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Research Article

Horizon scan of invasive alien species for the island of Ireland

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Abstract

Ireland, being an island situated on Europe's western seaboard, has a fewer number of native species than mainland European Union Member States (MS). 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 they are in continental MSs, where the native biodiversity is richer. A horizon scanning approach was used to identify the most likely invasive alien species (IAS) (with the potential to impact biodiversity) to arrive on the island of Ireland within the next ten years. To achieve this, we used a consensus-based approach, whereby expert opinion and discussion groups were utilised to establish and rank a list of 40 species 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, 15 terrestrial and seven marine IAS. 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 ten IAS (seven species out of ten), 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. This evidence-based list provides important information to the relevant statutory agencies in both the Republic of Ireland and Northern 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 1143/2014). 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.

Key words: signal crayfish, freshwater, marine, terrestrial, biosecurity, biodiversity, conservation

Introduction

Invasive alien species (IAS) are widely recognised as one of the greatest threats to biodiversity, particularly through their interactions with other drivers of change (Millenium Ecosystem Assessment 2005; Vilá et al. 2011; Blackburn et al. 2015; Dick et al. 2017; IPBES 2019). Predicting the arrival, establishment, spread and impact of IAS to any region is a challenging task; nevertheless, establishing a list of likely candidate species is a vitally important first step in complying with legislation (EU 2014) and mitigating the environmental and economic impacts associated with an established IAS. This information can then be promptly used to direct policy and target resources, on a national or cross-jurisdictional level, towards prevention, early detection and rapid response for the most impactful IAS.

Ireland, being an island, has fewer native species than mainland Europe, and therefore the potential impacts of damage to biodiversity by IAS are greater than in mainland Europe (Simberloff 1995; Stokes et al. 2006a; Cabot 2009). A workshop entitled, "Identification of emerging Invasive Alien Species with the potential to threaten biodiversity in Ireland" was held in April 2017 at the Institute of Technology, Sligo, Ireland. The workshop applied a horizon scan process to forecast IAS arrival, establishment and impact for the island of Ireland (both jurisdictions) and was attended by experts from the Republic of Ireland, Northern Ireland, and Great Britain. These experts were selected from a range of disciplines (scientific researchers, practitioners and responsible authorities) in order to provide a balance of expertise throughout terrestrial, freshwater and marine taxa.

Horizon scanning is the systematic process of conducting a contextualised search for potential threats and opportunities that need identification, to inform future decision-making and policy development (Sutherland et al. 2011; Peyton et al. 2019; Roy et al. 2014, 2019; Vilá et al. 2009). This is an essential tool for anticipating which IAS are most likely to arrive and which will cause the greatest impacts, such that preventative action can be taken. Accordingly, horizon scanning is recognised as an essential component in IAS management (Roy et al. 2015, 2019) and has been specifically used in several IAS exercises, such as: 1) identifying emerging IAS with the potential to threaten biodiversity in Great Britain (Roy et al. 2014); 2) prioritising prevention efforts for the introduction of IAS in the EU (Roy et al. 2015, 2019); and 3) identifying the top twenty key issues relating to IAS in Europe (Caffrey et al. 2014). In these studies and others (Parrott et al. 2009; Gallardo and Aldridge 2013), horizon scanning was utilised as an effective screening tool to identify potential IAS invasions and associated impacts, and also to inform efficient and effective management techniques.

The systematic approach for IAS identification differentiates horizon scanning from other, less robust, processes such as stand-alone literature searches and trend analysis (Sutherland and Woodroof 2009). Relevant evidence is obtained through literature, databases and expert knowledge. A horizon scanning exercise consists of several distinct phases and when effectively undertaken, provides decision-makers with information on which to base cogent but flexible strategies and plans for future environmental management (Sutherland and Woodroof 2009). Horizon scanning provides opportunities for conservation biology to be a proactive rather than a reactive science (Sutherland et al. 2018) where it can be used in a consensual process to prioritise prevention efforts for introduction of IAS (Roy et al. 2015, 2019) and to help inform rapid response measures to those IAS recently introduced (Caffrey et al. 2014).

The main aim of this work was to produce a list of the top 10 IAS in order of priority with a further continued ranking of the next 30 species most likely to arrive, establish and cause impacts to biodiversity in terrestrial, freshwater and marine biomes on the island of Ireland within the decade 2017–2027. A workshop was organised to generate this list, which can inform the statutory agencies and other concerned stakeholders in both jurisdictions in the need to prioritise the prevention, surveillance and rapid response for the most likely invaders. Pathways of introduction were also addressed to determine the most likely routes of introduction for these species to inform on biosecurity strategies for the management of these pathways. This exercise focussed on the pathways of introduction specific to Ireland, and serves to enhance the pathway analysis as carried out by MSs.

Materials and methods

For this horizon scan of IAS, we used an adapted version of the consensus method used by Roy et al. (2014) as outlined here. The main deviation from the Roy et al. methodology was in reducing the number of expert groups to three habitats, and focussing on pathways appropriate to the island of Ireland. The process involved two distinct phases.

1. Preliminary consultation between groups of experts in Freshwater, Terrestrial, and Marine species.
2. Consensus building among and between expert groups to provide a ranked list of species mostly likely to invade the island of Ireland, based on the probability of the arrival, establishment and impact of individual species.

Preliminary Consultation

Twenty-three experts in the marine, freshwater and terrestrial ecology were selected to complete the preliminary consultation phase of the study. This took place five months in advance of the workshop, and involved ecologists from both the Republic of Ireland and Northern Ireland. These were assigned to groups comprised of between 7–8 experts that included a group leader, co-leader/rapporteur and the core group. Experts were assigned to groups according to their complimentary expertise across taxa, with the intention of ensuring the best possible balance of expertise within each biome group, and within the workshop as a whole. When participants had confirmed their availability, they were provided with baseline information regarding the workshop and detailed information followed in March 2017.

Each expert received a group-relevant list of IAS (*via* email), selected from six relevant sources: (1) the species identified previously as High Risk in the GB horizon scanning for IAS (Roy et al. 2014), (2) the previous Invasive Species Ireland horizon scan (O'Flynn et al. 2014), (3) a marine list (Minchin 2014), (4) Non-native species APplication based Risk Analysis for Ireland (NAPRA 2014) major risk species, and (5) species not currently established in Ireland pursuant with the 37 species named in the EU Invasive Alien Species Regulation 1143/2014 and the EU Implementing Regulation (EU) 2016/1141 of 13 July 2016 adopting a list of IAS of Union concern.

Experts were invited to use these or alternative sources to suggest other IAS that may be likely to arrive, establish, spread and impact on native biodiversity within the next decade, together with supporting evidence (generally peer-reviewed publications but also grey literature, where the former was lacking). Experts were provided with relevant reference sources (MSFD 2012; Kelly et al. 2013a; Roy et al. 2014, 2015) and databases (e.g. DAISIE, NOBANIS, EASIN, GISID, CABI, EPPO), but were also asked to review and, if necessary, supplement these using other literature sources and their own and others' expert opinion. Suggested additional species proposed by individual experts were circulated to the expert group as a whole in advance of the workshop by the group leader, along with details of supporting literature. These additional species were brought forward for discussion in detail within the group. The total number of IAS that were assessed during this study was 348, with 80 marine, 87 freshwater and 181 terrestrial species (Figure 1).

Each expert group was provided with a spreadsheet template to ensure consistency in the collated information. Table columns had the following headings: species, taxonomic group, functional group, native range, likely pathway of arrival, and uncertainty (see below).

Guidance notes were provided. Functional groups were classified as primary producer, herbivore, omnivore, predator and parasite. Pathways of arrival were defined following IUCN classification (UNEP/CBD/SBSTTA/18/9/Add.1). Management of species or pathways was not to be considered. The likelihood of arrival, likelihood of establishment/spread and likelihood of impact on biodiversity was scored from 1 (very unlikely) to 5 (very likely). Impact on biodiversity was assessed by considering the following parameters, adapted from Branquart (2007) as used by Roy et al. (2014):

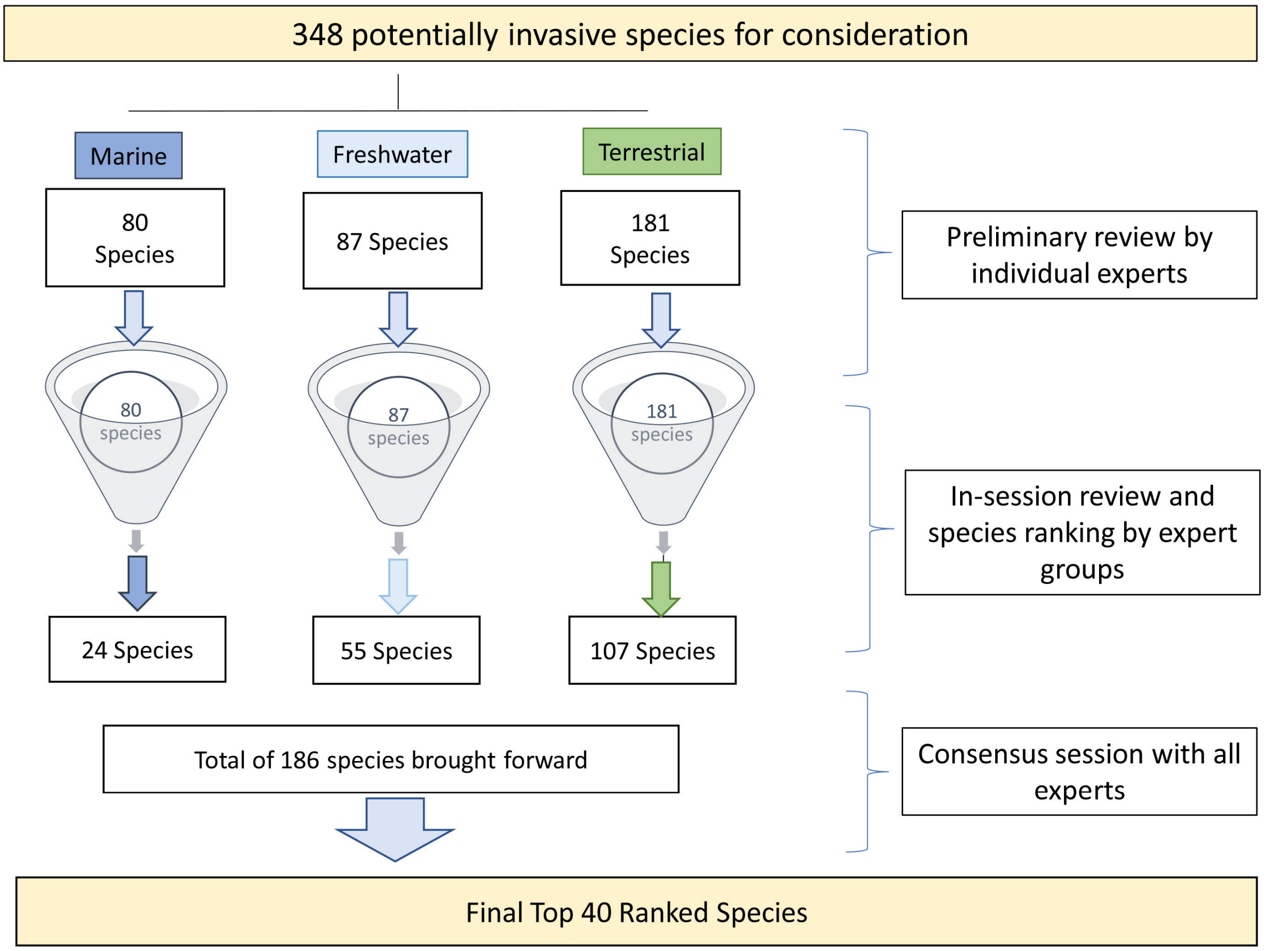

Figure 1. Consideration and consensus process for horizon scanning of IAS in Ireland.

1. Dispersal potential
2. Colonization of high conservation value habitats
3. Adverse impacts on native species:
   a) Predation/herbivory
   b) Competition
   c) Transmission of pathogens and parasites to native species
   d) Genetic effects
4. Alteration of ecosystem functions:
   a) Modification to nutrient cycling
   b) Physical modifications to the habitat
   c) Modifications of natural successions
   d) Disruption of food webs

An overall score for each species was determined as the product of the scores for likelihood of arrival (A), establishment (B) and impact (C) (maximum score = 125). Uncertainty was defined as the level of uncertainty on the overall assessment in terms of the quantum and quality of the information available on the particular species and also in terms of the overall uncertainty in the species' assessment (Kelly et al. 2013b). This was ranked as low, medium, high and very high, with the most certain invasions as low and the most uncertain as very high. Uncertainty scores were taken into account during the expert group discussions.

An agreed ranked list of IAS was produced by each group. This preliminary consultation phase was conducted over a three week period. The scores derived were only used to provide guidance for ranking the species, enabling a starting point for consensus, from which experts, across the three groups, could engage in debate, leading to modification of the score in some cases. For transparency, we retained the original scores. Only species considered as having a medium or high probability (scores of 3 or above) in all categories (arrival, establishment and impact) were taken forward to the next phase of the process, i.e. consensus-building across expert groups.

Consensus-building across expert groups

Consensus-building across the three expert groups took place at a workshop held at the Institute of Technology, Sligo on April 19th and 20th 2017. The workshop was held over two days, led by an independent chair and two technical facilitators. Three representatives from relevant GB statutory agencies and one Irish agency were invited to observe the process and contribute to methodological discussion.

The first meeting involved the chairperson, technical facilitators and group leaders to provide an overview of the IAS within their lists, with particular emphasis on justification of scores. The aim of this exercise was both to review the three lists and to ensure standardization of the approach to scoring during the preliminary consultation. Discussions between group leaders enabled the moderation of group scores, to create an aggregated, ranked list of species for each of the three biome groups.

All expert group participants joined the workshop for a short plenary session explaining the workshop process. The experts then immediately joined their respective group leaders and groups to review and refine the ranked list of IAS. Expert group participants were invited to make challenges for or against species within the lists. The combined expert opinion within groups was used to further refine the ranking. Throughout the discussions, the group provided expert opinion to support the decision-making process and the scores were used only as guidance for this process. The discussions enabled participants to review available information and consider uncertainty in preparation for the final session. The processes of collaborative review and consensus-building were repeated until the entire group had converged on a ranked list at the end of the afternoon. At the end of Day 1 the group leaders and co-leaders met with the chairperson, technical facilitators and observers to review the ranking among the groups.

On Day 2, all participants reconvened within their groups to review and refine the compiled and ranked list of IAS which would be brought forward to the concensus session. Ultimately, consensus was reached within groups on the basis of expert opinion provided through open discussion (a transparent process in which questions were openly asked and defences were given or opinions were modified) and majority voting. Discussions were most detailed for species ranked as high impact (with a high degree of certainty) within the aggregated list. This filtering resulted in 24 marine species, 55 freshwater species and 107 terrestrial species (total number/species = 186) being brought forward for the final consensus (Figure 1). The group sessions then concluded.

Day 2 continued with a final plenary synthesis session, involving all experts working together to determine the top ranked species likely to arrive, establish and impact on native biodiversity in the next ten years. Species were primarily ranked within a Top Ten by total score. Species ranked from 11–40 were also included as they were considered important for horizon scan purposes. Ranking of impact scores was also considered in the case of identical scores, with precedence given, in general, to those with higher impact score. Once consensus was reached, the workshop ended.

Results

The top forty IAS most likely to arrive, establish, spread and cause impacts to biodiversity on the island of Ireland are shown in Table 1, with a summary profile for each of the top ten species available in supplementary material Appendix 1. Supplementary Tables S1–S3 include all of the species that were considered in each of the freshwater, marine and terrestrial sessions. Information is provided on taxonomic and functional feeding groups, environment, native range, pathways of arrival and uncertainty for each species.

Fourteen of the 40 IAS are predators, eleven are herbivores (including three plant pests), six are omnivores, four are filter feeders, four are primary producers and one is a parasite. All six of these functional feeding groups are represented in the Top Ten species (Table 1).

The signal crayfish (*Pacifastacus leniusculus* Dana, 1852) was scored as the most likely species to arrive, establish and create impacts on biodiversity in Ireland (score = 125). Second was the Roe deer (*Capreolus capreolus* Linnaeus, 1758). Killer shrimp (*Dikerogammarus villosus* Sowinsky, 1894), salmon fluke (*Gyrodactylis salaris* Malmberg, 1957) and warm water barnacle (*Hesperibalanus fallax* Broch, 1927) were ranked as species three to five in the top ten list. These five species had the highest values for biological impact (5), with associated scores of 4 to 5 for arrival and establishment. The uncertainty scores for these species were also low for the signal crayfish, roe deer, killer shrimp and salmon fluke, indicating a high probability of invasion success for each of these species.

Freshwater species dominated the top ten species (seven of the top ten); in addition to signal crayfish, killer shrimp and salmon fluke, the others were floating pennywort (*Hydrocotyle ranunculoides* L.f. – ranked 6th), quagga

Table 1. Top 40 species emerging from horizon scan for Ireland. Species were scored according to their likelihood of arrival (A), their likelihood of establishing in the wild (B), and their impact on biodiversity (C). They were then ranked according to the product of those scores, taking uncertainty (UNCERT) into consideration. Prioritisation of species was based on the highest scoring paired with the highest uncertainty. For full list of Pathway Codes, see Table 2.

Rank	Species	Common name	Taxonomic Group	Functional Group	Environment	Native Range	Pathway of Arrival	A	B	C	PROD	UNCERT
1	*Pacifastacus leniusculus*	Signal crayfish	Crustacean	Omnivore	Freshwater	North America	M/E/FB; M/E/A; V/TS/FE	5	5	5	125	Low
2	*Capreolus capreolus*	Roe deer	Mammal	Herbivore	Terrestrial	Europe, Middle East	M/R/HW	5	4	5	100	Low
3	*Dikerogammarus villosus*	Killer shrimp	Crustacean	Predator	Freshwater	Ponto-caspian	V/TS/FE	5	4	5	100	Low
4	*Gyrodactylus salaris*	Salmon fluke	Monogenean	Parasite	Freshwater	Baltic Sea	V/TS/FE	4	5	5	100	Low
5	*Hesperibalanus fallax*	Warm-water barnacle	Crustacean	Filter feeder	Marine	Atlantic coast of tropical Africa	V/TS/BW; V/TS/HF	5	5	4	100	Medium
6	*Hydrocotyle ranunculoides*	Floating pennywort	Plant	Primary producer	Freshwater	North and South America, Africa	V/TS/S	5	5	4	100	High
7	*Dreissena rostriformis bugensis*	Quagga mussel	Mollusc	Filter feeder	Freshwater	Ponto Caspian	V/TS/S	4	4	5	80	Low
8	*Caulacanthus okamurae*	Pom-pom weed	Alga	Primary producer	Marine	Japan, NW Pacific	M/E/A	5	5	3	75	Low
9	*Eriocheir sinensis*	Chinese mitten crab	Crustacean	Predator	Freshwater	Eastern Asia	V/TS/S	5	3	5	75	Low
10	*Pseudorasbora parva*	Topmouth gudgeon; Stone moroko	Fish	Predator	Freshwater	NW Pacific	V/TS/FE	3	5	5	75	Medium
11	*Ondatra zibethicus*	Muskrat	Mammal	Herbivore	Terrestrial	North America	M/R/O	5	5	3	75	Medium
12	*Psittacula krameri*	Ring-Necked parakeet	Bird	Herbivore	Terrestrial	South Asia	S/U/ND	5	4	3	60	Medium
13	*Agrilus planipennis*	Emerald ash borer	Insect	Herbivore/ plant pest	Terrestrial	E Asia, E central China, Japan, Korea	M/E/O; M/E/H	4	3	4	48	High
14	*Agrilus anxius*	Birch borer	Insect	Herbivore/ plant pest	Terrestrial	North America	M/E/O; M/E/H	4	3	4	48	High
15	*Ensis leei*	American razor-clam	Mollusc	Filter feeder	Marine	NW Atlantic	V/TS/BW; M/E/A	5	5	2	50	Medium
16	*Dikerogammarus haemobaphes*	Demon shrimp	Crustacean	Predator	Freshwater	Ponto-caspian	V/TS/FE	5	4	3	60	Medium
17	*Orconectes limosus*	Spinycheek crayfish	Crustacean	Omnivore	Freshwater	Ponto-caspian	M/E/PAS	4	3	5	60	Medium
18	*Oncoryhnchus mykiss*	Rainbow Trout	Fish	Predator	Freshwater	North America	M/R/FW; M/E/A	5	3	4	60	Medium
19	*Squalius cephalus*	Chub	Fish	Predator	Freshwater	Europe	M/R/FW	4	4	3	48	Low
20	*Ludwigia grandiflora (+species)**	Water primrose	Plant	Primary producer	Freshwater	South America	V/TS/S	4	3	4	48	Low
21	*Microtus agrestis*	Field vole	Mammal	Herbivore	Terrestrial	Europe	M/TC/HM	4	4	3	48	Medium
22	*Cochlicella barbara*	Pointed snail	Mollusc	Herbivore/ plant pest	Terrestrial	Europe		**5**	**5**	**1**	25	Medium
23	*Procyon lotor*	Raccoon	Mammal	Omnivore	Terrestrial	North and Central America	M/E/BG; M/E/BG	4	3	4	48	Medium
24	*Tamias sibiricus*	Siberian chipmunk	Mammal	Herbivore	Terrestrial	Northern Asia (Kazahkstan to Japan)	M/E/O; M/E/PAS	5	3	3	45	Medium
25	*Hemigrapsus takanoi*	Brush-clawed shore crab	Crustacean	Predator	Marine	Asia (Pacific)	V/TS/HF	4	4	3	48	Medium
26	*Thymallus thymallus*	Grayling	Fish	Predator	Freshwater	Europe	M/R/FW	2	5	4	40	Medium
27	*Barbus barbus*	Barbel	Fish	Predator	Freshwater	Europe	M/R/FW	4	4	3	48	Medium
28	*Sander lucioperca*	Zander; Pikeperch	Fish	Predator	Freshwater	Europe	M/R/FW	4	3	4	48	Medium
29	*Orconectes virilis*	Virile crayfish	Crustacean	Omnivore	Freshwater	North America	M/E/PAS	4	3	4	48	Medium
30	*Obama nungara*	Flatworm	Trematode	Predator	Terrestrial	South America	M/TC/HM	5	3	3	45	High
31	*Myriophyllum heterophyllum*	American water-milfoil	Plant	Primary producer	Terrestrial	North America	M/E/O	3	4	4	48	High

Table 1. (continued) . Top 40 species emerging from horizon scan for Ireland.

Rank	Species	Common name	Taxonomic Group	Functional Group	Environment	Native Range	Pathway of Arrival	A	B	C	PROD	UNCERT
32	*Hylastes ater*	Black pine bark beetle	Insect	Herbivore/ plant pest	Terrestrial	Europe, Asia – China, Korea	M/TC/P	4	4	3	48	High
33	*Salvelinus fontinalis*	Brook trout; Brook charr; Sea trout	Fish	Predator	Freshwater	North America	M/R/FW; M/E/A	3	4	4	48	High
34	*Astacus astacus*	Noble Crayfish; Broad-fingered crayfish	Crustacean	Omnivore	Freshwater	Europe	M/E/PAS	4	3	4	48	High
35	*Celtodoryx ciocalyptoides*	sponge	Sponge	Filter feeder	Marine	NW Pacific	M/E/A	4	4	3	48	Very High
36	*Hemigrapsus sanguineus*	Asian shore crab	Crustacean	Omnivore	Marine	Asia (Pacific)	V/TS/BW; M/E/A	4	4	3	48	May be here already
37	*Myiopsitta monachus*	Monk parakeet; Grey-headed parakeet	Bird	Herbivore	Terrestrial	South America	M/E/PAS	4	4	2	32	Low
38	*Orconectes rusticus*	Rusty crayfish	Crustacean	Predator	Freshwater	North America (Ohio river basin)	M/E/PAS	3	2	5	30	Low
39	*Microtus arvalis*	Orkney vole	Mammal	Herbivore	Terrestrial	Orkney Islands, Scotland	M/TC/HM	3	4	3	36	Medium
40	*Threskiornis aethiopicus*	Sacred Ibis; African Sacred Ibis	Bird	Predator	Terrestrial	Sub-Saharan Africa	S/U/ND	4	3	3	36	Medium

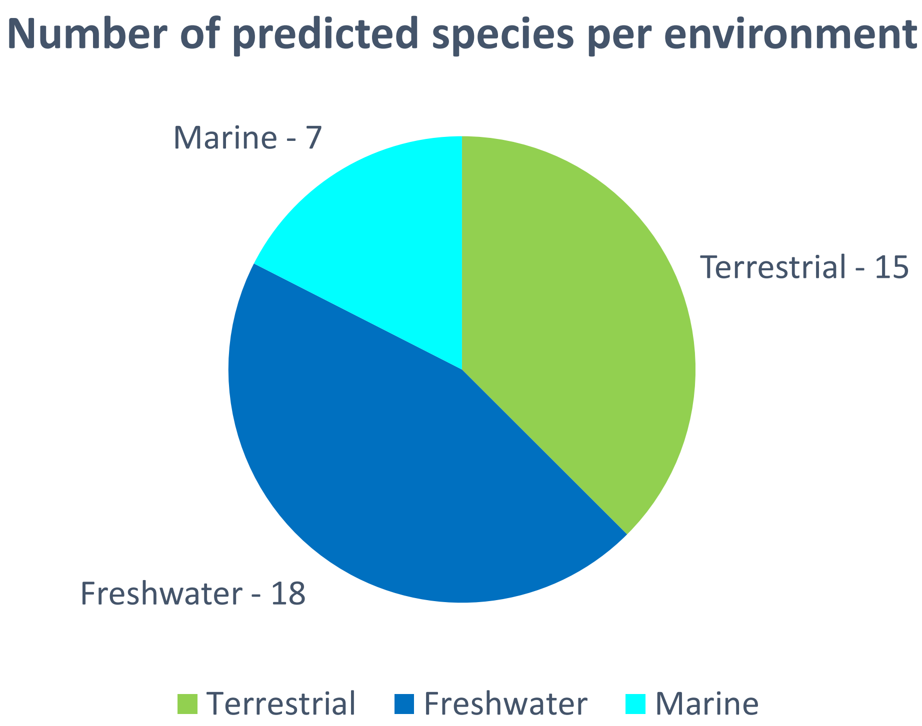

Figure 2. Freshwater species made up the greatest proportion of the horizon scan list for Ireland, followed by terrestrial species. Marine species made up the smallest group on the list.

mussel (*Dreissena rostriformis bugensis* Andrusov, 1897 – ranked 7th), chinese mitten crab (*Eriocheir sinensis* H. Milne-Edwards, 1853 – ranked 9th) and topmouth gudgeon (*Pseudorasbora parva* Bleeker, 1859 – ranked 10th). The marine pom-pom weed (*Caulacanthus okamurae* Yamada, 1933) was ranked at number 8.

The final list of top 40 species which will be a valuable resource for decision-making around IAS in Ireland includes eighteen freshwater, seven marine and fifteen terrestrial IAS (Table 1, Figure 2). Eleven of the forty

Table 2. IUCN Pathway codes.

Category		Subcategory	Code
Movement of commodity	Release in nature	Biological control	M/R/B
		Erosion control/dune stabilisation (windbreaks, hedges…)	M/R/EC
		Fishery in the wild	M/R/FW
		Hunting in the wild	M/R/HW
		Landscape/flora/fauna "improvement in the wild	M/R/L
		Introduction for conservation purposes or wildlife management	M/R/C
		Release in nature for use (other than above, e.g. fur, transport, medical use)	M/R/U
		Other intentional release	M/R/O
	Escape	Agriculture	M/E/AG
		Aquaculture/mariculture	M/E/A
		Botanical garden/zoo/aquaria	M/E/BG
		Farmed animals	M/E/FA
		Forestry	M/E/F
		Fur farms	M/E/FF
		Horticulture	M/E/H
		Ornamental purpose	M/E/O
		Pet/aquarium species	M/E/PAS
		Research (in facilities)	M/E/R
		Live food and live baits	M/E/FB
		Other escape from confinement	M/E/O
	Transport - Contaminant	Contaminant nursery material	M/TC/NM
		Contaminated bait	M/TC/B
		Food contaminant	M/TC/F
		Contaminant on animals	M/TC/A
		Contaminant on plants	M/TC/P
		Parasites on animals	M/TC/PA
		Parasites on plants	M/TC/PP
		Seed contaminant	M/TC/S
		Timber trade	M/TC/TT
		Transportation of habitat material	M/TC/HM
		Subclass Undefined	M/TC/U
Vector	Transport - stowaway	Container/bulk	V/TS/CB
		Hitchhikers in or on plane	V/TS/P
		Hitchhikers on ship/boat	V/TS/S
		Machinery/equipment	V/TS/M
		People and their luggage/equipment	V/TS/L
		Ship/boat ballast water	V/TS/BW
		Ship/boat hull fouling	V/TS/HF
		Vehicles	V/TS/V
		Other means of transport	V/TS/T
		Angling/fishing aquaculture equipment	V/TS/FE
		Organic packing material	V/TS/PM
		Subclass Undefined	V/TS/U
Spread	Corridors	Interconnected waterways/basins/seas	S/C/WS
		Tunnels and land bridges	S/C/TB
		Subclass Undefined	S/C/U
	Unaided	Natural dispersal across borders	S/U/ND
	Unknown	Unknown	S/U/U

species are crustaceans, with two freshwater amphipods (killer shrimp (*Dikerogammarus villosus*) and demon shrimp (*Dikerogammarus haemobaphes*)), seven decapods (including five freshwater crayfish, two marine crabs and one freshwater crab) and the warm-water barnacle. Freshwater fishes and terrestrial mammals are the next most common groups with seven and six species, respectively, listed in the Top 40. In terms

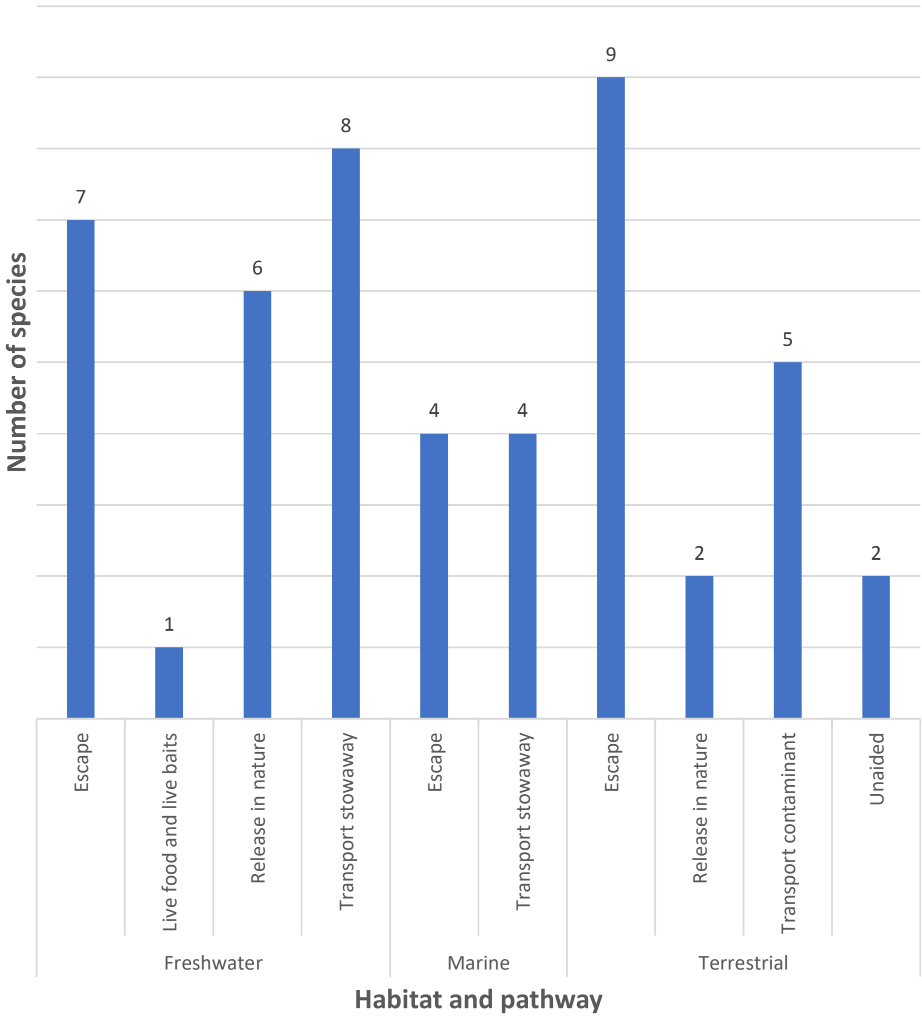

Figure 3. Pathway categories of introduction for freshwater, marine and terrestrial species.

of taxonomy, the remaining 16 species include: three birds, three freshwater plants, three molluscs (one from each of the three biomes), three insects (all terrestrial beetles), two trematode parasites (freshwater and terrestrial), one marine alga and one marine sponge.

The native range of the IAS in the list is trans-global (Table 1). Most of the freshwater fishes are European species, the quagga mussel, killer and demon shrimp (*Dikerogammarus haemobaphes* (Eichwald, 1841)) are Ponto-Caspian in origin. Some of the species that are native in Africa, the Americas and Asia are already present in Europe (e.g. ring-necked parakeet (*Psittacula krameri* (Scopoli, 1769)), rainbow trout (*Oncorhynchus mykiss* (Walbaum, 1792)), and floating pennywort (*Hydrocotyle ranunculoides* L.f.)).

Pathways of arrival for the Top 40 species are indicated in Figure 3. Escape (all three environments), transport stowaway (freshwater and marine) and transport contaminant (terrestrial) are the main pathways identified. Release into nature was an important component for both freshwater and terrestrial species. Unaided natural dispersal across borders was also identified for two of the bird species.

Discussion

The list of the Top 40 IAS that are most likely to arrive on the island of Ireland provides an essential resource for targeted invasive species management in both the Republic of Ireland and Northern Ireland. The consensus-building approach used for the Great Britain IAS horizon scan (Roy et al. 2014) was used here to combine the individual and team knowledge of experts across freshwater, marine and terrestrial biomes.

The IAS in the top 40 include representatives from a range of functional groups across freshwater, terrestrial and marine environments and with native distributions over a range of global regions. The origin of spread to Ireland for these "door-knockers" (NOBANIS 2015) may not be within native ranges, as transport and trade routes with Great Britain and continental Europe can provide opportunities for introductions of IAS already established there. For example, there is a rapid increase in the rate of new arrivals into Europe from temperate Asia (Roy et al. 2012) and at least 35 Ponto-Caspian species have arrived into Western Europe over the past three decades due to the interconnectivity of European waterways (Bij de Vaate et al. 2002). This Irish horizon scan ranks North American signal crayfish (*Pacifastacus leniusculus*) as the number one species most likely to invade Ireland and cause the greatest impact. This particular species is the most widespread alien crayfish in Europe (29 invaded territories as defined by Kouba et al. 2014, GB included), introduced for stocking and aquaculture purposes (Kouba et al. 2014). It is omnivorous, highly prolific (up to 400 eggs per female, mature at age 2–3), can live to 20 years. and is adaptable to a wide range of environments. *Pacifastacus leniusculus* is a carrier of the crayfish plague (*Aphanomyces astaci* – strains B and C) (OIE 2019), which is lethal for the Irish population of *Austropotamobius pallipes* (white clawed crayfish), having a 100% mortality rate. Its feeding habits, burrowing activity, reproductive rate and aggressiveness has a highly destructive effect on invaded ecosystems, allowing it to outcompete native crayfish, reducing local biodiversity and stability of river banks (Mazza et al. 2018; Veselý et al. 2015). *Pacifastacus leniusculus* is included in the List of Species of Union Concern which is annexed to the EU Regulation on IAS 1143/2014. Its management is challenging, requiring an integrated approach (Stebbing et al. 2014). Prevention of its introduction is recommended as by far the most practical approach.

The top species in the horizon scan were selected on the basis of probability of arrival, establishnment and biological impacts, giving us some insight into the dispersal of those high-scoring species between the freshwater, terrestrial and marine environments. Freshwater IAS are known as high impact invaders in many ecosystems in Europe and North America (Tricarico et al. 2010; Strayer 2010; Ricciardi and MacIssac 2011; Caffrey et al. 2011; O'Flynn et al. 2014; Lucy et al. 2013). This is reflected in the results of this horizon scan where seven out of the top ten ranked species are freshwater IAS.

There are five crayfish species present in the Irish horizon scan list. Crayfish are one of the most widely introduced freshwater taxa, usually introduced intentionally for aquaculture or ornamental reasons. Given their ability to adapt to a variety of conditions and to disperse over land, they often negatively and seriously impact the invaded ecosystems, (Thomas et al. 2019; Twardochleb et al. 2013).

Topmouth gudgeon (*Pseudorasbora parva*) is a small-bodied fish (< 10 cm) of the Cyprinidae family, originating from East Asia (Gozlan et al. 2010). It was introduced accidentally into Eastern Europe in the 1960s *via* the aquaculture trade. Its further spread in Europe has resulted from natural dispersal from aquaculture sites (Gozlan et al. 2010). Topmouth gudgeon has a high phenotypic plasticity in the expression of their life history traits, such as in their somatic growth rates and reproductive traits (e.g. fecundity, length and age at maturity, which has greatly facilitated its capacity to establish new populations and then colonise new waters (Britton and Gozlan. 2013). Whilst there is some concern over its negative ecological interactions with native fishes (Tran et al. 2015), the primary concern of its invasion is its potential transmission of the novel (and lethal) pathogen rosette agent (*Sphaerothecum destruens*) (Andreou et al. 2012; Sana et al. 2018).

Salmon fluke (*Gyrodactylus salaris*) is a small (< 1 mm) parasite that infects the skin, gills and fins of salmon, trout and some other species of freshwater fish (MI and IFI 2012). It causes gyrodactylosis, a serious notifiable disease that represents one of the biggest threats to the salmon population in Ireland. It is present in most countries of Europe and Scandinavia, although is currently absent from both Ireland and Great Britain. Based on experience in countries with Atlantic salmon populations that have become infected, if *G. salaris* establishes itself in Ireland, it could bring about a catastrophic collapse of the salmon stocks (Johnsen and Jensen 1986). It has several possible pathways of introduction, the most significant of which is the illegal importation of infected fish. Next in importance is the introduction of the parasite on contaminated fishing equipment. The parasite is very hardy and is capable of surviving for several days in damp conditions on wet angling equipment (e.g. wet landing nets, waders).

Killer shrimp (*Dikerogammarus villosus*), number three on the horizon scan list, is present in Great Britain (MacNeil et al. 2010), listed officially as “Occasional or few reports” (Dodd et al. 2014), but widely acknowledged as being established in GB catchments. Native to the Black Sea and Caspian Sea, it is a relatively recent invader in Europe, but has now been recorded in all major rivers in mainland Europe (Devin and Beisel 2006) with the primary vector of spread over long distances being ballast water and the hulls of boats (MacNeil et al. 2010). The likelihood of introduction of this species into Ireland has been assessed as “high” (risk of introduction = five), with a low level of uncertainty. *Dikerogammarus villosus* is tolerant of a wide range of habitats, freshwater and brackish (Bruijs et al. 2001), both lentic and lotic systems, and has a high reproductive rate (Pöckl 2007), making it highly likely to establish successfully on introduction to Ireland. Its impact on biodiversity is high, showing extremely aggressive behaviour towards native invertebrate species and causing significant changes in food-web dynamics (Dick and Platvoet 2000; Dick et al. 2002).

Chinese mitten crab (*Eriocheir sinensis*) is a large migrating crab with dense mats of hair (mittens) on its white-tipped claws. It is native to Eastern Asia and was first recorded in Ireland (Waterford estuary) in 2005, although viable populations never established in Irish rivers (J. Caffrey *pers. comm.*). It has the potential to cause significant economic and environmental damage where it becomes established (Clark et al. 1998). Migrating upstream from breeding grounds in brackish water, these large crabs can alter the morphological features of rivers and increase the amount of fine sediment in the watercourse through their burrowing activity, resulting in a threat to riverbank stability and land loss (Rosewarne et al. 2016). This species predates voraciously on a wide variety of aquatic invertebrates and fish eggs, and could outcompete native invertebrates (e.g. white-clawed crayfish) for food and resources. (Schrimpf et al. 2014).

Floating pennywort (*Hydrocotyle ranunculoides*) is an aquatic plant that is native to north America but naturalized in South America and parts of Africa. It was first recorded in Britain in the 1980s and is now widespread there, causing significant problems in infested watercourses, where it forms extensive floating carpets on the surface of the water (Ruiz-Avila and Klemm 1996). Its distribution in Ireland is very limited, having been recorded at four sites, mainly artificial ponds in Northern Ireland in the early 2000s (first record in 2002). Management programmes at all four sites significantly reduced the populations of this highly invasive species. *H. ranunculoides* was included in this exercise because of the fact that all known populations in the island are confined to isolated ponds. It has not yet appeared to be self-sustaining in the wild. Because of the biomass of vegetation produced, this species can cause significant flood risks in affected waters, while also adversely impacting native biodiversity, navigation and water-based amenity use of these aquatic resources (Newman and Duenas 2010).

Quagga mussel (*Dreissena rostriformis bugensis*) was discovered in Great Britain shortly after its nomination as the number one IAS in the GB horizon scan (Roy et al. 2014). Its presence in GB increases the probability of this species arriving here. Quagga mussel are ecosystem engineers in the same genus as the zebra mussel (*Dreissena polymorpha* (Pallas, 1771)), which has caused many biological impacts since arriving and establishing in Irish waters in the early 1990s (Minchin et al. 2005; Lucyand Panov 2014). Quagga mussel have been spreading widely in both Europe and North America (Karatayev et al. 2014; Aldridge et al. 2014) in recent years.

While the zebra mussel is restricted to benthic habitats with hard substrates, the quagga mussel can also settle on muddy benthos and in invaded waters it commonly outcompetes zebra mussels and becomes the dominant benthic organism in the soft sediments of lake systems (Sousa et al. 2009; Karatayev et al. 2014). Zebra mussel are known to spread effectively between and within countries attached (*via* byssal threads) to leisure craft moved between waterways (Minchin et al. 2005; Padilla et al. 1996) and it is expected that this may be an effective vector for the spread of quagga mussel, if it arrives to the island of Ireland.

Marine species ranked in Ireland's horizon scan include pom-pom weed (*Caulacanthus okamurae*), a turf-forming dark purple to brown, profusely and irregularly branched alga with a hornlike appearance at branched tips. It does not generally grow longer than 30 mm and is attached to the substrate by creeping stolons. It generally occupies rocky, intertidal and exposed habitats. *Caulacanthus okamurae* was introduced from Asia to southern California in 1999 and has since been recorded in France and SW Britain. *Caulacanthus* appears to displace macro-invertebrates, such as barnacles, limpets, and periwinkles, in the high intertidal zone while facilitating a more diverse array of small invertebrates and macroalgae (Smith et al. 2014). This is likely due to the formation of a turf habitat in the upper zone where turfs are uncommon.

The warm water barnacle (*Hesperibalanus fallax*) (Broch, 1927) is a warm water sessile thoracican barnacle native to most of West Africa, Morocco and Algeria (see Southward 2008 for identification details). With one exception, *H. fallax* was unrecorded in Europe before 1980, but has since been recorded in SW England, Wales, the Iberian peninsula, the Atlantic and English Channel coast of France, in the Southern North Sea, and in Guernsey (Southward et al. 2004). Its habitat ranges from 15 to 220 m depth and it can occur on a range of biological and man-made substrata, but not on rocks or harbour walls (Southward et al. 2004). Its occurrence on the seafan (*Eucinella verrucosa* (Pallas, 1766)) may adversely impact populations and there is concern that *H. fallax* might become a serious fouler of fish cages and other mariculture structures (Southward et al. 2004).

The terrestrial species ranked in this horizon scan are taxonomically diverse. The most prevalent species on the short-list for consideration were mammals (28), plants (23), insects (18), birds (10), amphibians (5), lepidoptera (5) and invertebtrates (4). The terrestrial vertebrates (birds and mammals) may be responsible for the greatest range of impacts on biodiversity (Vilá et al. 2009). Roe deer (*Capreolus capreolus*) was heavily debated when nominated as the highest risk species from the terrestrial group. Previously introduced breeding populations of roe deer (in Lissadell Estate and environs, Co. Sligo) were eradicated in *circa* 1905 (Stokes et al. 2006b). Roe deer are currently held in captivity in Wicklow and have produced young in the last five years (J. Dick *pers. obs.*; NPWS *pers. obs.*).

They are native to, and very widespread in GB, with their range expanding by a compound rate of 2.3% between 1972 and 2002 (Ward 2005). The similarity between habitat type in Great Britain and Ireland implies that they would be equally successful here. Further, new, less stressful forms of sedation for deer are now available, increasing the risk that deliberate introductions of this species for hunting purposes could occur by transport on boats, a known pathway of introduction for farmed deer species (such as red and fallow).

Sacred ibis, (*Threskiornis aethiopicus* (Latham, 1790)), a large wading bird native to Africa but commonly maintained in collections in GB, is known to prey opportunistically on birds, fish, amphibians and invertebrates, with high impacts on biodiversity (Baker and Hills 2008). It is most likely to arrive here by natural dispersal, making the design and implementation of preventative measures particularly challenging. *T. aethiopicus* is listed as a Species of Union Concern.

Three insects (*Agrilus planipennis* Fairmaire, 1888, *A. anxius* Gory, 1841 and *Hylastes ater* Paykull, 1800) ranked in the horizon scan can potentially enter Ireland as transport contaminants on plants or firewood, or alternatively as escapees from the horticulture or ornamental plant imports. All three are considered to be a significant threat to the diversity of native birch (*Betula* species) and ash trees (*Fraxinus excelsior* L.) in European countries at risk of invasion (Petter et al. 2020).

Identification and prioritisation of pathways are long standing key tenets for minimising the introduction of IAS (COP 6 Decision VI/23; UNEP/CBD/SBSTTA/18/9/Add.1; EU IAS regulation (EU 2014; Roy et al. 2014). However, establishing the real or possible pathways for IAS can be a challenge, even when assessing post-invasion (Roy et al. 2014). A review by Essl et al. (2015) indicated that throughout Europe, many invader pathways, particularly for freshwater and terrestrial species, remain unknown. Species can arrive *via* more than one pathway, making it difficult to assess the likelihood of arrival (Hulme 2009). Given that successful establishment often requires multiple introductions of an invader (Kolar and Lodge 2001) and that many factors including changing socioeconomics may affect the dissemination of propagules to new regions (Wilson et al. 2009; Essl et al. 2015), there are complex challenges in terms of pathway identification and subsequent management priorities. A major challenge in pathway prediction is an effective quantitative assessment of the risk posed (Pyšek et al. 2011; Essl et al. 2015). In the GB IAS horizon scan, Roy et al. (2014) predicted that the stowaway pathway (on land, air, or sea transport vehicles) is likely to be the most common mechanism of introduction but also predicted that multiple pathways of introduction are likely. Results from the current study indicate that multiple pathways exist for some species, indicating that more than one management measure will probably be necessary for prevention of each species. However, even in cases where there may be only one pathway, management is not always implemented. Four of the species on this horizon scan list are named on the EU IAS regulation (signal crayfish, floating pennywort, topmouth gudgeon and spiny cheek crayfish), requiring both jurisdictions to manage their prevention and spread.

The range of pathways for the 40 named IAS across the three environments calls for a diversity of prevention and management measures. These include effective risk assessment, improved detection, recording and inspection at ports and airports, full implementation of the Habitats Regulation in the ROI (EC 2011) and the Wildlife and Natural Environment Act (Northern Ireland) (NI 2011, 2019), to include management of trade including internet trade.

International agreements (e.g. the International Maritime Organisation's ballast water agreement) have effected a positive change in governance in terms of marine pathways. However, as long as there are ships that are equipped with ballast water tanks, there is no guarantee that ballast water will not be discharged and act as a pathway for spread of marine IAS. Codes of practice for pathways and IAS, similar to Check-Clean-Dry, need to be developed and promoted, and more training and citizen science events are needed to reach all ages and sectors in society. Knowledge exchange between scientists, practitioners and policy makers must be encouraged to improve channels of communication and thus improve understanding of individual roles and develop a co-ordinated approach to IAS management (Davis et al. 2018; Caffrey et al. 2014). This need for improved communication has been recognised by the establishment of Alien CSI COST Action programmes (Alien CSI 2020) and an upcoming EU project on Communication and Understanding of IAS (EU 2020).

The need for biosecurity to prevent introductions and spread of IAS has been emphasised in the literature (Caffrey et al. 2014 and references therein) but has been limited in terms of implementation across on the island of Ireland. One of the few consistent and coordinated biosecurity campaigns mounted in Ireland was in 2002, which resulted when Foot and Mouth disease threatened the country's livestock and economy. This coordinated response to a significant threat was successful and should serve as an example of what can be achieved if there is a will and determination to stop the introduction and spread of harmful organisms. Since 2002, there has been no coordinated approach to biosecurity targeted against IAS on the island of Ireland, a consequence of which has been the continued introduction and spread of IAS on the island. Coordinated and informed biosecurity against IAS that are already present in Ireland and those identified horizon scan species determined during the current study is paramount if biodiversity, human health and the economy are to be protected. Best practice as operated in New Zealand and Australia must be adopted and implemented here if we are to stop the IAS on the horizon scan list from gaining entry to the island of Ireland.

In terms of the changing political landscape, new UK IAS legislation has been prepared in advance of Britain's exit from the EU. This legislation is fully in line with the EU IAS regulation (EU 2014) and provides a degree of legal assurance. However, there are new shipping routes opening (e.g. a new freight shipping route from Waterford to Rotterdam opened in July 2019, described as a new pathway between Ireland and the continent), which "could help exporters post-Brexit". Such new routes could open further pathways, allowing freshwater, marine and terrestrial invaders identified in this horizon scan (among others) to be introduced to and spread throughout the island of Ireland.

Conclusion

This horizon scan provides an important tool for IAS management on the island of Ireland. Biosecurity efforts can be efficiently targeted to prevent the introduction and spread of these listed IAS species in both jurisdictions, maximising the resources available. The list also provides a focus for education and outreach programmes for communities and citizen science. Four of the species predicted to arrive, establish and spread in the next ten years are included in the EU IAS Regulation. As the process of identifying the 40 top IAS in this all-Ireland horizon scanning exercise was the consensual decision of experts throughout the island, it is recommended that it is used as a resource for subsequent risk assessments and for prioritisation of IAS management in both Northern Ireland and in the Republic of Ireland.

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Supplementary material

The following supplementary material is available for this article:

Table S1. Terrestrial species considered in session by expert group.
Table S2. Freshwater species considered in session by expert group.
Table S3. Marine species considered in session by expert group.
Appendix 1. Top Ten Species Profiles.

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