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Research Article

A new approach to horizon-scanning: identifying potentially invasive alien species and their introduction pathways

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Abstract

Invasive alien species (IAS) are considered an important threat to global biodiversity due to major ecological impacts. In 2014, the European Union (EU) introduced a regulation (EU) No 1143/2014 on the prevention and management of the introduction and spread of IAS. The first risk prioritized list of IAS of EU concern was adopted on the 3rd of August 2016. EU member states are required within 18 months to carry out a comprehensive analysis and prioritisation of the pathways of unintentional introduction and spread of these IAS in their territory. Horizon-scanning is a method of IAS prioritisation through the systematic analysis of potential future IAS and identification of new opportunities for IAS management. However, horizon-scanning has mostly been applied on a national basis only, leading to a fragmented approach within the EU and ignoring the potential for IAS to cross international borders. We present a novel framework for horizon-scanning applicable at a continental scale. Our method maximises the use of available data from climatically matched countries by applying a harmonisation and aggregation method, and elucidates the relationship between pathways, impact types and species groups for risk prioritised IAS. Application of the method produced a list of potential IAS for the Netherlands revealing that the international trade in plants and animals is the most important pathway for the introduction of IAS. The horizon-scanning provided a starting point for the design of preventative, early identification and rapid action measures for the effective management of potential IAS.

Key words: ecological impact, introduction pathways, non-indigenous species, prioritisation, risk

Introduction

Invasive alien species (IAS) are species whose human aided introduction and/or spread outside their natural past or present distribution threatens biological diversity, economy and/or public health (UNEP 2014a). IAS are considered to be one of the leading causes of global biodiversity loss (Moyle et al. 1986; Vitousek et al. 1997; García-Berthou et al. 2005).

Examples of IAS that pose a high risk to native species as a result of, for example, competition and predation, include the striped skunk *Mephitis mephitis* (Schreber, 1776), curly waterweed *Lagarosiphon major* (Ridl.) Moss, fanwort *Cabomba caroliniana* A. Gray, and pumpkinseed *Lepomis gibbosus* (Linnaeus, 1758) (Kay and Hoyle 2001; Van Kleef et al. 2008; Van Belle and Schut 2011; Matthews et al. 2012, 2013). For the purposes of this article, risk is defined as a combination of the consequences of an event (hazard) and the associated likelihood/probability of its occurrence (European Commission 2010).

Most economic costs generated by IAS in Europe result from reactive eradication and control measures (Colautti et al. 2006; Vilà et al. 2010; Sinden et al. 2011). Moreover, once established, IAS can rapidly expand their range across national borders (Shirley and Kark 2006). Therefore, prevention of initial introduction and spread between member states through coordinated international action is seen as the most cost-efficient measure to combat potential impacts (Pyšek and Hulme 2005; Shirley and Kark 2006; Essl et al. 2011; European Commission 2013; UNEP 2014a). Additionally, an effective early warning system that promotes rapid action when species elude preventative measures is required (Leung et al. 2002; García-Berthou et al. 2005; Finnoff et al. 2007; Coetzee et al. 2009; European Commission 2013). For both prevention and rapid action, it is essential that IAS that are likely to invade new territories are identified (Shine et al. 2010). In 2014, the European Union (EU) introduced a regulation (EU) No 1143/2014 on the prevention and management of the introduction and spread of IAS (European Commission 2014). The first risk prioritized list of IAS of EU concern was adopted on the 3rd of August 2016. Currently, 37 species are present on the list (European Commission 2015, 2016). However, the list is open to future alteration that provides opportunities for methodological improvement and the application of new information. Moreover, within 18 months of the adoption of the list, EU member states are required to carry out a comprehensive analysis and prioritisation of the pathways of unintentional introduction and spread of IAS in their territory (European Commission 2014). Pathways are defined as the routes and mechanisms of the introduction and spread of IAS (European Commission 2014).

When applied to alien species, horizon-scanning is the systematic search for potential IAS, their impacts on biodiversity and opportunities for impact mitigation that are currently poorly recognized, that informs policy and practice (Sutherland and Woodroof 2009; Sutherland et al. 2010; Roy et al. 2014). This approach is an important tool that contributes to the prevention, early identification and eradication of IAS in Europe (Caffrey et al. 2014; Shine et al. 2010). Generally, horizon-scanning has been applied on a regional rather than EU scale, e.g. in projects by the Great Britain Non-Native Species Secretariat (Parrott et al. 2009), the Belgium Forum on Invasive Species (D'hondt et al. 2015), and the RINSE (Reducing the Impacts of Non-native Species in Europe) project that focussed on Great Britain, France, Belgium and the Netherlands (Gallardo et al. 2013). This fragmented approach to risk prioritisation hampers effective international control and, in many cases, has relied on knowledge derived from small expert groups, which may reduce certainty (European Commission 2013; Roy et al. 2014).

Invasiveness in locations with similar ecological and climatic conditions is considered one of the most relevant criteria in predicting the invasive behaviour of a species (Williamson 1996; EPPO 2012). However, previous horizon-scans often neglected this important driver of species invasion. For example, the RINSE horizon-scanning project that focussed on Belgium, the Netherlands and the United Kingdom (Gallardo et al. 2013) carried out a retrospective bioclimatic match for a proportion of analysed species but this did not influence their final species classifications. The recent horizon-scan and pathway analysis carried out by NOBANIS (2015) does not include a formal climate match. Only the European-scale horizon-scan carried out by Roy et al. (2015) considered the influence of European climate zones on the potential future establishment of IAS in different European regions. Previous horizon-scanning methods have relied on labour-intensive expert consultation and, while often presenting an overview of potential introduction pathways for individual species, many do not include systematic analyses aimed at prioritising introduction pathways (e.g., Parrott et al. 2009; D'hondt et al. 2015). The recent pathway analysis carried out by NOBANIS (2015) is limited to Nordic and Baltic countries and only examines species recorded in the NOBANIS database and Danish, Norwegian, German and Irish alert lists. While Roy et al. (2015) present a limited pathway analysis, they examine pathways at a relatively high level of abstraction, omit statistical analyses, and do not consider pathways in relation to ecological impact types. The importance of these potential shortcomings was emphasised during the 7th European Conference on Biological Invasions in Pontevedra (Spain) by the adoption of a resolution stipulating that, by 2020, IAS and their introduction pathways in Europe should be identified and prioritised, priority species are controlled or eradicated, and that pathways are managed to prevent the introduction, establishment and spread of new IAS (Neobiota 2012).

In this study, we present a novel approach to horizon-scanning that aims to address these limitations by: 1) designing a method that may be applied on any continental scale; 2) combining risk classifications derived from existing sources thereby reducing the need for expert consultation; and 3) determining the frequency and statistical significance of ecological impact types and introduction pathways to facilitate pathway prioritisation. Our method maximises the use of available data on risk classifications from countries climatically matched to the target region by applying a harmonisation and aggregation method that produces a prioritised list of potential IAS. Subsequently, an inventory of origins, pathways and impact types of these species is compiled and analysed. The inventory may facilitate policy decisions relating to prevention, early detection and eradication of the identified potential IAS.

The aims of our study were threefold:

1. To develop a horizon-scanning method that may be applied on a continental scale for identifying potential IAS absent from or with a limited distribution, amenable to prevention or early eradication measures.
2. To identify the most prevalent pathways, geographical origins and impact types associated with these potential IAS that may assist in the design and prioritisation of prevention or early eradication measures.
3. To test this method in a case study, by producing a list of potential IAS for the Netherlands and analysing their most prevalent pathways, geographical origins and impact types.

Materials and methods

Horizon-scan framework

The horizon-scan aimed to identify a list of potential IAS most likely to be amenable to effective management interventions in the target region. Risk classifications of alien species obtained from regions climatically matched to the target region were harmonised, aggregated per species, and ranked to produce a risk prioritised list of alien species. The risk prioritised list was then screened using three criteria designed to identify new alien species that are most likely to be amenable to effective management interventions due to a limited distribution in, or absence from, the target region. Subsequently, an inventory of the origins, pathways and potential impacts of the high risk species (list of potential IAS) was undertaken, which serves as a basis for the design of preventative measures, and early detection and rapid response systems. The method consists of seven steps (Figure 1):

Step 1: Risk classifications are collected using the sources listed in Supplementary material Table S1 for species that are applicable either to the target region or for any region that is climatically matched to the target region according to the Köppen-Geiger climate classification (Rubel and Kottek 2010). The climate match is made on a national scale, however, if horizon-scans or risk assessments have been carried out for a region that includes a number of different countries, e.g., Western Europe or North America, then these may be included as well. If a risk classification of a particular species already exists for the target region, then this is used instead of risk classifications from other regions. However, information underpinning risk classifications from other regions may still be relevant if it is not included in the risk analysis for the target region, and supports the results contained in the risk analysis for the target region.

Step 2: There are multiple assessment methods currently in use that apply different terms to classify the same level of risk (e.g., high risk, black list and priority species). Therefore, harmonisation of risk categories is required prior to the aggregation of classifications. Harmonisation occurs by attributing a score of 1 (low risk), 2 (medium risk) or 3 (high risk) to the risk classifications applied in the original risk assessments (see example harmonisation in the case study for the Netherlands presented in the results section and Table 1). Decisions to allocate a certain risk classification to a harmonised risk category are based on interpretation, e.g., a black listed species suggests a high risk species. The proposed classification system is then verified using expert consultation and consensus during a workshop. In the case study of the Netherlands, five to six experts per taxonomic group were consulted. Expert judgements were then verified by all contributors. In cases where there is discussion over category harmonisation, e.g., if the number of categories in a particular system varies from the three categories contained within the harmonised system, the precautionary principle should be applied (Raffensperger and Tickner 1999) and species should be assigned to the higher harmonised risk category.

Step 3: A single aggregated risk score is derived either by calculating the average of all harmonised risk scores for each species, or by applying the maximum harmonised risk score which reflects a more precautionary approach. The average score was applied in the case study of the Netherlands for two reasons:

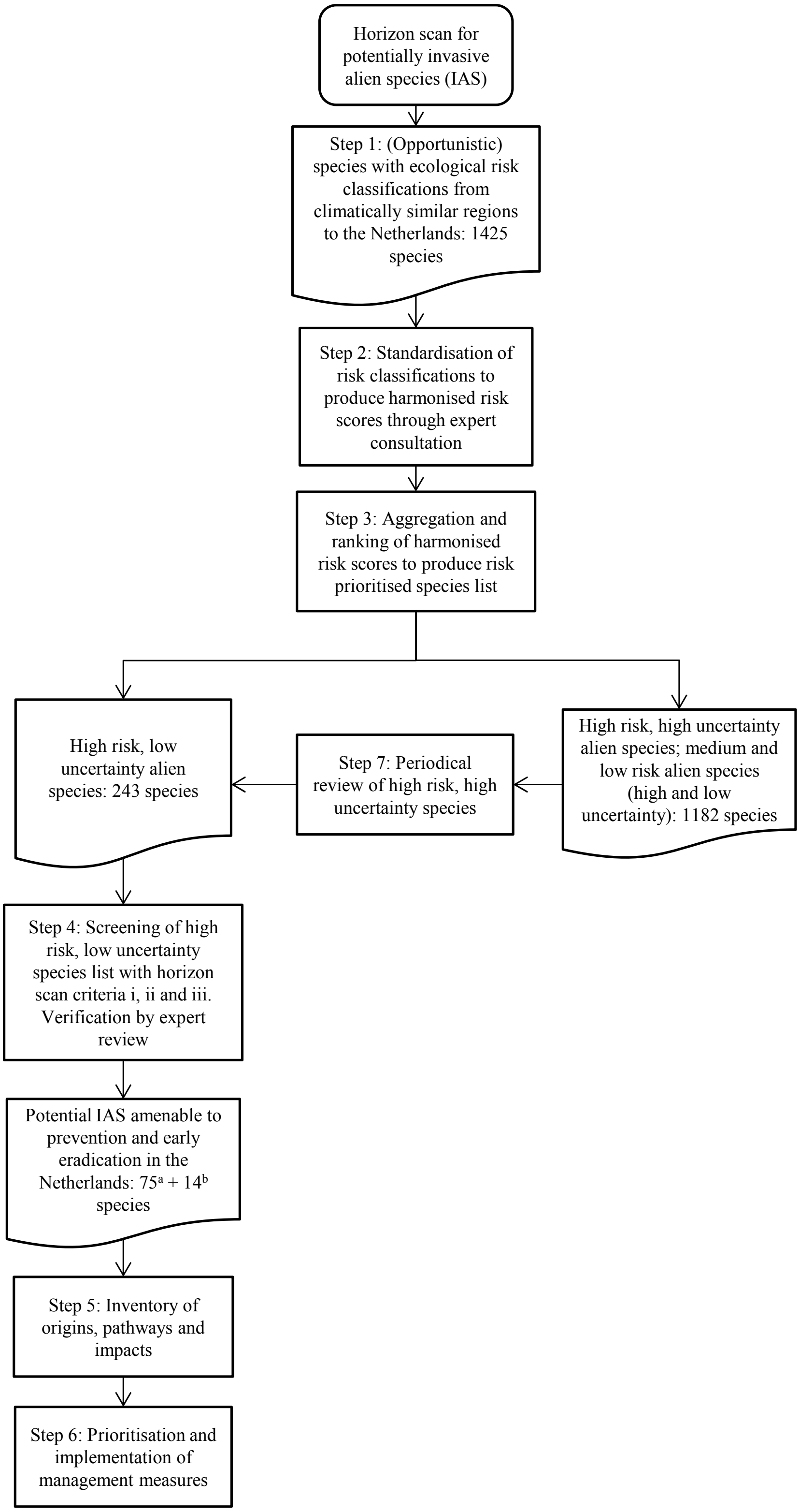


Figure 1. Processes involved in the horizon-scan method including number of species considered at each step of the Netherlands case study. [a] Number of species selected in steps one to four; [b] Number of species selected by taxonomic experts in step four.

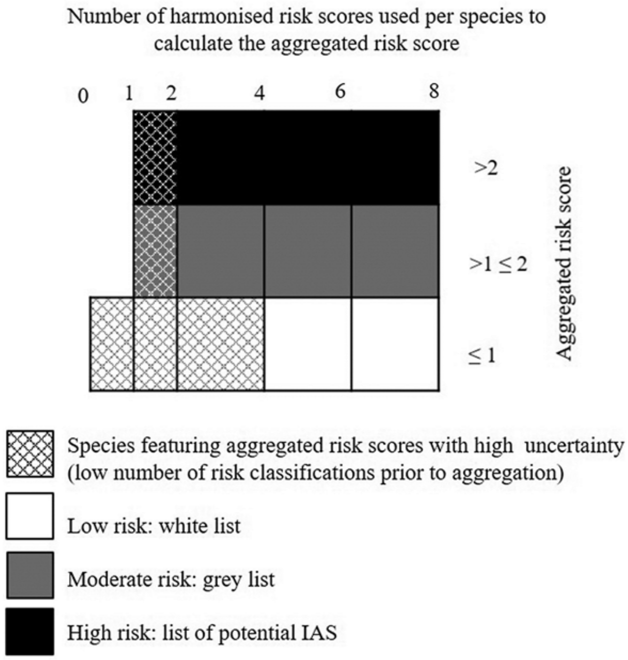


Figure 2. Matrix displaying prioritisation method for harmonised risk classifications.

1) Managers are limited in terms of the number of high risk species that can be targeted owing to resource limitations. The application of the maximum score reduces the ability of the method to discriminate between the highest risk species and other species thereby greatly increasing the number of species classified as high risk; 2) Application of the maximum score neglects lower risk classifications from other climatically matched regions. The species are then ranked according to the aggregated score in order to produce a risk-prioritised list of species from climatically matched regions. If only one harmonised risk score exists for a particular species then an aggregation of harmonised risk scores is not required, e.g., if a risk analysis has already been carried out for the target region (see Step 1).

The matrix presented in Figure 2 is a visual representation of the allocation of a final risk classification to the aggregated risk score, and how a measure of certainty is applied. Species are risk prioritised using the aggregated risk score as follows: aggregated risk score >2: high risk; aggregated risk score ≤ 2 and >1: moderate risk; aggregated risk score ≤ 1: low risk. Uncertainty thresholds were set using an arbitrary method that assumes that an aggregated risk score derived from a certain number of risk classifications is certain. This method is also dependent on the level of risk that a species poses. "Low uncertainty" is assigned to low risk, and moderate to high risk species with aggregated risk scores derived from ≥ 4 and ≥ 2 harmonised risk scores, respectively. The low risk group is allocated a stricter limit because of the potential for unobserved negative impacts. "High uncertainty" is assigned to all other species (hatched areas, Figure 2). Alternatively, certainty may be assessed by calculating the degree of variability from the mean of the underlying harmonised risk scores by deriving the standard deviation. Species ranked in groups other than the high risk, low uncertainty group should be reviewed periodically to determine whether a revision of either risk and / or certainty categories is required. For example, revisions may be required due to future climate change or if new introduction pathways are identified.

Step 4: High risk, low uncertainty alien species are then screened by experts using the following three criteria:

i. The alien species has not been recorded, but will be able to reproduce, in the target region.
ii. The alien species has been recorded, is able to reproduce, but is kept only in captivity in the target region.
iii. The alien species is able to reproduce and shows a limited distribution within the target region i.e. records exist for one or two locations only.

If the species is absent from the target area, the ability to reproduce is considered using available information from scientific literature and expert judgement in relation to climate match, habitat requirements, and the abiotic tolerances of the species in question. If the species is already present in the target region, ability to reproduce may be confirmed through the observation of a breeding population. Species fulfilling criterion i, ii or iii are classified as potential IAS for the target region amenable to prevention and early eradication. However, not all potential IAS (high risk species) will have been risk assessed for regions climatically matched to the target region and will have been excluded from steps 1 to 3. Therefore, expert consultation may be used to add species to the list of potential IAS for species where there is both a high level of certainty concerning their potential invasiveness, and their distribution complies with criteria i, ii and iii of the horizon-scan. In this case certainty is assessed according to the judgement of the relevant experts, which differs from the method applied in step 3 where the number of risk classifications is used to assess certainty.

Step 5: An inventory of the origins, pathways and potential ecological impact types of species on the list of potential IAS for the target region is undertaken by performing a literature search. The sources outlined in Table S1 were used in the literature search carried out during the Netherlands case study. Potential IAS are categorised according to habitat (e.g., terrestrial plant, freshwater animal, marine animal); taxonomy (i.e., mammals, fish, birds, amphibians, reptiles, macroinvertebrates and plants); introduction pathways utilized; and ecological impact type (i.e., competition, disease or other health effect / parasite carrier, habitat modification, predation, herbivory, introgression). Pathway information is classified according to the United Nations Environment Programme (UNEP) classification (UNEP 2014b): release in nature, escape from confinement, transport contaminant, transport-stowaway (i.e., the moving of live organisms attached to transporting vessels and associated equipment and media), and corridor (e.g., interconnected waterways). Theses pathways are divided into a number of sub-pathways that allow a more specific classification (Table S2). This system has been accepted as the official pathway classification for the EU.

Information may be obtained from horizon-scans, risk assessments, international databases and information portals, e.g., The European Network on Invasive Alien Species (NOBANIS), Delivering Alien Invasive Species Inventories for Europe (DAISIE), the Invasive Species Compendium, GB Non-native Species Secretariat), the World Register of Marine Species (WoRMS), and the European Alien Species Information Network (EASIN) (refer to Table S1 for a complete list of sources). It should be noted that, at the time of writing, DAISIE had not been updated since 2008.

Step 6: The recorded impact types of the potential IAS for the target region derived in step 5 are classified per introduction pathway and species group. The numbers of recorded impact types are then ranked to identify priority IAS groups and introduction pathways. Ranking is undertaken according to the frequency rather than severity of impact types. It is assumed that the frequency of impact types may be used to prioritise species groups and pathways for management interventions (preventative, early detection and rapid response systems), potentially leading to the greatest reduction in recorded impacts per intervention, thereby increasing cost-efficiency.

Step 7: A periodical review is recommended of all species identified as high risk with high uncertainty to determine if newly published risk assessments could lead to a reduction in the uncertainty scores. High risk species with reduced (low) uncertainty should then be screened using the criteria listed in step 4 to assess their suitability for addition to the list of potential IAS for the target region.

Case study

The horizon-scan framework was applied to create a list of potential IAS for the Netherlands that are most likely amenable to management intervention. All macro-organism species groups were considered for inclusion in the list (excludes viruses, bacteria, fungi and unicellular organisms). The Netherlands was considered climatically matched to Belgium, Germany, northern France, Denmark, Luxembourg, Ireland and England, and risk classifications for species were obtained for these regions (Step 1, Table 1). Due to resource limitations, the climate match was carried out with Western European countries only. We assume that risk assessments and horizon-scans carried out in Western Europe will incorporate species that are traded internationally and also imported from other parts of the world. Therefore, a global climate match is preferable if sufficient resources are available.

A list of additional species was obtained for the North American Great Lakes, representative of eastern American regions such as the Hudson and Chesapeake bay river basins, because of shipping pathways originating from these areas that have been strongly associated with alien species introductions to the Netherlands (Leuven et al. 2009). Subsequently, risk classifications were harmonised using the standardised risk classification displayed in Table 1, and the harmonisation method critically reviewed by

Table 1. Definition and harmonisation of individual risk classifications taken from regions climatically similar to the Netherlands.

Classification system / protocol	Category				Reference / website
Invasive Species Environmental Impact Assessment (ISEIA)		Watch list (Moderate risk)	Black list (High risk)	Alert list (High risk)	Branquart (2007); Parrott et al. (2009); http://ias.biodiversity.be
Fish Invasiveness Scoring Kit (FISK)	Low	Medium	High		Copp et al. (2009); Cefas (2010)
Danish list system			Black list	Observation list	Danish Ministry of Environment (2014)
German- Austrian black list information System (GABLIS)	White list			Black list, Grey list	Rabitsch et al. (2013); Nehring et al. (2010); Essl et al. (2011)
UK-adapted Australian Weed Risk Assessment	Low risk	Moderate risk	Urgent, critical		Thomas (2010)
RINSE meta-list			Black list	Alert list	Gallardo et al. (2013)
North American Great Lakes[b]			Non-indigenous[a]	Watch list[a]	GLANSIS (2014)
Irish risk classification system			Priority list (most unwanted, amber)[a]	Watch list (most unwanted, amber)[a]	Kelly et al. (2013)
Invasive species list			Listed[a]		Muséum national d'Histoire naturelle (2013)
Standardised risk classification	1	2	3	3	

[a] Species classified as high risk according to the precautionary principle (Raffensperger and Tickner 1999); [b] National Oceanic and Atmospheric Administration – NOAA, Great lakes aquatic nonindigenous species information system – GLANSIS.

experts from a number of Dutch environmental organisations during a workshop (Step 2). The organisations involved included consultancies in nature conservation (Bargerveen Foundation, Natuurbalans-Limes Divergens), non-governmental organisations specialized in ecological field surveys and data compilation for various taxonomic groups, The Mammal Society (Bureau van de Zoogdiervereniging); Reptile, Amphibian and Fish Conservation Netherlands (RAVON); Sovon, The Dutch Centre for Field Ornithology; The Netherlands Floristic Research Foundation (FLORON); and the Radboud University, Institute for Water and Wetland Research, Department of Environmental Science and Department of Animal Ecology and Physiology.

Harmonised risk scores were aggregated by calculating the average score (aggregated risk score). Species were risk prioritised according to their aggregated risk scores (Step 3, Figure 2). The experts representing the organisations listed above were requested to screen species classified as high risk and low uncertainty by applying the horizon-scan criteria (Step 4). The resulting list comprised potential IAS that are amenable to prevention and early eradication measures in the Netherlands (Table S3).

Information on habitat type, taxonomical group, pathways and ecological impact types derived during the inventory and analysis (Steps 5 and 6) was collected during a literature search from a variety of sources (Table S1) using the official scientific name as the search term for each species according to the Integrated Taxonomic Information System (ITIS 2016). These data were supplemented by information found in all available Dutch, Belgian and British risk assessments carried out for these species. Additionally, a statistical analysis examining the significance of each introduction pathway, shared by different IAS, to the number of recorded ecological impact types recorded for those IAS was carried out by applying Chi squared and Fisher's exact tests. Data for the statistical analysis was obtained during the literature search. A significant result suggests that management of the introduction pathway may lead to a reduction in the recorded impacts of the IAS related to it. Valid results were obtained from the Chi-squared tests of the escape from confinement and transport stowaway pathways only. All other pathway data sets violated the assumptions of Chi-squared and a Fisher's exact test was applied instead of Chi-squared in these cases. The level of association between significantly related pathway types and ecological impact types was analysed using Cramer's V statistic. Statistical analyses were carried out using IBM SPSS 20.

Table 2. Risk prioritised species.

Prioritisation matrix colour code[a]	Aggregated risk score	Number of species	Uncertainty
	>2	75[b]	Low
	>2	600	High
	>1 and ≤ 2	31	Low
	>1 and ≤ 2	117	High
	≤ 1	0	Low
	≤ 1	434	High

[a] Refer to Figure 2; [b] Seventy five species were derived from the horizon-scan method. A further fourteen were added based on expert judgement. In total eighty nine species were prioritised as high risk species (potential IAS for the Netherlands).

Results

The number of species considered at each step of the case study horizon-scan for the Netherlands is displayed in Figure 1.

List of species that have been evaluated for ecological risk in regions climatically matched to the Netherlands

Risk classifications determined for regions climatically matched to the Netherlands were collected for 1425 species, hybrids, varieties and subspecies (Step 1; Figure 1). The number of risk classifications collected per species ranged from one to eight. Following the harmonisation, aggregation and ranking of risk scores (Steps 2 and 3) 243 species were prioritised as high risk, low uncertainty species.

Risk prioritised species amenable to prevention or early eradication in the Netherlands

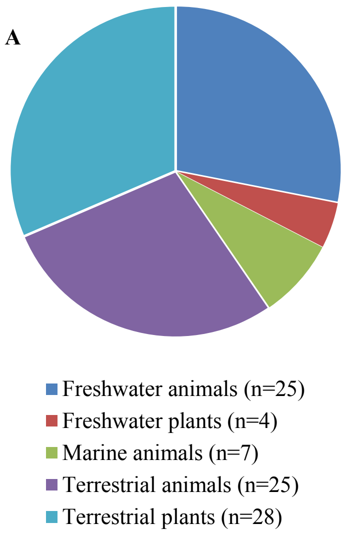
Of the 243 high risk, low uncertainty species, 75 satisfied the horizon-scan criteria and were classified as potential IAS amenable to prevention and early eradication in the Netherlands (list of potential IAS for the Netherlands). Fourteen additional potential IAS were added based on expert judgement (Step 4).

The 1182 high risk (high uncertainty), and medium and low risk (high and low uncertainty) alien species were not screened with the horizon-scan criteria due to time and budgetary limitations. Six hundred of the 1182 species were allocated to the high risk, high uncertainty list; 31 species were allocated to the medium risk, low uncertainty list; 117 species were allocated to the medium risk, high uncertainty list; zero species were allocated to the low risk, low uncertainty list and 434 species were allocated to the low risk, high uncertainty list (Table 2, Figure 2).

Inventory of list of potential IAS for the Netherlands (Steps 5 and 6)

Freshwater and terrestrial animals and terrestrial plants appeared most frequently on the list of potential IAS for the Netherlands, followed by marine animals and freshwater plants (Figure 3a). Asia and North America were the most frequently listed geographical origins (native range) of concern, followed by Russia, South America, Africa and southern Europe (Figure 3b). Hybrid species were considered not to have a native range. The pathway utilised most frequently for potential IAS for the Netherlands was escape from confinement (Figure 4a). The most frequently utilised sub-pathways classified under the escape from confinement pathway were the pet and aquarium trade, and introductions for ornamental purposes, both of which are associated mainly with freshwater and terrestrial animals, and terrestrial plants. Terrestrial plants are associated with the horticulture sub-pathway, while the botanical and zoological garden sub-pathway is utilised mainly by terrestrial plants and animals.

Identification of introduction pathways associated with IAS that cause the highest number of ecological impact types allows prevention measures to be applied



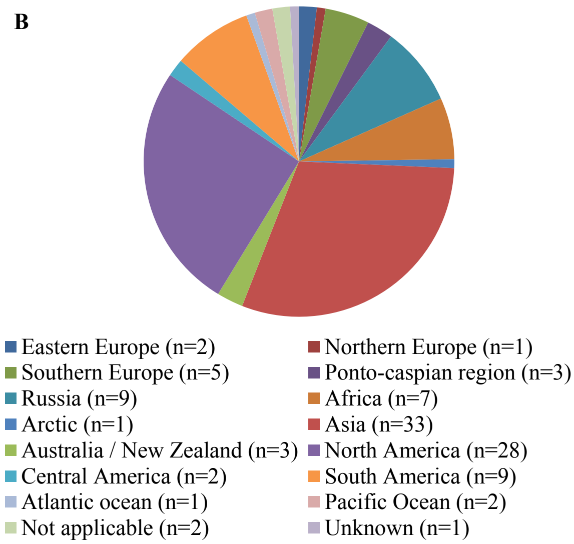


Figure 3. (A) Relative contribution of ecosystem groupings to the list of potential IAS for the Netherlands; (B) Geographic origin of species present on the list of potential IAS for the Netherlands.

on a wider and potentially more cost-effective scale than measures aimed at individual IAS. Overall, the escape from confinement pathway was associated with the highest number of ecological-impact types attributed to the potential IAS for the Netherlands, followed by the transport stowaway and transport contaminant pathways (Figure 4b). The most frequently occurring impact types that were attributed to species utilising the escape from confinement pathway were competition with native species, followed by habitat modification, and disease or other health effect/parasite carrier. Impact types associated most frequently with the transport stowaway pathway were competition, predation, and habitat modification. The most frequently occurring impact types relating to the transport contaminant pathway were competition, predation, and disease or other health effect/parasite carrier.

The results of the Chi-squared and Fisher's exact tests indicated that there is a significant relationship between the tested pathways and the number of ecological impact types χ^2 (5) = 14.052, $P < 0.05$ and $P < 0.05$ respectively. Cramer's V statistic was 0.22 ($P < 0.05$) indicating a moderate association between the escape from confinement and transport–stowaway pathways, and the number of ecological impact types. Therefore, effective management interventions targeting the introduction pathways of potential IAS rather than individual species may be an effective approach leading to reductions in the number of ecological impacts recorded.

Figure 5 details the number of ecological impact types attributed to sub-pathways classified under escape from confinement. The identification of sub-pathways encourages further improvements in cost-effectiveness by targeting specific sub-pathways associated with IAS with the highest number of impact types. The highest frequency of impact types occurred for the pet and aquarium trade, followed by the trade in ornamentals and escapes from botanical gardens, zoos or aquaria. Of these three sub-pathways, competition, habitat modification and disease or other health effect/parasite carrier impact types were most frequently recorded.

Discussion

Horizon-scanning framework

This study presents a novel framework for horizon-scanning that maximally benefits from existing national and regional knowledge, such as horizon-scans, risk assessments and invasive species lists, by applying a harmonisation and aggregation method to risk classifications that produces a list of potential IAS amenable to prevention and early eradication measures for a target region. The framework may be applied on a national, international or continental scale. Only species with an existing risk classification from climatically matched regions can be included in our horizon-scanning approach. Other species are assessed using expert judgement. However, the application of

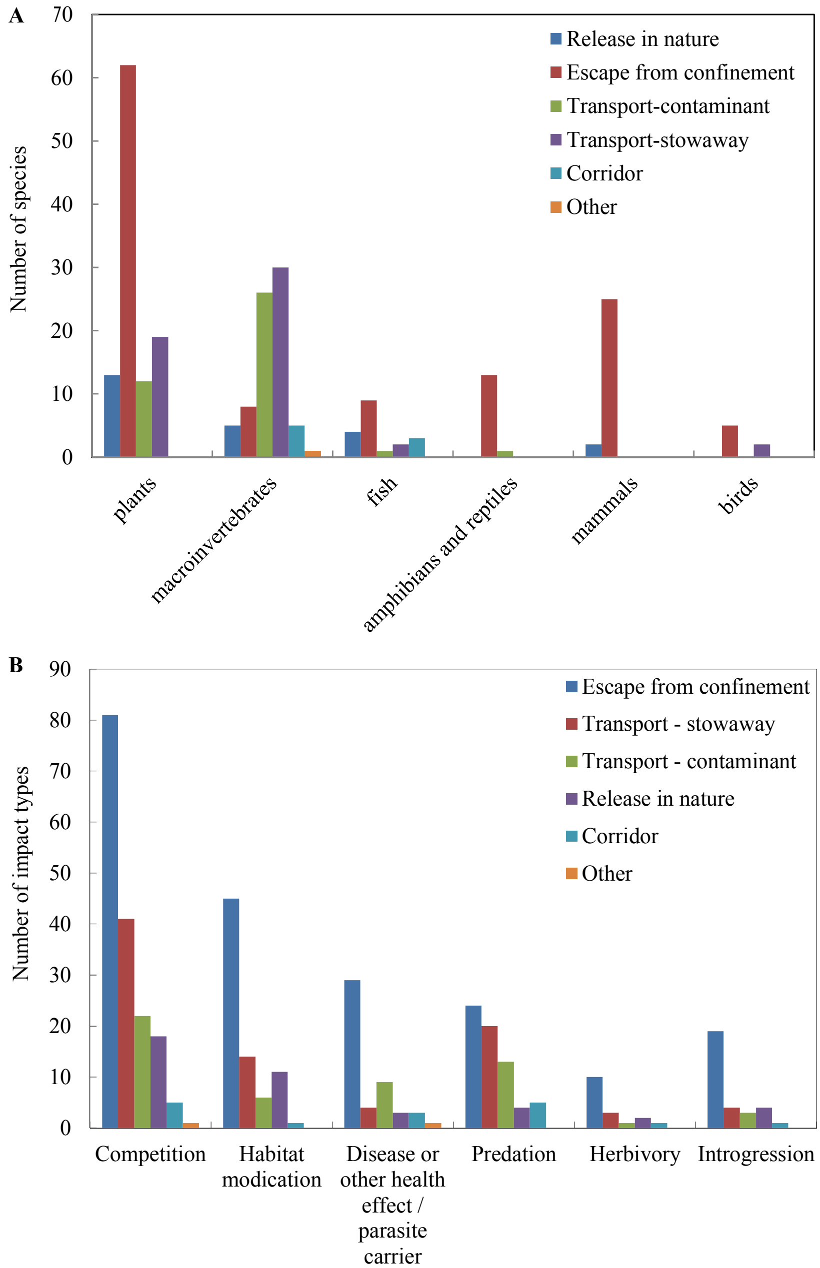


Figure 4. (A) Possible introduction pathways of potential IAS to the Netherlands per taxonomic group; (B) Number of impact types recorded in regions climatically matched to the Netherlands per introduction pathway.

existing classifications greatly reduces the number of species requiring expert judgement compared with traditional risk prioritisation methods. Expert judgement may be supplemented by a literature study examining, for example, species traits that may increase the risk of invasiveness in the target region.

The horizon-scanning process aimed to produce a list of invasive alien species that are likely to negatively impact biodiversity in the target region (high risk species with low uncertainty). The list provides a strong basis for cost-efficient management measures. Expert judgement was applied to verify this high risk list and identify other high risk species omitted from the list because they were not previously risk prioritised or assessed for climatically matched regions. Expert knowledge was not used to screen the 600 high risk, high uncertainty species because of time and budgetary limitations. However, further screening using expert judgement may be applied if time and budget allows.

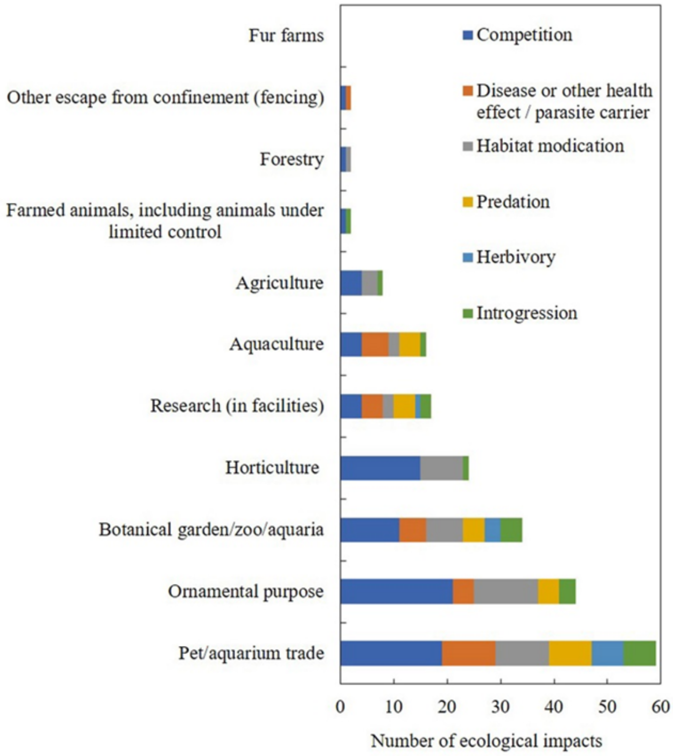


Figure 5. Occurrence of impact types per pathway classified as escape from confinement.

A number of sources of uncertainty have been identified during the design and application of the horizon-scan framework. The principle that existing risk classifications may be applied to other, climatically matched regions is supported by Wittenberg and Cock (2001) who state that the only variable consistently correlated with invasiveness in one region is invasiveness elsewhere (Verbrugge et al. 2012b). However, regional differences in assessment methodology will introduce uncertainty. Ecological impacts vary and are weighted differently according to region-specific habitat characteristics and conservation aims (Verbrugge et al. 2012b). During the harmonisation process we assumed that the risk level is the same even though risk classifications differ. Moreover, variation between risk classifications may also stem from local environmental variables other than those controlled for when a climate match is applied, e.g., predator abundance, vegetation cover and soil type. To reduce this uncertainty and resolve possible inconsistencies between national risk classifications, only species that received a high risk rating in two or more of the surrounding countries are included in the list of potential IAS for the target region. Moreover, the application of the precautionary principle when harmonising risk categories prior to the aggregation of harmonised risk scores and when interpreting the potential impacts of IAS reduces the potential for underestimation of risks. Finally, it could not be established with certainty whether criterion 3 of the horizon-scan was fulfilled by a high proportion of alien macro-invertebrate species due to a limited direct availability of distribution data for the Netherlands.

During the application of the horizon-scan framework, either the average or the maximum harmonised risk score may be used to derive the aggregated risk score for a particular species. Uncertainty reduction is a requirement of the EU regulation on IAS and will also facilitate public support and acceptance by stakeholders. The average aggregated risk score was derived from all harmonised risk scores for a particular species that leads to a reduction in influence of individual methodologies, knowledge obtained from small expert groups, locally specific habitat conditions and varying national conservation goals. However, the application of the maximum risk score is in agreement with the precautionary principle (Raffensperger and Tickner 1999) and the observation that the only variable consistently correlated with invasiveness in one region is invasiveness elsewhere (Wittenberg and Cock 2001). It is expected that, contrary to an approach using the average score, the application of the maximum score will produce a relatively long list of high risk species which may require further risk prioritisation and may be impractical in view of limited budgets. The average aggregated risk score was used in the case study of the Netherlands in order to produce a relatively short list of potential IAS directly amenable to cost-effective management interventions.

The horizon-scan framework omits alien species that have not been previously risk assessed in climatically matched regions. Moreover, due to resource limitations, the case study includes a climate match between the Netherlands and other European countries only, which may have resulted in the omission of risk classified alien species originating from climate matched regions outside Europe. It is recommended that a climate match is undertaken between the target region and all other countries or regions. High risk species assessed in regions not climatically matched to the target region may become invasive in the target region because of a climatic tolerance that is not reflected in their global distribution. To account for this, more emphasis is focused on the identification of dominant introduction pathways during the meta-analysis. The results of the analysis can be used in the design of pathway-based measures that indirectly target potential IAS that use dominant pathways but not identified during the horizon-scan. In addition, expert knowledge is applied to add potential IAS that either have broad environmental tolerances or have not been previously assessed for climatically matched regions, but are considered, with a high degree of certainty, to pose a high ecological risk to the target region and fulfil at least one of the horizon-scan criteria. However, expert knowledge may not always be objective, accurate, consistent or reproducible (Hulme 2012). To counter this, our horizon-scan method utilises experts from multiple organisations representing as many taxonomic groups as possible. Taxon bias may be reduced by ensuring that specialists are equally distributed over taxonomic groups and have similar experience. The consultation of experts with complementary knowledge across taxonomic groups and environments ensures a broad collective knowledge base to undertake a comprehensive horizon-scan in an open, rigorous and time-efficient way (Roy et al. 2014). Moreover, by using all available horizon-scans and priority lists from climatically matched countries, the results of a wide range of assessments based on multiple expert opinions are aggregated, significantly reducing the effect of potential individual errors. However, it is important to note the unpredictable nature of IAS introductions and the resulting imperfect nature of horizon-scanning lists (Roy et al. 2014). For example, a determination of the actual temperature tolerance of a species can only be carried out under laboratory conditions due to the multitude of potentially confounding factors that exist in the field. Moreover, alien species that may not establish in an average year, may establish during years characterised by temperature extremes, with the advent of future climate change, or in urban locations where local climate conditions may be more favourable (Vermonden et al. 2010; Leuven et al. 2011; Verbrugge et al. 2012a; Collas et al. 2014). However, a precautionary approach to climate matching which takes inter-annual temperature extremes and climate change into account could address this issue. These potential limitations suggest that the horizon-scanning framework should be viewed as a single tool in a suite of measures to aid the design of management interventions aimed at preventing the impacts of potential IAS.

Case study results

Our results pertaining to the geographical origin of the list of potential IAS for the Netherlands (Figure 3c) are supported by Welcomme (1991), Vilà et al. (2010) and García-Berthou et al. (2005), who state that, in contrast to other taxa such as plants and terrestrial vertebrates, freshwater species introduced to Europe come mostly from North America and enter through mid-latitude countries in Western Europe (France, the UK, and Germany).

Trade pathways are frequently linked to potential IAS introductions globally (Bowmer et al. 1995; Randall and Marinelli 1996; Kay and Hoyle 2001; Perrings et al. 2005; Westphal et al. 2008; Brunel 2009; Matthews et al. 2013). For example, one third of the aquatic species listed in the Invasive Species Specialist Group's top 100 worst invasive species, and 40% of plant species introductions to Europe in general are attributed to the trade in ornamental plants (Padilla and Williams 2004; Gooijer et al. 2010; Martin and Coetzee 2011). This is similar to the combined contribution made by the ornamental and aquarium plant trade, and landscape or floral improvement pathways observed in our study (35% of all introductions of potential IAS). Internet retailing, and plant and animal hobbyist forums facilitate international transactions (Kay and Hoyle 2001; Westbroek 2014; Faulkes 2015; Humair et al. 2015; Mazza et al. 2015), and are implicated in the introduction of a number of species in the Netherlands, e.g., curly waterweed (*Lagarosiphon major*), fanwort (*Cabomba caroliniana*), striped skunk (*Mephitis mephitis*), Reeves' muntjac (*Munctiacus reevesi* (Ogilby, 1839)), sika deer (*Cervus nippon* Temminck, 1838) and non-native squirrel species (Van Belle and Schut 2011; Matthews et al.

2012a; Matthews et al. 2013; Dijkstra 2014; Hollander 2015).

We observed a high frequency of impact types relating to the pet and aquarium trade, and the trade in ornamentals and escapes from botanical gardens, zoos or aquaria. This combined with the statistically significant relationships observed for introduction pathways and ecological impact types suggests that effective management interventions focussing on these pathways will yield the largest reduction in the number of ecological impacts of potential IAS for the Netherlands. A single pathway focussed intervention may prevent the introduction of many potential IAS. For example, voluntary covenants may prevent the introduction of multiple potential IAS via trade pathways (Verbrugge et al. 2014). In the absence of punitive tariffs, watertight trade regulations and certainty in risk assessment (Perrings et al. 2005), preventative measures, early detection and rapid response systems that focus on pathways management represent the frontline in the prevention of biological invasions (Hulme 2009).

Implications for policy

The EU is introducing a system of prevention, early detection and rapid response measures to protect member states against the impacts of IAS (European Commission 2014, 2015). Important elements of this system are the comprehensive analysis of pathways of unintentional introduction and spread of IAS in member states and the identification of pathways which require priority action (European Commission 2013). The horizon-scan and inventory presented here address this need by firstly identifying potential IAS and secondly identifying pathways and impact types specific to these species. The identification of priority pathways will assist in the design of effective border controls consisting of a targeted and cost-effective surveillance system that facilitates the rapid response to invasions required by the EU (European Commission 2013). Regular updates to the list of potential IAS and identification of newly emerging introduction pathways by periodically repeating the horizon-scan will facilitate the early detection of potential IAS in the target region. For example, ecosystem change brought about by habitat modifiers (eco-engineers) is one of the most dramatic ecological effects of IAS (Crooks 2002). If habitat modifiers are introduced disproportionately through a particular pathway, that pathway should be prioritised. Furthermore, impact analyses per introduction pathway may be incorporated into a pathway-based risk analysis that is used to assess and manage all risks moving along the same pathway and, for example, provide input for the design of instruments to prevent IAS introduction such as blacklisting, the direct regulation of pathways such as ballast water, and codes of conduct (Shine et al. 2010; Matthews et al. 2012b; Verbrugge et al. 2014). The horizon-scan method may also be used to establish a white list of low risk species (Shine et al. 2010), that could be applied on an EU scale. Any species not on this white list would require screening prior to importation to an EU member state.

Future research

Uncertainty and the application of expert knowledge continue to pose a challenge for the assessment of potential impacts of IAS in regions where the species are absent. Moreover, the assertion that impacts that occur in one region will occur in another, based on a climate match alone, neglects the fact that successful invasion depends on multiple other environmental variables such as predator-prey interactions, competition with native species and diseases. Future research should be aimed at reducing these areas of uncertainty in the risk assessment of IAS. Additionally, an exploration of alternative approaches to the validation of standardised risk scores, additional to expert consultation, is desirable. Future methodological development may be aimed at revealing the contribution that risk assessment methods make to the aggregated risk score, relative to less rigorous risk prioritisation methods. Further research that identifies the relative severity of impacts in climatically matched regions may improve the accuracy of risk prioritisation and assessment of IAS and their introduction pathways. It is recommended that further research is conducted on the distribution of alien macro-invertebrate species with suspected limited distribution in the Netherlands and that future horizon-scans consider microorganisms and meiofauna. In addition, symbionts, parasites and commensals were not considered in this study and future updates to the horizon-scan for potential IAS in the Netherlands should incorporate these species groups.

Conclusion

The novel approach to horizon-scanning presented here may be applied on any continental scale, maximises the use of available data from climatically matched countries, and elucidates the relationship between species groups, pathways and impacts. Horizon-scanning provides a starting point for the design of preventative, early identification and rapid action measures for the effective management of potential IAS.

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References

Bowmer KH, Jacobs SWL, Sainty GR (1995) Identification, biology and management of *Elodea canadensis*, Hydrocharitaceae. *Journal of Aquatic Plant Management* 33: 13–19

Branquart E (ed) (2007) Guidelines for environmental impact assessment and list classification of non-native organisms in Belgium. Belgian Biodiversity Platform, Belgium, 4 pp

Brunel S (2009) Pathway analysis: aquatic plants imported in 10 EPPO countries. *OEPP/EPPO Bulletin* 39: 201–213, https://doi.org/10.1111/j.1365-2338.2009.02291.x

Caffrey JM, Baars J-R, Barbour JH, Boets P, Boon P, Davenport K, Dick JTA, Early J, Edsman L, Gallagher C, Gross J, Heinimaa P, Horrill C, Hudin S, Hulme PE, Hynes S, MacIsaac HJ, McLoone P, Millane M, Moen TL, Moore N, Newman J, O'Conchuir R, O'Farrell M, O'Flynn C, Oidtmann B, Renals T, Ricciardi A, Roy H, Shaw R, Weyl O, Williams F, Lucy FE (2014) Tackling invasive alien species in Europe: the top 20 issues. *Management of Biological Invasions* 5: 1–20, https://doi.org/10.3391/mbi.2014.5.1.01

Cefas (2010) Decision Support Tools, Identifying Potentially Invasive Non-native Marine and Freshwater Species: Fish, Invertebrates, Amphibians. http://www.cefas.co.uk/projects/risks-and-impacts-of-non-native-species/decision-supporttools (accessed 25 August 2014)

Coetzee JA, Hill MP, Schlange D (2009) Potential spread of the invasive plant *Hydrilla verticillata* in South Africa based on anthropogenic spread and climate suitability. *Biological Invasions* 11: 801–812, https://doi.org/10.1007/s10530-008-9294-2

Colautti RI, Bailey SA, Van Overdijk CDA, Amundsen K, MacIsaac HJ (2006) Characterised and projected costs of nonindigenous species in Canada. *Biological Invasions* 8: 45–59, https://doi.org/10.1007/s10530-005-0236-y

Collas FPL, Koopman KR, Hendriks AJ, Verbrugge LNH, van der Velde G, Leuven RSEW (2014) Effects of desiccation on native and non-native molluscs in rivers. *Freshwater Biology* 59: 41–55, https://doi.org/10.1111/fwb.12244

Copp GH, Vilizzi L, Mumford J, Fenwick GV, Godard MJ, Gozlan RE (2009) Calibration of FISK, an invasiveness screening tool for nonnative freshwater fishes. *Risk Analysis* 29: 457–467, https://doi.org/10.1111/j.1539-6924.2008.01159.x

Crooks JA (2002) Characterizing ecosystem-level consequences of biological invasions: the role of ecosystem engineers. *Oikos* 97: 153–166, https://doi.org/10.1034/j.1600-0706.2002.970201.x

Danish Ministry of Environment (2014) Invasive Arter. http://naturstyrelsen.dk/naturbeskyttelse/invasive-arter/ (accessed 02 August 2014)

D'hondt B, Vanderhoeven S, Roelandt S, Mayer F, Versteirt V, Adriaens T, Ducheyne E, San Martin G, Grégoire JC, Stiers I, Quoilin S, Branquart E (2015) Harmonia+ and Pandora+: risk screening tools for potentially invasive plants, animals and their pathogens. *Biological Invasions* 17: 1869–1883, https://doi.org/10.1007/s10530-015-0843-1

Dijkstra V (2014) Amerikaanse rode eekhoorn. *Nieuwsbrief Kijk op Exoten* 7: 14–15

Essl F, Nehring S, Klingenstein F, Milasowszky N, Nowack C, Rabitsch W (2011) Review of risk assessment systems of IAS in Europe and introducing the German-Austrian Black List Information System (GABLIS). *Journal for Nature Conservation* 19: 339–350, https://doi.org/10.1016/j.jnc.2011.08.005

EPPO (2012) EPPO prioritization process for invasive alien plants. *Bulletin OEPP/Bulletin* 42: 463–474

European Commission (2010) Common staff working paper: Risk assessment and mapping guidelines for disaster management. European Commission, Brussels, Belgium, 42 pp

European Commission (2013) Proposal for a regulation of the European parliament and of the council on the prevention and management of the introduction and spread of invasive alien species. European Commission, Brussels, Belgium, 36 pp

European Commission (2014) Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species. *Official Journal of the European Union* 317: 35–55

European Commission (2015) Adopting a list of invasive alien species of Union concern pursuant to Regulation (EU). Draft commission implementing regulation (EU). European Commission, Brussels, Belgium, 3 pp

European Commission (2016) Commission implementing regulation (EU) 2016/1141 of 13 July 2016 adopting a list of invasive alien species of Union concern pursuant to Regulation (EU) No 1143/2014 of the European Parliament and of the Council. *Official Journal of the European Union* 189: 1–4

Faulkes Z (2015) The global trade in crayfish as pets. *Crustacean Research* 44: 75–92, https://doi.org/10.18353/crustacea.44.0_75

Finnoff D, Shogren JF, Leung B, Lodge D (2007) Take a risk: preferring prevention over control of biological invaders. *Ecological Economics* 62: 216–222, https://doi.org/10.1016/j.ecolecon.2006.03.025

Gallardo B, Zieritz A, Aldridge DC (2013) Targeting and prioritisation for INS in the RINSE project area. Cambridge Environmental Consulting, Cambridge, United Kingdom, 98 pp

García-Berthou E, Alcaraz C, Pou-Rovira Q, Zamora L, Coenders G, Feo C (2005) Introduction pathways and establishment rates of invasive aquatic species in Europe. *Canadian Journal of Fisheries and Aquatic Sciences* 62: 453–463, https://doi.org/10.1139/f05-017

GLANSIS (2014) Great Lakes Non-indigenous Species Information System. http://www.glerl.noaa.gov/res/Programs/glansis/glansis.html (accessed 23 August 2014)

Gooijer Y, Terryn L, Elferink E, van der Weijden W (2010) Pathways of non-native species introductions to the Netherlands. Report CLM 737-2010. Foundation Centre for Agriculture and the Environment, Culemborg, the Netherlands, 56 pp

Hollander H (2015) Reeves' muntjac (*Munctiacus reevesi*) and sika deer (*Cervus nippon*) in the Netherlands. *Lutra* 58: 45–50

Hulme PE (2009) Trade, transport and trouble: managing invasive species pathways in an era of globalization. *Journal of Applied Ecology* 46: 10–18, https://doi.org/10.1111/j.1365-2664.2008.01600.x

Hulme PE (2012) Weed risk assessment: a way forward or a waste of time? *Journal of Applied Ecology* 49: 10–19, https://doi.org/10.1111/j.1365-2664.2011.02069.x

Humair F, Humair L, Kuhn F, Kueffer C (2015) E-commerce trade in invasive plants. *Conservation Biology* 29: 1658–1665, https://doi.org/10.1111/cobi.12579

ITIS (2016) The Integrated Taxonomic Information System. http://www.itis.gov/ (accessed 11 February 2016)

Kay SH, Hoyle ST (2001) Mail order, the internet, and invasive aquatic weeds. *Journal of Aquatic Plant Management* 39: 88–91

Kelly J, O'Flynn C, Maguire C (2013) Risk analysis and prioritisation for invasive and non-native species in Ireland and Northern Ireland. A report prepared for the Northern Ireland Environment Agency and National Parks and Wildlife Service as part of Invasive Species Ireland, 59 pp

Leung B, Lodge DM, Finnoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society B-Biological Sciences* 269: 2407–2413, https://doi.org/10.1098/rspb.2002.2179

Leuven RSEW, Hendriks AJ, Huijbregts MAJ, Lenders HJR, Matthews J, van der Velde G (2011) Differences in sensitivity of native and exotic fish species to changes in river temperature. *Current Zoology* 57: 852–862, https://doi.org/10.1093/czoolo/57.6.852

Leuven RSEW, Van der Velde G, Baijens I, Snijders J, Van der Zwart C, Lenders HJR, Bij de Vaate A (2009) The river Rhine: a global highway for dispersal of aquatic invasive species. *Biological Invasions* 11: 1989–2008, https://doi.org/10.1007/s10530-009-9491-7

Martin GD, Coetzee JA (2011) Pet stores, aquarists and the internet trade as modes of introduction and spread of invasive macrophytes in South Africa. *Water SA* 37: 371–380, https://doi.org/10.4314/wsa.v37i3.68488

Matthews J, Beringen R, Collas FPL, Koopman KR, Odé B, Pot R, Sparrius LB, van Valkenburg JLCH, Verbrugge LNH, Leuven RSEW (2012a) Knowledge document for risk analysis of the non-native Curly Waterweed (*Lagarosiphon major*) in the Netherlands. Radboud University, Nijmegen, the Netherlands. Reports Environmental Science 414, 43 pp

Matthews J, Van der Velde G, Bij de Vaate A, Leuven RSEW (2012b) Key factors for spread, impact and management of *Quagga mussels* in The Netherlands. Radboud University, Nijmegen, the Netherlands. Reports Environmental Science 404, 120 pp

Matthews J, Beringen R, Lamers LPM, Odé B, Pot R, van der Velde G, van Valkenburg JLCH, Verbrugge LNH, Leuven RSEW (2013) Knowledge document for risk analysis of the non-native Fanwort (*Cabomba caroliniana*) in the Netherlands. Radboud University, Nijmegen, the Netherlands. Reports Environmental Science 443, 46 pp

Mazza G, Aquiloni L, Inghilesi AF, Giuliani C, Lazzaro L, Ferretti G, Lastrucci L, Foggi B, Tricarico E (2015) Aliens just a click away: the online aquarium trade in Italy. *Management of Biological Invasions* 6: 253–261, https://doi.org/10.3391/mbi.2015.6.3.04

Moyle PB, Li HW, Barton BA (1986) The Frankenstein effect: impact of introduced fishes on native fishes in North America. In: Stroud RH (ed), Fish Culture in Fisheries Management. American Fisheries Society, Bethesda, United States of America, pp 415–426

Muséum national d'Histoire naturelle (ed) (2013) Inventaire National du Patrimoine Naturel. http://inpn.mnhn.fr/accueil/index (accessed 23 August 2014)

Nehring S, Essl F, Klingenstein F, Nowack C, Rabitsch W, Stöhr O, Wiesner C, Wolter C (2010) Schwarze Liste invasiver Arten: Kriteriensystem und Schwarze Listen invasiver Fische für Deutschland und für Österreich. BfN-Skripten 285, Bonn, Germany, 185 pp

Neobiota (2012) Time to act! Biological invasions need a strong European legal framework urgently! RESOLUTION adopted by the participants of the "7th European Conference on Biological Invasions" of the European Working Group on Biological Invasions – NEOBIOTA. http://www.oekosys.tu-berlin.de/fileadmin/fg35/Forschung/Downloads/Neobiota/Resolution_2012.pdf (accessed 15 October 2015)

NOBANIS (2015) Invasive alien species pathway analysis and horizon scanning for countries in northern Europe. TemaNord 2015:517, Nordic Council of Ministers, Copenhagen, Denmark, 229 pp, https://www.nobanis.org/globalassets/nobanis-projects/invasive-alien-species---pathway-analysis-and-horizon-scanning-for-countries-in-northern-europe.pdf (accessed 23 December 2016)

Padilla DK, Williams SL (2004) Beyond ballast water: aquarium and ornamental trades as sources of invasive species in aquatic ecosystems. *Frontiers in Ecology and the Environment* 2: 131–138, https://doi.org/10.1890/1540-9295(2004)002[0131:BBWAAO]2.0.CO;2

Parrott D, Roy S, Baker R, Cannon R, Eyre D, Hill M, Wagner M, Preston C, Roy H, Beckmann B, Copp GH, Edmonds N, Ellis J, Laing I, Britton JR, Gozlan RE, Mumford J (2009) Horizon scanning for new invasive non-native animal species in England. Natural England, Sheffield, United Kingdom, 111 pp

Perrings C, Dehnen-Schmutz K, Touza J, Williamson M (2005) How to manage biological invasions under globalization. *Trends in Ecology & Evolution* 20: 212–215, https://doi.org/10.1016/j.tree.2005.02.011

Pyšek P, Hulme PE (2005) Spatio-temporal dynamics of plant invasions: linking pattern to process. *Ecoscience* 12: 302–315, https://doi.org/10.2980/i1195-6860-12-3-302.1

Rabitsch W, Gollasch S, Isermann M, Starfinger U, Nehring S (2013) Erstellung einer Warnliste in Deutschland noch nicht vorkommender invasiver Tiere und Pflanzen. BfN-Skripten 331, Bonn, Germany, 154 pp

Raffensperger C, Tickner J (eds) (1999) Protecting Public Health and the Environment: Implementing the Precautionary Principle. DC: Island Press, Washington, USA, 411 pp

Randall JM, Marinelli J (1996) Invasive Plants: Weeds of the Global Garden. Brooklyn Botanic Garden, Brooklyn, New York, United States of America, 111 pp

Roy HE, Adriaens T, Aldridge DC, Bacher S, Bishop JDD, Blackburn TM, Branquart E, Brodie J, Carboneras C, Cook EJ, Copp GH, Dean HJ, Eilenberg J, Essl F, Gallardo B, Garcia M, García-Berthou E, Genovesi P, Hulme PE, Kenis M, Kerckhof F, Kettunen M, Minchin D, Nentwig W, Nieto A, Pergl J, Pescott O, Peyton J, Preda C, Rabitsch W, Roques A, Rorke S, Scalera R, Schindler S, Schönrogge K, Sewell J, Solarz W, Stewart A, Tricarico E, Vanderhoeven S, van der Velde G, Vilá M, Wood CA, Zenetos A (2015) Invasive alien species – Prioritising prevention efforts through horizon scanning ENV.B.2/ETU/2014/0016. European Commission, 227 pp

Roy HE, Peyton J, Aldridge DC, Bantock T, Blackburn TM, Britton R, Clark P, Cook E, Dehnen-Schmutz K, Dines T, Dobson M, Edwards F, Harrower C, Harvey MC, Minchin D, Noble DG, Parrott D, Pocock MJO, Preston CD, Roy S, Salisbury A, Schönrogge K, Sewell J, Shaw RH, Stebbing P, Stewart AJA, Walker KJ (2014) Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. *Global Change Biology* 20: 3859–3871, https://doi.org/10.1111/gcb.12603

Rubel F, Kottek M (2010) Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorologische Zeitschrift* 19: 135–141, https://doi.org/10.1127/0941-2948/2010/0430

Shine C, Kettunen M, Genovesi P, Essl F, Gollasch S, Rabitsch W, Scalera R, Starfinger U, Ten Brink P (2010) Assessment to support continued development of the EU Strategy to combat invasive alien species. Final Report for the European Commission. Institute for European Environmental Policy (IEEP), Brussels, Belgium, 297 pp

Shirley SM, Kark S (2006) Amassing efforts against alien invasive species in Europe. *PloS Biology* 4: 1311–1313, https://doi.org/10.1371/journal.pbio.0040279

Sinden J, Gong W, Jones R (2011) Estimating the costs of protecting native species from invasive animal pests in New South Wales, Australia. *Environmental & Resource Economics* 50: 203–226, https://doi.org/10.1007/s10640-011-9468-8

Sutherland WJ, Bardsley S, Bennun L, Clout M, Côté IM, Depledge MH, Dicks LV, Dobson AP, Fellman L, Fleishman E, Gibbons DW, Impey AJ, Lawton JH, Lickorish F, Lindenmayer DB, Lovejoy TE, Nally RM, Madgwick J, Peck LS, Pretty J, Prior SV, Redford KH, Scharlemann JP, Spalding M, Watkinson AR (2010) A horizon scan of global conservation issues for 2010. *Trends in Ecology & Evolution* 25: 1–7, https://doi.org/10.1016/j.tree.2009.10.003

Sutherland WJ, Woodroof HJ (2009) The need for environmental horizon scanning. *Trends in Ecology & Evolution* 24: 523–527, https://doi.org/10.1016/j.tree.2009.04.008

Thomas S (2010) Here today, here tomorrow? Horizon scanning for invasive non-native plants. Plantlife International, Salisbury, United Kingdom, 19 pp

UNEP (2014a) Convention on Biological Diversity (CBD). http://www.cbd.int/ (accessed 23 August 2014)

UNEP (2014b) Pathways of Introduction of Invasive Species, Their Prioritization and Management. Note by the Executive Secretary. UNEP Convention on Biological Diversity, Subsidiary Body On Scientific, Technical and Technological Advice eighteenth meeting, Montreal, 23–28 June 2014. https://www.cbd.int/doc/meetings/sbstta/sbstta-18/official/sbstta-18-09-add1-en.pdf (accessed 14 August 2014)

Van Belle J, Schut J (2011) Risicoanalyse stinkdieren in Nederland. Altenburg & Wymenga Ecologisch Onderzoek, Feanwâlden, the Netherlands. A&W rapport 1629, 17 pp

Van Kleef H, van der Velde G, Leuven RSEW, Esselink H (2008) Pumpkinseed sunfish (*Lepomis gibbosus*) invasions facilitated by introductions and nature management strongly reduce macro-invertebrate abundance in isolated water bodies. *Biological Invasions* 10: 1481–1490, https://doi.org/10.1007/s10530-008-9220-7

Verbrugge LNH, Schipper AM, Huijbregts MAJ, van der Velde G, Leuven RSEW (2012a) Sensitivity of native and non-native mollusc species to changing river water temperature and salinity. *Biological Invasions* 14: 1187–1199, https://doi.org/10.1007/s10530-011-0148-y

Verbrugge LNH, Van der Velde G, Hendriks AJ, Verreycken H, Leuven RSEW (2012b) Risk classifications of aquatic non-native species: application of contemporary European assessment protocols in different biogeographical settings. *Aquatic Invasions* 7: 49–58, https://doi.org/10.3391/ai.2012.7.1.006

Verbrugge LNH, Leuven RSEW, van Valkenburg JLCH, van den Born RJG (2014) Evaluating stakeholder awareness and involvement in risk prevention of aquatic invasive plant species by a national code of conduct. *Aquatic Invasions* 9: 369–381, https://doi.org/10.3391/ai.2014.9.3.11

Vermonden K, Leuven RSEW, van der Velde G (2010) Environmental factors determining invasibility of urban waters for exotic macroinvertebrates. *Diversity and Distributions* 16: 1009–1021, https://doi.org/10.1111/j.1472-4642.2010.00702.x

Vilà M, Basnou C, Pysek P, Josefsson M, Genovesi P, Gollasch S, Nentwig W, Olenin S, Roques A, Roy D, Hulme PE, DAISIE partners (2010) How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. *Frontiers in Ecology and the Environment* 8: 135–144, https://doi.org/10.1890/080083

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. *Science* 277: 494–499, https://doi.org/10.1126/science.277.5325.494

Welcomme RL (1991) International introductions of freshwater fish species into Europe. *Finnish Fisheries Research* 12: 11–18

Westbroek S (2014) Exotic mammals in trade and captivity in the Netherlands: Risks of establishment as a precursor to invasiveness. Bureau van de Zoogdiervereniging, Nijmegen, the Netherlands. Report number 2015.032

Westphal MI, Browne M, Mackinnon K, Noble I (2008) The link between international trade and the global distribution of invasive alien species. *Biological Invasions* 10: 391–398, https://doi.org/10.1007/s10530-007-9138-5

Williamson MH (1996) Biological Invasions. Chapman & Hall, London, United Kingdom, 244 pp

Wittenberg R, Cock MJW (eds) (2001) Invasive alien species: A toolkit of best prevention and management practices. CAB International, Wallingford, United Kingdom, 228 pp

Supplementary material

The following supplementary material is available for this article:

Table S1. Overview of information sources.

Table S2. Categorisation of pathways for the introduction of alien species (adapted from UNEP 2014b).

Table S3. List of potential IAS amenable to prevention and early eradication measures in the Netherlands.

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