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Research article

The economic costs, management and regulation of biological invasions in the Nordic countries

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ABSTRACT

A collective understanding of economic impacts and in particular of monetary costs of biological invasions is lacking for the Nordic region. This paper synthesizes findings from the literature on costs of invasions in the Nordic countries together with expert elicitation. The analysis of cost data has been made possible through the InvaCost database, a globally open repository of monetary costs that allows for the use of temporal, spatial, and taxonomic descriptors facilitating a better understanding of how costs are distributed. The total reported costs of invasive species across the Nordic countries were estimated at $8.35 billion (in 2017 US$ values) with damage costs significantly outweighing management costs. Norway incurred the highest costs ($3.23 billion), followed by Denmark ($2.20 billion), Sweden ($1.45 billion), Finland ($1.11 billion) and Iceland ($25.45 million). Costs from invasions in the Nordics appear to be largely underestimated. We conclude by highlighting such knowledge gaps, including gaps in policies and regulation stemming from expert judgment as well as avenues for an improved understanding of invasion costs and needs for future research.

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1. Introduction

Invasive alien species (IAS), defined by the EU as those alien species whose introduction or spread has been found to threaten or adversely impact upon biodiversity and related ecosystem services (EU, 2014) are considered the second greatest driver of biodiversity loss (Bellard et al., 2016). In addition to impacts to biodiversity and ecosystem services, they can impose severe human health risks (Stoett et al., 2019) and negatively impact economies and livelihoods (Diagne et al., 2021; Shackleton et al., 2019). Several international policies (e.g. Convention on Biological Diversity, European Regulation 1143/2014, hereinafter EU IAS Regulation) are now in place to prevent the introduction of IAS and mitigate their negative impacts. Besides these EU-level and international agreements, regional bodies are also in place to identify and tackle the growing threats of IAS among countries that historically trade intensively, exhibit similar IAS introduction pathways, and have overlapping biogeographies. For example, the European Network on Invasive Alien Species (NOBANIS project) started as a Nordic collaboration funded by the Nordic Council of Ministers to respond to the recommendations from the 6th meeting of the Convention on Biological Diversity in 2002 (NOBANIS, n.d.).

The Nordic region consists of Denmark, Norway, Sweden, Finland, Iceland, and the autonomous territories connected to these states (i.e. the Faroe Islands, Greenland, Svalbard and Åland). The Nordic countries form a distinctive region by virtue of their strong historical ties and the tradition of intergovernmental cooperation across national boundaries (Czarny, 2017). Among others, two key factors distinguish this region from the rest of Europe in terms of patterns of biological invasions. First, the colder climate and snow- and ice cover at higher latitudes affect species survival and have so far largely limited the number of species that have successfully established (Kaiser and Kourantidou, 2021). Second, trade and trading routes may historically have been less intensive in the Nordic region compared to central and southern Europe, because of its location on the periphery of the continent, seasonal ice cover, and political developments restricting international trade. These factors may have contributed to reduced IAS incursions in Nordic countries compared to others (Seebens et al., 2017), but also, their identification and impacts may have equally been understudied and lack synthetic assessment. Nevertheless, there is no clear-cut evidence in support of this argument and for certain species the available evidence suggests trans-Arctic invasions and trans-Atlantic transfers of species, facilitated through natural shifts (i.e. opening of the Bering Strait in the Pilocene) and anthropogenic activity (i.e. the trips of Vikings) (see more details in Essink and Oost (2019) for the case of *Mya arenaria*).

In many parts of the Nordic region, particularly those in the Arctic, there are still many uncertainties regarding species distributions and impacts of IAS, especially in remote areas that are difficult to access and conduct research. This challenge is pronounced in the Arctic marine environment where costs of field work are high and frequency of data collection is limited (Kaiser and Kourantidou, 2021). The first national strategies to structure the response to the incursion of alien species and map the spread, abundance and impacts of IAS were published in 2007 in Norway, in 2008 in Sweden, in 2012 in Finland, and in 2014 in Denmark (adopted in 2015 - L317/35, 2014). The first legally binding act, that also applies to the Nordic countries (with the exception of Norway and Iceland), is the EU IAS Regulation that came into force in 2015. No national strategy on IAS has been developed in Iceland thus far.

Despite a plethora of ecological impact studies, distribution assessments and other natural science research on IAS in the Nordic countries and adjacent systems (AMAP, 2017; Bevanger, 2021; Wasowicz et al., 2020), socio-economic aspects remain understudied particularly in Arctic contexts (Kourantidou et al., 2015) and, in particular, a collective understanding of costs of invasions across the region is still lacking. This gap in knowledge hinders decision making for policy and cross-country collaboration in the area, such as where management spending would be most efficient and which areas need further research. To address this challenge and highlight existing knowledge gaps in costs of invasions in the Nordic region, we utilized the latest version of the InvaCost database, the largest and most comprehensive database to date that brings together and standardizes monetary costs from negative impacts of IAS derived from peer-reviewed and grey literature across the globe (Diagne et al., 2020). This version of the database contains detailed information on the costs (e.g. cost types, impacted sectors, regional attributes, cost estimation reliability, etc.) associated with over 1100 IAS, 80 of which have recorded costs in the Nordic countries. Using InvaCost along with expert knowledge, we assess the state-of-the-art on negative economic impacts of IAS in the Nordic region. This also allows us to highlight knowledge gaps and research unevenness across different dimensions. Specifically, we explore how cost reporting is distributed across space, time, taxonomic groups, cost types and sectors of the economy affected, which, combined with regional expert knowledge, help shed light on needs and priorities for management and policy design on IAS in the Nordics.

2. Materials and methods

2.1. InvaCost database and complementary searches

This paper presents findings from a systematic literature review and expert elicitation on economic costs of IAS in Nordic countries. Monetary costs were available from InvaCost, a global repository dedicated to monetary cost estimates of IAS-related expenditures (Diagne et al., 2020, 2021). Since its first publication, this living-database has been updated three times to include more species (especially plants), non-English sources, and data from recent years, namely 2017–2020. The current InvaCost v4.1 database includes 300 data entries for Sweden, Denmark, Iceland, Finland, and Norway. These InvaCost entries comprise sources in English and non-English literature (Angulo et al., 2021); 22 languages are now included in the latest version. This database version (4.1) included a supplemental literature search including local Nordic languages and utilized input from country experts. Expert teams for each country followed a standardized procedure to search for additional sources, using (1) a variety of search engines, including Web of Science, Google Scholar, Google, and opportunistic searches using (2) national online resources with potentially relevant information (including government websites and repositories of grey literature), (3) researchers' personal contacts and (4) their own specialized knowledge (see Supplementary material File 1 for more details). Each country's expert team summarized their key findings in a qualitative manner (Supplementary material File 3) and offered reflection on the broader implications for IAS management and national strategies.

2.2. Data obtained and data processing

The supplementary search focuses on Nordic countries only and encompasses Nordic languages, resulting in 40 new reference documents (Denmark: 15, Finland: 8, Iceland: 4, Norway: 6, Sweden: 7). This more than quadruples the number of entries from 70 (in InvaCost 3.0) to 300 in version 4.1 of InvaCost. The supplementary search also provided the first species-specific data on monetary costs for Iceland. We did not find any literature on economic costs of IAS for the Faroe Islands or Greenland; note though that relevant targeted language searches were not performed (e.g. Faroese or Greenlandic). We checked for spatial, temporal or other overlaps in cost entries and when this was the case we retained the cost for the longest period and/or the largest area. We also prioritized species-specific costs over lump sum costs including multiple species. We did not remove any overlapping entries related to potential costs, e.g. for different management strategies for a species or potential damage if no management occurs, as these are all potential costs that have been described for a species and could occur. The dataset used for the analysis is provided in Supplementary material file 4 (Nordic database).

Cost data in InvaCost are standardized to a common currency (2017 US$) for comparability given the heterogeneous nature of the underlying studies. For the standardization, the World Bank's market exchange rate was used and inflation was accounted for using the Consumer Price Index of the year the cost was estimated for in each study (Diagne et al., 2020). However, given that costs are reported over different durations, we annualised each cost such that a row of data or a single data entry corresponds to a single year. This conversion was performed using the *expandYearlyCosts* function of the *invacost* R package (Leroy et al., 2020), whereby the total cost over a given period (e.g. $1 million over 10 years) is divided across those years (i.e. $100 thousand per year). This process also conservatively removed any cost entries that occurred over an unspecified time period (i.e. unknown probable starting and/or ending years), so as not to bias temporal trends towards certain years (Leroy et al., 2020). The cost entries that included non-Nordic countries (2 entries in our dataset on the species *Marenzelleria* spp.), were excluded from the analysis, as part of our conservative approach to estimating costs. This filtering and expansion process resulted in 706 expanded entries. Note, that even though InvaCost 4.1 was used for the analysis, the number of the expanded entries has been corrected for some references like Paini et al. (2016) (relevant period of probable starting and ending year corrected to 2016–2016), resulting in a small number of entries than InvaCost 4.1 would normally yield (751).

Most of the data were collected having in mind a time horizon of up to 2020. Considering however that opportunistic searches were conducted (through contacts with regional experts for example) and that some of the costs included projections/extrapolation for the future, there are costs referring to 2021. To assess temporal trends of invasion costs across the Nordic countries over time, we considered 10-year means since 1960 (the first year with published invasion costs). We examined costs as a function of the "Impact year", which reflects the time at which invasion costs likely occurred based on probable starting and ending years (Leroy et al., 2020). In this way we obtained an estimate of annual average costs over the entire reported period, for all costs considered. For producing temporal trends, we used the *summarizeCosts* function of the *invacost* package (Leroy et al., 2020), illustrating decadal averages in costs across the Nordic countries.

2.3. Cost descriptors

InvaCost records costs across a range of descriptors to catalogue the type of cost, source material information, temporal duration, among others. Here, we used the following descriptors to analyse costs to Nordic countries (see Diagne et al. (2020) and online "Descriptors" document at doi.org/10.6084/m9.figshare.12668570 for further information): a) Method reliability: reflecting the perceived reliability of the type of publication and cost estimation methodological approach; estimates from pre-assessed materials (peer-reviewed articles and official reports), or from grey material but with documented, reproducible and traceable methods, were designated as "High" reliability; all other entries were designated as having a "Low" reliability; b) Implementation: logging whether the cost was realized or empirically incurred ("Observed") or whether it was based on predictions or costs expected over time or space ("Potential"); c) Country: reporting the official country where the cost was incurred; d) Type of cost: describing whether the cost falls under the category of "Damage" (damages or losses due to the invasions, i.e., costs for repair, resource losses, medical care), "Management" (expenditure such as control, monitoring, prevention, eradication) or "Mixed" (a combination of both or cases where reported costs could not be distinguished); e) Impacted sector: demarking the sector affected by each cost (e.g. agriculture, fisheries, forestry, health); f) Environment: recording which environment type the species causing the cost is associated with i.e. aquatic, semi-aquatic, terrestrial (per the official InvaCost definition semi-aquatic refer to species that either habitually utilizes both aquatic and terrestrial habitats, for reproduction, development and/or foraging-e.g. *Aedes albopictus, Neogale vison* (formerly named *Mustela vison* and *Neovison vison*)*, Branta canadensis* or emergent plant species that commonly occurs in wetlands e.g. *Phragmites australis, Spartina alterniflora*); g) Taxonomy: taxonomic units of each cost, from kingdom through to subspecies (as per the available information); h) Publication year: referring to the year that the study and/or costs were published. In those cases where information was unclear among certain categories, for example, if costs spanned multiple sectors simultaneously and could not be distinguished therein or if costs were incurred from multiple or unspecified taxa (except where those multiple taxa were defined), or countries, they were categorised as "Diverse/Unspecified". At the national level, we also present total costs qualified by the population densities of each country. Since human populations among the Nordic countries are considerably different (e.g., Iceland vs Sweden), and both damage and management costs relate to human population size (Haubrock et al., 2021c), qualifying national costs using human population density provides a basis to forecast the costs per person over a consistent unit of space.

3. Results

3.1. Reliability and implementation of costs in Nordic region

Between 1960 and 2021, the total reported cost of IAS across the Nordic countries was estimated at $8.35 billion (in 2017 US$ values), which is the result of 284 database cost entries, expanding to 706 annual estimates. Most of those costs were derived from highly reliable sources (Fig. 1). Additionally, the majority of the costs (~77%) for the region were derived from predictions or expectations ("Potential" costs, $6.47 bil), rather than costs that were realized or empirically observed ("Observed" costs, $1.89 bil; Fig. 1). However, a good proportion (~70%) of the "Observed" costs were deemed as highly reliable based on the method of estimation ($1.32 bil) (Note that small differences in decimals (rounding errors) may lead to small discrepancies between the numbers depicted in this Figure and the ones discussed in the text). Close to half of the cost entries in the database originated from references in Nordic languages (Norwegian ~15.1%, Danish ~17.5%, Swedish ~5.7%, Finnish ~4%, Icelandic ~0.3%) and the rest from references in English (57.3%) (4 entries were available in both English and Finnish, but have been classified under the "English" language references for estimating those percentages).

The largest share of invasion costs was recorded in Norway ($3.23 bil.) followed by Denmark ($2.20 bil.), Sweden ($1.45 bil.) and Finland ($1.11 bil.), while reported costs in Iceland were substantially smaller ($25.45 mil.). When "Observed" costs were only considered, Norway was still the first in terms of invasion costs, but those were reduced by about three times in magnitude ($846.16 mil.), with Sweden ranked second ($389.15 mil.) and Denmark third ($207.29 mil.), followed by Finland ($64.76 mil.) and Iceland ($20.21 mil.; Fig. 1).

When qualified based on population density (persons per km^2; Worldometer data for 2020; https://www.worldometers.info/population/europe/northern-europe/), Norway had the highest total cost ($215 mil.), then Finland ($61.7 mil.), Sweden ($58.0 mil.), Denmark ($16.1 mil.) and Iceland ($8.48 mil.). Considering qualified observed costs by this population density, Norway remained highest ($56.4 mil.), then Sweden ($15.6 mil.), Iceland ($6.74 mil.), Finland ($3.6 mil.) and Denmark ($1.51 mil.).

3.2. Types of costs and environments affected

For a large portion of total costs, there was no specification of the environment in which the IAS caused monetary costs (40%, $3.34 bil.). Costs of terrestrial IAS reached $3.13 bil., followed by costs from aquatic taxa with $1.67 bil., and lastly semi-aquatic taxa with $0.22 bil. Interestingly, when only "Observed" costs were considered, aquatic costs made up more than half the costs (60%, $1.14 bil.) and terrestrial costs

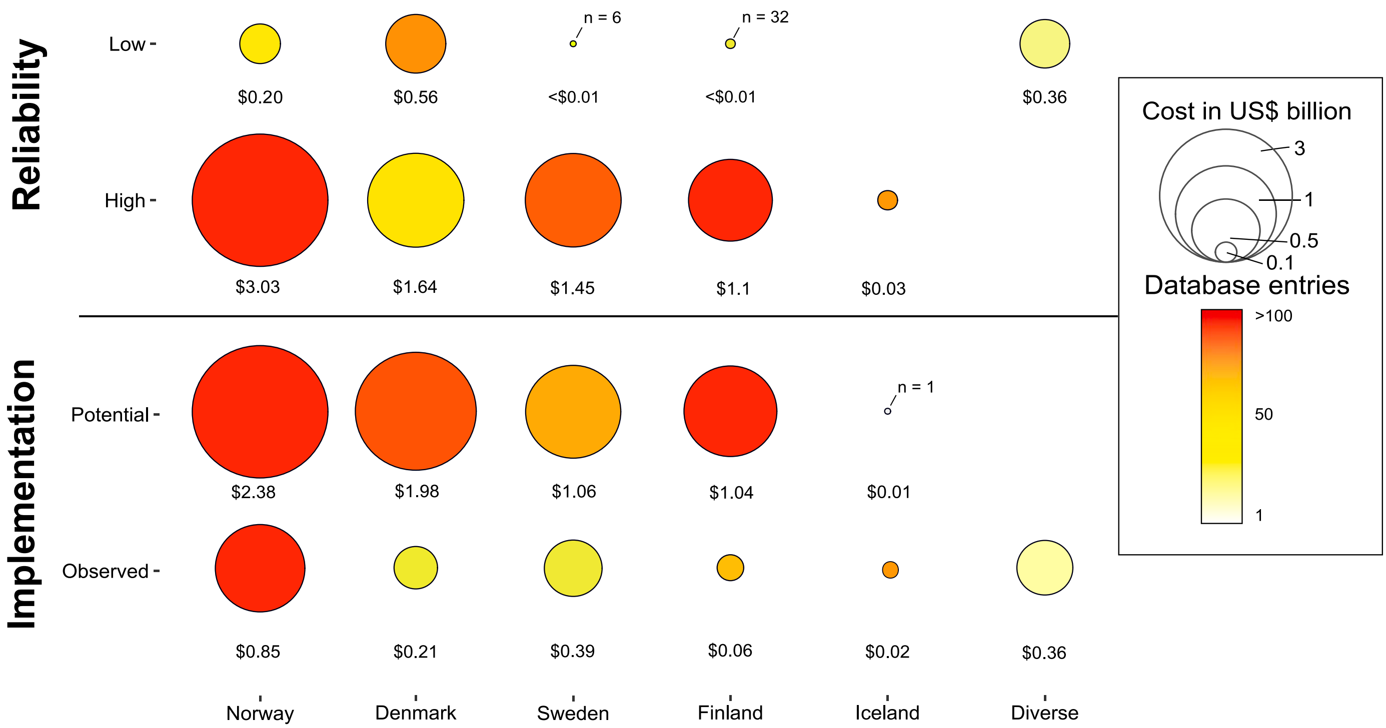

Fig. 1. Balloon plot indicating total published invasion costs and expanded cost entry numbers for Nordic countries, according to method reliability ("High" or "Low") and implementation ("Observed" or "Potential"). The colours of each balloon indicate the number of expanded database entries and their size indicates the magnitude of costs embedded in each category (billion US$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

followed (35%, $0.66 bil.) (see Fig. 2). Costs to both diverse/unspecified and semi-aquatic environments contributed less than $0.1 bil. each.

In Norway, "Observed" costs were predominantly from aquatic IAS, particularly owing to the salmon fluke, while in Denmark and Sweden, terrestrial IAS caused the highest costs (Fig. 3a). Invasion costs in Finland were largely from mixed groups of species attributed to multiple environments, whereas the only reported observed costs in Iceland were for a single semi-aquatic IAS (i.e. American mink, *Neogale vison*) (Fig. 3a).

The vast majority of costs associated with biological invasions across the Nordic countries were due to damages or losses (total costs: 63%, $5.28 bil.; observed costs: 80% $1.52 bil.), followed by management costs (total costs: 36%, $3.02 bil.; observed costs: 17%, $0.32 bil.). Mixed costs contributed $0.06 bil. from the overall total costs and equally $0.06 bil. when observed costs were considered (Supplementary material File 2 Fig. 1). Reported damage costs were higher than management expenditure in Norway and Sweden, but the reverse trend was found for Denmark and Iceland; Finland had largely unspecified, i.e. Mixed cost types, thus the costs could not be distinguished (Fig. 3b).

Overall, when considering total costs (the sum of potential and observed costs) the agricultural industry was the most severely affected of all impacted sectors in all Nordic countries, except Norway and Iceland, with total costs of $3.38 bil. Costs to "Authorities-Stakeholders" (governmental services and/or organizations such as conservation agencies, forest services that allocate efforts for the management of biological invasions; $2.94 bil.) followed, then by costs across diverse

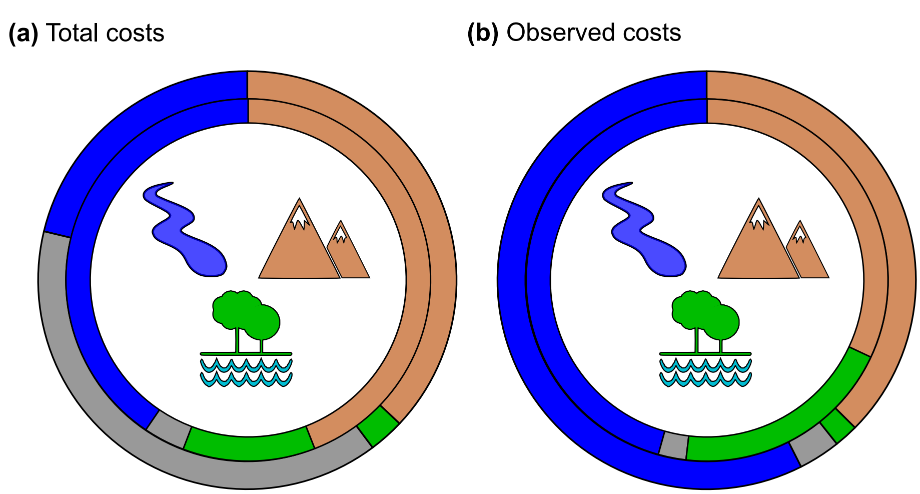

Fig. 2. Impacted environments of IAS across the Nordic countries in terms of Total costs (a) and Observed costs (b). The proportions depicted in the outer circle correspond to the magnitude of costs and in the inner circle to the number of expanded cost entries. Blue color represents aquatic species, brown terrestrial, green semi-aquatic and grey diverse/unspecified. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

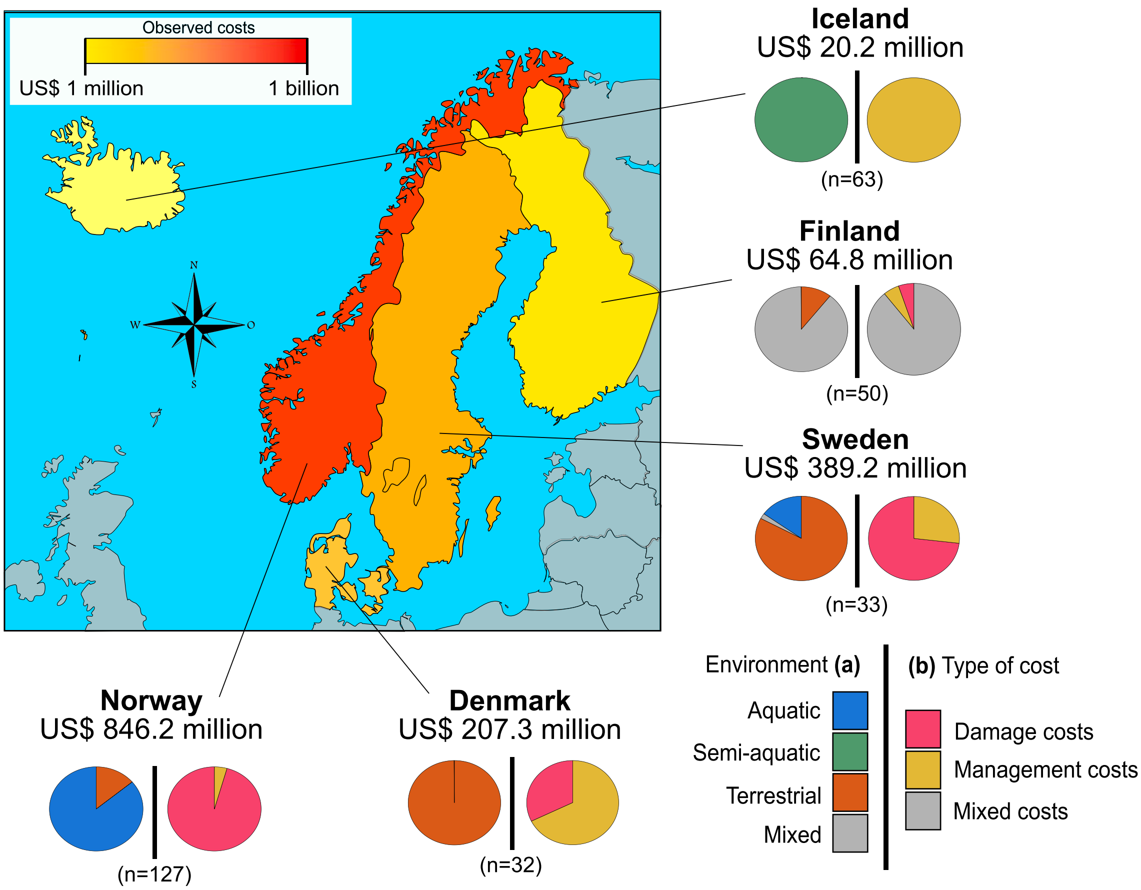

Fig. 3. Map of Nordic countries in InvaCost classified by magnitude of reported cost, along with pie charts indicating a) the portion of IAS costs in each type of environment (Aquatic, Semi-aquatic, Terrestrial or Mixed) on the left, and b) the type of costs they represent (Damage, Management or Mixed costs) on the right. The map includes only costs that have been characterized as "Observed". The number of expanded cost entries (n) are provided below each pie chart.

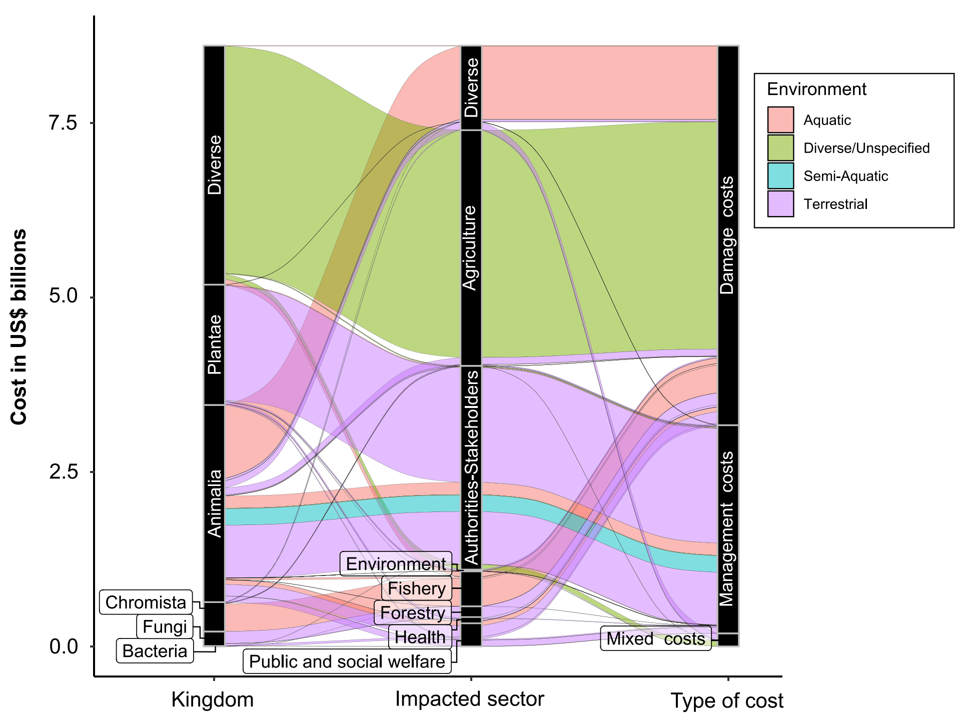

Fig. 4. Flow of total invasion costs (shown in $ billion on the y-axis) per impacted environment across kingdoms, types of costs and impacted sectors. Blue color represents aquatic environments, brown terrestrial, green semi-aquatic and grey diverse/unspecified. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

sectors ($0.93 bil.). Costs to "Fisheries" (or more accurately "aquatic species production", considering that farmed species are also included; $0.5 bil.) were found to be the next highest among all other sectors (Fig. 4). All other sectors (Environment, Forestry, Health, Public and Social Welfare) were impacted with less than $0.5 bil. Considering "Observed" costs only, costs inferred to diverse sectors ($0.71 bil.) were the highest, followed by costs to "Fisheries" ($0.36 bil.) and "Authorities-Stakeholders" ($0.33 bil.). The remainder of sectors were impacted with less than $0.25 bil. (see Supplementary material File 2 Table 1-per sector for more details on costs per sector and per country).

Overall, $2.52 bil. was attributed to invasive animals, $1.8 bil. to plants and much less to other taxa such as chromists ($0.41 bil.), fungi ($0.21 bil.) and bacteria (<$0.01 bil.); note though that $3.41 bil. were not assigned to a specific taxonomic group (i.e., "Diverse/Unspecified") (Fig. 4). When considering "Observed" costs only, invasions from animals were still found to be the most costly category ($1.25 bil.), but this time followed by chromists ($0.37 bil.) and fungi ($0.18 bil.), with plants being several magnitudes lower ($0.04 bil.). Details on the distribution of total and observed costs per kingdom across cost types can be found in Supplementary material File 2 Figs. 2 and 3, and sectors can be found in Supplementary material File 2 Figs. 4 and 5. Interestingly, the share between damage and management costs was similar for animals, while for plants most of the costs reported were management costs with very limited records of damage costs (see Supplementary material File 2 Fig. 2). When considering "Observed" costs, the damage costs for animals considerably dominated management costs, while costs related to chromists and fungi, that were the second and third most costly taxa respectively, comprised almost exclusively of damage costs (see Supplementary material File 2 Fig. 3 and Table 2). Where defined, animal costs exceeded plant costs in all Nordic countries, both for damage and management costs, whereas management costs exceeded damage costs only in Denmark and Iceland (Supplementary material File 2 Table 2). Particularly large shares of damage costs were by chromists in undefined Nordic countries.

The Japanese knotweed (*Reynoutria japonica*) and the salmon fluke (*Gyrodactylus salaris*) (in Norway) were identified as the costliest species across the Nordic countries ($1.14 bil. and $0.78 bil., respectively across all countries). Supplementary material File 2 Table 3 shows the ranking among the costliest species across all Nordic countries for "Total" and "Observed" costs, respectively. When "Observed" costs were considered separately, salmon fluke in Norway came out as the costliest ($0.71 bil.), followed by the haptophyte *Prymnesium polylepis* in Denmark and Sweden ($0.36 bil). Looking at the costliest species in each country separately based on total costs, Denmark's costliest IAS was the house mouse, *Mus musculus* ($0.32 bil.), Finland's the Colorado potato beetle, *Leptinotarsa decemlineata* ($0.32 bil.), Sweden's and Iceland's the American mink ($0.2 bil. and $0.02 bil. respectively), and for Norway the Japanese knotweed remained the costliest ($1.12 bil.) (Supplementary material File 2 Table 4).

3.3. Temporal trends of costs

The average annual reported cost over the past ~6 decades (1960–2021) was estimated at $134.76 mil., when considering total costs. Considering "Observed" costs alone, annual costs averaged at $30.49 mil. per decade in the same period (Fig. 5). Total costs exhibited an increasing trajectory over time up to the year 2021. Although at a lower order of magnitude, observed costs exhibited a similar, positive trend until 2010, which then decreased until 2021 — likely due to time lags in cost reporting after incurrence (Fig. 5). Temporal trends according to cost type are shown in Supplementary material File 2 Fig. 4 for "Observed" costs only.

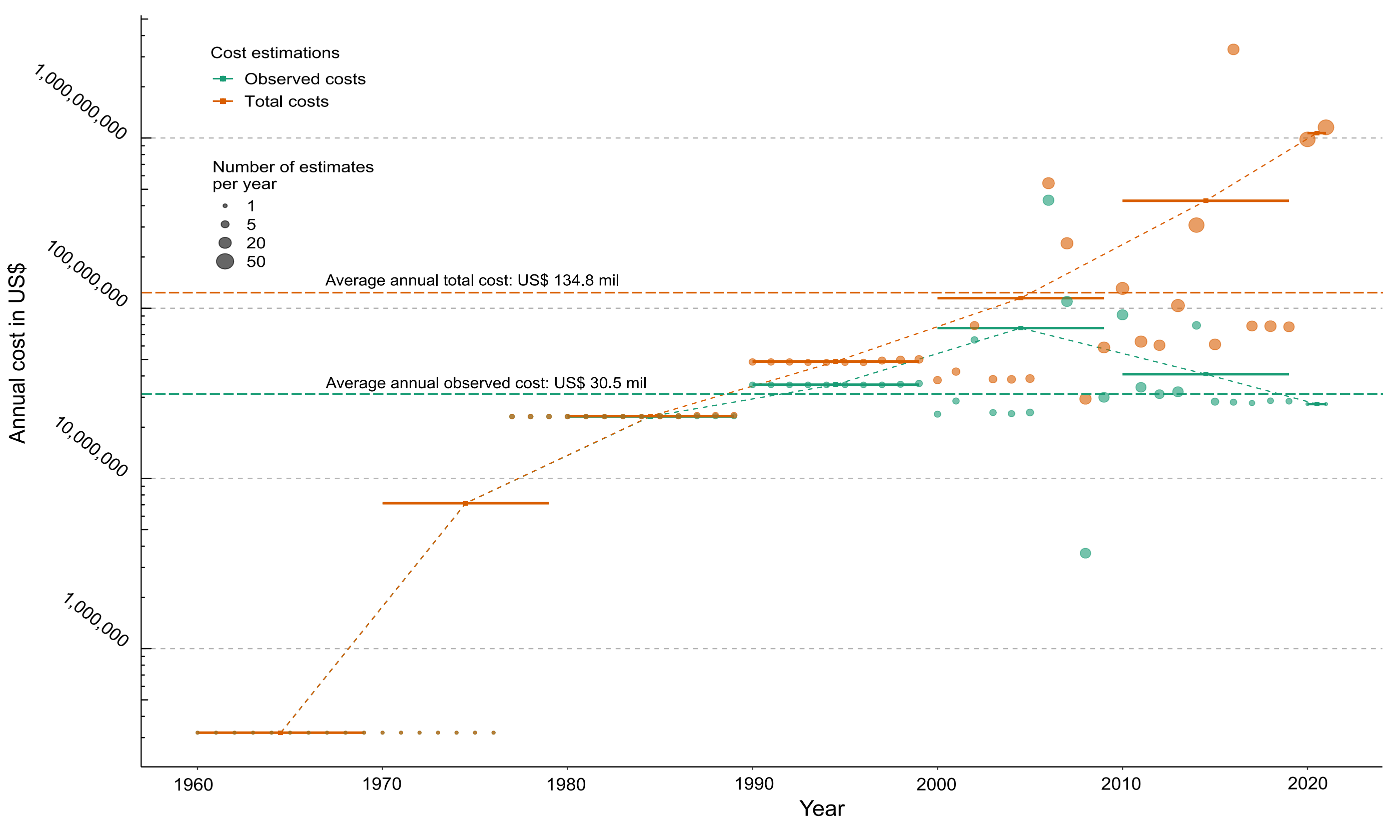

Fig. 5. Total (observed and potential) and observed-only annual reported costs resulting from invasions in the Nordic region from 1960 to 2021 at 10-year increments (with the exception of 2020–2021 which were averaged over two years). Horizontal lines represent annual mean over their respective 10-year intervals. Individual points are annual totals. Note that the y-axis is shown on a $\log_{10}$ scale.

4. Discussion

According to the Global Register of Introduced and Invasive Species (GRIIS, 2021) and the Global Invasive Species Database (GISD, 2021), the number of IAS present in the Nordic countries is much higher than the number of IAS with costs reported in the InvaCost database, hence the costs of invasion in the Nordic countries appear to be greatly underestimated. Underestimating the invasion costs hinders progress towards implementing management measures and budgeting accordingly, which ultimately exacerbates costs (Ahmed et al., 2022). Further, it impedes efforts to help prioritise invasion-related problems, including prevention that is generally cheaper than long-term management, considering that policy makers often face limited budgets to address conservation challenges. Specifically, costs are unavailable for at least 86.9% of known IAS in Denmark, 94.4% in Sweden, 89.2% in Finland, 85.7% in Iceland and 84% in Norway. This is not unique to Nordic countries, and other studies have shown that most regions had documented costs for only 2%–10% of invasive alien species: for example, Argentina (Duboscq-Carra et al., 2021), Asia (Liu et al., 2021), Australia (Bradshaw et al., 2021), France (Renault et al., 2021), Germany (Haubrock et al., 2021a), Mexico (Rico-Sánchez et al., 2021), Singapore (Haubrock et al., 2021b) and the United Kingdom (Cuthbert et al., 2021a,b). This may imply that efforts to identify IAS are disproportionately larger than efforts to understand their monetary costs. It may also signify harder-to-value impacts which do not affect easily quantified assets but rather require non-market valuation methods. Similar to the UK, Nordic countries may exhibit gaps whereby costs are widely unknown, but where reported they are unevenly distributed towards the most notorious IAS. Knowledge gaps may also exist with respect to taxonomic groups and the “smalls rule”, whereby research leans towards larger taxa (particularly animals and plants) rather than microorganisms, for which biogeography is less frequently resolved (Carlton, 2009). Indeed, just seven of the Nordic IAS with costs were attributed to chromists, fungi, viruses or bacteria, which highlights the need for expanding the scope of research across more taxa. Coupled with broader unknowns in reporting of IAS in Nordic countries and globally, the true proportion of unreported economic impacts is likely to be even higher than found in this study.

The large difference between observed and potential costs can be in some cases the result of insufficient resources, including for research, therefore hindering understanding of invasion losses and making timely detection, monitoring, prevention and management particularly challenging. At the same time, potential costs may also partly limit confidence in decision-making, policy and funding to combat invasions. However, this pattern is not unique to the Nordic countries, but is also apparent across other European states (Haubrock et al., 2021c) and wider geographic regions (e.g. North America in Crystal-Ornelas et al. (2021)). Arguably, even though predicting costs over time or space do add value to policy and management discourse, more research effort is needed to empirically observe costs. This effort can result from transdisciplinary and cross-country collaboration between academics, industry, governmental organizations and other relevant stakeholders who ought to bring together their expertise and join forces in understanding the different dimensions and nature of the costs triggered by invasions (Vaissière et al., 2022). The way Nordic countries are ranked in terms of costs is different when total and observed costs are considered (as shown in Fig. 1). This large difference between total and observed costs that drives the reversion of the order, is largely attributed to a single reference by Paini et al. (2016) that focuses on potential agricultural costs from IAS. Denmark has the largest annual crop production values across the Nordics which has largely influenced the estimated costs. The work by Paini et al. (2016) also largely drives the costs for the agricultural sector which turns out to be the most highly impacted by invasions in the Nordic countries, a finding that may seem unexpected considering the relatively limited size of the agricultural sector in higher-latitude regions such as Scandinavia.

Global trends (Cuthbert et al., 2021a,b) as well as regional ones (Crystal-Ornelas et al., 2021; Haubrock et al., 2021c; Kourantidou et al., 2021) consistently indicate that costs from aquatic IAS are minimal compared to those of terrestrial IAS. That is because aquatic systems often receive less research effort, are associated with relatively limited human infrastructure, and harbour impacts that are more challenging to observe. The findings for the Nordic countries, however, contrast this general trend. The “Observed” economic costs of aquatic species in the Nordic countries soared to more than half of the costs (60%, $1.14 bil.), driven mainly by IAS in Norway and Sweden. Semi-aquatic costs were an order of magnitude lower than both terrestrial and aquatic invasions, however, in contrast to the substantial contributions of semi-aquatic taxa to the global total (Cuthbert et al., 2021a,b). In the Nordic countries, this could reflect a lack of costs for the costliest semi-aquatic taxa at the global level, such as mosquitoes which vector disease to humans and cause healthcare costs. The dominance of aquatic costs is not surprising however, given the longevity and global leadership of the Nordic aquaculture and fisheries industries on several crustacean and fish species (Paisley et al., 2010). The exponential growth of aquaculture in recent decades has often been linked to the introduction and use of non-native species (De Silva et al., 2009). This has not gone unnoticed in the Nordic countries, as several IAS generating economic costs in these countries are either species used in aquaculture, related to fisheries, or introduced pathogens affecting native species of economic importance. For example, according to FAO (2021), the Pacific oyster *Magallana gigas* (formerly *Crassostrea gigas*) was introduced for aquaculture purposes in Norway. There the species was cultivated on a small scale between 1980s and 2000s, and is now starting to be harvested in small quantities. Similarly, aquaculture introductions in Limfjorden, Denmark, have resulted in local populations. At the same time, the Pacific oyster was also introduced to other parts of the country but through accidental releases from aquaculture farms in neighbouring Germany or the Netherlands. As such, in those locations it enters economic activity primarily through other channels, including local collection and tourism consumption.

Other species include the tench or doctor fish *Tinca tinca* that are fished in small quantities in Denmark and Sweden, the red king crab *Paralithodes camtschaticus* that has turned into a very valuable commercial fishery in Norway with an average catch of around 1800 tonnes per year in the last 20 years, and the signal crayfish *Pacifastacus leniusculus* in Finland often exceeding 100 tonnes annually in recent years (probably also in Sweden, but not specifically included into FAO database). However, some of these species have serious ecosystem impacts and result in substantial economic costs either in the same country or in neighbouring ones, while their economic impacts have not been thoroughly assessed in most cases, nor has their management been optimized in terms of balancing costs and benefits (Skonhoft and Kourantidou, 2021). In addition, introduced pathogens, such as the oomycete *Aphanomyces astaci*, the causal agent of crayfish plague, cause enormous impacts on wild populations of the noble crayfish *Astacus astacus* (Bohman et al., 2006; Jussila et al., 2015); or the bacteria *Aeromonas salmonicida* and the salmon fluke *Gyrodactylus salaris* on key farmed and wild-harvested species such as Atlantic salmon *Salmo salar* (Harris et al., 2011). Given the widespread use of these flagship species in aquaculture and fisheries across the Nordic countries, the impact of exotic pathogens may result in large losses even though not all of them are assessed in monetary terms. Similarly, aquatic plants commonly used in aquaria, such as waterweeds *Elodea canadensis* or *E. nuttallii*, that are widely distributed in the southern Nordic mainland (Hussner, 2012), have been very costly in terms of both damages and management (i.e. in Finland through negative impacts on nature based tourism and fisheries (Karjalainen et al., 2017)).

The very small observed costs for plants identified, is also an interesting finding, but without necessarily a clear ecological reason underpinning it, considering the numerous recorded invasive plants in several countries across the Nordics (see for example Bevanger, 2021;

Arianoutsou et al., 2021). Despite a high level of diversity in plant invasions, it is possible that there is less scope for invasive plants to impact for example sectors such as agriculture due to climatic conditions. It is also possible that this finding could reflect particularly low research effort for these groups and/or relatively high observed costs of certain taxa, such as salmon fluke, making plants seem smaller in terms of costs. It is worth noting nevertheless that there are high potential costs (due to mainly Japanese knotweed), suggesting that further work is required to measure plant costs empirically.

The knowledge produced locally, often also beyond academic institutions, can be fully transferred to the international scientific community; thus, the resulting database used in this study can improve connections among scientists and practitioners, because it can help promote best practices in localities with similar problems across countries (Nuñez et al., 2019; Angulo et al., 2021). Such collaborations and synergies are very much needed to understand the challenges of ongoing and expected invasions and build collective and coordinated strategies that can help face the costs and risks that these invasions encompass, and to some extent these already exist for the Nordic region (e.g. NOBANIS, 2015). In cases when the management is required at larger scales, there are often inherent tensions. To ensure smooth and effective management solutions, capacities for collaborative actions from the local to the regional scales should be based on nested governance, collaborations and communication across scales (Soulé and Terborgh, 1999; Wyborn and Bixler, 2013; Bixler et al., 2016). Thus far, transboundary plans that cross political boundaries have focused mostly on the conservation of endangered species (see for example Sanderson et al. (2002); Olsoy et al. (2016)), or migratory species (see for example Murray and Fuller (2012); López-Hoffman et al. (2017)). Transboundary conservation efforts include initiatives for transboundary policies and investments that can help facilitate those and offer opportunities for higher quality conservation outcomes through coordinated management across borders (Mason et al., 2020). Successful examples of such transboundary conservation plans include the Yellowstone to Yukon Conservation Initiative (Chester, 2015) and the potential Half Earth project (Ellis and Mehrabi, 2019), among many others, but despite their success and advances at multiple levels in enhancing conservation, they continue to face governance-related challenges. When it comes to invasive species, such initiatives for transboundary management are less developed and continue to face challenges, such as those related to the feasibility of eradication, the costs of biosecurity surveillance and the narrow scope within which biosecurity efforts occur (i.e. focusing on specific sectors only) (Kark et al., 2015). Nevertheless, the potential of such collaborative efforts at preventative levels for example (i.e., through information sharing, biosecurity planning) as well as management levels (i.e., as demonstrated through economic models assessing gains from cooperation), can have significant benefits and examples of that are available globally and regionally, including in parts of the Nordic countries (Kark et al., 2015; Kaiser and Kourantidou, 2021; Skonhoft and Kourantidou, 2021). Actions such as biosecurity surveillance, preventative planning and sharing of expertise across countries are key to successful mitigation and management of invasions and have space for improvement across Europe and the Nordics (Angulo et al., 2021; Polaina et al., 2020; Kark et al., 2015).

Providing regional estimates of economic costs may help to coordinate regional policies and foster the guidance of invasive species management that spans large geographic areas (Epanchin-Niell, 2017; Aizen et al., 2018). Regional cost estimates could help prioritisation, where necessary, and cost-efficient management actions. For example, accurate (to the extent possible) cost assessment could aid appropriate resource allocation and promote accordingly appropriate management actions, when inadequate management actions could trigger greater invasion costs in the future, particularly if biosecurity measures fail to prevent new invasion events (Ricciardi et al., 2021; Ahmed et al., 2021). This becomes even more important in light of intensified climate shifts and increased anthropogenic activity in northern latitudes which in turn call for increased cross-country, inter- and trans-disciplinary research effort to handle uncertainty and advance mitigation, adaptation and resilience to change. Further, it is important to note that while IAS management actions often take place within national or regional boundaries, invaded sites rarely coincide with socio-political boundaries. Nevertheless, the capacity of different countries to cope with invasions varies significantly depending on socio-economic and environmental factors (Latombe et al., 2022), with a lack of coordination between countries being one of the most recurrent problems in addressing their management (e.g. between EU member states, Caffrey et al., 2014).

The sections that follow provide a more detailed qualitative assessment of invasions in each country that encompasses national policies and regulation, expert opinion and knowledge gaps.

4.1. Overview of invasion costs, management and policies in Denmark

The review of the literature for invasions in Denmark provided evidence that IAS are generally well documented, with a lot of work done on risk assessments, which includes several cases of potential introductions. While there are some knowledge gaps regarding ecological or biological features of these invasions, along with ecosystem impacts, there is a much greater paucity of studies on the economics and management of these species. However, the underrepresentation of social sciences in invasive species research is not unique to Denmark, but rather a trend that applies more broadly (Abrahams et al., 2019; Anderson and Valenzuela, 2014).

A few species attracted most of the scientific and public attention, as is often the case with IAS. In Denmark the most studied species ecologically are the terrestrial plants and animals such as the raccoon dog, giant hogweed, brown rat, American mink, or Japanese rose. These are also the types of species for which one finds most of the research efforts to understand costs and losses and translate them into monetary units. Not surprisingly, the species for which costs and impacts are studied in more detail are typically the ones with a direct and noticeable impact to the Danish economy or human health such as the brown rat, American mink and (new introductions/recolonization of) the wild boar. The latter two are also species for which domesticated versions are profitable in Danish animal husbandry, and thus motivate and facilitate greater clarification of net benefits and costs from invasions. This explains some of the effort directed at weighing net benefits before the species have become widespread introductions. For the majority of the rest of the IAS present in Denmark or those that present a high risk as potential future invaders, there are no comprehensive estimates of costs. Extrapolation from costs of these species that are present in other countries as invasive, is therefore a common practice. The targeted search resulted in information for 58 species, of which there are monetary costs on 16 out of 30 of the introduced species and on 25 out of 28 of the potential introductions. Thus, surprisingly, the frequency of monetary estimates is higher for species that might become invasive if introduced than for the ones that are already established. One caveat to this is that this review only includes 58 out of the 130 species that the Ministry of Environment of Denmark identifies as invasive (Miljøstyrelsen 2, 2017).

The Danish literature as a whole, although useful in its endeavour to provide a better understanding of the status of invasions and their costs, lags behind in incorporating one of the most important lessons of social scientific research for IAS management. That is, that the costs, benefits and damages are functions of the population spread and density over time and space (Ahmed et al., 2021), so that total cost figures at a single point in time are less useful than functions that distinguish and translate management decisions and expenditures into long run expected outcomes. Relatedly, estimates measuring potential IAS threats to Denmark primarily rely on cost-transfer from other places where the species are already invasive, potentially reflecting the well-established notion that prevention is less costly than control and/or eradication (Cuthbert et al., 2021a,b; Leung et al., 2002). However, in most cases they do not directly incorporate the total costs of prevention as functions of the amount of preventative action taken, or of a quantitative estimate of the likelihood of the species arriving.

Danish national rules that were first adopted in 2014 (and implemented in 2015) along with EU's first legally binding act on IAS from 2014, determine today's regulation and management of IAS in Denmark (L317/35, 2014). Specifically, in addition to the EU's act, Denmark has adopted national legislation in regard to particular problematic IAS, either because of negative impacts on Danish biodiversity or because of negative effects on human health or other commercial operations at a national level. Regulatory provisions for invasive species are included in various national mandates and acts beyond the 2014 law: Naturbeskyttelsesloven (Protection of Nature Act), Jagt og vildtforvaltningsloven (Danish Hunting Act), Fiskeriloven (Fisheries Act), Lov om drift af landbrugsjorder (Act on farming agricultural land), Lov om planteskadegørere (Organisms Harmful to Plants Act), Dyreværnsloven (Animal Protection Act), Lov om hold af dyr (Keeping Livestock Act) and Miljøbeskyttelsesloven (Environmental Protection Act).

Under these laws and state mandates the management responsibility falls under a number of different public authorities which include: The Environmental Protection Agency, the Agriculture and Fisheries Agency, and the Danish Veterinary and Food Agency - all of which are under the Ministry of Environment and Food (Miljøstyrelsen 2, 2017). In addition to these, there are specific action plans and laws in place for a few selected species with high costs and risks such as the raccoon dog (adopted in 2009), the American mink (adopted in 2007) and Giant hogweed (adopted in 2004/2006/2009/2016/2017). Guidelines for control target primarily invasive knotweeds, black cherry, giant hogweed, wild parsnip and the Japanese rose (Buttenschøn, 2013; Buttenschøn and Thamdrup, 2012; Naturstyrelsen, 2012; Retsinformation, 2017; Skov and naturstyrelsen, 2010; Weidema, 2006). Together these constitute the legal framework for the management of IAS in Denmark. Furthermore, the agencies are cooperating with The Hunters' Association of Denmark in relation to executing the practical task of regulating invasive animals. Due to high numbers of agencies involved in regulating the IAS in Denmark, coordination and management problems can be hard to prevent. This can lead to cost-efficiency losses. The implementation of the action plan targeting the raccoon dog is a good example that illustrates this problem; in this case, the communication between the hunters and Naturstyrelsen was inadequate; new rules had been developed that allowed new hunting techniques, in part due to findings that the reproductive capacities for local populations differed from other locations, but the changes, and how to implement the new techniques, had not been clearly passed on to the hunters charged with regulating the stock of raccoon dogs. Thus the hunters reported that they were misinformed on the actual regulating activities in their hunting area and fewer IAS were removed than desired. The population is now considered non-eradicable and the regulations continue to evolve, such as opening a year-round season, requiring ongoing commitment to communication (Naturstyrelsen, 2015; FACE, 2021). More details about the species listed as being of national and regional concern can be found in Supplementary material File 3 - Detailed expert report.

4.2. Overview of invasion costs, management and policies in Finland

Policy and public awareness of IAS in Finland was low until the early 2000s and did not reach substantial levels until the publication of a national strategy for IAS (Niemivuo-Lahti, 2012), which was the first attempt to compile national information on the spread, abundance and impacts of IAS. Probably as a result of this low awareness, the availability of literature on costs of IAS in Finland is quite limited. Studies on terrestrial plants and animals were more common compared to aquatic ones, a trend that is not unique to Finland (Cuthbert et al., 2021a,b).

Key gaps in knowledge emerged because of the focal attention to a limited number of species only, often for a snapshot in time, making it difficult to draw any wider conclusions (see Supplementary material File 3 - Detailed expert report). In Finland, species-specific prioritized management actions have been introduced for established species of national and EU-concern, such as giant hogweed, American skunk-cabbage, signal crayfish and raccoon dog (Niemivuo-Lahti, 2012). In addition, the European rabbit has been well-studied due to its close proximity to people and visible impacts in both urban and natural areas (van Ham and Genovesi, 2013).

The lack of documented costs of IAS in Finland could possibly be associated with the large number of actors who share the responsibility for IAS management. Those include, for example, the regional Centres for Economic Development, Transport and the Environment (ELY Centres) and municipalities that are responsible for promoting environmental protection in their respective areas, as well as the Finnish Transport Infrastructure Agency that is among others responsible for vegetation management along the roads. Further, the national network of conservation areas falls under the duties of Metsähallitus (Parks&Wildlife Finland), while the Finnish Wildlife Agency also plays a role in the management of IAS. Another blind spot is that a lot of the eradication work is carried out by volunteers and the value of their work is often not counted in cost estimates (Aspelund and Ryttäri., 2010). The situation has improved during the past 10 years as the fragmented landscape of actors responsible for IAS monitoring and management actions in Finland has been gathered to form the Advisory Board on alien species issues nominated by the Government. It is led by the Ministry of Agriculture and Forestry, and is represented by all national actors in the field from NGOs to authorities.

The recent leap in attention for management of IAS, as well as efficiency and costs of measures, has mainly been driven by new EU-legislation that forced Finland to gather information for reporting and for prioritizing management actions that would benefit the most. The first legally binding Acts were the EU IAS Regulation that came into force in 2015 and the national Act on Managing the Risk Caused by Alien Species in 2016 (Ministry of Agriculture and Forestry, 2015). Further, the goal has been to have aquatic IAS introductions regulated through the international Ballast Water Management Convention that came into force in 2017 as well as through the corresponding changes in the national law. These legislations provide the current framework to manage IAS in Finland. The primary management strategy in Finland was developed based on the risks arising from alien species and the costs and benefits of the prevention measures (Ministry of Agriculture and Forestry, n.d.). Meanwhile, a lot of emphasis has gone into educational actions to raise awareness about the risks and restrictions regarding IAS. For example, the VieKas LIFE (Finvasive LIFE, 2018–2023) is the largest and most ambitious project on awareness building, mapping and controlling of invasive alien plant species in Finland.

4.3. Overview of invasion costs, management and policies in Iceland

While Iceland's geographic remoteness has limited the number of invasions (Gunnarsson et al., 2015; von Schmalensee, 2010), not much is known about socio-economic impacts of IAS present in Iceland, as nearly all the literature is focused on distribution or ecological effects. This is not surprising considering that IAS research in Iceland involves relatively few active scientists. In addition, public and governmental awareness of socio-economic effects of IAS seems in general very limited. Observed economic costs were reported only for American mink in relation to general mink control and a three-year experimental eradication project, in both cases paid for by the government and municipalities (Hersteinsson et al., 2012; Robertson et al., 2020; von Schmalensee, 2010). However, despite the general absence of monetary costs, it is known that there are several other IAS present in Iceland affecting socio-economic wellbeing (see Supplementary material File 3 - Detailed expert report). For example, relevant literature does not exist for prominent IAS that are known or suspected to cause economic or social costs, such as *Lupinus nootkatensis*, *Anthriscus sylvestris*, *Heracleum* species*, Cancer irroratus* and ascidians such as *Ciona intestinalis*. Registration of costs of IAS in Iceland is insufficient, and reported costs are thus greatly underestimated. Paini et al. (2016) describe future potential costs from IAS yet to be introduced, that might negatively influence agriculture crops. However, these estimates should be interpreted with caution, since a considerable proportion of agriculture crops in Iceland (hay excluded) are grown in greenhouses (Sturludóttir et al., 2021), where IAS either have no or little access, or can be managed with more ease compared to outdoor-grown crops (a consideration not included in Paini et al. (2016)).

Thus far, no national plan or strategy on IAS has been made in Iceland. IAS are mentioned briefly in the country's strategy for the implementation of the Convention on Biological Diversity (MENR (Ministry for the Environment and Natural Resources), 2008) and the action plan that follows it (MENR, 2010), but neither provide sufficient coverage regarding IAS (e.g. strategy, action plan and its implementation, responsibility of stakeholders, management, risk assessment, monitoring, mitigation etc.).

According to the Icelandic law on nature conservation (no. 60/2013, in effect since 2015), import and distribution of alien species is prohibited without permission from the Environment Agency of Iceland. According to the Icelandic law on the introduction of animals for agriculture (no. 54/1990), this does however not apply to livestock nor does it apply to exotic plant species that have been used for horticulture, gardening, landscaping, land reclamation and forestry unless importation is prohibited by regulation. Those who want to introduce alien species must apply for a permission and provide a risk assessment. The import, cultivation and distribution of alien plants are mostly regulated through two lists (regulation no. 583/2000): (A) a list of plant species of which all import is prohibited, published in 2011, and (B) a list of alien plant species that can be cultivated in Iceland, which has yet to be published more than two decades after the regulation came into effect.

In 2010, Regulation no. 515/2010 on ballast water entered into force. This resulted in a ban of the discharge of ballast water within the jurisdiction of Iceland unless it is managed or treated according to standards specified in the International Convention for the Control and Management of Ships Ballast Water and Sediments (IMO, 2020 edition). The effect of this regulation on the accidental import of alien species in ballast water has not been evaluated in practice, neither with enforcement or any kind of monitoring.

Despite legal efforts to limit the imports of alien species, many newly established non native species have been observed in different Icelandic habitats in recent years, but incomplete information on their introduction and spread has been published in the scientific or grey literature (Sindri Gíslason, Menja von Schmalensee and Róbert A. Stefánsson, personal observations; RagnarsdóttirMetúsalemsson, 2020; Wasowicz et al., 2020; Gunnarsson et al., 2015; Ramos-Esplá et al., 2020). A persistent problem is the lack of adequate, updated official species lists of alien and invasive species as well as risk assessments for their impact and spread. Species lists found in international databases on alien and/or invasive species in Iceland are either vastly outdated, inaccurate, or simply wrong. For example, some IAS do not appear on international lists and some of the species on the lists are either native or have never been established in Iceland (Menja von Schmalensee, Róbert A. Stefánsson and Sindri Gíslason, personal observations). The lack of consensus on which alien species are or are likely to be invasive is delaying or even obstructing their timely management and hampering the documentation of IAS socio-economic costs in Iceland.

Additionally, with respect to IAS management Icelandic policies and legislation are very weak and sometimes inadequate (von Schmalensee et al., 2013). The Environment Agency and municipalities have permission to manage IAS to reduce their distribution and abundance and the minister for the environment and natural resources can, with a proposal from the Icelandic Institute of Natural History (Icelandic Institute of Natural History, 2021), allow hunting or removal of alien species (law no. 60/2013). These rules have only been applied in a limited number of cases, involving *Neogale vison* (countrywide management), *Lupinus nootkatensis, Anthriscus sylvestris* and a few *Heracleum* species (local and temporary management projects). Legal authority to take samples from ballast water of ships to monitor and verify whether the regulation (no. 515/2010) on ballast water is enforced or not, has never been utilized, in spite of the growing concern of increasing number of aquatic IAS in Iceland.

4.4. Overview of invasion costs, management and policies in Norway

Norway developed its first strategy against alien species in 2007. The first years however, the awareness of the consequences to nature and society of these species was rather low. The awareness has increased in more recent years. Most focus has been on assessment of the ecological impacts of alien species. An important tool is the Alien Species List, that is published by the Norwegian Biodiversity Information Centre, and is the primary tool for assessing the ecological impacts of all alien species in Norway. This list is regularly revised. The socio-economic impacts of IAS in Norway and the need to use appropriate socio-economic tools in order to prioritise efforts to reduce the negative effects on ecology and society of these species have been growing over time in Norway. This has resulted in cost estimations for eradication of many alien species, and has helped draw attention on the use of suitable socio-economic tools for prioritizing efforts in the newly published cross-sectoral strategy (see Supplementary material File 3 - Detailed expert report).

The Norwegian Environmental Agency (Norwegian Environmental Agency, 2020) is the authority responsible for administering the regulations of alien species. However, a cross-sectoral strategy on IAS has been developed in Norway, where different sectors are responsible for environmental impacts within their respective responsibilities. Norway is involved in international cooperation on alien species and has obligations with respect to a number of international conventions and agreements, in addition to trade regimes and border controls (Norwegian Environmental Agency, 2020).

The aim of the Norwegian regulation for alien species is to hinder their introduction, spread and any negative impact on the environment. The focus has mainly been on preventive measures as it is difficult and costly to limit spread and damage once they are established (Norwegian Ministry of the Environment, 2007). However, the latest cross-sectional strategy (Norwegian Environmental Agency, 2020) also underlines the need to limit spread and eradicate or control already established alien species, realising that there is a huge number of alien species in most parts of the country, including in conservation areas and ecosystem types of great value. The new cross-sectoral strategy further emphasises the need to prioritise efforts to get the best benefit-cost-ratio for money spent, and the need for more knowledge about the species, impacts on ecosystem services and the economy (not ecological impacts only which is currently included in the Alien Species List), control measures, costs of impacts and control measures, etc. The latest review of alien species that have been established in Norway after 1800 was conducted in 2018 according to the GEIAA method for risk assessment (Sandvik et al., 2019). The following species of regional concern were listed as having high or very high risk: *Esox lucius, Phoxius phoxinus, Rutilus rutilus, Scardinius erythrophthalamus, Mysis relicta and Bombus terrestris* (Artsdatabanken, 2020).

The recently published "Action strategy against alien invasive species 2020–2025" (Ministry of Climate and Environment, 2020) called for assessments of benefits and costs of control programs for IAS. In response to this call, Blaalid, et al. (2021) (see also Magnussen et al. (2019)) used an ecosystem services approach to assess damage costs for alien species and develop and test a prioritisation tool for IAS management. Their tool bypasses the difficulties of assessing benefits and costs in similar monetary terms by creating a new unit of expression that expresses the total cost in USD per benefit point.

Magnussen et al. (2015) offered some preliminary estimates for the potential damage costs of alien species in Norway. Based on estimates for a handful of species and transfer of estimates of damage costs from other countries, the study reported the total annual costs of alien species in Norway in the range between 1.4 and 3.9 billion NOK (i.e. $179–500 million) (2015). The study underlines that this estimate is uncertain, due to lack of primary Norwegian valuation studies of damage costs. In more recent years there have been several studies of costs and cost-benefit point ratios for alien terrestrial vascular plants (Blaalid et al., 2021; Magnussen et al., 2021). However, the aim of these studies has been to be able to prioritise efforts to eradicate or control these plants, and the total costs of control programs for these plants have not been estimated. It is clear that the total costs of eradication for the approximately 70 plants included in the prioritisation estimations are several hundred million NOK.

4.5. Overview of invasion costs in Sweden

Most of the influential works in the cost-benefit literature on IAS in Sweden, found in both peer-reviewed articles and grey literature, were written before the EU IAS Regulation came into force in 2015 (see Supplementary material File 3 - Detailed expert report). For instance, the focus on health effects (and subsequent high costs) (Gren et al., 2007) is not reflected in the way the EU IAS Regulation is implemented, where mainly threats to natural ecosystems are in focus, both in terms of species listed and the interpretation of actions to be taken.

Most studies relied on estimates of identified IAS, so mainly falling under the category of post-establishment assessment. Species-specific management actions in Sweden have been introduced for IAS that are widely spread, namely the signal crayfish (Havs- och Vattenmyndigheten och Naturvårdsverket, 2018). The primary management strategy in Sweden, however, is risk-based and strongly linked to the analysis of introduction pathways (Ebenhard, 2019).

After the EU IAS Regulation, one of the main methods used to include biodiversity values in the cost-benefit reports of the Swedish Environmental Protection Agency (SEPA) was based on willingness-to-pay studies (conducted in neighbouring countries) for one or a few habitat types from which extrapolations were made. Additionally, an EU-wide valuation of Natura 2000) habitats (ten Brink et al., 2011) has been used, again with doubtful accuracy at the national level.

The first National Strategy for alien species in Sweden (published in 2008) was an important stepping-stone to management measures against IAS (Swedish Environmental Protection Agency, 2008). The first legally binding Acts were the EU IAS Regulation that came into force in 2015, implemented in Sweden through changes in the Environmental Code, The Environmental supervision ordinance (2011:13) and the new National Ordinance on IAS (2018:1939). These provisions give the authorities both liability and authorization to enforce the EU IAS Regulation as well as to provide guidance. There is also an authorization to take measures despite landowner's opposition. The SEPA, the Swedish Agency for Marine and Water Management and the Swedish Forest Agency are such national competent authorities that, according to the EU IAS Regulation, are in charge of applying the Regulation, and the County administrative boards are responsible for eradication, management and restoration measures. Landowners are responsible for eradication and management measures directly according to article 7 in the EU IAS Regulation. At present there is no list of species of national or regional concern, but preparatory work is ongoing. The National Strategy for alien species is currently under revision.

5. Conclusions

The present study highlights extensive gaps in knowledge and reporting of economic costs of IAS across the five Nordic countries. Analysis of several cost descriptors from the InvaCost database along with expert views have helped us shed light on key trends and unevenness across taxonomic, spatial and temporal scales, as well as on types of reported costs and sectors of the economy affected.

The costs to society incurred by IAS can be approached in various ways and some types of costs are more difficult to evaluate than others, such as those that impact biodiversity, ecosystem services or recreation or more broadly those that require non-monetary valuation methods (Kelemen et al., 2014; Small et al., 2017). Rather straightforward costs include observed or estimated damage costs or yield loss caused by IAS (e.g. damages to infrastructure, crops or natural resources of value to humans) and observed or estimated expenditures on IAS management (e.g. prevention, eradication, monitoring). More complex approaches are needed to estimate negative impacts on biodiversity, ecosystem services and human well-being (Iwamura et al., 2020; Linders et al., 2019; Schaffner et al., 2020), or the willingness of society to pay to avoid certain impacts (Roberts et al., 2018). In some cases, the presence of introduced species may bring benefits alongside costs, thus resulting in controversies along with proponents and opponents of those species (Kourantidou and Kaiser, 2019). Such cases further complicate management of biological invasions as decision-making requires extensive knowledge about the species and its impacts, the cost-effectiveness and feasibility of interventions, as well as stakeholder perceptions and behaviour (Crowley et al., 2017; Dietz et al., 2005; Kourantidou et al., 2022; Novoa et al., 2018; Woodford et al., 2017). Stakeholder perception can in addition be influenced by IAS charisma, which can complicate responses to IAS even further (Jarić et al., 2020).

The consultation with country-experts and the systematic and targeted searches in Nordic languages resulted in a much more complete picture of the economic impacts of invasions compared to previous works relying on English searches only (Haubrock et al., 2021c). In fact, the use of sources beyond just English enhances completeness and reduces knowledge gaps (Angulo et al., 2021).

Climate change and increased anthropogenic activities are generally expected to increase the number of alien species in the Nordic region in the future (Holopainen et al., 2016). For example, the region is 'catching up' in terms of the frequency of new and emerging tree diseases that have surfaced mainly through plant trade and unintentional human-spread (e.g. see Section 9.5.1 in Weidema (2000) for the Dutch elm disease). Climate warming directly affects organisms' life cycles – in some cases, making conditions more suitable for diseases or damage to occur; for example by enabling multiple generations per growing season (Jönsson & Bärring, 2011). As climate is warming most rapidly in the Arctic (Serreze and Barry, 2011), intensified climate change and human activity are exposing Nordic countries to rapid change and increased IAS risk, while climate change-invasion synergies remain poorly constrained (Ricciardi et al., 2021). Increasing tourism, travel to remote areas, and the emergence of trans-Arctic shipping routes are creating more opportunities for biological invasions (Kaiser and Kourantidou, 2021; Miller and Ruiz, 2014).

On the policy front, challenges persist and go beyond the national borders and regulatory instruments. The EU IAS Regulation for example has influenced invasive species policies in a number of ways across the Nordics. Cost assessments of IAS prior to the implementation of the EU IAS Regulation considered for example health effects and associated costs (Gren et al., 2007) while more recent studies focus on potential costs related to managing species of EU or national concern to limit ecosystem impacts (Pädam et al., 2019; Pädam et al., 2020). At the same time confusion persists for some IAS that have positive contributions to the economy e.g. through provisioning ecosystem services. For example, the commercial exploitation of the high-impact Pacific oyster (*Crassostrea gigas/Magallana gigas*) is in accordance with EU regulations for prevention and management of the introduction and spread of IAS (EU IAS Regulation) and the species is listed within Annex IV of the European Commission Council Regulation owing to its long history and economic importance. In the case of the invasive signal crayfish, which started gaining a larger market share compared to the declining native noble crayfish (that has also been affected by crayfish plague), the Finnish strategy changed as a result of its EU listing as a species of concern.

Finland's prior management objective to restore the productivity of crayfish stocks by introducing plague-resistant signal crayfish was dismissed following its listing (Kirjavainen and Sipponen, 2004) and its stocking and selling are nowadays restricted by law (Erkamo et al., 2019). Similarly, restocking of signal crayfish or rearing in natural populations ceased in Sweden, a year after the EU IAS Regulation entered into force (2015). However, as mentioned in Article 9 of the Regulation, established and widespread species of socio-economic interest can be used under certain authorisations. Therefore, following a risk analysis, national legislation was amended to allow fishing and handling only in specially designated regions, granting fishing licences and establishing a minimum size, among other restrictions.

As the true costs of IAS are likely greatly underestimated in the Nordic countries, it is important to take steps to improve the recording and publishing of these costs. Such steps might include: a) prioritizing the publications of cost values that might be available at institutes or governmental authorities, but have to date remained unpublished, b) encouraging stakeholders to improve recordings on IAS costs (e.g. due to direct damage or control efforts) and to make these records easily accessible, and c) increasing the cooperation and communication between natural and social scientists and across borders regarding the presence, range expansion and costs of IAS.

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Author contributions

Melina Kourantidou and Laura N.H. Verbrugge led the study conception and design. All authors contributed to material preparation, data collection and analysis. Melina Kourantidou, Phillip J. Haubrock, Ross N. Cuthbert, Elena Angulo, Christophe Diagne, Franck Courchamp led the data analysis. The first draft of the manuscript was written by Melina Kourantidou, with key contributions from Laura N.H. Verbrugge, Phillip J. Haubrock and Ross N. Cuthbert. Country-specific information in the main text and in supplementary material were drafted by each country's team of experts. All authors commented on previous versions of the manuscript, read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are provided in the Supplementary Material

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Appendix A. Supplementary data

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