May 2019

Comprehensive analysis of pathways of unintentional introduction and spread of invasive alien species – report of the UK

Summary

- Article 13 of EU regulation 1143/2014 requires Member States to carry out a comprehensive analysis of the pathways of unintentional introduction and spread of invasive alien species of Union concern (at least) in their territory. This report provides the results of the UK's analyses.
- An analysis based solely on the 49 species listed as being of Union concern was considered unlikely to be comprehensive. A more substantial analysis was therefore undertaken, using all established non-native species in Great Britain (n=1954). However, to ensure the 49 species of Union concern were also considered a separate analysis based on these species was undertaken and used to inform the final identification of 'priority pathways'.
- Several methods for identifying priority pathways were tested based on the numbers of species introduced by each pathway, their impact, changes in pathways over time and differing levels of confidence associated with each pathway. From this a final approach was chosen, with pathways ranked based on the intermediate impact of species introduced since 1950 (to ensure analysis focussed on recently active pathways). Those pathways responsible for the majority of impact were identified as potential priorities.
- In total, 36 pathways of introduction were identified with eight unintentional pathways (including escape pathways) prioritised based on the analysis of GB established species and a further two prioritised based on the analysis of species of Union concern. These were: (1) hull fouling, (2) horticulture escapes, (3) contaminants of ornamental plants, (4) ballast water, (5) stowaways on fishing equipment, (6) other stowaways, (7) contaminants of aquaculture animals, (8) ornamental escapes (from wildlife collections), (9) pet escapes and (10) zoo or botanic garden escapes.
- While this prioritisation reduced the long list of 36 pathways to a more manageable list of 10, there were still too many to manage in the first tranche of pathway action plans, given limited resources in the UK. As a result the top 5 pathways were considered initial priorities: (1) hull fouling, (2) horticulture escapes, (3) contaminants of ornamental plants, (4) ballast water, (5) stowaways on fishing equipment. For pragmatic reasons the pathway 'zoo and botanic garden escapes' was included as a sixth priority, given that a pathway action plan for zoos and aquaria was already in place in 2016 (before the Union list was adopted).
- This analysis only considered the potential risk posed by pathways; however, the feasibility of managing pathways (i.e. reducing risk) has not yet been taken into account. This should be considered to help identify where management effort would have most effect. While this analysis used invasive alien species that have established in GB and species of Union concern to inform prioritisation, it could be extended to consider species identified by horizon scanning. Indeed, Great Britain's horizon scanning exercise will be repeated in 2019 and could be used to further inform pathway priorities.

Contents

1. Introduction

With numbers of invasive non-native species increasing globally, preventing introductions by managing pathways is a priority (CBD, 2014a, Lodge et al., 2016) and one of the most cost-effective forms of management (Davies and Sheley, 2007, Pyšek and Richardson, 2010, Brancatelli and Zalba, 2018, Hulme et al., 2018). However, there are large numbers of diverse pathways and their management can be expensive and complex (Hulme, 2009, Essl et al., 2015, Saul et al., 2017). With limited resources, pathway management must therefore be prioritised (Mack et al., 2000, Hulme, 2009, Hulme, 2015, Lodge et al., 2016, McGeoch et al., 2016). Ideally such prioritisation should focus on those pathways likely to do the most harm (i.e. introduce the most species that cause serious impacts) and for which risk reduction will be cost-effective (CBD, 2014b, Essl et al., 2015, Cassey et al., 2018b).

In the EU, regulation 1143/2014 aims to prevent or manage the introduction and spread of invasive alien species. Provisions for pathway management are divided between two articles, with intentional introductions primarily addressed by Article 7 and unintentional introductions addressed by Article 13. Article 13 (1) requires Member States to carry out a comprehensive analysis of the pathways of unintentional introduction and spread of invasive alien species of Union concern at least in their territory, as well as in their marine waters, and identify the pathways which require priority action ('priority pathways') because of the volume of species or of the potential damage caused by the species entering the Union through those pathways. This report provides the results of the UK’s analysis.

To facilitate analysis it is first necessary to define the scope of the requirement. Article 13 (1) specifies that analysis should include only unintentional introduction pathways; however, the distinction between intentional and unintentional pathways in not always clear (Hulme, 2009, Working Group on Invasive Alien Species, 2018). For example, the ‘escape’ pathway includes species that are intentionally imported into a Member State, but which escape confinement unintentionally. Indeed, official guidance differs on which pathways to consider intentional and unintentional (e.g. Harrower et al. (2018) state that only ‘contaminant’ and ‘stowaway’ are unintentional pathways, whereas the Commission’s reporting guidance http://cdr.eionet.europa.eu/help/ias_regulation/material/IAS-guidelines indicates that only ‘release in nature’ is considered intentional). To avoid confusion and ensure this analysis is comprehensive, all pathways were included regardless of intent. However, in the identification of ‘priority pathways’ only escape, contaminant and stowaway pathways are considered (*sensu* Hulme (2009)). In addition, Article 13 (1) makes reference to pathways of *introduction and spread* in the territory, but requires that ‘priority pathways’ are identified based on … species *entering the Union* through those pathways. This analysis therefore focusses on pathways that have the potential to introduce species to the UK or allow spread between Member States within the European Union.

Comprehensive pathway analysis should include, at least, species of Union concern. However, the current list of species of Union concern is ad-hoc and does not represent the wide range of pathways that pose a potential threat to the UK, or indeed the European Union (Working Group on Invasive Alien Species, 2018). It is particularly lacking species for which the primary pathway of introduction is as a contaminant or stowaway (e.g. marine species), which are arguably the main pathways of *unintentional* introduction. To ensure this analysis was comprehensive, a broader approach has therefore been taken that assesses the threat from a far wider range of introduction pathways. To do this, analysis was based on pathways that have introduced all of the established non-native species in Great Britain since 1950 (data on all established non-native species was available; however, the 1950 cut off point was used to ensure only recently active pathways were considered). Given that the EU regulation requires species of Union concern to be taken into account as a minimum, a separate analysis was also conducted for this group of species, including the 37 species initially listed by Commission Implementing Regulation 2016/1141 as well as the 12 species subsequently listed by Commission Implementing Regulation 2017/1263. Both analyses were used to inform the identification of 'priority pathways' for the UK.

This report provides the results of both separate analyses and the conclusions of both to inform the final selection of 'priority pathways'. It does not report on the development of subsequent pathway action plans. Each separate analysis is provided in full as annexes, with summarised methods, results and conclusions provided below.

2. Methods

2.1. Pathway analysis using all established non-native species in Great Britain

[note: detailed methods are provided in Annex 1 and only summarised here]

Introduction pathway data were extracted from the Non-native Species Information Portal (NNSIP) for all established non-native species in Great Britain (excluding parasites, parasitoides, fungi and microorganisms, for which comprehensive data was lacking) (n=1954). Expert judgement (involving 36 experts) was used to score each of these species (from minimal to massive) according to its biodiversity impact, following a similar elicitation method to that used by Roy et al. (2014a).

A number of different methods for ranking pathways were tested. This included methods based on counts of non-native species alone, counts of only those species considered invasive, scores of pathway impact based on the individual impact of each introduced species, different levels of uncertainty associated with each pathway and temporal changes in pathway activity. From these, a final prioritisation method was chosen that ranked pathways based on the total impact of species introduced by the pathway since 1950. In this way pathways were ranked based on their recent impact, rather than simply by the number of species introduced.

In many cases multiple introduction pathways were listed for individual species, indicating uncertainty over which was the original introduction pathway. In these cases, the impact score for that species was divided equally between pathways (described as the intermediate impact score). However, a minimum impact score (i.e. based only on species exclusively introduced by that pathway) and maximum impact score (i.e. based on all possible species introduced by the pathway) were also calculated for each pathway to indicate a range of possible impact values. Priority pathways were determined by ordering pathways based on their intermediate impact score. An arbitrary cut-off point, indicating 90% of species' impact was used to indicate a subset of pathways that could be considered 'priority pathways'.

2.2. Pathway analysis using only species of Union concern

[note: detailed methods are provided in Annex 1 and only summarised here]

Introduction pathway data was extracted for all 49 species of Union concern from risk assessments published by the European Commission. All of these species were considered likely to cause serious impacts in the EU and so no attempt was made to differentiate them based on impact. Analysis was therefore based on a count of species per pathway. A minimum, intermediate and maximum count of species per pathway was determined, based on the number of pathways associated with each species. Potential cut-off points were indicated for this analysis, based on 90% and 75% of species.

2.3. Combining analyses

The analysis based on established GB species was used to indicate the main priority pathways of unintentional introduction, given that this analysis was considered the more comprehensive and included a wider range of contaminant and stowaway pathways. This was cross-referenced with the top pathways identified by the analysis of species of Union concern, with the highest ranking pathways added to the list of 'priority pathways' if they were not already included.

2.4. Pathway terminology

In some cases the pathway terminology used here differs slightly from that used in the CBD classification. Horticultural escape here includes garden plants that have escaped into the wild (this is 'ornamental purpose other than horticulture' in the CBD classification. Ornamental escapes (collections) here refers to animal escapes from private collections and waterfowl collections (this is part of part of the pet / aquarium / terrarium pathway in the CBD classification). The CBD pathways 'contaminant of plants' and 'contaminant of animals' have both been subdivided here into more detailed pathways (i.e. contaminants of plants in agriculture, aquaculture, forestry or for ornamental use; contaminants of animals for agriculture, aquaculture or fish stocking)

3. Results

[note: detailed results of each separate analysis are provided in Annex 1 and Annex 2]

Analysis of GB non-native species established since 1950 identified 33 different pathways (Fig 1). Three of these caused particularly large impacts (based on intermediate impact scores): (1) hull fouling, (2) horticulture escapes and (3) contaminants of ornamental plants. Adding the next five ranked pathways ((4) ballast water, (5) stowaways on fishing equipment, (6) other stowaways, (7) contaminants of aquaculture animals, (8) ornamental escapes (from wildlife collections)) accounted for just over 90% of impact. Error bars indicated high confidence in species associated with some pathways (e.g. horticultural escapes and contaminants of ornamental plants), but considerable uncertainty in others (e.g. hull fouling). In particular, there was generally a high level of uncertainty in pathways for aquatic invertebrates (Annex 1).

Analysis based only on species of Union concern identified 28 different pathways (Fig 2). Two of these introduced by far the largest proportions of species (horticultural and pet escapes). However, the importance of other pathways was less clear, with relatively small numbers of species associated with each and overlapping error bars indicating potentially interchangeable rank positions.

With both analyses combined a total of 36 pathways were identified (Table 1). The eight pathways identified by the analysis of GB established species (above) were also associated with 39% of the species of Union concern. Pet escapes were not identified as a priority pathway by the GB analysis, but was one of the largest pathways for species of Union concern along with horticultural escapes. Adding this pathway to the eight priority pathways identified by the GB analysis would increase coverage of species of Union concern to 59%. Adding zoo escapes would increase this further to 67% and contaminants of nursey material to 74%.

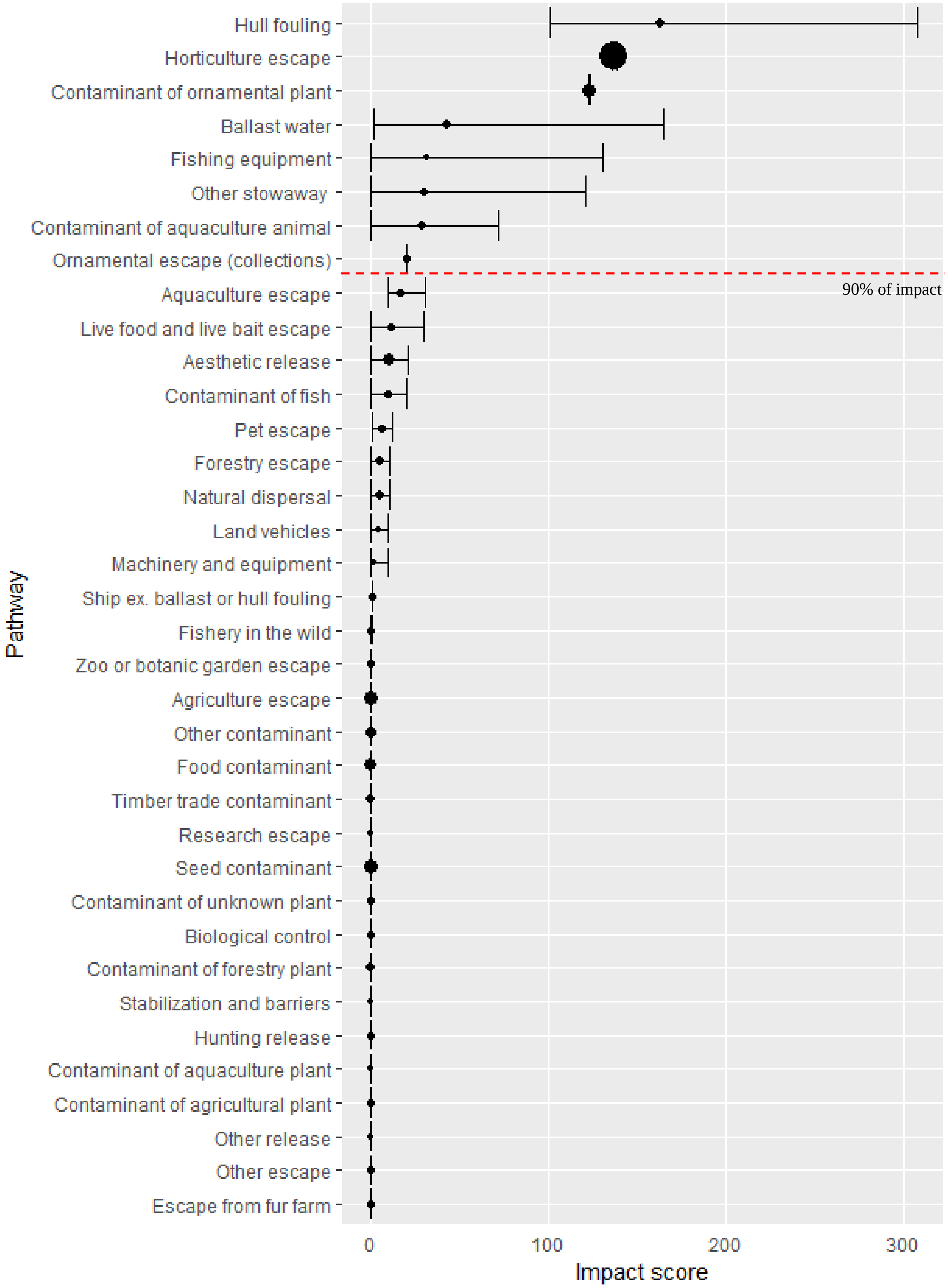


Figure 1. Pathway ranks using weighted impact scores for all established non-native species in GB. Point size indicates total number of species introduced since 1950, while position of points with error bars indicates the sum of impact values for the minimum, intermediate and maximum number of species introduced by each pathway since 1950. Pathways are ordered from top to bottom based on intermediate count. Those above the dashed red line are associated with more than 90% of impact (based on weighted pathway score).

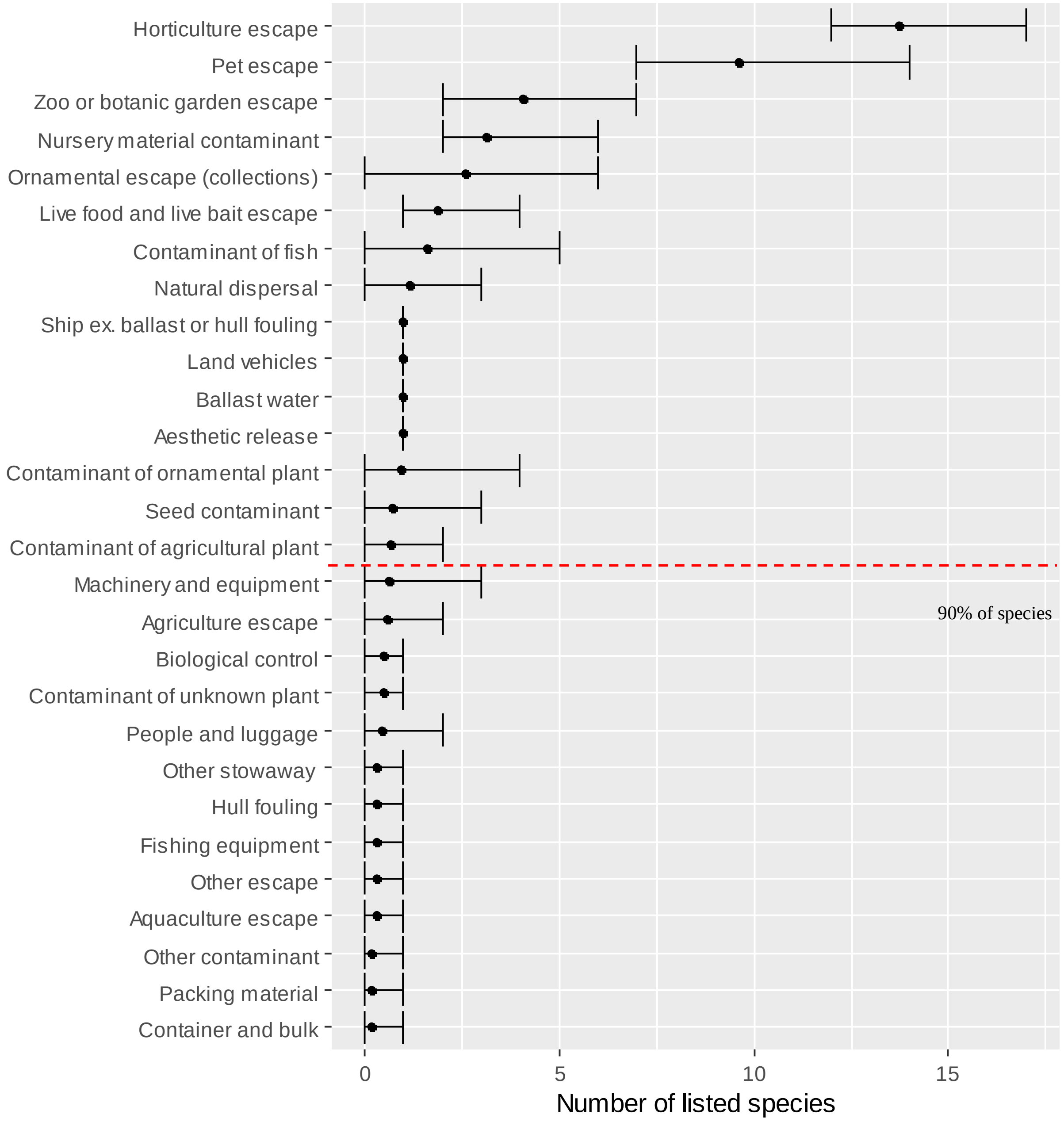


Figure 2. Pathway ranks based on introduction pathways of the 49 Union concern species. Point position is based on the intermediate count, with error bars showing minimum and maximum count of species per pathway. Pathways are ordered from top to bottom based on intermediate count. Pathways above the dashed red line are associated with more than 90% of all species included in the study (using intermediate count).

Table 1. Pathways of introduction of GB established non-native species and species of Union concern. Pathways are ordered according to the impact scores calculated by the analysis of all established species in GB. Pathways in **bold** are those considered 'priority pathways' based on scores from both the GB analysis and analysis based on species of Union concern. In all cases the intermediate number (or impact) of species is given for each pathway, followed by the minimum and maximum figures in brackets. Impact score = sum of impact scores for all species introduced by pathway. No. NNS = total number of species introduced by pathway. No. IAS = total number of species with more than minimal impacts. No. SoUC = number of species of Union concern potentially introduced by the pathway. An example species for each pathway is given.

Rank	Pathway	Example species*	Impact score	No. NNS	No. IAS	No. SoUC
1	**Hull fouling**	***Didemnum vexillum***	**163.5 (101-307.2)**	**17.1 (5-36)**	**8.2 (2-19)**	**0.33 (0-1)**
2	**Horticulture escape**	***Heracleum mantegazzianum***	**138.2 (136.8-139.6)**	**317.4 (284-352)**	**20.5 (19-22)**	**13.75 (12-17)**
3	**Contaminant of ornamental plant**	***Thaumetopoea processionea***	**123.3 (122.7-123.8)**	**73 (65-81)**	**6.5 (6-7)**	**0.95 (0-4)**
4	**Ballast water**	***Caprella mutica***	**43.2 (2-165.2)**	**13.2 (5-28)**	**4.8 (2-12)**	**1 (1-1)**
5	**Fishing equipment**	***Dikerogammarus villosus***	**31.9 (0-131)**	**1.2 (0-5)**	**1.2 (0-5)**	**0.33 (0-1)**
6	**Other stowaway**	***Potamopyrgus antipodarum***	**30.2 (0-121)**	**1 (0-4)**	**1 (0-4)**	**0.33 (0-1)**
7	**Contaminant of aquaculture animal**	***Crepidula fornicate***	**29.2 (0-72.2)**	**7.2 (1-17)**	**4 (0-10)**	**none**
8	**Ornamental escape (collections)**	***Oxyura jamaicensis***	**20.1 (20.1-20.1)**	**4 (4-4)**	**3 (3-3)**	**1.58 (0-4)**
9	Aquaculture escape	*Oncorhynchus mykiss*	17.2 (10-31)	3.7 (2-6)	2.2 (1-4)	0.33 (0-1)
10	Live food and live bait escape	*Astacus leptodactylus*	11.7 (0-30)	2.5 (1-5)	1.2 (0-3)	1.87 (1-4)
11	Aesthetic release	*Lacerta bilineata*	10.9 (0-21.7)	29.2 (1-59)	2.3 (0-5)	1 (1-1)
12	Contaminant of fish	*Pseudorasbora parva*	10 (0-20.1)	1.3 (0-3)	1.3 (0-3)	1.62 (0-5)
13	**Pet escape**	***Psittacula krameri***	**6.6 (1-12.3)**	**6.2 (4-9)**	**3.2 (1-6)**	**9.62 (7-14)**
14	Forestry escape	*Acer pseudoplatanus*	5.6 (0-11.2)	9.9 (4-17)	1 (0-2)	none
15	Natural dispersal	*Harmonia axyridis*	5.5 (0.1-11.2)	18.5 (11-27)	0.8 (0-2)	1.17 (0-3)
16	Land vehicles	*Meconema meridionale*	5 (0-10)	1 (0-2)	0.5 (0-1)	1 (1-1)
17	Machinery and equipment	*Rangia cuneata*	1.7 (0-10)	1.5 (1-3)	0.2 (0-1)	0.65 (0-3)
18	Ship ex. ballast or hull fouling	*Rattus norvegicus*	1 (1-1)	2.5 (2-3)	1 (1-1)	1 (1-1)
19	Fishery in the wild	*Crassostrea gigas*	0.5 (0-1)	1 (0-2)	0.5 (0-1)	none
20	**Zoo or botanic garden escape**	***Hystrix brachyura***	**0.2 (0.2-0.2)**	**3 (3-3)**	**2 (2-2)**	**4.08 (2-7)**
21	Agriculture escape	*Aegopodium podagraria*	0.1 (0-0.1)	7.5 (4-11)	0	0.58 (0-2)
22	Food contaminant	*Blatta orientalis*	0.1 (0-0.1)	7.5 (5-10)	0	none
23	Other contaminant	*Acaena novae-zelandiae*	0.1 (0-0.1)	2 (1-3)	0.5 (0-1)	0.2 (0-1)
24	Timber trade contaminant	*Ips cembrae*	0.1 (0-0.1)	5.5 (5-6)	0	none

25	Research escape	*Xenopus laevis*	0 (0-0.1)	1.3 (1-2)	0.3 (0-1)	none
26	Seed contaminant	*Ambrosia artemisiifolia*	0 (0-0.1)	4.5 (2-7)	0	0.7 (0-3)
27	Contaminant of unknown plant	*Pineus strobi*	0 (0-0)	3 (3-3)	0	0.5 (0-1)
28	Biological control	*Laricobius erichsonii*	0 (0-0)	3 (3-3)	0	0.5 (0-1)
29	Contaminant of forestry plant	*Pristiphora erichsonii*	0 (0-0)	2 (2-2)	0	none
30	Hunting release	*Phasianus colchicus*	0 (0-0)	0.5 (0-1)	0	none
31	Stabilization and barriers	*Carpobrotus edulis*	0 (0-0)	0.8 (0-2)	0	none
32	Contaminant of agricultural plant	*Lehmannia valentiana*	0 (0-0)	0.5 (0-1)	0	0.67 (0-2)
33	Contaminant of aquaculture plant	*Neodexiospira brasiliensis*	0 (0-0)	0.5 (0-1)	0	none
34	Nursery material contaminant	*Persicaria perfoliata*	0 (0-0)	0 (0-0)	0	3.12 (2-6)
35	Container and bulk	*Vespa velutina nigrithorax*	0 (0-0)	0 (0-0)	0	0.17 (0-1)
36	Packing material	*Vespa velutina nigrithorax*	0 (0-0)	0 (0-0)	0	0.17 (0-1)

* note that species given as examples may be associated with more than one pathway, for example four possible introduction pathways are listed for *Dikerogammarus villosus*.

4. Discussion

Based on this analysis it is recommended that the following pathways should be considered ‘priority pathways’ in the UK: (1) hull fouling, (2) horticulture escapes, (3) contaminants of ornamental plants, (4) ballast water, (5) stowaways on fishing equipment, (6) other stowaways, (7) contaminants of aquaculture animals, (8) ornamental escapes (from wildlife collections), (9) pet escapes and (10) zoo or botanic garden escapes. While listed as ten separate pathways here (following CBD classification) it may be useful to consider grouping or separating some of these for the purposes of action planning. For example, hull fouling could be separated based on vessels used in freshwater or marine environments, given that mitigation of these may differ.

This short-list represents those pathways that have been found to cause the greatest impact in GB since 1950 (based on the numbers of species introduction and categorical impact scores based on expert judgement) as well as two other pathways that appear to be particularly important for the introduction of species of Union concern. While the cut-off point for this short-list is somewhat arbitrary, it provides a pragmatic list for which effective pathway management should prevent a substantial proportion of future impacts. However, it does not preclude the management of other pathways as needed and this analysis provides useful information on their likely relative risk.

There are a number of limitations to this analysis. Only the risk posed by pathways was considered; however, given the complexities and costs involved it may be more feasible to reduce this risk more for some pathways and less for others. The feasibility of management has not been taken into account in this analysis and could be considered for the future. Such an approach could consider the effectiveness, practicality, cost, negative consequences and degree of acceptance of different pathway management strategies (similar to Booy et al. (2017)).

While this analysis used invasive alien species that have established in GB since 1950 and species of Union concern to inform prioritisation, it could be extended to consider species identified by horizon scanning. Great Britain will be repeating its horizon scanning exercise in 2019. The results of this process could be added to this analysis to consider whether key additional pathways need to be considered.

Annex 1. Comprehensive analysis of introduction pathways of all established non-native species in Great Britain

1. Introduction

The invasion process can be defined as a series of barriers that a species must overcome in order to enter, establish, spread and cause impacts in a new area (Blackburn et al., 2011). An introduction pathway is the means by which a species overcomes the first of these barriers (i.e. 'geography' and 'captivity or cultivation') and arrives in the environment in a new location as a result of human mediation (Essl et al., 2015). It can therefore be broadly defined as "any means that allows the entry" of a species (FAO 2007) encompassing a wide range of activities, routes and vectors (CBD, 2014a) including intentional and unintentional introduction as diverse as contaminants arriving attached to artificial marine debris (Therriault et al., 2018), plants escaping from gardens (Dehnen-Schmutz and Touza, 2008), animals released as part of religious practices (Everard et al., 2019) and quarry introduced for hunting (Scanes, 2018).

There are many different non-native species pathways, with the number, diversity and intensity in any given region linked to the diversity of its trade, travel and transport (Hulme, 2009, Essl et al., 2015, Seebens et al., 2015, van Kleunen et al., 2015). Pathways differ not only in the types of activities and vectors involved, but also the scale at which they operate, the routes that they take, the environments in which they move and the taxa that they introduce (e.g. Hulme et al., 2008, Copp et al., 2010, van Kleunen et al., 2015, Turbelin et al., 2017). This ultimately means that introduction pathways vary considerably in terms of their potential to introduce harmful invasive non-native species (Wilson et al., 2009, Pysek et al., 2011, Pergl et al., 2017, Saul et al., 2017).

With numbers of invasive non-native species increasing globally, preventing introductions by managing pathways is a priority (CBD, 2014a, Lodge et al., 2016) and one of the most cost-effective forms of management (Davies and Sheley, 2007, Pyšek and Richardson, 2010, Brancatelli and Zalba, 2018, Hulme et al., 2018). This has been demonstrated theoretically (e.g. Leung et al., 2014) and practically for a number of specific measures (Lodge et al., 2016), although evidence of the effectiveness of prevention can be limited by the availability of consistently collated data (Essl et al., 2015). Examples of the effectiveness of prevention include that of New Zealand where, after the introduction of stringent biosecurity legislation, the number of non-native mammal introductions reduced dramatically (Armon and Zenetos, 2015). Similarly, in Europe the introduction of pathway management measures appears to have resulted in a decline in the incident of new introductions through aquaculture (Katsanevakis et al., 2013a).

Managing introduction pathways can be complicated and expensive. For example, complex negotiations over 25 years have been required to bring the ballast water convention into force (IMO, 2004) and this is expected to require as many as 75,000 vessels to install ballast water management systems costing an estimated $640,000-$947,000 (USD) per vessel (David and Gollasch, 2015). With limited resources (Chapter 2), large numbers of pathways, high costs and considerable complexity, the management of introduction pathways must therefore be carefully prioritised (Mack et al., 2000, Hulme, 2009, Hulme, 2015, Lodge et al., 2016, McGeoch et al., 2016). This prioritisation must focus on those pathways likely to do the most harm (i.e. introduce the most species that cause serious impacts) and for which risk reduction is likely to be cost-effective (CBD, 2014b, Essl et al., 2015, Cassey et al., 2018b).

In order to prioritise introduction pathways for management it is first necessary to classify them (Hulme et al., 2008), ideally using consistent terminology to allow for comparative analysis across databases and other sources of relevant information (Harrower et al., 2018). A number of different classification schemes have been developed (e.g. those used by UCN/ISSG GISD, CABI ISC, DAISIE, NNSIP and NOBANIS, discussed in the report of the Working Group on Invasive Alien Species (2018)). However, recent efforts have been made to adopt a single classification under the auspices of the Convention on Biological Diversity (CBD, 2014a), to which many major non-native species databases have been mapped (Saul et al., 2017, Tsiamis et al., 2017, Pagad et al., 2018). An advantage of this classification is that it utilises a hierarchy of pathways (following Hulme et al., 2008), which allows for analysis at different levels, starting with intentional and unintentional; then release, escape, contaminant, stowaway, corridor and unaided; before separating pathways into more detailed lower sub-categories (CBD, 2014a). It has also recently been accompanied by comprehensive guidance in an attempt to ensure pathways are clearly defined and easy to consistently apply (Harrower et al., 2018).

Guidance for the prioritisation of pathways suggests criteria to take into account (CBD, 2014b, Essl et al., 2015). However, methods to support prioritisation are still at an early stage of development and yet to be broadly agreed (McGeoch et al., 2016). Different approaches have been used, for example based on an analysis of the volume, intensity and frequency of vectors that transport propagules (i.e. vector analysis and pathway risk analysis; Carlton and Ruiz, 2005, Copp et al., 2010, Leung et al., 2014, Lodge et al., 2016, Brancatelli and Zalba, 2018) or modelling approaches that incorporate proxies for propagule pressure (e.g. Bradie et al., 2015). However, one of the most common methods is to rank pathways based on numbers of past introductions (e.g. CBD, 2014a, Essl et al., 2015, Nunes et al., 2015, McGeoch et al., 2016, Zieritz et al., 2016, Saul et al., 2017).

Past introductions can be used to rank or assess pathways based on numbers of all non-native species (Katsanevakis et al., 2013b, CBD, 2014b, Nunes et al., 2014, Roy et al., 2014b, Turbelin et al., 2017); however, this does not take into account the very large differences in impact between species (e.g. Kumschick et al., 2015). To do this a more limited number of studies have incorporated measures of species impact (McGeoch et al., 2016), usually based on the number of species introduced by pathways considered to be invasive (NOBANIS, 2015, Nunes et al., 2015, e.g. Saul et al., 2017). More comprehensive cross-taxa assessments of pathway impact are complicated because they require methods for comparing differing impact levels across taxa (Essl et al., 2015) and have rarely been completed (but see Madsen et al. (2014)). Indeed, Saul et al. (2017) stress the need for more rigorous assessments of impact to support pathway prioritisation. In addition to species impact, other variables may have an important effect on pathway ranking (Essl et al., 2015). For example, considerable uncertainty around which pathways introduced species could affect ranking (Scalera and Genovesi, 2016). Temporal changes in pathways may also have an important affect, given that the activity of pathways can change considerably through time (e.g. Faulkner et al., 2016, Zieritz et al., 2016, García-Díaz et al., 2018).

While some pathway ranking methods are more detailed than others, further work is required to develop comprehensive pathway ranking methods that incorporate species impacts, pathway uncertainty and temporal change (Essl et al., 2015). However, it is not clear whether such methods would improve upon more straightforward methods already developed. Given that different methods may be more or less practical to apply, but could have a substantial effect on the ranking of pathways and ultimately the prioritisation of management, it is important to investigate the differences, advantages and disadvantages of each approach. To do this a dataset is required that includes comprehensive information about non-native species, their impacts and other variables that may be of importance (such as year of introduction, continent of native origin and environmental information).

In Great Britain (GB), the Non-Native Species Information Portal (NNSIP) provides a comprehensive dataset of non-native species information, including introduction pathway (Roy et al., 2014b). To these has recently been added comprehensive environmental (biodiversity) impact scores for all established non-native species (Chapter 2). This provides a novel dataset with which to test different pathway ranking methods and explore the extent to which different methods result in different ranks. Pathways in the NNSIP database do not follow those of the CBD classification and so need to be mapped in order to provide consistency, in line with international initiatives. This therefore provides an opportunity to consider the practicalities of mapping the CBD classification to pathways at a national scale (one of the first national applications since adoption of the classification) and its use in supporting the prioritisation of pathway management in GB.

The main aim of this study is therefore to consider the implications of applying different pathway ranking methods to inform management, using GB as a case study. In doing so, a range of ranking methods will be developed and tested, including a comprehensive approach that incorporates cross-taxa impact assessment, pathway uncertainty and temporal change. The implications for pathway management in GB will be explored, as well as the practicalities of using the CBD classification at a national scale.

2. Methods

2.1. Mapping NNSIP and CBD pathways

NNSIP data were extracted (December 2015) for all established non-native species in GB (excluding microorganisms, parasites, parasitoids and fungi), providing for each species: taxonomic information, environmental group, continent of native origin, year of first record in the wild, introduction pathway and notes describing the introduction pathway for the majority of species. Recently added environmental (biodiversity) impact scores (Chapter 2) were also extracted, providing a maximum impact score for each species using a five-point categorical scale (minimal, minor, moderate, major and massive) designed to reflect impact at increasing levels of ecological organisation (from individuals to communities) (Chapter 2). NNSIP pathways were mapped to the CBD classification automatically where possible (coded in R) and manually where not (Fig 1.1). Automatic mapping was used where NNSIP pathways were the same as CBD pathways (e.g. NNSIP release biocontrol = CBD release biological control). In some cases pathways were not synonymous, but could be mapped directly using a series of rules based on the NNSIP pathway combined with taxonomic or environmental information (see supporting information, Appendix C). The large majority of species mapped in this way were correctly classified; however, a minority were not. All were therefore checked and manually corrected if necessary.

In some cases there was no direct match between an NNSIP and CBD pathway (e.g. the NNSIP ‘stowaway marine’ was split between seven CBD pathways: ‘fishing equipment’, ‘ship excluding ballast or hull’, ‘machinery and equipment’, ‘ballast water’, ‘hull fouling’ and ‘other’) (Fig 1.1). In these cases the NNSIP ‘notes’ field was reviewed and used to manually determine the most appropriate CBD pathway. This was straightforward in most cases, but where notes were lacking, further research using major databases (i.e. GISD, DAISIE, CABI ISC, NNSS portal) and the primary literature was carried out to determine the appropriate pathway(s).

To support analysis, each pathway was codified (Table 1.1). The first letter of this code indicated the broad pathway (i.e. release, escape, contaminant, stowaway, unaided), followed by three or four letters indicating the CBD subcategory. Where an additional level of detail was added (i.e. to ‘contaminants of plants’ and ‘contaminants of animals’), this was provided by adding an additional three or four letters after the subcategory.

Only the original pathway of introduction for each species was used; pathways of subsequent introduction and / or spread were excluded. Where the original pathway of introduction was unclear (i.e. it could have been one of multiple pathways) all possible introduction pathways were recorded for that species.

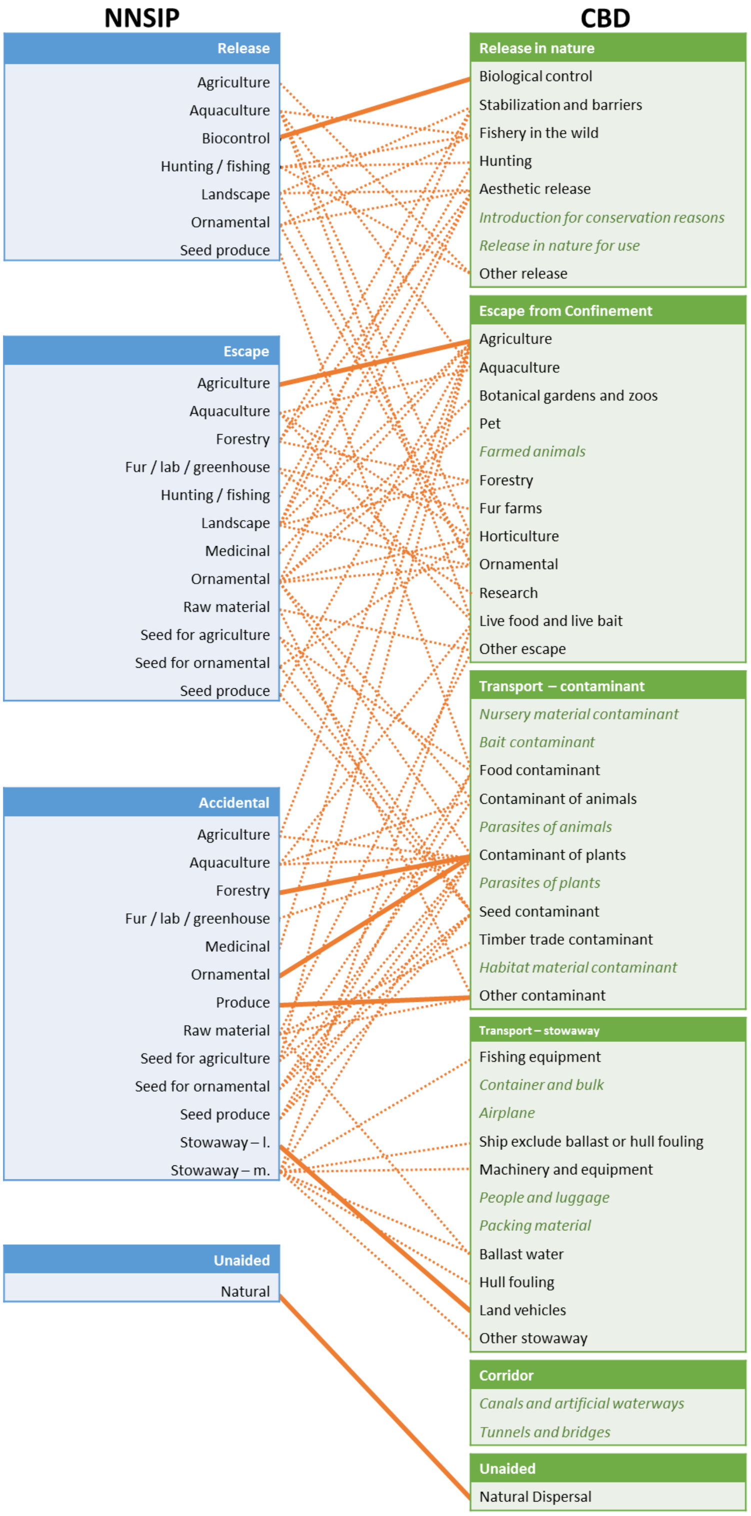


Figure 1.3 Alignment of pathways within the NNSIP and CBD classification schemes, based on pathways assigned within the NNSIP database to established non-native species in GB. Thick lines represent NNSIP pathways which align with a single CBD pathway. Thin dotted lines represent pathways that correspond to multiple CBD pathways. NNSIP pathways follow those of Roy et al. (2014b) CBD pathways follow those modified by the recommendations of Harrower et al. (2018). CBD pathways in italics were those not represented in the NNSIP database.

Table 1.2 Pathway codes used in this study and the pathways to which they relate. Pathways are organised into a three level hierarchy (intent, broad pathway and subcategory). They follow the CBD classification as modified by (Harrower et al., 2018) except for contaminant of animals and contaminant of plants which were further divided by sector (using sectors already defined for escape pathways). Only pathways active in GB are included in this table.

Intent	**Broad pathway**	**Pathway sub-category**	**Code**
INTENTIONAL	RELEASE	Biological control	R_BIO
		Stabilization and barriers	R_STAB
		Fishery in the wild	R_FHRY
		Hunting	R_HUNT
		Aesthetic release	R_AES
		Other release	R_OTR
	ESCAPE	Agriculture	E_AGRI
		Aquaculture	E_AQC
		Botanical gardens and zoos	E_ZOB
		Pet	E_PET
		Forestry	E_FOR
		Fur farms	E_FUR
		Horticulture	E_HORT
		Ornamental	E_ORN
		Research	E_RES
		Live food and live bait	E_LFB
		Other escape	E_OTR
UNINTENTIONAL	CONTAMINANT	Food contaminant	C_FOOD
		Contaminant of animals	C_ANI_AGRI, C_ANI_AQC, C_ANI_FISH, C_ANI_UNK
		Contaminant of plants	C_PLT_AGRI, C_PLT_AQC, C_PLT_FOR, C_PLT_ORN, C_PLT_UNK
		Seed contaminant	C_SEED
		Timber trade contaminant	C_TMBR
		Other contaminant	C_OTR
	STOWAWAY	Fishing equipment	S_ANG
		Ship ex. ballast or hull fouling	S_SHH
		Machinery and equipment	S_EQUIP
		Ballast water	S_BALL
		Hull fouling	S_HULL
		Land vehicles	S_LVEH
		Other stowaway	S_OTR
UNAIDED		Natural dispersal	U_NAT

2.2. Developing pathway scoring methods to support ranking

To compare methods for ranking pathways it was first necessary to score pathways. This was done using a range of different scoring methods that incorporated counts of species, impact, uncertainty and temporal change, each of which is described below and in Box 1.1.

Species count (Method 1)

This method (Method 1) scored pathways based on the total number of all possible non-native species recorded as being associated with each pathway (Box 1.1). This represented the maximum number of species recorded as being associated with each pathway and is therefore the same as Method 3c (see 'incorporating uncertainty' below).

Incorporating impact (Methods 2a and 2b)

Two different methods for incorporating impact into pathway scoring were used, based on categorical impact scores held by the NNSIP. The first (Method 2a) used a similar approach to Method 1, but counted only those species considered to be invasive (i.e. those that scored more than 'minimal' impact). The second method (Method 2b) converted the categorical impact score of all species into a value using a logarithmic scale (minimal = 0.01, minor = 0.1, moderate = 1, major = 10, massive =100). This logarithmic scale was used as it was considered to most closely reflect the increasing levels of ecological organisation used by the categorical impact scores (e.g. i.e. minor impacts affected individuals whereas moderate impacts affected populations etc.). Pathways were then scored based on the sum of species impact values for each pathway (Box 1.1).

Incorporating uncertainty (Methods 3a, 3b and 3c)

Where the original pathway of introduction for a species was known with confidence, only a single pathway was listed for that species (because only one pathway could be the original introduction pathway). However, in some cases multiple pathways of introduction were listed because the original was uncertain. The minimum (Method 3a) number of species likely to have been introduced by a pathway was therefore determined by counting only those species for which a single pathway was given. Conversely, the maximum (Method 3c) number of species potentially introduced by a pathway was calculated by counting all species associated with the pathway, regardless of whether other pathways were also listed. This was therefore the same as Method 1. An intermediate (Method 3b) number of species introduced by a pathway was also calculated. This was done by dividing the score for each species evenly between the number of potential introduction pathways associated with it (Box 1.1). For example, if a species could have been introduced by three different pathways, the minimum method would score each pathway '0', the maximum would score each '1' and the intermediate would score each pathway '0.33' for that species. While applied here (Box 1.1) to counts of species (modified from Method 1), it could also be applied to calculate a minimum, intermediate and maximum impact score in combination with Methods 2a and 2b. This is demonstrated, in part, in Method 4 below.

Box 1.1 Scoring methods used to rank pathways. Methods were divided into those that incorporated species count (Method 1), impacts (Methods 2a and 2b), uncertainty (Methods 3a, 3b and 3c), temporal changes (not specifically listed) and a combination of methods (Method 4). All pathways were scored and ranked using each method.

Method 1. Count of all species

Every non-native species associated with a pathway is scored 1 (regardless of the number of other pathways that could have introduced the species). The sum of these scores is calculated for each pathway.

Method 2a. Count of invasive non-native species

Every invasive non-native species (i.e. those that have more than minimal impact) is scored 1. The sum of these scores is calculated for each pathway. Non-native species that have minimal impact are not included.

Method 2b. Sum of impact scores

Every non-native species is allocated an impact value based on its categorical impact score, as follows: minimal = 0.01, minor = 0.1, moderate = 1, major = 10, massive = 100. The sum of these scores is calculated for each pathway.

Method 3a. Minimum count

Every non-native species exclusively associated with a single pathway is scored 1. All other species (i.e. those associated with more than one possible original pathway of introduction) are excluded. The sum of these scores is calculated for each pathway.

Method 3b. Intermediate count

A score of 1 for each non-native species is divided equally between the number of pathways by which it could have been originally introduced. For example, where a species has four possible introduction pathways, each pathway receives a score of 0.25 for that species. The sum of these scores is calculated for each pathway.

Method 3c. Maximum count

This was the same as Method 1 (count method), i.e. all species were counted with a score of 1 regardless of the number of other possible pathways of introduction.

Method 4. Combined methods

This method combines Method 2b, Method 3b and an element of time. To concentrate on recently active pathways, only non-native species introduced since 1950 are included. Each of these species is allocated an impact value based on its categorical impact score (Method 2b), which is then divided equally between possible pathways of original introduction (Method 3b). The sum of these scores is calculated for each pathway.

Incorporating temporal change

To investigate whether pathway ranks changed over time, pathway scores were determined using the count method (Method 1) with species divided into four different 50 year periods (1800-1849, 1850-1899, 1900-1949 and 1950-2000) based on their year of first record in the wild in GB.

Combined methods (Method 4)

To produce a single method (Method 4) that incorporated impact, uncertainty and temporal change a number of methods were combined. Method 2b (sum of impact values) was combined with Method 3b (intermediate number of species) such that the impact value for each species was evenly divided between its potential pathways of introduction (Box 1.1). For example, where two different pathways were listed for a single species that had an impact value of 10, a score of 5 was allocated to each pathway. Temporal change was incorporated by only including species introduced since 1950. This cut off was used so that scoring was based on most recently active pathways.

2.3. Comparing ranks

Pathway scores produced by each method were used to rank pathways in order of importance, highest (rank position = 1) to lowest score; where ties occurred rank was assigned alphabetically by pathway name. The similarity, or difference, between these lists of ranked pathways was then compared using Kendall's tau (b) correlation coefficient. This compared the sequence of ranks in each list and determined the degree of concordance (pathways ranked in the same order) and discordance (pathways ranked in opposite order) between ranks. The correlation statistic was a number between -1 and +1, with numbers closer to -1 indicating strong negative correlation, those closer to +1 indicating strong positive correlation and those closer to 0 indicating no correlation.

The degree to which incorporating impact affected resulting ranks was investigated by comparing ranks produced using Methods 2a and 2b (impact methods) to those produced by Method 1 (count method). Ranks produced by Method 2a and Method 2b were also compared to each other, to investigate whether they produced similar or dissimilar results. The degree to which uncertainty affected the results of ranking was investigated by comparing ranks based on Method 3a (the minimum number of species), Method 3b (intermediate number of species) and Method 3c (maximum number of species – same as Method 1). To investigate the degree to which temporal change affected the results of ranking, ranks based on the count of species in each fifty year period were compared to each other. Finally, ranks produced by Method 1 (count method) were compared to ranks produced by Method 4 (combined methods) to investigate the degree to which incorporating a range of different approaches resulted in ranks that were different to the standard approach of using species count.

To explore which scoring method was likely to produce ranks that better align with the management objective of reducing impact, the cumulative impact of pathways ranked by different scoring methods (Methods 1, 2a, 2b and 4) was compared. Cumulative impact was determined based on the sum of impact values for species established after 1950. It was particularly important that the top ranking pathways reflected management priorities and so the cumulative impact of the top 5 pathways ranked by Method 1 was compared to that of Method 4.

2.4. Displaying uncertainty

Method 4 (combined methods) was used to rank GB pathways for further analysis. This used the sum of impact values for the intermediate number of species introduced after 1950 to rank pathways; however, there was uncertainty around these values. To visualise this the sum of impact values for the minimum and maximum number of species introduced after 1950 was also calculated. These were represented as either a range around the intermediate score (tables), error bars (point plots) or shading (line plots).

All coding was undertaken in R version 3.4.1. (R Core Team, 2017), primarily using the tidyr package (Wickham and Henry, 2018) and rworldmap (South, 2011).

3. Results

3.1. Availability of pathways data

Of the 1954 established non-native species in the GB NNSIP database, at least one possible pathway of original introduction was known for 1710 (88%); while the pathway of introduction was unknown for 168 (9%) and data was unavailable (NIL) for a further 76 (4%). The species with known pathways included a range of broad taxa (plants, n=1336; invertebrates, n=318; and vertebrates, n=56) from different environments (terrestrial, n=1561; freshwater, n=80; marine, n=68; marine and freshwater, n=1) and native origin (Africa, n=75; Asia-Temperate, n=253; Asia-Tropical, n=37; Australasia, 82; Europe, n=753; North America, n=171; Pacific, n=11; South America, n=66; no native origin, n=99; no data, n=163). All species for which the introduction pathway was unknown or unavailable caused minimal impact, these comprised mainly invertebrates (n=182), as well as plants (n=61) and one vertebrate.

Table 1.2 The number of established non-native species in GB associated with each broad CBD pathway category. Where more than one pathway was assigned to a species (because of uncertainty over which was the original introduction pathway) each species / pathway combination was counted, hence the total number of species in this table (n=2497) is more than the total number in the NNSIP database (n=1954). In some cases no pathway way known for the species (unknown), whereas for others pathway data was missing from the NNSIP database (NIL).

Broad pathway category	**Number of species associated with each broad pathway**
Release	194
Escape	1230
Contaminant	640
Stowaway	152
Corridor	0
Unaided	37
Unknown	168
NIL	76
TOTAL	2497

3.2. Ability to map NNSIP pathways to CBD classification

All introduction pathways were mapped to the CBD classification and hierarchy (Fig 1.1). This resulted in 2,497 species / pathway combinations (including NIL and unknown) (Table 1.2), with multiple pathways allocated to some species where the original introduction pathway was uncertain (1 pathway, n=1208 species; 2 pathways, n=379; 3 pathways, n=86; 4 pathways, n=32; 5 pathways, n=4; 6 pathways, n=1). Automatic rules were used to fit 1596 (64%) pathway entries (for 1416 species), of which 281 were manually corrected (for 230 species). The remaining 894 pathway entries (for 538 species) were fitted manually. In two cases CBD pathways were split to provide additional detail. ‘Contaminants of plants’ was divided into five pathways to reflect the purpose of importing the plant (agriculture, aquaculture, forestry, ornamental and unknown). ‘Contaminants of animals’ was divided into four pathways (aquaculture, agriculture, fish imports and other). While in many cases the majority of species within an NNSIP pathway mapped directly to a CBD pathway, it was rare that that the pathways matched exactly. This resulted in many cross links between NNSIP and CBD pathways (Fig 1.1).

In total, established non-native species in GB were introduced by 31 (out of 45) different pathways from the CBD classification. Fourteen pathways were not represented (release: conservation in wild, release in nature for use; escape: farmed animals; contaminant: nursery material contaminant, bait contaminant, parasites on animals, parasites on plants, habitat material contaminant; stowaway: container and bulk cargo, airplane, packing material, people and their luggage; corridor: canals and artificial waterways, tunnels and bridges) and are therefore not included further in analysis. The number of pathways increased to 38 when the split in plant and animal contaminant pathways was taken into account. Of the known pathways, 63% were intentional, 35% unintentional and 2% unaided. At sub-category level the escape pathway was largest (55%), followed by contaminants (28%), releases (9%) and stowaways (7%); no species were introduced via the corridor pathway (Table 1.2).

3.3. Comparing pathway scoring methods for ranking pathways

Different pathway scoring methods produced different ranks (Table 1.3, Table 1.4, Fig 1.2). When both impact methods (Method 2a and 2b) were compared to the count method (Method 1) there were considerable differences in the resulting ranked lists of pathways ($\tau = 0.37$, and $\tau = 0.28$ respectively) (Table 1.3a, Table 1.4a, Figs 1.2a, 2b). However, ranks produced by each impact method were more similar to each other ($\tau = 0.71$) (Table 1.3a, Table 1.4a, Fig 1.2c).

There were fewer differences between pathways ranked by each uncertainty method, with ranks based on Method 3b (intermediate number of species) similar to those based on Method 3a (minimum number of species) and Method 3c (maximum number of species – same as Method 1) (Table 1.4b). However, when ranks based on Method 3a and Method 3c were compared to each other, there was a higher degree of dissimilarity ($\tau = 0.67$) (Table 1.3b, Table 1.4b).

Pathway ranks changed over time, with a tau score no greater than 0.65 between any 50 year period (Table 1.4c). The similarity between ranks reduced as the gap between periods increased, for example dropping to $\tau = 0.41$ between 1801-1850 and 1951-2000.

Combining methods into a single approach (Method 4) resulted in pathway ranks that were the least similar to the count method (Method 1) ($\tau = 0.26$) (Table 1.3a, Table 1.4d, Fig 1.2d). This was largely because Method 1 ranked pathways higher that introduced large numbers of species, even when few of these species caused significant impacts (e.g. seed contaminants and agricultural escapes). In total, half of the top ten pathways ranked by Method 1 were absent from the top ten priorities identified by Method 4 (Table 1.4a). Where there were pathways common to the top ten ranks produced by each scoring method, the rank position of these pathways differed markedly (Table 1.4a). For example, hull fouling was identified by Method 4 as the highest ranking pathway, but only the eighth rank using Method 1. This difference was due, in part, to the large proportion of hull fouling species that caused significant impacts; however, it also related to the recent increase in the introduction of harmful species via this pathway.

The cumulative impact curve for pathways ranked by Method 4 (combined methods) was steeper than for pathways ranked by other methods (Fig 1.3); while pathways ranked by Method 1 (count method) produced the shallowest curve. The cumulative impact of pathways ranked by Method 1 was close to half (54%) that of pathways ranked by Method 4 (Fig 1.3, inset table).

Table 1.3 Comparison of top 10 pathways ranked by different pathway scoring methods. Pathways marked * are unique and do not appear in the other ranked lists. For full explanation of pathway codes refer to Table 1.1.

a. Count (Method1), impact (Method 2a and 2b) and combined (Method 4) methods compared.

Rank	Method 1	Method 2a	Method 2b	Method 4
1	E_HORT	E_HORT	E_HORT	S_HULL
2	C_SEED*	R_AES	S_HULL	E_HORT
3	R_AES	S_HULL	S_BALL	C_PLT_ORN
4	E_AGRI*	S_BALL	R_AES	S_BALL
5	C_PLT_ORN	C_ANI_AQC	C_ANI_AQC	S_ANG
6	C_FOOD*	E_PET*	E_AQC	S_OTR
7	C_OTR*	E_ORN	C_PLT_ORN	C_ANI_AQC
8	S_BALL	C_PLT_ORN	S_OTR	E_ORN
9	S_HULL	E_AQC	S_ANG	E_AQC
10	U_NAT*	R_FHRY	R_FHRY	E_LFB

b. Pathways ranked by different levels of certainty (minimum number of species (3a), intermediate number of species (3b) and maximum number of species per pathway (3c)).

Rank	Method 3a (minimum)	Method 3b (intermediate)	Method 3c (maximum)
1	E_HORT	E_HORT	E_HORT
2	C_PLT_ORN	C_SEED	C_SEED
3	C_SEED	C_PLT_ORN	R_AES
4	E_AGRI	E_AGRI	E_AGRI
5	C_FOOD	R_AES	C_PLT_ORN
6	U_NAT	C_FOOD	C_FOOD
7	C_OTR	C_OTR	C_OTR
8	C_TMBR*	S_BALL	S_BALL
9	C_PLT_FOR*	S_HULL	S_HULL
10	R_AES	U_NAT	U_NAT

Table 1.4 Kendall's tau b correlation coefficients indicating concordance between pathways ranked by different scoring methods (for method descriptions refer to Box 1.1). Method 1 (count of all non-native species), Method 2a (count of invasive non-native species) and Method 2b (sum of impact values) were compared to each other (a). Uncertainty methods (Methods 3a, 3b and 3c) were compared to each other (b). Methods used to rank species in different time periods were also compared to each other (c). Finally, Method 4 (combined methods) was compared to Method 1 (d). Rank ties were handled alphabetically. Where pathways were absent from one scoring method but not the other the rank was set to the lowest position.

a. Concordance between pathways ranked by count of all non-native species (Method 1), count only of invasive species (Method 2a) and sum of impact values of all species (Method 2b).

	Method 1	**Method 2a**	**Method 2b**
Method 1	1.00	0.37	0.28
Method 2a	-	1.00	0.71
Method 2b	-	-	1.00

b. Concordance between pathways ranked by counts of minimum (Method 3a), intermediate (Method 3b) and maximum (Method 3c – note this is the same as Method 1) number of species associated with each pathway.

	Method 3a	**Method 3b**	**Method 3c**
Method 3a	1.00	0.80	0.67
Method 3b	-	1.00	0.87
Method 3c	-	-	1.00

c. Concordance between pathways ranked (using Method 1) based on species that were introduced in different fifty year time periods.

	1951-2000	**1901-1950**	**1851-1900**	**1801-1850**
1951-2000	1.00	0.51	0.55	0.41
1901-1950	-	1.00	0.65	0.56
1851-1900	-	-	1.00	0.60
1801-1850	-	-	-	1.00

d. Concordance between pathways ranked by the total number of non-native species per pathway (Method 1) and combined methods (Method 4).

	Method 1	**Method 4**
Method 1	1.00	0.26
Method 4	-	1.00

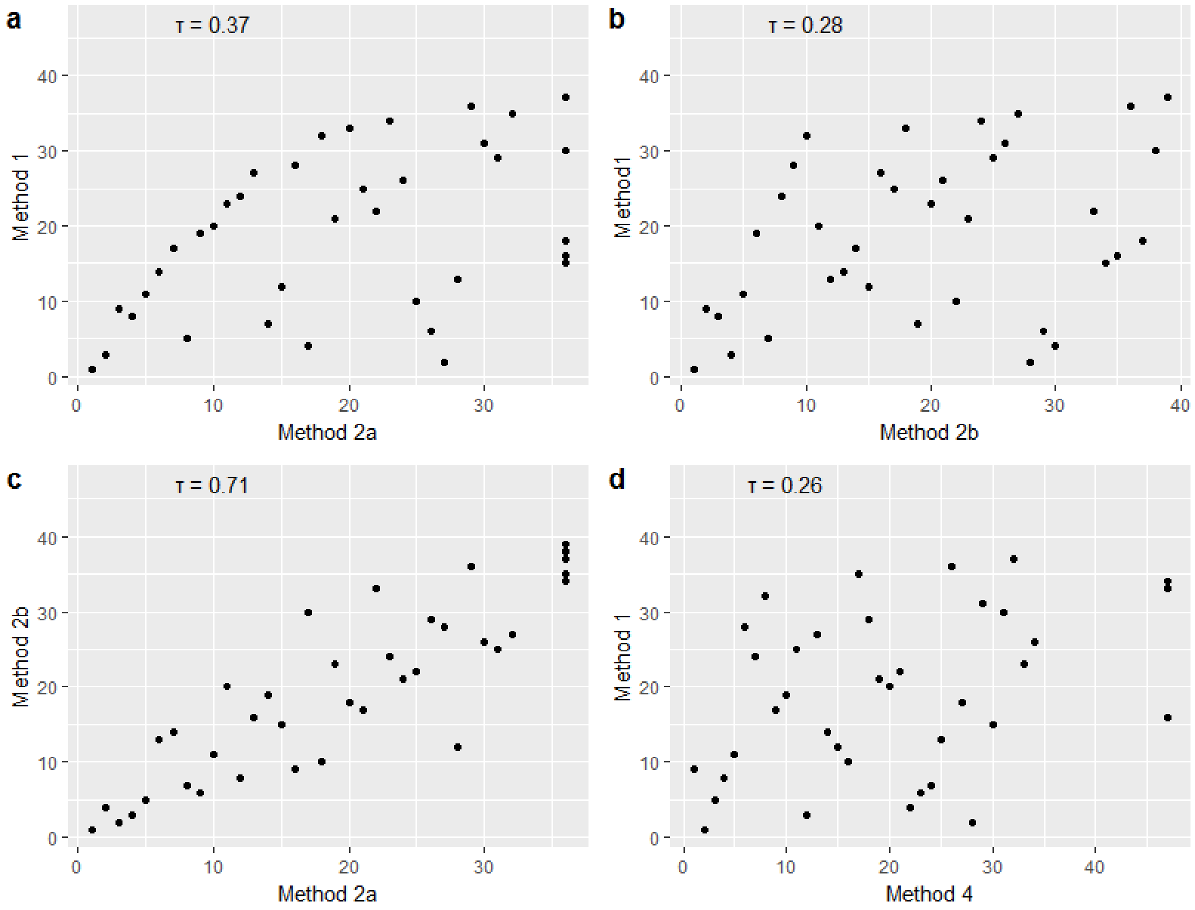
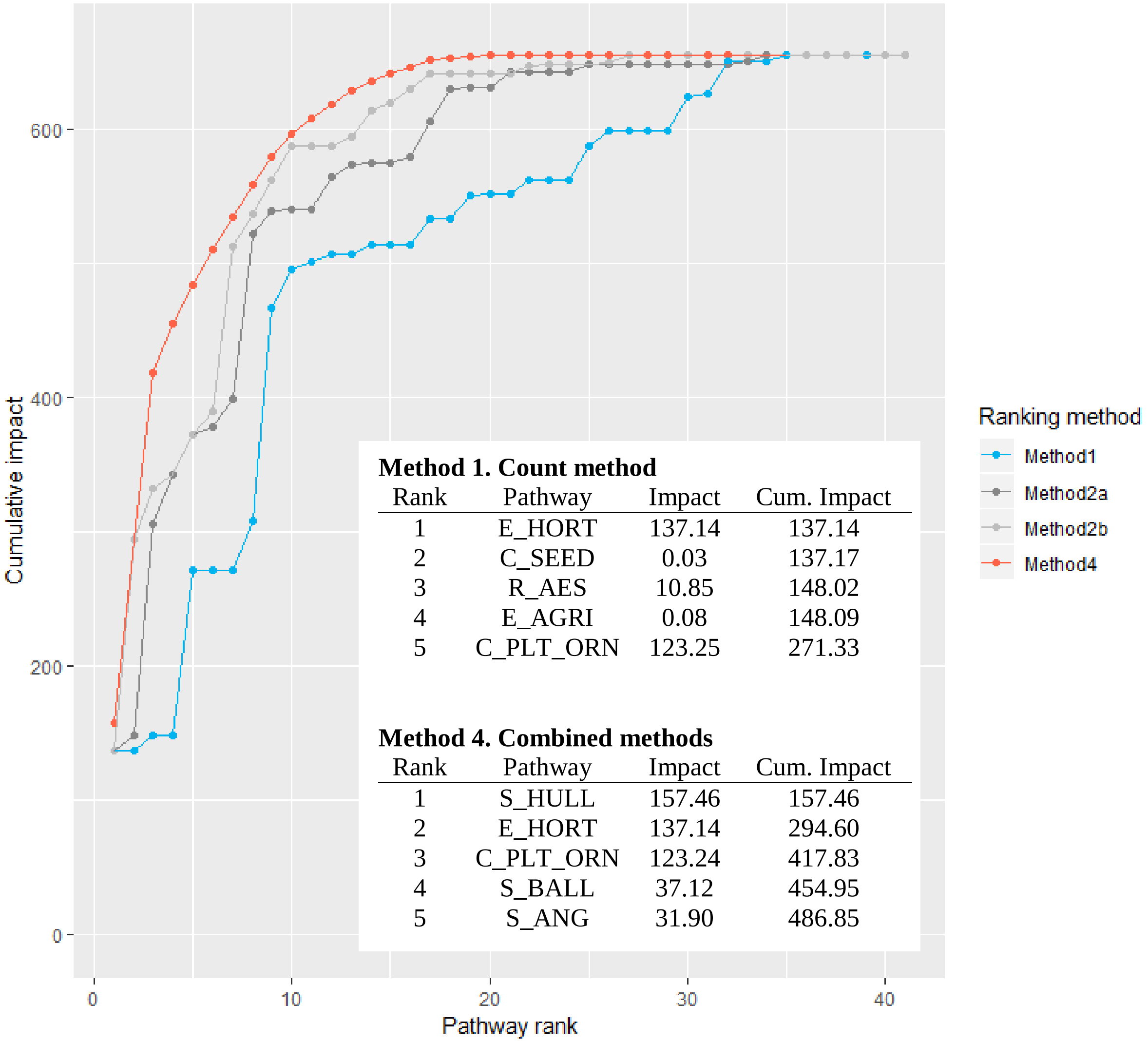


Figure 1.4 Plots illustrating the concordance, or lack thereof, between pathways ranked by selected scoring methods. Low levels of concordance were found between ranks produced by impact scoring methods (Methods 2a and 2b) and count method (Method 1) (panels a and b). However, ranks produced using impact scoring methods were more closely correlated with each other (panel c). The lowest level of concordance was found between ranks produced by combined methods (Method 4) and count method (Method 1) (panel d).



Method 1. Count method

Rank	Pathway	Impact	Cum. Impact
1	E_HORT	137.14	137.14
2	C_SEED	0.03	137.17
3	R_AES	10.85	148.02
4	E_AGRI	0.08	148.09
5	C_PLT_ORN	123.25	271.33

Method 4. Combined methods

Rank	Pathway	Impact	Cum. Impact
1	S_HULL	157.46	157.46
2	E_HORT	137.14	294.60
3	C_PLT_ORN	123.24	417.83
4	S_BALL	37.12	454.95
5	S_ANG	31.90	486.85

Figure 1.5 Difference in cumulative impact of pathways ranked by different scoring methods:Method 1 (count of all non-native species established in GB), Method 2a (count of invasive species only), Method 2b (sum of impact values) and Method 4 (combined methods). Points denote the cumulative impact (based on logarithmic scale applied to categorical scores) for pathways in rank order. Inset table indicates sum of impact values for species introduced by each pathway (Impact) and cumulative impact of pathways ranked by each method (Cumulative Impact). For full explanation of pathway codes refer to Table 1.1.

3.4. Ranking pathways of non-native species introduction in Great Britain

To explore pathway ranks further in GB, Method 4 (combined methods) was used (Fig 1.4), with additional detailed provided for the top ten pathways based on species established since 1950 (Table 1.5) and all established species (Table 1.6). Hull fouling (S_HULL) was identified as the highest ranking pathway (Fig 1.4). While this introduced relatively few species overall, those established after 1950 had larger combined impacts than species introduced by other pathways (Table 1.5). This was qualified by considerable uncertainty, with 86% of post-1950 species associated with this pathway also associated with at least one other pathway. Even so, the minimum number of potential introductions (bottom error bar, plot Fig 1.4) indicated this was still an important pathway and the maximum number indicated it could be substantially higher impact than others (top error bar, plot Fig 1.4). The majority of species introduced by this pathway were marine invertebrates, with smaller numbers of freshwater invertebrates and marine plants (Table 1.5). However, the freshwater species introduced by this pathway were particularly impactful (e.g. *Corbicula fluminea*, *Dreissena bugensis*, *Dikerogammarus villosus*, *Dikerogammarus haemobaphes*, *Rangia cuneata*). A number of high impact marine species were also introduced by this pathway (e.g. *Styela clava, Didemnum vexillum, Sargassum muticum* and *Undaria pinnatifida*). There has been a rapid increase in the impact of this pathway since 1950 (Fig 1.6), with species introduced that have native origins from all over the world (Table 1.5, column entitled 'Species origin'). However, impactful species recently introduced by hull fouling originated primarily from Europe (Table 1.5, column entitled 'Impact origin').

By contrast, horticultural escapes (E_HORT), the next highest ranking pathway, introduced by far the largest number of species (in total and since 1950) with low uncertainty (Fig 1.4). However, a smaller proportion of these species caused substantial impacts (Table 1.5). This pathway mainly introduced terrestrial plants, but also a small number of freshwater plants (Table 1.5). The number of species introduced by this pathway has been growing since the late 1700s and, while the proportion of species introduced by other pathways has increased, it is still the dominant pathway in terms of numbers of species introduced (Fig 1.5). However, in terms of recent impacts this pathway is less dominant (Fig 1.6). Including the most recent introductions, it appears that the impact of the horticultural escape pathway may be stabilising or even decreasing (Fig 1.6); however, this may be an artefact of lag in the ability of experts to detect impact (Chapter 2). Large numbers of horticultural escapes came from across the globe, with particularly large numbers from native origins in Europe and temperate Asia (Table 1.5, column entitled 'Species origin'). However, in terms of impact since 1950, species with native origins in North America have caused the most impact (Table 1.5, column entitled 'Impact origin').

The ornamental plant contaminant pathway (C_PLT_ORN) was the fifth largest in terms of total numbers of species introduced, but was ranked third by combined methods (Fig 1.4). Nine percent of species introduced by this pathway since 1950 have caused impacts, some of which have been particularly severe (e.g. *Arthurdendyus triangulatus*). There was a high degree of certainty in the species associated this pathway as there was often a clear trophic relationship between the non-native species and its plant host (e.g. *Arge berberidis* the berberis sawfly, *Cameraria ohridella* the horse-chestnut leaf miner and *Otiorhynchus crataegi* the privet weevil). This pathway primarily introduced terrestrial invertebrates; however, it also introduced freshwater invertebrates, terrestrial plants and possibly one freshwater plant (Table 1.5).

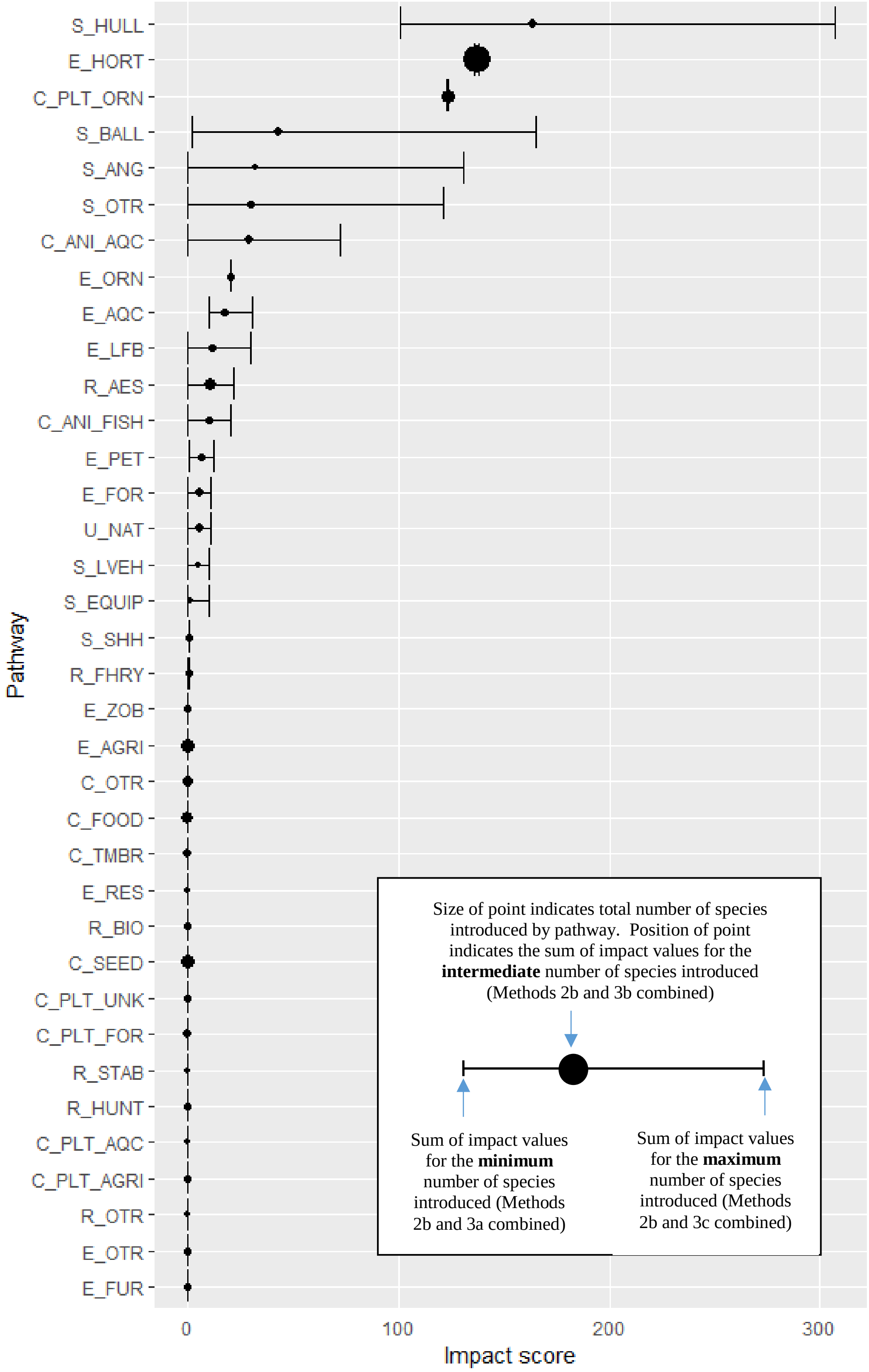


Figure 1.6 Pathways ranked by combined methods (Method 4), indicating potential priorities in GB. Point size indicates total number of species introduced since 1950, while position of points with error bars indicates the sum of impact values for the minimum, intermediate and maximum impact of species introduced by each pathway since 1950 (illustrated by inset). For full explanation of pathway codes refer to Table 1.1.

Table 1.5 Top 10 pathways ranked by combined methods (Method 4) and associated statistics, based on non-native species that established in GB after 1950. No. NNS = total number of species introduced by pathway. No. INNS = total number of species with more than minimal impacts. Impact = sum of species' impact scores. Impact = sum of impact scores. Origin number = line weight indicates number of species; origin impact = line weight indicates sum of impact scores. The number of species from each broad taxa (P = plant, I = invertebrate, V = vertebrate) and environment is given. In all cases the intermediate number (or impact) of species is given followed by the minimum and maximum figures in brackets. For full explanation of pathway codes refer to Table 1.1.

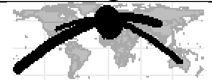
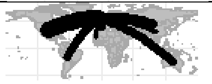
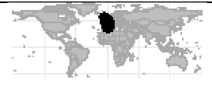
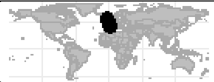
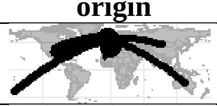
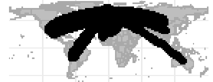
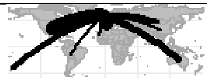
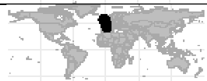
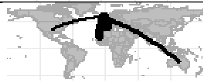
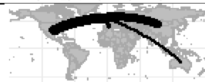
Pathway	No. NNS	No. INNS	Prop. INNS	Impact	Species native origin	Impact native origin	Terrestrial	Freshwater	Marine
S_HULL	17.1 (5-36)	8.2 (2-19)	0.48	163.5 (101-307.2)				I 2.2 (1-6)	I 13.8 (4-27) P 1.1 (0-3)
E_HORT	317.4 (284-352)	20.5 (19-22)	0.06	138.2 (136.8-139.6)			P 305.4 (273-339)	P 12 (11-13)	
C_PLT_ORN	73 (65-81)	6.5 (6-7)	0.09	123.3 (122.7-123.8)			I 60 (53-67) P 5.5 (5-6)	I 7 (7-7) P 0.5 (0-1)	
S_BALL	13.2 (5-28)	4.8 (2-12)	0.36	43.2 (2-165.2)			I 1 (1-1) P 1 (1-1)	I 1.2 (0-5)	I 9.8 (3-20) P 0.2 (0-1)
S_ANG	1.2 (0-5)	1.2 (0-5)	1	31.9 (0-131)				I 0.8 (0-4)	I 0.2 (0-1)
S_OTR	1 (0-4)	1 (0-4)	1	30.2 (0-121)				I 1 (0-4)	
C_ANI_AQC	7.2 (1-17)	4 (0-10)	0.55	29.2 (0-72.2)				I 0.2 (0-1) V 0.8 (0-2)	I 4.1 (0-10) P 2.1 (1-4)
E_ORN	4 (4-4)	3 (3-3)	0.75	20.1 (20.1-20.1)			V 1 (1-1)	I 2 (2-2) V 1 (1-1)	
E_AQC	3.7 (2-6)	2.2 (1-4)	0.59	17.2 (10-31)				I 2.5 (2-3)	I 1.2 (0-3)
E_LFB	2.5 (1-5)	1.2 (0-3)	0.47	11.7 (0-30)			I 1 (1-1)	I 1 (0-2)	I 0.5 (0-2)

Table 1.6 Top 10 pathways ranked by combined methods (Method 4) and associated statistics, based on all established non-native species in GB. No. NNS = total number of species introduced by pathway. No. INNS = total number of species with more than minimal impacts. Impact = sum of species' impact scores. Impact = sum of impact scores. Origin number = line weight indicates number of species; origin impact = line weight indicates sum of impact scores. The number of species from each broad taxa (P = plant, I = invertebrate, V = vertebrate) and environment is given. In all cases the intermediate number (or impact) of species is given followed by the minimum and maximum figures in brackets. For full explanation of pathway codes refer to Table 1.1.

Pathway	No. NNS	No. INNS	Prop. INNS	Impact	Species native origin	Impact native origin	Terrestrial	Freshwater	Marine
S_HULL	26.4 (5-58)	10.5 (2-24)	0.40	207.5 (101-428.4)				I 5.2 (1-12)	I 18.4 (4-39) P 2.8 (0-7)
E_HORT	865 (762-980)	86.9 (75-100)	0.10	474.3 (417.6-539.9)			P 844 (743-957)	P 21 (19-23)	
C_PLT_ORN	115.8 (104-129)	7.5 (7-8)	0.06	133.7 (133.1-134.3)			I 94 (87-102) P 10.3 (8-13)	I 10.5 (10-11) P 0.5 (0-1) V 0.5 (0-1)	
S_BALL	29.6 (11-59)	9 (3-20)	0.30	107 (12.1-316.5)			I 1 (1-1) P 8.5 (6-12)	I 5.2 (1-12)	I 14.2 (3-32) P 0.6 (0-2)
S_ANG	1.2 (0-5)	1.2 (0-5)	1	31.9 (0-131)				I 1 (0-4)	I 0.2 (0-1)
S_OTR	4.5 (3-8)	3 (2-6)	0.67	41.3 (11-132)			I 1 (1-1) P 1 (1-1)	I 2 (1-5)	I 0.5 (0-1)
C_ANI_AQC	17.4 (6-36)	6.7 (1-15)	0.38	64.5 (1.1-175.4)				I 0.2 (0-1) V 1.2 (0-3)	I 10.8 (4-22) P 5.2 (2-10)
E_ORN	7.2 (4-11)	5.7 (3-9)	0.79	31.3 (20.1-43.2)			V 4.2 (1-8)	I 2 (2-2) V 1 (1-1)	
E_AQC	6.2 (3-10)	4.7 (2-8)	0.76	72.3 (10.1-141.2)				I 2.5 (2-3) V 2 (1-3)	I 1.7 (0-4)
E_LFB	3.3 (1-7)	1.2 (0-3)	0.35	11.7 (0-30)			I 1 (1-1)	I 1 (0-2)	I 1.3 (0-4)

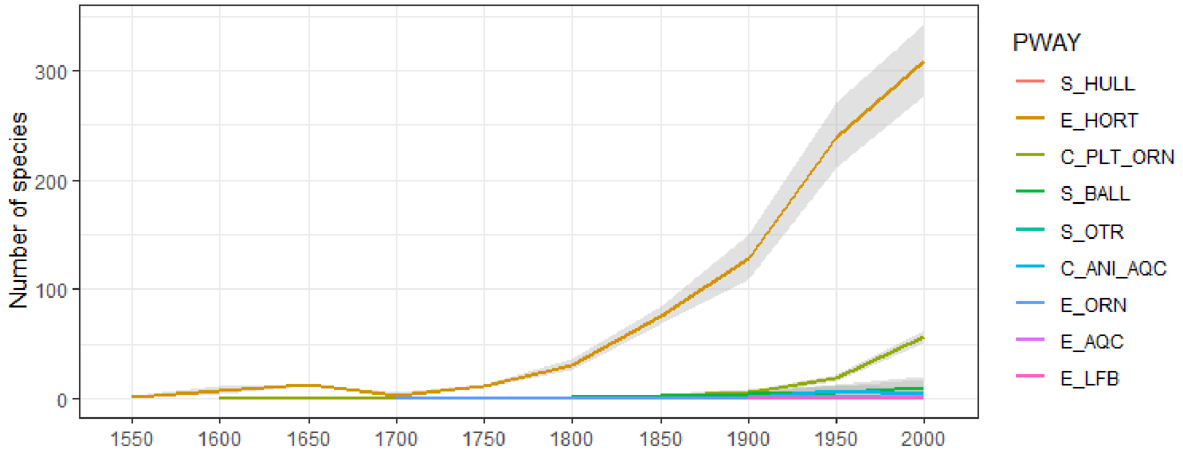
Of the remaining pathways a group of four (ranks 4-7) stood out as having more potential impact than others (ballast water stowaways, S_BALL; angling stowaways, S_ANG, ‘other’ stowaways, S_OTR and contaminants of aquaculture animals, C_ANI_AQC), albeit with considerable uncertainty (note S_OTR primarily related to stowaways on equipment such as pumps and water sports equipment used in freshwaters abroad). These all occupied a similar position, given their intermediate impact scores and wide error bars; although, ballast water (S_BALL) scored slightly higher. The pathways angling stowaways (S_ANG) and ‘other’ stowaways (S_OTR) scored similarly as they were associated with the same small group of particularly high impact species (including *Dikerogammarus haemobaphes*, *D. villosus*, *Dreissena bugensis* and *Hemimysis anomala*). The contaminant of aquaculture animals pathways was associated with a larger number of species introduced since 1950 (n=17), most of which were marine (n=14), but with lesser impacts. A further group of 10 pathways caused more than negligible impacts (ranks 8-17), with ornamental escapes (E_ORN), aquaculture escapes (E_AQC), life food and bait (E_LFB), aesthetic release (R_AES) and contaminants of fish (C_ANI_FISH) scoring higher than others (but with high uncertainty in all cases). Nineteen pathways were associated with little if any impact based on species introduced since 1950, despite relatively large numbers of species introduced in some cases (e.g. agricultural escapes, E_AGRI; contaminants of food, C_FOOD; and seed contaminants, C_SEED).

3.5. Taxonomic, environmental and temporal patterns

Pathways changed over time in terms of numbers of species introduced (Fig 1.5), but particularly in terms of impact (Fig 1.6). While the numbers of species introduced by the horticultural escape (E_HORT) pathway increased rapidly throughout the 19th and 20th century (Fig 1.5a), in terms of impact it has plateaued in recent years (Fig 1.6a). Numbers and proportions of species introduced by the contaminant of ornamental plants pathway (C_PLT_ORN) increased towards the end of the 20th century, as did those introduced by hull fouling (S_HULL) and ballast water (S_BALL) to a lesser degree (Fig 1.5a and b),. However, in terms of impact there has been a considerable increase in hull fouling (S_HULL) and contaminants of ornamental plants (C_PLT_ORN) (Fig 1.6a and b)

The highest levels of uncertainty were associated with invertebrates and aquatic (freshwater and marine) species (Fig 1.7). Twenty-five pathways introduced terrestrial non-native species that have established since 1950, of which 13 introduced plants, 13 introduced invertebrates and 5 introduced vertebrates (Fig 1.7a). In terms of impact, the key terrestrial pathways were horticultural escapes (E_HORT; terrestrial plants) and contaminants of ornamental plants (C_PLT_ORN; terrestrial invertebrates). In the freshwater environment, 14 pathways introduced species that have established since 1950, of which 2 introduced plants, 10 introduced invertebrates and 6 introduced vertebrates (Fig 1.7b). By far the largest uncertainty was associated with freshwater invertebrate pathways, which was also the group associated with the largest impacts. Key freshwater pathways in terms of impact included horticultural escapes (hull fouling (S_HULL), ballast (S_HULL), angling (S_ANG) and other (S_OTR) stowaways, for invertebrates; horticultural escapes (E_HORT) for plants). Few freshwater vertebrates have been introduced since 1950; these were introduced mainly as contaminants of fish stocks (C_ANI_FISH), escaped pets (E_PET) or contaminants of other aquaculture animals (C_ANI_AQC). Ten pathways introduced marine non-native that have established since 1950, of which four introduced marine plants and ten introduced invertebrates (no marine vertebrates have been introduced since 1950, or indeed at all in GB) (Fig 1.7c). The majority of marine impacts since 1950 have been caused by hull (S_HULL) and ballast (S_BALL) stowaways, as well as contaminants of aquaculture animals.

a. Number of species introduced



b. Proportion of species introduced by pathways over time.

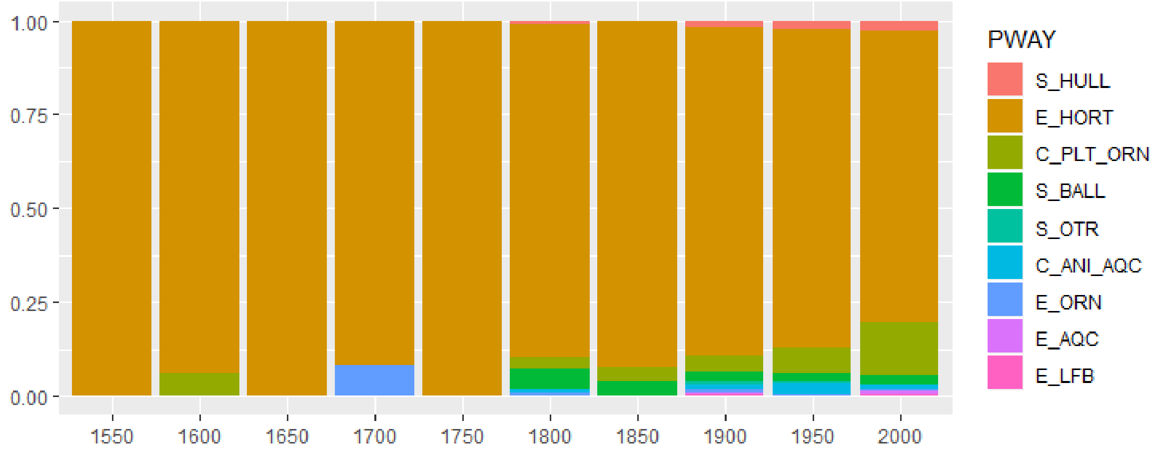
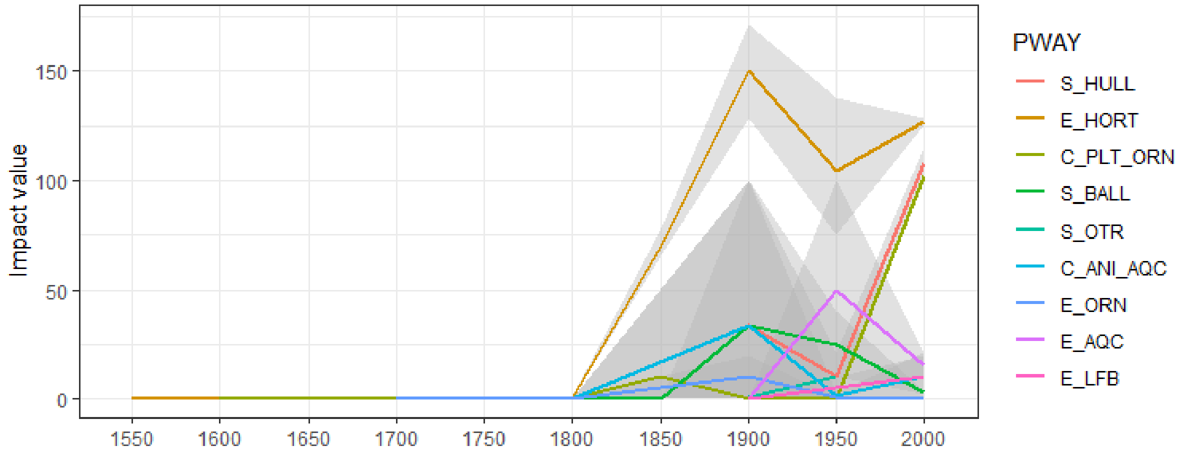


Figure 1.7 Number (a) and proportion (b) of species for each of the top ten pathways over time (50 year periods). Trends are based on intermediate number of species that have established in GB (Method 3b). Shading (panel a) indicates minimum (Method 3a) and maximum number of species (Method 3c). For full explanation of pathway codes refer to Table 1.1.

a. Impact of introduced species by pathways over time.



b. Proportion of impact caused by species introduced by pathways over time.

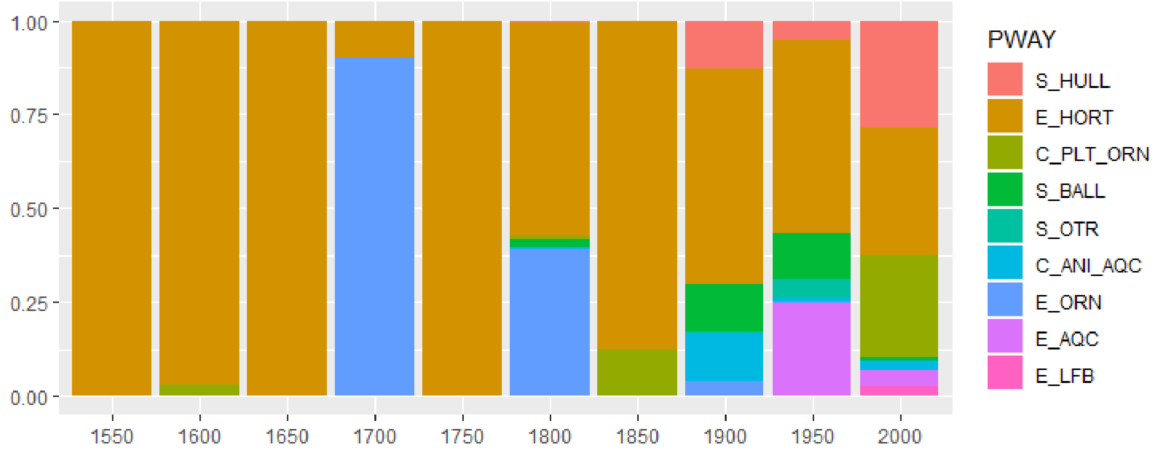
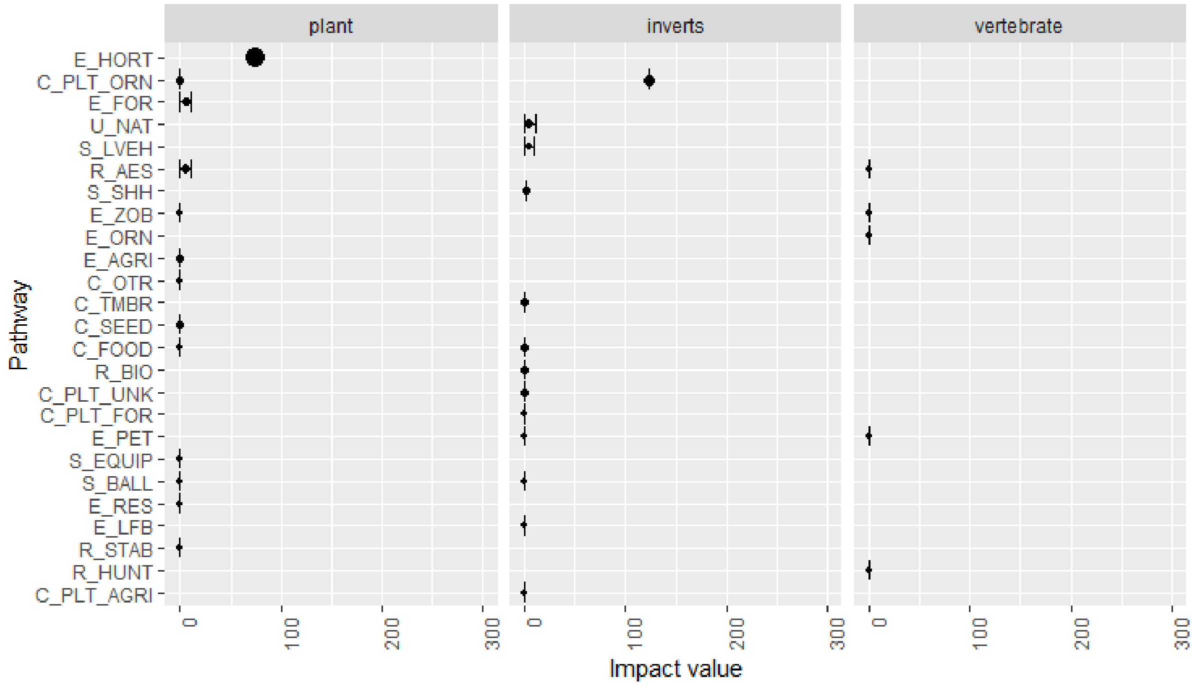
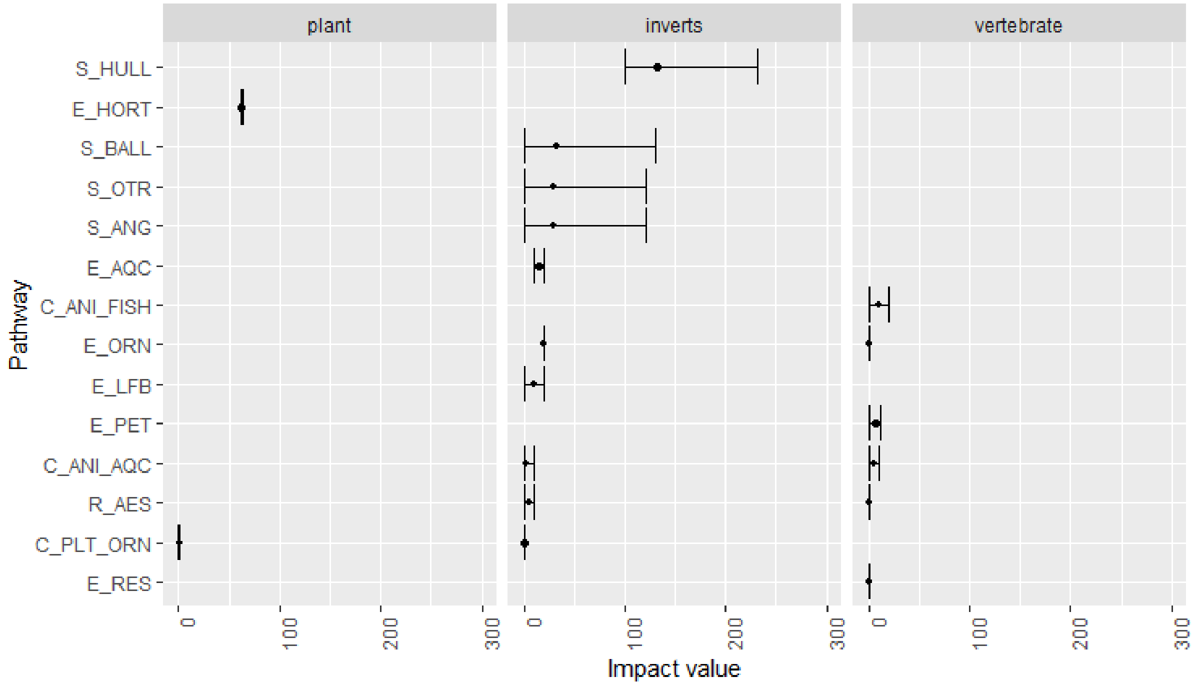


Figure 1.8 Impact (a) of and proportion of impact (b) of species introduced by each of the top ten pathways over time (50 year periods). Trends are based on the sum of impact values for species associated with each pathway, using the intermediate number of species introduced (Method 2b combined with Method 3b). The minimum (Method 3a combined with Method 2b) and maximum impact (Method 3c combined with 2b) of each pathway is indicated (shading in panel a). For full explanation of pathway codes refer to Table 1.1.

a. Terrestrial environment



b. Freshwater environment



c. Marine environment

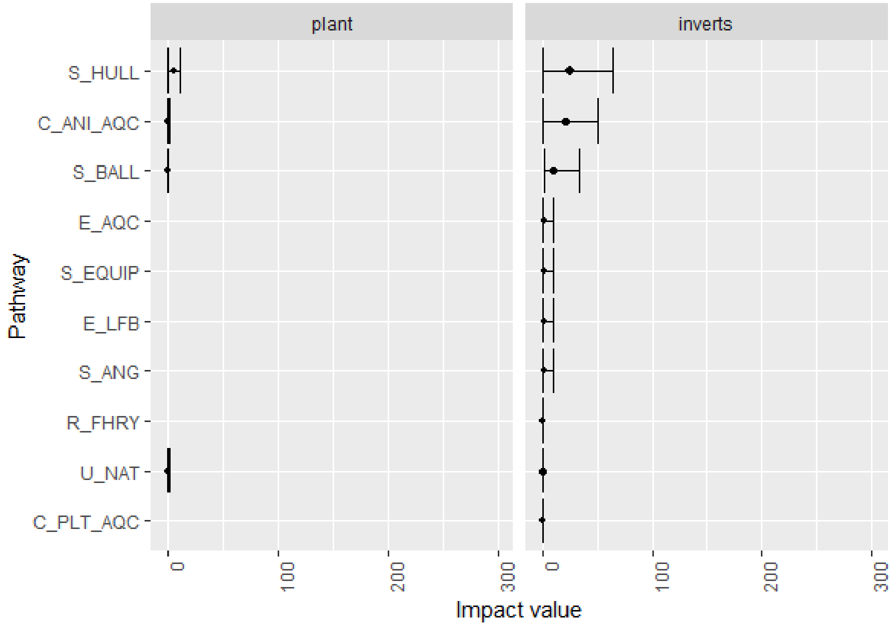


Figure 1.9 Pathways ranked by combined methods (Method 4) separated by taxa and environment. Point position indicates the intermediate impact of each pathway, while error bars indicate the minimum (Method 2b combined with Method 3a) and maximum (Method 2b combined with Method 3c) impact. Point size indicates the number of species introduced (using the intermediate method, Method 3b). All methods included only species that established in GB after 1950. Wide error bars indicate low certainty in pathway impact. For full explanation of pathway codes refer to Table 1.1.

3.6. Correlation between total species number and proportion invasive

The total number of all non-native species introduced by each pathway was plotted against the proportion of those species that were invasive (i.e. caused more than minimal impact) (Fig 1.8). The correlation between the total number of species and invasive proportion was negative, with pathways either introducing many species or a large proportion of invasive species, but not both. Higher ranked pathways were those further from the bottom left corner of this plot (i.e. low numbers of species and small proportion invasive).

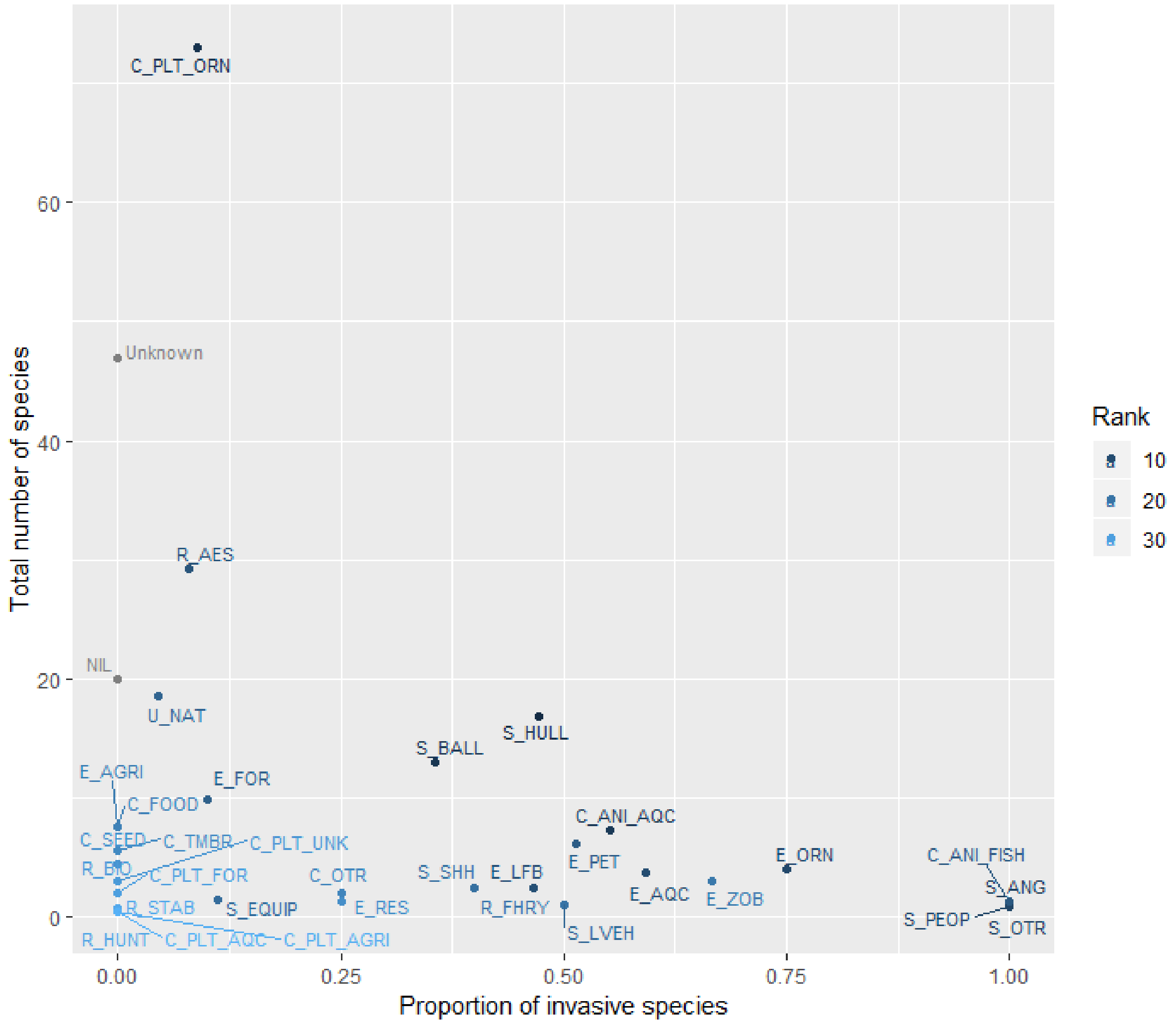


Figure 1.10 Comparison of total number of species introduced by each pathway and the proportion that were invasive (i.e. scored more than minimal impact), based on species established in GB since 1950. Colour indicates rank determined using Method 4 (combined methods), with darker colours indicating higher rank. To aid visualisation the horticultural escape pathway has been excluded from this figure (total number of species 317.4, proportion invasive 0.06). For full explanation of pathway codes refer to Table 1.1.

4. Discussion

This study found that pathway ranks differed substantially depending on the scoring method used. Given that the ultimate aim of pathway ranking is to identify management priorities (CBD, 2014a, Lodge et al., 2016), this is important as it suggests that different pathways would be prioritised depending on the method used. While different ranking approaches have been developed, often based on number of all non-native species (e.g. Katsanevakis et al., 2013b, CBD, 2014b, Nunes et al., 2014, Roy et al., 2014b, Turbelin et al., 2017); and in some cases assessments of species impact (e.g. Madsen et al., 2014, NOBANIS, 2015, Saul et al., 2017), these have not been compared to consider the extent to which they differ. This study found that methods that accounted for impact performed better than those based on numbers of species alone. This is perhaps intuitive given that the objective of management is to reduce impact (Essl et al., 2015), but was also demonstrated by the cumulative impact reduction that would be expected by prioritising pathway management using different ranking methods. Incorporating uncertainty produced less pronounced differences, with relatively high levels of concordance between ranks produced using minimum, intermediate and maximum numbers of species. However, uncertainty did have a strong impact on the ranking of some pathways, particularly those ranked in higher positions. For example, five of the top ten pathways ranked by the combined methods (Method 4) would be ranked differently depending on whether the minimum, intermediate or maximum number of species was taken into account. Temporal change also affected pathway ranks, with both the number of species introduced by pathways and the impact of pathways changing over time. Overall, these findings suggest that a combined approach to pathway ranking, taking into account impact, uncertainty and temporal change is likely to perform better than other methods. They also demonstrate that uncertainty should be clearly documented and communicated to support decision-making.

Using combined methods (i.e. Method 4) to rank pathways provided much of the information needed to support pathway prioritisation (Essl et al., 2015); however, it did not include an assessment of the feasibility of pathway management. This is critical for prioritisation as the management of some pathways will be more feasible than others which, with limited resources, may influence management decisions (Lodge et al., 2016). For example, it may be relatively feasible to introduce measures to reduce the risk of zoo escapes in GB (e.g. restrictions on keeping, codes of practice, regulation of holding facilities) but much harder to prevent species arriving via the unaided pathway from continental Europe (e.g. Asian hornet (Marris et al., 2011) or Asian shore crab (Seeley et al., 2015)). Methods to assess the feasibility of pathway management are therefore required and should complement the scoring methods identified here. These could use similar criteria to those used to assess the feasibility of managing species such as the effectiveness, practicality, cost, negative consequences and acceptability of pathway management (Booy et al 2017). Indeed, the need to assess the feasibility of pathway management is similar to that required for the prioritisation of species management, which is discussed later in this thesis (Chapters 4 and 5).

Central to the ability to analyse and rank non-native species pathways is the use of robust pathway classification systems (Essl et al., 2015). While adopting the CBD classification (CBD, 2014a) helps to ensure consistency, it is likely to require updates and improvements as it continues to be applied (Harrower et al., 2018). For example, with non-native species introduced to GB it was useful to add a level of detail to some of the particularly broad CBD pathways (i.e. plant contaminants and animal contaminants). In these cases, pathways were separated based on the sectors involved (e.g. agriculture, aquaculture, fisheries, forestry, ornamental) as it is generally at this level that management intervention would occur. Indeed, it may be useful in classification systems to consider breaking all pathways down to units at which management is likely to be feasible. It was possible to map NNSIP pathways to CBD pathways (similar to findings of Saul et al. (2017) for DAISIE and GISD pathway categories, as well as Tsiamis et al. (2017) for EASIN); however, it was rare that pathways mapped directly without at least some manual corrections. This was primarily because of differences in the way the NNSIP and CBD classifications were structured (e.g. NNSIP grouped all accidental introductions, while CBD separated contaminants and stowaways), the level of pathway detail used by each classification scheme and ambiguity in the interpretation of pathways. These findings highlight a challenge for the coordination of pathway management at an international scale. On one hand such schemes need to be consistently applied, but on the other they need to improve and develop as lessons are learned from their application. In addition, even with extensive guidance (Harrower et al., 2018) pathway definitions can still be ambiguous. There is therefore a need to determine how such schemes can be updated and ambiguities clarified while maintaining consistency. This could potentially be done through the development of standards (in a similar way to International Standards for Phytosanitary Measures, https://www.ippc.int) which could be developed and maintained at an international level, for example via platforms such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services or the IUCN’s Invasive Species Specialist Group.

Interestingly, the number of non-native species introduced by pathways was negatively correlated with the proportion that were invasive (i.e. caused more than minimal impacts). In other words, pathways that introduced many non-native species tended to be associated with lower proportions of invasive species (e.g. horticultural escapes), while pathways associated with high proportions of invasive species tended to introduce relatively few species overall (e.g. angling stowaways). No pathways introduced both many species and a high proportion that were invasive; although some of the high ranking pathways introduced relatively large numbers of both (e.g. hull fouling and ballast water). The relationship between number of species introduced and proportion invasive could help to indicate different management strategies to reduce risk. For example, pathways that introduce large number of species but few that cause severe impacts are likely to require selective management methods. These could include blacklisting for intentional (release and escape) introductions (e.g. Essl et al., 2011b) or for unintentional pathways (contaminant and stowaway) methods targeting specific high risk routes, origins, vectors or activities (EU, 2014, e.g. Haack et al., 2014). On the other hand, broader interventions may be more appropriate for pathways that introduce few species of which a large proportion are invasive. This could include white listing for intentional pathways, which would focus on allowing only the relatively small number of low impact species to be kept / used (Hulme, 2015). While for unintentional introductions, broad biosecurity measures may be required to reduce risk across activities (e.g. Anderson et al., 2014).

This is one of the first pathway ranking studies to explicitly incorporate uncertainty in the original pathway of introduction in its outputs. In doing so, this study showed that pathway uncertainty was common for many (36% of) species and particularly so for aquatic species and invertebrates. Uncertainty had the potential to affect the results of ranking. For example the wide error bars on the pathway ranked highest by the combined methods (hull fouling) showed the maximum impact could be twice that indicated by the intermediate impact score, while the minimum impact would reduce its rank from first to at most third place. The method used to incorporate uncertainty here was based on the number of pathways listed for each species. This provided a useful means of both assessing and displaying uncertainty; however, there were a number of limitations. Where only one pathway was listed for a species it was assumed that this was the original introduction pathway. However, it is possible in some cases that even though a single introduction pathway was listed there was still uncertainty that it was the original pathway (e.g. *Potamopyrgus antipodarum* was most likely associated with drinking water barrels (Ponder, 1988) but it is difficult to know this with certainty). Similarly, where multiple pathways were listed for a species, it was assumed that each had an equal chance of being the original introduction pathway; however, some may have been more likely to be the original than others (e.g. *Dreissena bugensis* may have been introduced by numerous pathways; however some, such as hull fouling, seem more likely than others (Bij de Vaate et al., 2013)). Future studies should therefore consider ways of adapting the methods used here to assign specific confidence or probability scores (e.g. following those used by Mastrandrea et al., 2011, Hawkins et al., 2015) to species associated with each pathway.

In order to determine a minimum, intermediate and maximum number of species per pathway it was necessary to only consider the original (first) introduction pathway for these species, with subsequent pathways of introduction (i.e. those that introduced further individuals of the same species) excluded from analysis; although other studies have not made this distinction (e.g. Pysek et al., 2011, CBD, 2014b, Roy et al., 2014b, Pergl et al., 2017, Saul et al., 2017, Van Gossum and Rommens, 2017). This was, in part, because it was not known with confidence the degree to which subsequent pathways contributed to the establishment and spread of additional populations (and therefore the impact of the species). Subsequent pathways may be inconsequential, for example they may not lead to any further populations, or may add individuals to an already widespread population therefore causing little additional impact. On the other hand, subsequent pathways could cause considerable additional impact, for example the escape of fallow deer from deer parks has likely facilitated the spread of this species throughout GB, despite release for hunting being the original introduction pathway (Lever, 2009). This issue highlights some of the complexity involved in pathway analysis and the need to account for trends in the impacts of pathways overtime. Further development is needed to account for subsequent pathways, which would need to consider not only when these became active but the extent to which they have contributed to each species' impact.

Two different methods for incorporating species impact were tested in this study, with advantages and disadvantages to each. Method 2a ranked pathways by counting only the number of species that were considered invasive (i.e. scored more than minimal impact). This had the advantage of using invasive species as the unit of measurement, which is more intuitive and can be communicated clearly. However, a disadvantage was that information was lost, because differences in the severity of impact between invasive non-native species were not taken into account (i.e. minor impacts were treated the same as massive). The alternative, Method 2b, converted all categorical impact scores into values, with rank determined by the sum of these values. Applying post-hoc values to categories in this way can be problematic as they may not accurately reflect the distances between qualitative levels; however, a logarithmic scale was considered a good fit as the qualitative categories were designed to reflect impacts at increasing orders of ecological organisation (Blackburn et al., 2014, Hawkins et al., 2015). This approach also produced results that correlated closely with those produced using Method 2a, which indicated that both methods came to a similar conclusion. Method 2b was considered the more appropriate for use in the final analysis of pathways in GB as it used all species (rather than excluding a proportion) and provided a means of distinguishing between impact levels.

The importance of taking temporal changes into account when assessing pathways was demonstrated. The number of species introduced by pathways changed over time, as did the impact of pathways, resulting in considerably different pathway ranks between fifty year time periods. While the horticultural pathway historically introduced by far the most species over time and this was still the case by the end of the 20th century; in terms of impact the horticultural escape pathway appeared to plateau after 1900, while horticultural contaminants and hull fouling increased rapidly. This result should be treated with caution, as the plateau in the horticultural pathway may be the result of lag in detecting impact (Chapter 2); however, it highlights that the threat from some pathways is changing considerably and increasing rapidly in the case of horticultural contaminants and hull fouling. It is therefore important that change over time is incorporated into scoring methods used to rank pathways, as has been recommended (Wilson et al., 2009, Essl et al., 2015, Zieritz et al., 2016, García-Díaz et al., 2018). The combined approach used here (Method 4) did this relatively simply by limiting assessment to those species that established after 1950. This is a point after which technical and logistical improvements have resulted in the increased spread of species (Hulme, 2009, Essl et al., 2011a) and was considered sufficiently recent to include the most relevant modes of transport (by air, sea and over-land), while providing a large enough dataset on which to perform analysis. Future development should consider ways by which the trajectory of a pathway's impact over time (i.e. the rate at which impact is increasing or decreasing) could be further incorporated, perhaps by modelling predicted future pathway impacts (Lodge et al., 2016).

Historical trends in pathway impacts do not necessarily indicate future risk; nevertheless, recent trends in the impact of introduction pathways may provide some insight. The accuracy of this will only be tested over time; however, an indication may be provided by comparing the pathways identified here to those predicted to introduce future invasive species as identified by horizon scanning (Roy et al., 2014a). Twenty out of the top 30 species identified by horizon scanning were associated with high ranking pathways identified by this study (primarily hull fouling or horticultural escapes), suggesting a good alignment between the pathways identified here and those identified by horizon scanning; however, there were also differences. None of the top 30 species were predicted to be introduced as contaminants of ornamental plants (four were forestry contaminants, but these were not considered contaminants of ornamental plants), and the remaining ten species were associated with at least six different pathways (aquaculture escapes, contaminants of fish, unaided, forestry contaminants, contaminants of raw material and contaminants of produced). Overall, it would appear that using past trends in pathway impact is a potentially useful proxy for near future risk; however, for more long distance forecasts more predictive ways of modelling future risk would be required (Lodge et al., 2016). These would need to consider the effect of lag in the detection of impacts (Chapter 2) and the role of propagule pressure (Lockwood et al., 2009, Cassey et al., 2018a), which is linked to changes in global markets, demographics and climate (Hulme, 2015, Seebens et al., 2015).

This study helps to indicate potential pathway management priorities in GB, notwithstanding the need to assess the feasibility of pathway management. Despite numerous introduction pathways that introduced non-native species to GB (n=38 at sub-category level), relatively few were responsible for the majority of impacts since 1950 (three pathways were responsible for the majority of post-1950 impact). Nineteen pathways had negligible impact (i.e. introduced species that exclusively caused minimal impact), despite several introducing large numbers of species (e.g. agricultural escapes, food contaminants, seed contaminants). This demonstrates an immediate advantage of ranking, that relatively large and complex lists of pathways can be reduced to more manageable short lists. Of the higher impact pathways, hull fouling, horticultural escapes and contaminants of ornamental plants stood out as pathways that caused most impact, with the impact of hull fouling and contaminants of ornamental plants increasing rapidly in recent years. Both hull fouling and horticultural escapes have already been identified as priorities in GB (Defra, 2015), which is supported by this result. Both marine and freshwater hull fouling are a concern, with marine species being introduced from a wide range of native origins (but particularly the pacific ocean) and invasive freshwater species predominantly having their native origins in Europe (which are primarily assocaited with the Ponto-Caspian region of south-eastern, Gallardo et al., 2015). Horticultural escapes had native origins from across the globe; however, aquatic plants with native origins in North America appear to be associated with a disproportionate degree of impact (see also Chapter 2). While contaminants of ornamental plants is often considered a risk from the perspective of plant health (e.g. Halstead, 2011, Scrace, 2018), it has not received as much attention in relation to introducing invasive non-native species that pose a wider environmental threat. This may deserve more attention in GB, particularly in relation to terrestrial invertebrates with native origins in Australia. However, managing these may not be straightforward, given that they often go undetected in imports and can be difficult to control (Sluys, 2016). Beyond the top three pathways, ballast water, angling stowaways, stowaways ‘other’ and contaminants of aquaculture animals all caused relatively high impacts, but with considerable uncertainty. Further investigation may be necessary to attempt to reduce uncertainty here where feasible; however, following the precautionary principle these pathways could be considered high risk until proven otherwise. While these are the highest ranking pathways based on species established since 1950, this does not preclude the possibility that other pathways could be a priority, particularly when the feasibility of management is taken into account. For example, contaminants of imported fish have been identified as a serious threat in the past (Pinder and Gozlan, 2003) and it may be relatively straight forward to tighten existing controls on this pathway to reduce future risk.

This study shows the value of comprehensive datasets of all non-native species established in a given region for helping to identify pathways that have not only introduced the most species, but have had the most impact. The methods developed and tested here show that impact, temporal change and uncertainty should be taken into account when prioritising pathways. This finding has relevance to those responding to national (Defra, 2015), regional (EU, 2014) and international commitments (CBD, 2014a) to prioritise prevention effort. It is hoped that the methods developed here will contribute to those initiatives. Nevertheless, further development is required, not only to improve our ability to forecast the risk of future pathways, but in particular to assess the feasibility of pathway management in order to support prioritisation.

Annex 2. Analysis of pathways of introduction of species of Union Concern

1. Background

This paper reports on the analysis of unintentional introduction pathways using only the 49 species listed as being of Union concern.

2. Methods

Introduction pathway data was extracted from risk assessments published by the European Commission and used to support the listing of species of Union concern. All introduction pathways were extracted and re-classified to align with the CBD pathway framework, following the guidance of Harrower et al. (2018) and Saul et al. (2017). This resulted in a list of pathways associated with each species, with individual species associated with multiple pathways in many cases. All of these species were considered likely to cause serious impacts in the EU and so no attempt was made to differentiate them based on impact.

Analysis was based on the number of species associated with each pathway, with priority given to those pathways associated with most species. A minimum, intermediate and maximum count for each pathway was calculated based on the number of pathways associated with each species, following the approach set out in Annex 1 (above) and defined below:

- Minimum count: Every non-native species exclusively associated with a single pathway is scored 1. All other species (i.e. those associated with more than one possible original pathway of introduction) are excluded. The sum of these scores is calculated for each pathway.

- Intermediate count: A score of 1 for each non-native species is divided equally between the number of pathways by which it could have been originally introduced. For example, where a species has four possible introduction pathways, each pathway receives a score of 0.25 for that species. The sum of these scores is calculated for each pathway.

- Maximum count: Every non-native species associated with a pathway is scored 1 (regardless of the number of other pathways that could have introduced the species). The sum of these scores is calculated for each pathway.

Of these counts, the intermediate was considered the most appropriate for use in prioritising pathways, as this avoided double counting species associated with multiple pathways (i.e. total intermediate score for all pathways was the same as the number of species included in the study). The intermediate count was therefore used to rank pathways from those that introduced most to least species, with minimum and maximum scores used to indicate uncertainty in rank position.

3. Results

In total 28 pathways were identified for the 49 species of Union concern. Large proportions of species were associated with the horticultural escape (28%) or pet escape pathways (20%) (Table 1), with error bars indicating that these pathways would be priorities regardless of whether the minimum, intermediate or maximum count method was used (Fig 1). Relatively small numbers of species were associated with other pathways and error bars for these indicated that their rank position would change in many cases depending on whether a minimum, intermediate or maximum count was used (Fig 1). In total 75% of species introductions were associated with a group of eight pathways (horticultural escapes, pet escapes, zoo escapes, contaminants of nursery material (mainly soil), escaped live food and bait, contaminants of imported fish, escapes from ornamental collections and introductions via natural spread from a region outside of the UK), while 90% of introductions were associated with a total of 16 pathways (Figs 1 and 2).

The largest pathways were associated with escapes, which is arguably both intentional and unintentional. Focussing strictly on unintentional contaminant and stowaway pathways produced relatively few clear priorities, with each pathway associated with a relatively small number of species (mean = 0.8), often with wide error bars (mean min = 0.3, mean max = 2.1). Nevertheless, the top ten contaminant and stowaway pathways included: contaminants of nursery material (soil), contaminants of important fish, stowaways on ships, ballast water, stowaways on vehicles moving overland, contaminants of ornamental plants, contaminants of agricultural plants and stowaways on equipment.

4. Discussion

Horticultural escapes and pet escapes were clear priorities based on an analysis of species of Union concern. However, priorities among other pathways were less clear, with relatively small numbers of species divided between 26 different additional pathways. Of these, zoo escapes, contaminants of nursery material (soil), escapes from ornamental collections, live food and bait escapes and contaminants of imported fish were perhaps the next highest priorities (representing 75% of species introductions).

Escape pathways can be considered both intentional and unintentional, given that species are intentionally imported into an area, but that their presence outside of containment is unintentional. If only contaminant and stowaway pathways were considered for analysis the following pathways could be considered priorities: contaminants of nursery material (soil), contaminants of important fish, stowaways on ships, ballast water, stowaways on vehicles moving overland, contaminants of ornamental plants, contaminants of agricultural plants and stowaways on equipment.

The limitations of this analysis highlight the need to take a more comprehensive approach. Article 13 is designed to address unintentional pathways of introduction, yet the very large majority of species listed as being of Union concern are listed because they are deliberately imported into Member States (i.e. as ornamental plants, pets or for use in zoos). This is highlighted by the lack of marine species included on the list. If Article 4 (relating to intentional introductions) is implemented fully, the majority of these species should be of little concern. A more comprehensive approach is required that includes a wider range of species better representing contaminant and stowaway pathways.

Table 1. Pathway ranks based on introduction pathways of 49 Union concern species. Minimum = count of species exclusively associated with the pathway. Intermediate = weighted score for each pathway calculated by dividing a score of 1 between the number of pathways associated with each pathway (e.g. for a species associated with four introduction pathways each pathway would score 0.25). Maximum = count of all species associated with pathway, regardless of other pathways with which they are associated. Rank position is determined based on intermediate count (highest to lowest).

Rank	Pathway Code	Minimum	Intermediate	Maximum
1	Horticulture escape	12	13.8	17
2	Pet escape	7	9.6	14
3	Zoo or botanic garden escape	2	4.1	7
4	Nursery material contaminant	2	3.1	6
5	Ornamental escape (collections)	0	2.6	6
6	Live food and live bait escape	1	1.9	4
7	Contaminant of fish	0	1.6	5
8	Natural dispersal	0	1.2	3
9	Ship ex. ballast or hull fouling	1	1.0	1
10	Ballast water	1	1.0	1
11	Land vehicles	1	1.0	1
12	Aesthetic release	1	1.0	1
13	Contaminant of ornamental plant	0	1.0	4
14	Seed contaminant	0	0.7	3
15	Contaminant of agricultural plant	0	0.7	2
16	Machinery and equipment	0	0.7	3
17	Agriculture escape	0	0.6	2
18	Biological control	0	0.5	1
19	Contaminant of unknown plant	0	0.5	1
20	People and luggage	0	0.5	2
21	Other escape	0	0.3	1
22	Fishing equipment	0	0.3	1
23	Other stowaway	0	0.3	1
24	Hull fouling	0	0.3	1
25	Aquaculture escape	0	0.3	1
26	Other contaminant	0	0.2	1
27	Packing material	0	0.2	1
28	Container and bulk	0	0.2	1

Fig 1. Pathway ranks based on introduction pathways of 49 Union concern species, showing points based on intermediate count and error bars based on minimum and maximum count. Pathways are ordered from top to bottom based on intermediate count. Pathways above the dashed red line are associated with more than 90% of all species included in the study (using intermediate count).

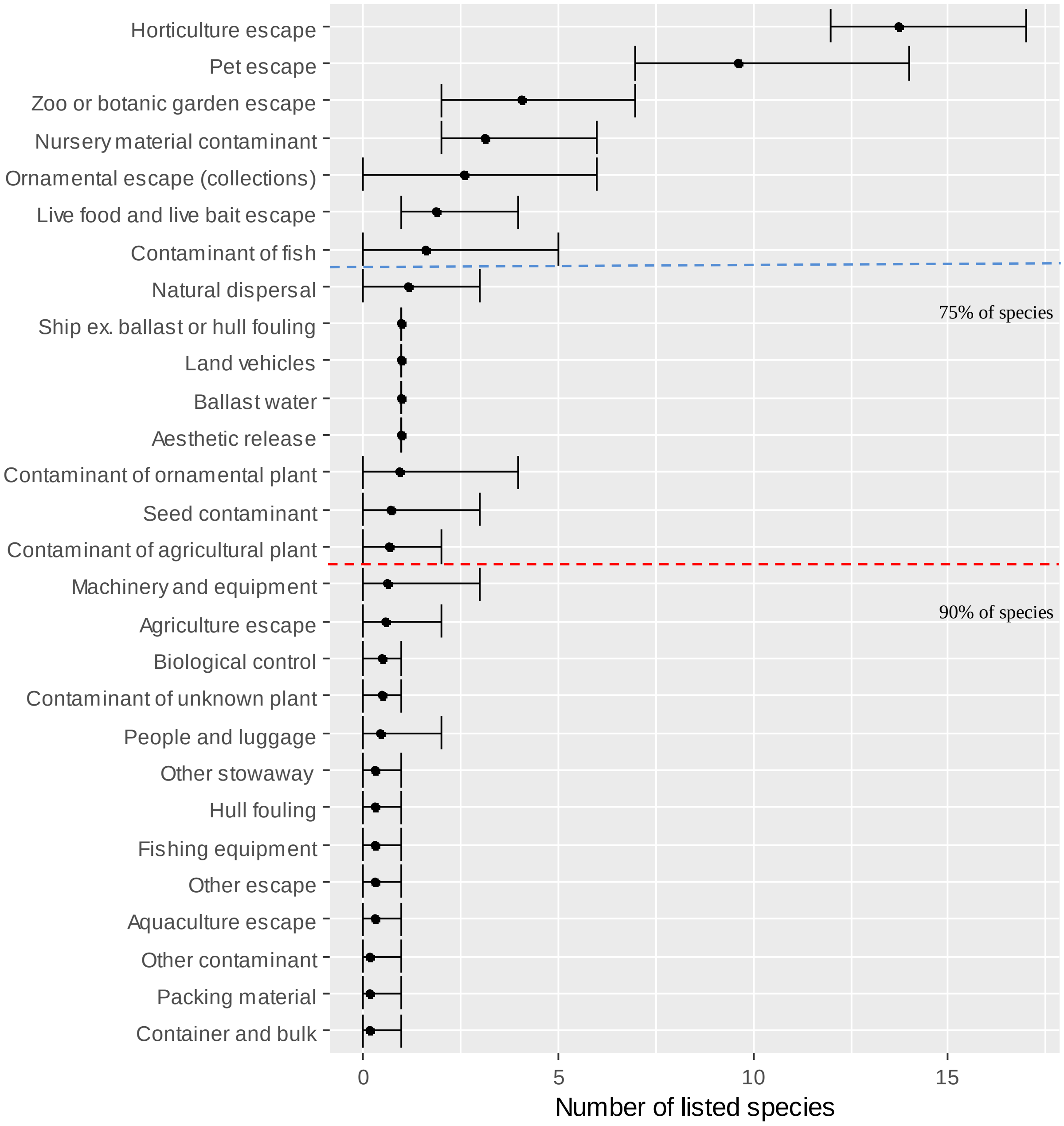
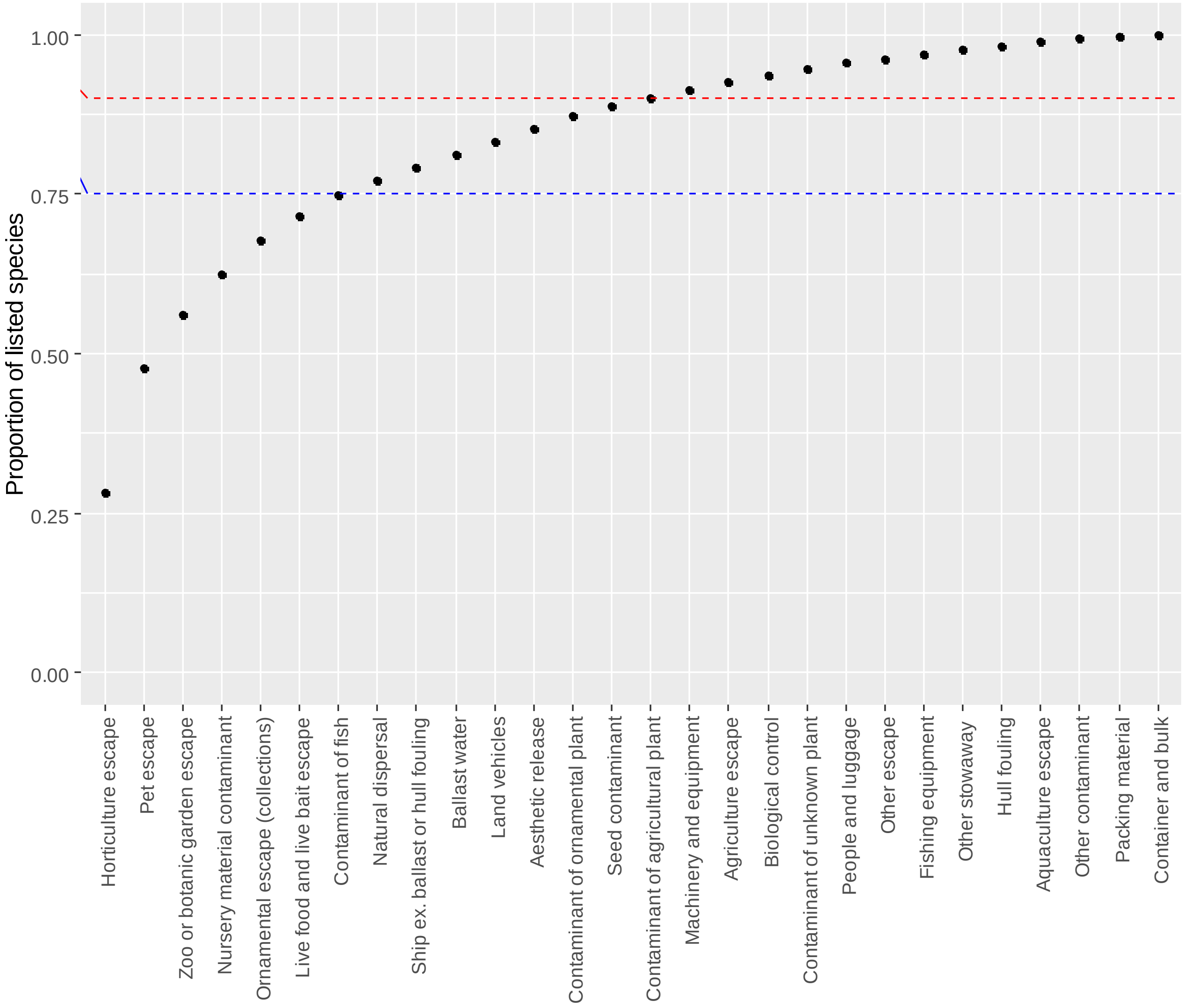


Fig 2. Cumulative proportion of Union concern species introduced by different pathways (based on weighted score for intermediate number species). 90% impact line is indicated (red dashed line)



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