = 273.25$, df = 1, $p < 0.001$).

Discussion

Here, we have shown that large groups of both surface-dwelling and buried *C. fluminea* (30 ind. group^{-1}; 1179 ind. m^{-2}) can be completely killed following 1- or 5-minute steam exposures, respectively. Similarly, we have highlighted that large 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. However, encapsulation of *C. fluminea* within substrate can substantially reduce the efficacy of open-flame treatments on *C. fluminea* mortality. While the results presented here are promising, additional research is needed to confirm the effectiveness of thermal shock treatments under natural field conditions. In particular, the buffering effects of both deeper and different substrate types, and deeper water submergence, should be assessed. See Coughlan *et al.* (2019b) for further in-depth discussion.

5.2.3 Substrate disruption and thermal shock treatments

Aim of the study

Using simulated bivalve beds, we assessed the effects of substrate disruption, i.e. raking, combined with multiple exposures to various rapidly applied thermal shock treatments, which consisted of steam, or low- or high-intensity open-flame burns. We hypothesised that substrate disruption prior to the application of extreme heat would result in greater mortality of *C. fluminea*.

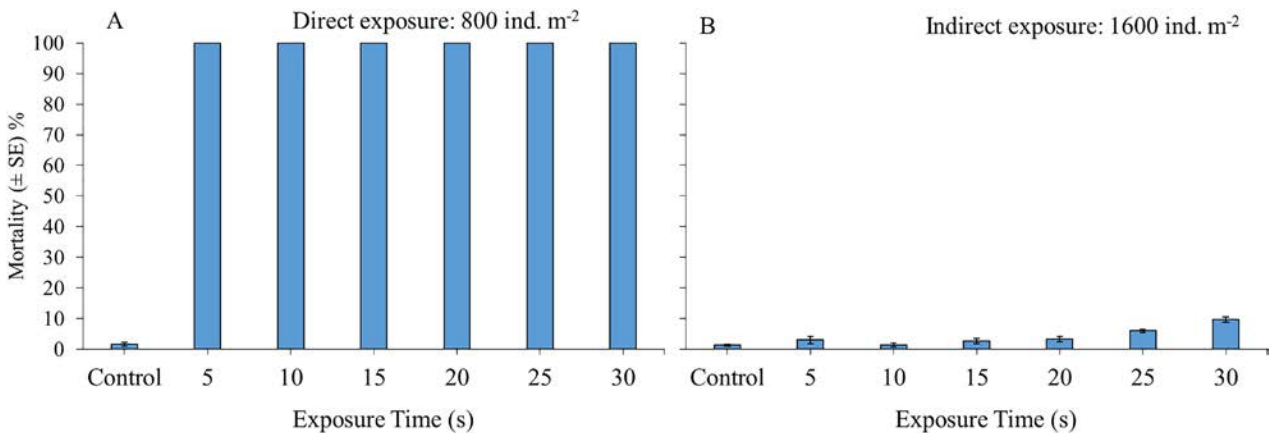


Figure 5.13. Mortality (mean ± SE) of adult *C. fluminea* specimens 24 hours after direct (i.e. specimens residing on top of substrate) or indirect (specimens encapsulated within 2.5 cm of substrate) exposure to open-flame treatments for up to 30 seconds. (A) 50 specimens (800 ind. m^{-2}) and (B) 100 specimens (1600 ind. m^{-2}) ($n = 3$ replicates). SE, standard error.

Materials and methods

Adult *C. fluminea* specimens were collected from the River Barrow in Ireland and transported to QML, NI. Only living specimens were selected for the experimental work. To mimic field scenarios, adult *C. fluminea* (SH 18–20 mm) specimens were embedded in patches of damp sand. Groups of 30 *C. fluminea* specimens were randomly mixed into a damp sand layer to create each simulated patch, which is representative of a real-life *C. fluminea* bed structure (25 cm × 25 cm; ~4 cm deep: 480 ind. m^{-2}). Combined applications of rake and thermal shock treatments were then examined. The initial raking phase was used to churn up and furrow the substrate, to expose greater numbers of *C. fluminea* specimens to the subsequent thermal shock treatments. Specimens were exposed to a continuous jet of steam (≥100°C; 350 kPa; Kärcher SC3 Steam Cleaner), a low-intensity open-flame burn (~1000°C; ASAB weed burner AS-09463: butane gas) or a high-intensity open-flame burn (~1000°C, 400 kPa: Rothenberger RoMaxi Power Burner: butane gas) for 2.5 minutes, following 30 seconds of patch raking (using a Fiskars soil rake). Each examined combination of raking and thermal shock was subject to single, double, or triple treatment applications ($n = 3$ replicates per experimental group). Control groups were likewise formed into sand patches, which were each raked for up to three consecutive 30-second periods and allowed to air dry for 2.5 minutes following each raking event. Control patches were not exposed to thermal shock treatments. Following a 15-minute cooling period, initiated after the final thermal shock treatment had occurred, specimens were immediately extracted from the patch and returned to the CT room. Replicates were then placed individually in 600 mL of dechlorinated tap water taken from a continuously aerated source (11–13°C) for a 24-hour recovery period, after which mortality was assessed. Specimens were considered dead if they were gaping, failed to respond to a tactile stimulus or did not reclose. All data analyses were undertaken using the R statistical software environment. Bivalve mortality rates were analysed in relation to thermal shock and rake treatments, and their interaction, using binomial GLMs. Tukey tests via estimated marginal means were used for post-hoc pairwise comparisons.

Results

Up to 100% *C. fluminea* mortality was observed following triple rake and thermal shock applications via high-intensity open-flame burn treatments (Figure 5.14). Thermal shock and rake treatments interacted significantly ($\chi^2 = 19.13$, df = 6, $p = 0.004$). While significant mortality was always induced via hot

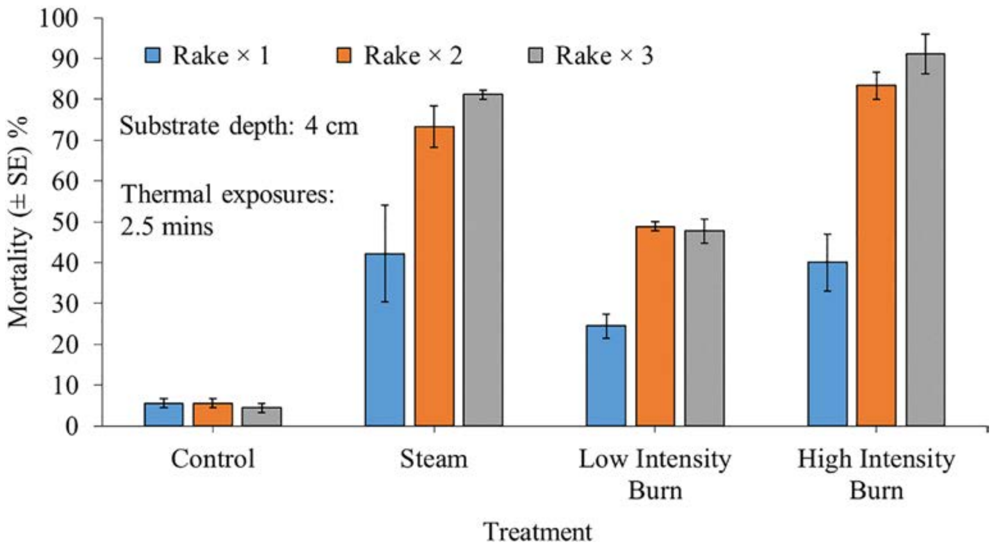


Figure 5.14. Mortality (mean ± SE) of 30 adult *C. fluminea* specimens (480 ind. m^{-2}), encapsulated in 4 cm of damp sand substrate, 24 hours following exposure to the application of combined 30-second rake and 2.5-minute thermal shock treatments. Thermal treatments consisted of steam spray (≥100°C) or low- or high-intensity open-flame exposure (~1000°C). All treatments were performed once, twice or three times (*n* = 3 specimens per experimental group). SE, standard error.

thermal shock compared with controls (all $p < 0.01$), there was no significant difference among thermal shock treatments following single-rake applications (all $p > 0.05$). In contrast, after double- and triple-rake applications, differences among heat treatments were apparent. Mortality rates were significantly higher following steam or high-intensity open-flame treatments relative to low-intensity burning after multiple raking treatments (all $p < 0.01$). Although high-intensity open-flame treatments tended to be most effective overall, both steam and high-intensity open flame always caused similar levels of *C. fluminea* mortality (all $p > 0.05$).

Discussion

Multiple applications of combined substrate disruption (i.e. raking) and thermal shock treatments increased *C. fluminea* mortality. In particular, high-intensity burns were more efficacious than low-intensity burns, especially following multiple applications. Interestingly, steam spray treatments were also highly effective. Overall, applications of raking combined with thermal shock treatments could be used as a rapid-response tool to control emerging and established populations of *C. fluminea* found residing within exposed river, lake and canal beds. However, while these results are very promising, additional research is needed to confirm the effectiveness of substrate description and multiple thermal shock treatments under natural field conditions. See Coughlan *et al.* (2019b) for further in-depth discussion.

5.2.4 Best practice for control of Asian clam

Although a variety of control methods have been attempted, such as dredging and benthic barriers, most have been found to be ineffective, with only limited success at best. Nevertheless, the more commonly employed methods are detailed in this section. In addition, thermal shock control methods, as described in previous sections of this report, are noted in this section. However, in-field testing of these thermal shock treatments is still required. To date, no known method of *C. fluminea* control has delivered complete eradication. Site-specific conditions, such as water depth, flow rate and substrate type, at the area of infestation may determine the control approach used.

Mechanical removal

Mechanical dredging methods, particularly box dredging, can substantially reduce the density and biomass of *C. fluminea* populations (Sheehan *et al.*, 2014). However, these methods are non-selective and could be damaging to native biodiversity. Further assessment of dredge removal efficiency on a variety of substrate types is required, as is examination of associated medium- and long-term impacts to native biodiversity, water quality and ecosystem functioning.

Benthic barriers

Using benthic barriers, such as sheets of polyethylene or rubber, can achieve a substantial, but short-term, reduction in both *C. fluminea* density and biomass (Wittmann *et al.*, 2012a,b). However, this strategy remains expensive and labour-intensive, and can have detrimental impacts on native species, without achieving complete eradication of the targeted *C. fluminea* populations.

Thermal shock

Dry ice. Commercially available DI pellets (i.e. solid CO_2 pellets at −78°C) have been shown to effectively kill *C. fluminea* in laboratory trials (Coughlan *et al.*, 2018). Innovative research has demonstrated that DI can potentially be used for effective, rapid-response control and potential eradication of *C. fluminea* populations. It appears that the extreme cold produced will freeze the substrate around *C. fluminea* and cause death through thermal shock. However, in-field testing is still required.

Open flame. The application of open-flame heat torch treatments can potentially be used to kill populations of *C. fluminea* inhabiting exposed substrate in dewatered areas, such as during low flow (Coughlan *et al.*, 2019b). The effectiveness of these control methods can be further improved by multiple applications, and by raking or furrowing the substrate to increase the penetrative effects of these treatments. However, in-field testing is still required. In particular, the medium- and long-term impacts of thermal shock methods on native biodiversity remain to be examined.

Post-control monitoring

To properly evaluate the efficacy of the implemented control measures, and monitor the natural recovery of the native habitat, post-control assessment is necessary. Such monitoring should be conducted immediately after the control operations are concluded, to assess the need for further control. Additional follow-up assessments should be conducted on an annual basis. Surveys for reassessment of target areas can be conducted in the same manner as the pre-control assessment, and these results can be compared. If required, appropriate remediation measures to enhance habitat recovery can be considered in consultation with appropriate experts and agencies. This may include the replanting, relocation or transplantation of extirpated native species. Further control treatment can be considered, if necessary.

Additional considerations

An appropriate risk assessment, which includes health and safety considerations, should be carried out before any control or survey work is undertaken. If required, permission or licences from the appropriate authorities to carry out invasive species control work must be procured. Special consideration and stakeholder engagement will need to be given to Natural Heritage Areas, Special Areas of Conservation, Special Protection Areas and waterways. The requirements listed under each control method are not prescriptive and provide information only on the principal items required.

Further Information on Asian clam is available from the NBDC,[8] to which sightings can also be reported.[9]

8 http://www.biodiversityireland.ie/asian-clam/

9 https://records.biodiversityireland.ie/

6 Communications for Prevention, Control and Eradication of Invasive Alien Species

Communications activity relating to the project is summarised in Table 6.1.

6.1 Information Harmonisation and Educational Value of Databases

Since 2016, the EU has required MSs to prevent, control and eradicate selected IAS designated as species of Union concern. To improve these conservation efforts, online information systems are used to convey IAS information to the wider public, often as a means to bolster community-based environmental monitoring. Despite this, information standardisation and quality among online databases remain poorly understood.

Table 6.1. Communications arising from the project

Peer-reviewed publications	International	11
Workshops and outreach events	International	4
	National	9
	Regional	7
Social media	ResearchGate – followers	78
	ResearchGate – reads	658
	Twitter – impressions	813,409
	Twitter – followers	1532
	Facebook – followers	372
Signage	Roadside treatment sites	10
Conferences	International	7
	National	7
Broadcast media (documentaries, interviews and articles)	Television	4
	Radio	6
	Print	3
Meetings (external to project) and collaborations	International	7
	National	3
Citizen science campaigns (4 months long)	National	2

6.1.1 *Aim of the study*

Here, we assess the harmonisation and educational value of four major international IAS databases: the Invasive Species Compendium of the Centre for Agriculture and Bioscience International (CABI), EASIN, the Global Invasive Species Database (GISD) and the European Network on Invasive Alien Species (NOBANIS). However, although NOBANIS is available online, the database has not been updated in recent years, as it no longer receives active funding support. Nevertheless, these four databases were chosen for evaluation, as they are specifically designed to provide information on the topic of IAS at European and global scales, with both animal and plant species listed. Although 66 species are currently designated as being of EU concern, 17 of these were only designated in the past 3 months (at the time of writing); therefore, we opted to assess database information for the original 49 species.

6.1.2 *Materials and methods*

To assess database harmonisation and educational value, for each species, selected databases were evaluated for content they contained in relation to (1) species “identification”, (2) EU “distribution”, (3) ecological and/or economic “impacts”, (4) “control” options and (5) the citation of relevant “source material” for further information. A 5-point scale was constructed to facilitate comparative assessment among databases. For each topic, the scale was composed of five possible scores (1–5), which enumerated a basic description of the information presented within the database, i.e. 1 = none given, 2 = little, 3 = some, 4 = detailed and 5 = highly detailed.

Crucially, the assessor, although familiar with the concept of IAS, and having participated in a number of citizen science surveys of flora and fauna, was not an expert in the identification of IAS. A lack of familiarity was considered essential to reduce potential unconscious bias during database assessment, especially in relation to the determination of species identification. As EASIN is a platform that encompasses multiple IAS information resources, this database was scored first in relation to the downloadable brochure describing IAS designated as of EU concern.[10] EASIN was then separately scored in respect of the interactive information factsheets,[11] which allow users to search and view IAS profiles online. For both assessments of EASIN, species distribution scores are based on a related European Commission report by Tsiamis *et al*. (2017), *Baseline Distribution of Invasive Alien Species of Union Concern*, rather than limited distribution information presented in the brochure or factsheets, as the highly detailed report is freely available for download from the EASIN website. All databases were accessed in November 2019.

Ordinal logistic regression models were fitted to test for differences in ordered scores among different data sources and between broad taxonomic groups. First, a model was fitted to examine differences in relation to the 'total' score (i.e. product across the five topics). Second, a series of models were used to examine topic-specific score differences among sources and taxa (i.e. animals vs plants).

6.1.3 Results

Total scores differed significantly among sources. Median total scores were ordered as follows: CABI (800) > EASIN (factsheet) (135) > EASIN (brochure) (40) = GISD (40) > NOBANIS (1) (Figure 6.1A). CABI scores were significantly greater than all other sources (all $p < 0.001$), and EASIN (factsheet) scored significantly better than EASIN (brochure), GISD and NOBANIS (all $p < 0.05$). NOBANIS scored significantly lower than all other sources (all $p < 0.001$). Median scores were statistically similar between animals (105) and plants (135) (Figure 6.1B). However, although non-significant, median scores showed a trend towards being higher for plants rather than animals in the EASIN (factsheet) and GISD databases (Figure 6.1C).

Individual topics were also consistently significantly different among sources, but not between taxonomic groups or their interaction with sources. For species identification information, median scores were ordered as follows: CABI (4) = EASIN (factsheet) (4)

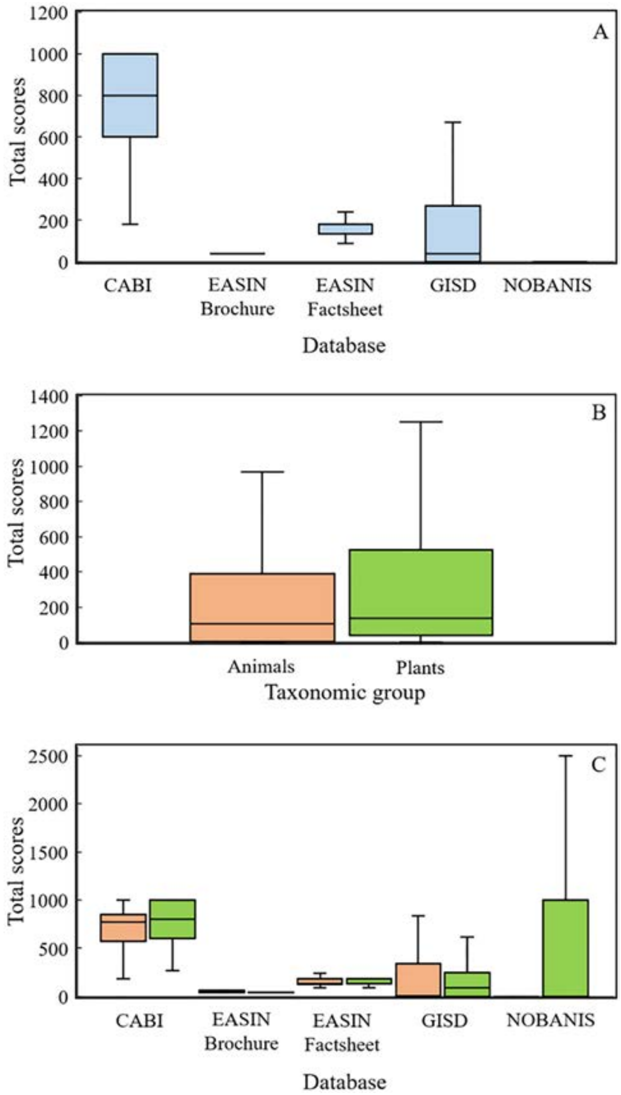


Figure 6.1. Total median scores achieved by online databases for harmonisation of information provided for 49 invasive alien species of Union concern. Total database scores were determined from the product of scores attained across five discrete assessment topics for each species. Total median scores, with interquartile ranges and maximum and minimum values, are compared (A) among databases, (B) between the major taxonomic groups of animals and plants and (C) among the major taxonomic groups in relation to source database.

> EASIN (brochure) (2) = GISD (2) > NOBANIS (1) (Figure 6.2A). Median scores for plants and animals were each 3.

10 https://ec.europa.eu/environment/nature/pdf/IAS_brochure_species.pdf

11 https://easin.jrc.ec.europa.eu/easin/CitizenScience/Factsheets

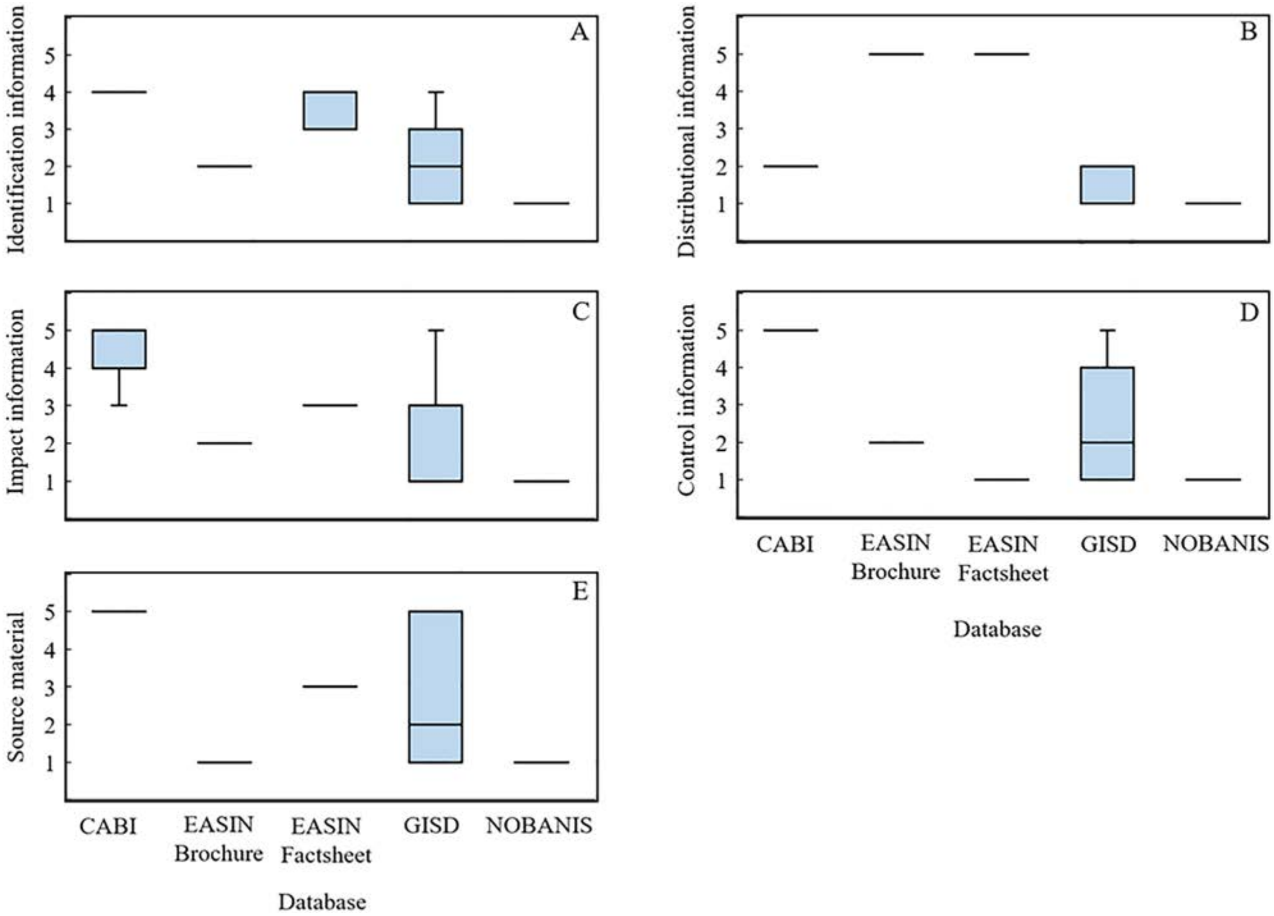


Figure 6.2. Median scores achieved by online databases in relation to five discrete topics used to establish the educational value of information provided for 49 invasive alien species of Union concern. Median scores, with interquartile ranges and maximum and minimum values, are shown for (A) species "identification", (B) EU "distribution', (C) ecological and/or economic "impacts', (D) control options and (E) the citation of relevant "source material' for further information.

In contrast, in relation to distributional information, score source medians were greatest for the two EASIN datasets (both 5), followed by CABI (2) > GISD (1) = NOBANIS (1) (Figure 6.2B). Median animal and plant scores were equal (both 2). CABI had the highest median score for the impact information topic (4), followed by EASIN (factsheet) (3) > EASIN (brochure) (2) > GISD (1) = NOBANIS (1) (Figure 6.2C). Animal median impact scores (2) were lower than plants here (3), yet not significantly. For control information, scores were ordered as CABI (5) > EASIN (brochure) (2) = GISD (2) > EASIN (factsheet) (1) = NOBANIS (1) (Figure 6.2D), while animal and plant scores were similar (both 2). With regard to source material (i.e. use of citations), CABI again exhibited the highest median score (5), followed by EASIN (factsheet) (3) > GISD (2) > EASIN (brochure) (1) = NOBANIS (1) (Figure 6.2E). Animal and plant source material were similar (both medians = 3).

6.1.4 Discussion

The assessed IAS databases show little harmonisation of information concerning IAS of Union concern. Although all species of interest are included in CABI and both EASIN databases, only 27 and 12 IAS of Union concern are listed in GISD and NOBANIS, respectively. The lack of inclusion of these species is concerning given their increased importance from an EU perspective, especially in the case of NOBANIS, which is a European-orientated database, although it no longer receives funding support. Overall, CABI had the highest education value per topic, except in relation to the EU distribution of the assessed species. In this case, the availability of a highly detailed species distribution report (i.e. Tsiamis *et al.*, 2017) bolstered both EASIN datasets. Nevertheless, the overall educational value of all databases can be further improved. For example, while CABI ranked highest for the topic of IAS control options (CABI median = 5), 12 of the assessed species scored ≤4 (i.e. 24.5%). Accordingly, no single database currently provides for a complete and thorough overview of the assessed IAS of Union concern. As EASIN is the European Commission's official online mechanism to disseminate information for these blacklisted IAS, it is recommended that action be taken to further increase the educational value of this database. Furthermore, as separate information sources are provided by the EASIN online platform, we suggest that essential information presented within the downloadable brochure, the interactive information factsheets and the detailed species distribution report (i.e. Tsiamis *et al.*, 2017) be amalgamated into a single searchable database. Overall, increased resolution, currency and availability of key information regarding species of Union concern could help mitigate the spread and proliferation of environmentally and economically costly invasive species.

6.2 Communications, Outreach and Citizen Science: Spreading the Word About Invasive Alien Species

The purpose of this outreach programme was to disseminate the importance of IAS prevention, control and eradication to all relevant stakeholders. The stakeholders in question were from all strata of society and all activity types, and included infrastructure designers, academics, local authorities and the general public. The main objective was to maximise outreach throughout the island of Ireland by taking advantage of all available media in a dynamic fashion and measuring the reach achieved. Wherever possible, all the various strands of communication used were monitored as a whole, and an opportunistic approach was taken in order to "piggyback" on events and broadcasts, keeping the project in the public eye and increasing the audience at every opportunity (Illingworth, 2017). The outreach programme described here includes a citizen science recording initiative, the Winter Heliotrope Challenge – an Irish nationwide competition that was run seasonally over two successive years.

6.2.1 *Aim of the study*

The principal objective of this study was to measure and evaluate the reach achieved by the strategic and dynamic use of a communications plan within a specific project. Prevention of IAS spread requires changing the behaviour of a wide variety of stakeholders.

6.2.2 *Materials and methods*

A list of readily available or easily established communication resources was generated and a list of stakeholders was drawn up under three categories – public, professionals and policymakers.

Stakeholder groups were matched with the appropriate medium by which to contact them, both at a broad and at a more detailed level. A schedule of communications was drafted as a support document. Three keywords were chosen for social media postings to keep the message clear and consistent: (1) "Invasive Species" (to clearly identify the problem), (2) "Biodiversity" (what we are aiming to protect) and (3) "Biosecurity" (the management mechanism being promoted).

The project team chose to share only articles that were supported by scientific research, and which could be readily understood by the general public. Social media accounts were streamlined with the title "Invasive Aliens" and identical cover images and profile pictures, giving the Invasive Aliens "brand" a recognisable and stable image (Hartmann *et al.,* 2005; Jin, 2012). After the first month, it was decided to focus mainly on Twitter, with Facebook posting by default.

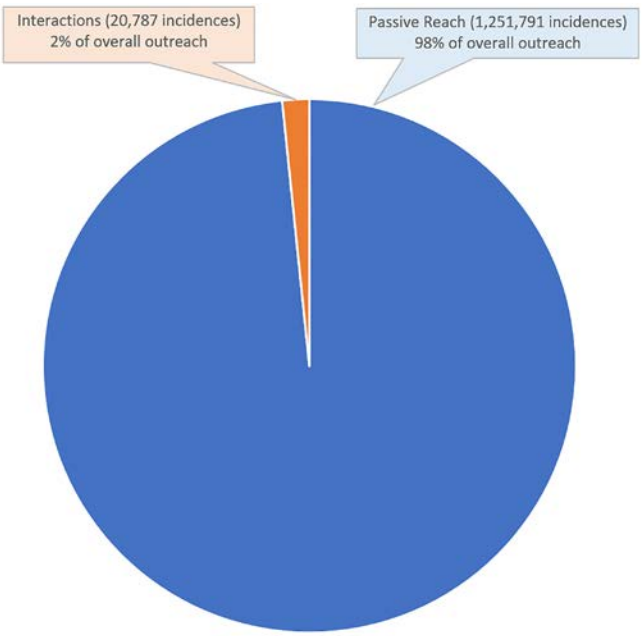
This media work was undertaken by members of the project team, on top of their scientific research, rather than by media professionals. We developed relationships with programme makers and national and regional broadcasters. Programmes and publications were actively promoted on the Invasive Aliens platforms before and after broadcast/publication. The television and radio programmes that the project team contributed to were used to launch a social media-driven citizen science campaign, the Winter Heliotrope Challenge, run in conjunction with Ireland's NBDC, which created a dedicated platform for reporting sightings of winter heliotrope (*P. pyrenaicus*). Participants were asked to photograph the plant and provide details of its location and abundance. All records generated were included in the NBDC's database for the national record, which routinely feeds into the GBIF database. Outreach also included attendance at community events. "Passive reach" (the number of users passively exposed to a message, image or link because it appears on their Twitter or Facebook feed, or is presented to them on broadcast media) was compared against "interactions" (the number of users who engaged with a message, image or link by "liking", commenting or following the link). The Winter Heliotrope Challenge was viewed as a standalone event.

6.2.3 Results

The results presented in Figure 6.3 showed that the channel of communication that achieved the greatest reach generated the fewest interactions. Conversely, the channel of communication that achieved the smallest reach generated the greatest percentage of interactions. The overall results of the study showed a wide variance in the extent of passive reach at different stages. In months in which television and radio programmes were broadcast, reach was high, leading to an apparent decrease in overall passive reach over the 2-year period in question. In contrast, there was a steady growth in interactions, illustrating a growing engagement from the audience (Figure 6.4).

Table 6.2 shows an analysis of the trends in outreach achieved over the period of the study.

In year 2, the Winter Heliotrope Challenge resulted in a 97% increase in average recordings of heliotrope per day, or an overall increase of 457 recorded sightings.



Channel of Communication	Total no. of incidences of reach	% of incidences which were interactive	Details
Broadcast media	593,000	0	Total of 7 broadcasts, including television and radio
Workshops	118	58	Total of 4 workshops, averaging 30 people
Public events	820	33	Total of 2 public events, averaging 420 people
Citizen science	152	100	Total of 2 events

Figure 6.3. Proportion of overall outreach moments identified as either interactive or passive.

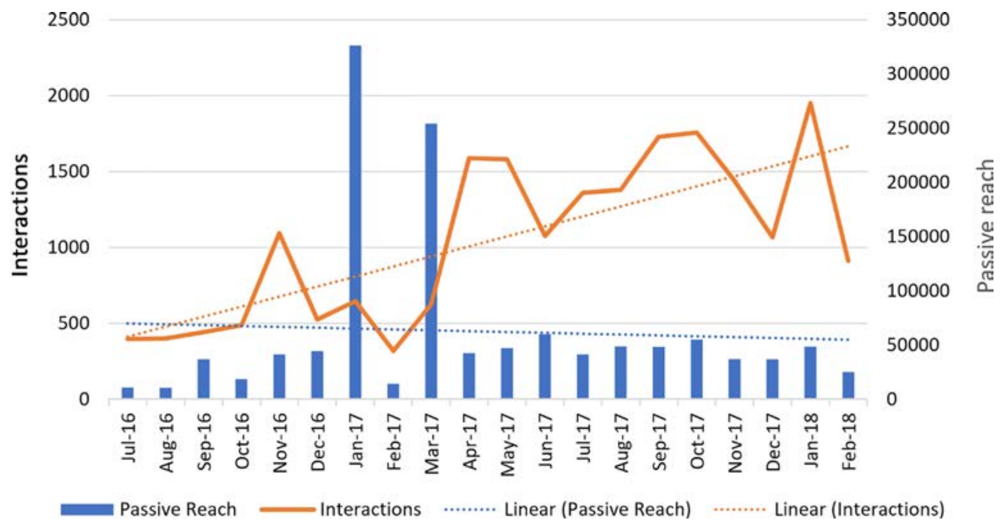


Figure 6.4. Number of passive contacts and interactions per month. Peaks in passive reach reflect times when programmes were broadcast, reaching a large audience. A steady overall growth in interactions can be seen.

5.2.4 Overall findings

The results from this study show that a strategic communications plan is a considerable asset in focusing and monitoring an outreach campaign. This outreach campaign delivered a broad outreach message in a passive manner, as well as engaging relevant stakeholders at more localised, focused, interactive events. The media that generated the greatest reach resulted in the lowest percentage rate of interaction with stakeholders, while the more localised, focused events generated the greatest level of interaction.

6.2.5 Discussion

Our results confirm that a communications plan is a practical and relatively effective way to maintain the primary focus of a cohesive outreach programme, while allowing for flexibility in reacting to opportunities that arise. From the outset, we identified our key stakeholders and how they could best be reached. Our principal target audiences were the general public and professional ecologists. Our aim was to communicate issues around IAS in an appropriate manner and to raise awareness. Awareness is a necessary precursor to instigating prevention measures against the introduction and spread of IAS (Bremner and Park, 2007; Eiswerth *et al.,* 2011). Quantitative measurement of the effectiveness of communication was difficult to achieve. We identified the strengths and weaknesses of the various channels of communication used by measuring “passive reach” (reflecting the extent of dissemination) and “interactions” (reflecting the intensity of the dissemination), and comparing the two (Figure 6.4). Passive reach reflected the most extensive communications, but may only have influenced the audience on a subliminal level. Passive users see social media as a way to gather news by following other accounts and reading what is shared by sources they trust on social media (Wolf, 2017).

In relying on the general public to engage in any management of or application of control measures

Table 6.2. Results from analysis of the Winter Heliotrope Challenge showing positive trends in outreach achieved over the course of the project

Year	Records	Recorders	Counties	Tweets	Days run	Average records per day
2016/17 (no.)	188	38	18	13	31	6
2017/18 (no.)	645	114	28	20	54	12
Change (no.)	+457	+76	+10	+7	+23	+6
Change (%)	+243	+200	+56	+74	+74	+97

for IAS, or even to report the presence of IAS, there is an inherent risk of misidentification by a non-expert group. This can result in misreporting of IAS, or non-recognition of IAS. Awareness of IAS among the public does not reflect accuracy in identifying and reporting IAS. There is, therefore, an inherent risk in relying on citizen science participation in IAS programmes without supplying adequate support (Cohn, 2008; Campbell *et al.,* 2017).

In terms of the types of engagement achieved by this outreach programme, interactions implied that the audience engaged with the information and, therefore, had a more intense or conscious experience of their awareness being raised, implying deeper learning (Jucan and Jucan, 2014). We used a range of media, and each of these facilitated the delivery of the message to a different extent and intensity.

Broadcast media

The greatest passive reach came from the broadcast media (860,000 individual contacts).

Social media

During the study period, our social media platforms (Facebook and Twitter) generated both passive contacts (657,822) and interactions (3% of the passive reach). It was important to maintain a consistent tone and manage the frequency of posting so that our presence was regular, but not so frequent that less engaged followers would be overwhelmed and leave.

Citizen science

Our experiment with citizen science was the Winter Heliotrope Challenge, repeated over two seasons, in the course of which a total of 152 people participated.

Public events

Public events generated an estimated audience of 820, an estimated 33% of whom interacted with the project by asking questions or making follow-up contact. We attended as many local community events as possible, presenting to audiences when asked and engaging with attendees. Face-to-face communication has a much greater impact than broadcast or social media (Schüttler *et al.,* 2010).

Workshops

During the study period, local workshops brought us into contact with 118 people, 58% of whom actively engaged in conversation with the presenter around the subject of IAS, either during the event or later. The average attendance at these workshops was 17 people.

In evaluating the success of the outreach campaign, it becomes clear that mindful planning and focusing of citizen science and public events and workshops allows us to take advantage of valuable opportunities and maximise their impact and the potential “ripple effect” through communities (Illingworth, 2017; Spicer, 2017).

Conclusion

Our world is saturated with communication outputs of many types, and it is difficult for the general public to distinguish between reliable information and “fake news”. As scientists, we have a responsibility to share the findings of our research with the public in a way that they trust and understand. This limited study showed that, by devoting human resources to outreach and structuring efforts around a robust communications plan, it is possible to establish a large audience and become a trusted resource for information on an environmental topic. Each medium has its strengths and weaknesses, but if the broad reach of broadcast media and social media is cleverly used to support more focused outreach events, such as citizen science, public events and workshops, a momentum can be generated around topics such as IAS, and this can be sustained.

In the end, it is this sustained delivery of a focused message from a trusted source that sets the seed for behavioural change. A carefully constructed communications plan is the foundation that underpins an effective outreach programme.

7 Recommendations

This project has highlighted the need for effective biosecurity to prevent the introduction and spread of IAS. It is recommended that the biosecurity focus should be targeted at the top 40 freshwater, terrestrial and marine species identified in the horizon scan, and particularly on the top 10 IAS listed. The challenge of implementing effective biosecurity to prevent introductions and spread can be tackled using a number of measures.

1. Establish a biosecurity steering group for the island of Ireland that will draw on scientists, practitioners, regulators and stakeholder groups throughout the country. This membership should include experts from relevant agencies abroad (e.g. the Great Britain Non-native Species Secretariat).
2. Develop a national biosecurity strategy for Ireland, which would draw heavily on existing biosecurity strategies that are available for other countries. From this, produce practical and cogent national biosecurity guidelines, in compliance with Principal Action No. 4 in section 7.5.2 of the River Basin Management Plan (2018–2021).
3. Research what is best biosecurity practice abroad and determine how and why it works. It may be worthwhile liaising closely with, or even visiting, countries where it is acknowledged that biosecurity is effectively operated (e.g. New Zealand, Australia, Norway, South Africa) and interviewing/consulting with the main architects of these campaigns.
4. Establish a legally binding national biosecurity declaration form (like those for countries in the Australasian region) to be completed upon entry to the country. Establish a protocol for the disinfection of sports, hunting, angling and other recreational equipment entering the country, with a requirement for certificates of disinfection. Provide cleaning and disinfection facilities at points of entry, with an amnesty bin for contaminated or prohibited items. (Look at systems that are currently in place in countries such as Iceland, Norway, New Zealand, Australia and Fiji, and in regions such as Hawaii.)
5. Develop dedicated biosecurity protocols/standard operating procedures/guidelines for government departments, in compliance with Target 4.4 of the National Biodiversity Action Plan (NBAP) (2017–2021). Best practice guidelines developed in this project to prevent the spread of Asian clam and winter heliotrope should be disseminated widely, shared via the NBDC website.
6. Develop a range of comprehensive IAS/biosecurity training courses or packages that would be dedicated to the specific needs of different target and stakeholder groups. Blended training (to include online and hands-on elements) would probably provide the best option, spearheaded through a third-level institution.
7. A policy of providing a broad-based and networked communication strategy, including citizen science initiatives, was shown by this project to be effective for educating the public in relation to relevant aspects of IAS. Communication on the impacts and management of IAS must be sustained via competent authorities, relevant industry groups, conservation projects involving the public, and by educators at all levels.
8. Provide biosecurity training to all government departments, port and customs staff and representatives from the various potential target groups listed at the end of this chapter. It will be important to ensure that all government departments provide biosecurity training for their staff, in compliance with Target 4.4 of the current NBAP.
9. Develop and promote a national biosecurity strategy campaign (with a logo and message, similar to Check, Clean, Dry) to generate public awareness. One shortfall of the Check, Clean, Dry campaign (now acknowledged in the UK) is the lack of consideration for the need to disinfect, particularly to prevent the spread of parasites and pathogens (e.g. salmon fluke, crayfish plague, ash dieback). Consider amending this campaign to include disinfection, i.e. Check, Clean, Disinfect, Dry.

10. Create awareness among all target groups (see provisional list below) of the existence, adverse impacts and costs/legal implications associated with IAS. Highlight the importance of good biosecurity practice to prevent the introduction and spread of IAS (it may be necessary to alter the message depending on the specific target group). Information campaigns could use the following platforms: social media, apps, advertising (in specialist magazines, local and national print media, national and local radio and television), dedicated radio and television programmes, nationwide talks/lecture series, local and regional demonstrations/workshops, practical biosecurity demonstrations at major events in Ireland (e.g. Bloom gardening festival, National Ploughing Championships, Liffey Descent canoe race).
11. Develop a suite of practical, easy-to-use, environmentally safe, efficient and cost-effective cleaning and disinfection tools for use by different target groups [e.g. angler disinfection bags and disinfection kit boxes, as currently used by Inland Fisheries Ireland (IFI) staff; permanent disinfection stations, as used at some major angling venues in Ireland; canoe/kayak cleaning chutes; HydroHoist facilities in marinas].
12. Continue to research the availability of suitable and environmentally safe cleaning/disinfectant agents for use in decontaminating clothing, gear and equipment.
13. Continue to research new and innovative biosecurity approaches to control IAS present in the country. A number of peer-reviewed scientific papers linked to this project focusing specifically on this topic have recently been published. Some of this formative research work, however, needs to be field tested and brought into practical use to provide rapid-reaction tools for dealing with new IAS introductions and the spread of species already in the country.
14. In cooperation with IFI, pilot a boat licensing scheme for major state lakes in the west of Ireland (e.g. Corrib, Conn, Mask, Caragh) to monitor boat movements and implement biosecurity when boats are being moved. Based on the results from a 3-year pilot exercise, this could be rolled out for the rest of the country.
15. A funding contribution to implement the proposed national biosecurity strategy could be sought from key stakeholders (e.g. airlines, shipping companies, the food industry) to augment funding from government sources. Consider also the implementation "user-pays" approach to fees, similar to the system in New Zealand, where the Ministry for Primary Industries recovers the costs for biosecurity inspections and other services it supplies to importers.
16. Explore the possibility of including high-impact IAS present in Ireland that are not "species of Union concern" on a type of "noxious species" list that has designated legislative standing.
17. In respect of rapid-response initiatives to tackle IAS problems without delay, consideration should be given to the following:
    (a) Prepare dedicated contingency plans for IAS that are not yet present in Ireland.
    (b) Prepare early-engagement initiatives with the regulatory authorities (e.g. EPA, NPWS, IFI) to achieve agreements on rapid-response actions and methodologies. Develop a system for the pre-clearance of control mechanisms such as piscicides (e.g. rotenone) and a clearance protocol to immediately treat new IAS incursions, without having to wait on regulatory approval.
    (c) Provide for early-engagement and specialist training of groups to rapidly react to incursions. (These could be trained volunteers or groups that may be contracted for the application of rotenone, or shooting, trapping, electrofishing, or herbicide/pesticide/insecticide application, etc.)

Potential target groups include the following: state and semi-state departments, politicians, local authorities, port authorities, customs, airline and shipping companies, tourist groups, the food industry, building contractors, auctioneers, farmers, private forestry owners, the horticulture, plant nursery and aquaculture industries, primary, secondary and third-level education institutions, stakeholder groups (e.g. anglers, boaters, cruiser operators, hunters) and the public.

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Abbreviations

ANOVA	Analysis of variance
CABI	Centre for Agriculture and Bioscience International
CBD	Convention on Biological Diversity
CT	Computerised tomography
DAERA	Department of Agriculture, Environment and Rural Affairs
DAFOR	Dominant, abundant, frequent, occasional, rare
df	Degrees of freedom
DI	Dry ice
EASIN	European Alien Species Information Network
EPA	Environmental Protection Agency
EU	European Union
GBIF	Global Biodiversity Information Facility
GIS	Geographical information system
GISD	Global Invasive Species Database
GLM	Generalised linear models
IAS	Invasive alien species
IFI	Inland Fisheries Ireland
MS	Member State
MSPA	Morphological spatial pattern analysis
NBAP	National Biodiversity Action Plan
NBDC	National Biodiversity Data Centre
NI	Northern Ireland
NOBANIS	European Network on Invasive Alien Species
NPWS	National Parks and Wildlife Service
PPE	Personal protective equipment
QML	Queen’s University Marine Laboratory
RGR	Relative growth rate
SH	Shell height

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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Prevention, Control and Eradication of Invasive Alien Species

Authors: Frances E. Lucy, Joe Caffrey, Jaimie T.A. Dick, Eithne Davis and Neil E. Coughlan

Identifying Pressures

Invasive alien species (IASs) are animals and plants that have been introduced, either accidentally or deliberately to a region where they are not present, and have serious negative consequences where they establish. IASs are recognised globally as one of the greatest pressures on the biodiversity of terrestrial, freshwater and marine ecosystems; they also cause damage to the built environment and create considerable associated costs and challenges in terms of control and management. In recent decades, increasing international trade and travel to Ireland has heightened the ever-present risk of new introductions of IASs on this island. Implementing the management measures outlined in legislation, particularly the EU IAS Regulation (1143/2014) and the Invasive Alien Species (Enforcement and Permitting) Order (Northern Ireland) 2019, requires considerable resource from government departments and agencies. The challenge of implementing effective biosecurity to prevent introductions was evident during this research. This project used a horizon scanning method to identify 40 high-impact species that are most likely to arrive, establish and create pressures on biodiversity in Ireland in the next 10 years.

Informing Policy

This research project informs policy on the prevention, early detection and rapid eradication of IASs, and their management in accordance with the internationally agreed hierarchical approach to combatting IASs. This island's policies on prevention, early detection and rapid eradication of IASs expected to arrive in Ireland can focus on the 40 freshwater, terrestrial and marine species identified in the project's horizon scan. The two species considered most likely to arrive are the freshwater signal crayfish and the roe deer; a number of robust measures should now be implemented to prevent these introductions. A policy of providing a broad-based and networked communication strategy, including citizen science initiatives, was shown to be effective for educating the public on an invasive plant – the winter heliotrope. Engagement on IAS biosecurity with the farming community indicated that more outreach is required to clarify the difference between noxious weeds and invasive species. IAS codes of practice were developed to inform the management of winter heliotrope and Asian clam. These can be used by local authorities, agencies or industries as management tools to prevent the spread of these species.

Developing Solutions

Field trials carried out on winter heliotrope indicate that the most effective method for its eradication on roadsides is using a specific herbicide. Laboratory experiments on the control of a range of aquatic invasive plants and invertebrates showed that several proprietary aquatic disinfectants can be used in 'check, clean, disinfect, dry' biosecurity measures for recreation events on rivers and lakes. Experiments using thermal shock treatment both with and without substrate disruption caused lethal effects on Asian clams. Field trials are required to test these methods further, but they show promise for use in areas of special conservation to mitigate impacts on protected species and habitats. International databases are considered effective information tools for managing IASs. Communications outputs from this project ranged from journal articles, television programmes and workshops to Twitter and Facebook posts. Communication resulted in diverse stakeholder engagement from scientists, citizen scientists, practitioners, industry stakeholders, journalists and schoolchildren. Involvement from proactive and informed citizens who will engage with the authorities is vital for the prevention and management of IASs.

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