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RESEARCH ARTICLE

Alien species in Norway: Results from quantitative ecological impact assessments

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Abstract

1. Due to globalisation, trade and transport, the spread of alien species is increasing dramatically. Some alien species become ecologically harmful by threatening native biota. This can lead to irreversible changes in local biodiversity and ecosystem functioning, and, ultimately, to biotic homogenisation.

2. We risk-assessed all alien plants, animals, fungi and algae, within certain delimitations, that are known to reproduce in Norway. Mainland Norway and the Arctic archipelago of Svalbard plus Jan Mayen were treated as separate assessment areas. Assessments followed the Generic Ecological Impact Assessment of Alien Species (GEIAA) protocol, which uses a fully quantitative set of criteria.

3. A total of 1,519 species were risk-assessed, of which 1,183 were species reproducing in mainland Norway. Among these, 9% were assessed to have a severe impact, 7% high impact, 7% potentially high impact, and 49% low impact, whereas 29% had no known impact. In Svalbard, 16 alien species were reproducing, one of which with a severe impact.

4. The impact assessments also covered 319 so-called door-knockers, that is, species that are likely to establish in Norway within 50 years, and 12 regionally alien species. Of the door-knockers, 8% and 10% were assessed to have a severe and high impact, respectively.

5. The impact category of most species was driven by negative interactions with native species, transformation of threatened ecosystems, or genetic contamination. The proportion of alien species with high or severe impact varied significantly across the different pathways of introduction, taxonomic groups, time of introduction and the environments colonised, but not across continents of origin.

6. Given the large number of alien species reproducing in Norway and the preponderance of species with low impact, it is neither realistic nor necessary to eradicate all of them. Our results can guide management authorities in two ways. First, the use of quantitative assessment criteria facilitates the prioritisation of management resources across species. Second, the background information collected for each species, such as introduction pathways, area of occupancy and ecosystems affected, helps designing appropriate management measures.

KEYWORDS

door-knocker species, ecological effect, ecological impact, evidence-based management, genetic contamination, invasion potential, invasive species, quantitative impact assessment

1 | INTRODUCTION

The spread of alien species as a result of human activities is a global problem with massive ecological consequences (Kumschick et al., 2015), identified as one of the five major direct drivers of global change (Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2019). Alien species may threaten native biota by competing with, preying upon, parasitising, infecting or genetically contaminating native species (Lockwood, Hoopes, & Marchetti, 2013). These processes may lead to the local loss of species or genotypes, resulting in a homogenisation and reduction of global biological diversity (Olden, Poff, Douglas, Douglas, & Fausch, 2004; Sax & Gaines, 2003). In addition to affect single native species, alien species may also modify habitats and change landscape features (so-called ecosystem engineering; Crooks, 2002; Richardson et al., 2000).

Through the Convention on Biological Diversity (CBD), many governments have committed to "Prevent[ing] the introduction of, control[ling] or eradicat[ing] those alien species which threaten ecosystems, habitats or species" (United Nations [UN], 1992, Article 8 [h]). This goal is reinforced by, for example, the Aichi Target 9 (CBD, 2010, Article 13) and the European Union (EU, 2014, Article 1; see also Roy et al., 2018). These international obligations are followed up in national legislation, for example, in Norway's aim "to prevent the import, release and spread of alien organisms that have or may have adverse impacts on biological or landscape diversity" (KLD [The Royal Norwegian Ministry of Climate and Environment], 2015a, §1).

In partial fulfilment of these legal requirements, the Norwegian government has adopted a policy of carrying out ecological impact assessments of alien species at regular intervals (KLD [The Royal Norwegian Ministry of Climate and Environment], 2015b). The body responsible for organising these assessments is the Norwegian Biodiversity Information Centre (NBIC; *Artsdatabanken* in Norwegian). The first assessment was carried out in 2007 (Gederaas, Salvesen, & Viken, 2007), the second in 2012 (Gederaas, Moen, Sandmark, & Skjelseth, 2013) and the third was completed in 2018. This last assessment included all alien species that are reproducing in Norway in the wild or may be expected to do so within 50 years, according to a recent inventory (Sandvik et al., 2019a), and that fulfil some additional delimitations. The impact assessments followed a quantitative method developed specifically for this aim, the Generic Ecological Impact Assessment of Alien Species (GEIAA; Sandvik et al., 2019b).

Here, we present the main results of the third impact assessment of alien species in Norway. The goal of the study was to present and analyse the results of these ecological impact assessments, and to quantify the taxonomic, ecological, geographic and temporal variation in impact. Furthermore, we present data on pathways, affected ecosystems and areas of occupancy, which may help authorities to prioritise their control and eradication efforts.

2 | MATERIALS AND METHODS

2.1 | Definitions and delimitations

We define *alien species* (see Box 1) in accordance with IUCN (World Conservation Union, 2000, pp. 4–5). However, this definition is very broad, and not all species that are alien according to the definition were risk-assessed. We operationalised the definition by adding four delimitations.

1. *Historical delimitation*: An alien species was not risk-assessed if it had established with a stably reproducing population in Norway by the year 1800. (This year was chosen to avoid species from being listed in both the Red List and the Alien Species List, as all species established in Norway before 1800 are considered for the Norwegian Red List; see Henriksen & Hilmo, 2015, p. 12; cf. International Union for Conservation of Nature [IUCN], 2012a, p. 34.)
2. *Geographical delimitation*: A species was risk-assessed as alien only if it crossed national borders or the maritime boundaries of the Norwegian Economic Zone during its introduction. Assessments were thus carried out separately for mainland Norway (including coastal islands) and for the Norwegian territories in the Arctic (Svalbard and Jan Mayen). This delimitation excludes species that have merely been introduced to novel areas within Norway, while being native to other parts of the country.
3. *Ecological delimitation*: Alien species were risk-assessed if they were (or had been) reproducing in Norway in the wild, that is, if they produced viable offspring outdoors and without human management (equivalent to establishment category C2 or higher, following Blackburn et al., 2011). Species that had been in large-scale use in Norway to produce goods or services by the year 1700 (traditional production species) were omitted from the assessment.
4. *Taxonomic delimitation*: Alien taxa were risk-assessed if they are ranked as species. Unicellular or genetically modified organisms were not included in the assessment. Some alien taxa below the species level were also risk-assessed, if their ecology or life history was regarded as sufficiently distinct. (Unless risk-assessed separately, alien taxa below the species level were assumed to share the risk category of the species-level taxon to which they belong [or to be native], if the latter was risk-assessed as alien [or if it was native, respectively].)

The species fulfilling these delimitations constituted a clearly defined subset of the inventory of neobiota in Norway (Sandvik et al., 2019a). The only exception was 24 species of arthropods (Collembola, Hymenoptera other than Aculeata, and terrestrial Isopoda), for which the previous risk categories (Gederaas et al., 2013) were kept without new assessments and which were therefore excluded from the subsequent analyses.

In addition, we risk-assessed some selected species that did not meet the geographical delimitation (i.e. *regionally alien species*, defined in Box 1) or the ecological delimitation (i.e. *door-knockers* or species having *distance effects*, defined in Box 1). These are not included in the subsequent analyses.

2.2 | Impact assessment

Alien species in Norway were risk-assessed using GEIAA. This method has been described in detail elsewhere (Sandvik et al., 2019b), but we present a list of the nine criteria in Table 1 and give a short overview of the method in Appendix A in the Supporting Information. Each species was scored for its invasion potential and its ecological effect, which determined the placement of the species in the two-dimensional impact matrix (Figure 1). According to the placement in this matrix, species were assigned to one of the five impact categories no known impact (NK), low impact (LO), potentially high impact (PH), high impact (HI) or severe impact (SE; see Table 1 and Figure 1).

In 2016, following an open announcement, NBIC appointed 52 experts in ecology and taxonomy from 15 different Norwegian research institutions (including universities, museums, private research institutes and governmental agencies). Twelve expert committees covering all relevant taxonomic groups were established.

The assessment procedure consisted of three steps. The expert groups carried out preliminary assessments in 2017, using a

Box 1 Definitions of key terms

Alien species: "A species, subspecies or lower taxon occurring outside of its natural range (past or present) and dispersal potential (i.e. outside the range it occupies naturally or could not occupy without direct or indirect introduction or care by humans)[,] includ[ing] any part, gametes or propagule of such species that might survive and subsequently reproduce" (IUCN [World Conservation Union], 2000, pp. 4–5).

Area of occupancy (AOO): The specific area that is inhabited by a species and that is essential for the survival or reproduction of its individuals, measured as the total area of occupied 2 km × 2 km grid cells, excluding cases of vagrancy (International Union for Conservation of Nature [IUCN], 2017, pp. 48–49).

Dark figure: The correction factor by which a known number/area has to be multiplied in order to obtain the estimated total number/area (total = known × dark figure). The dark figure is unknown by definition and must be based on expert judgement.

Distance effect: Ecological effect of a species that is unable to reproduce in the wild. For example, a park tree may kill visiting pollinators by toxic nectar; or escapees from farming may affect native biota before dying.

Door-knocker: An alien species that does not currently reproduce in Norway in the wild, but that can be expected to do so within 50 years. (Door-knockers may be species that [a] are not yet present in Norway, that [b] are present but do not currently reproduce in Norway, or that [c] currently only reproduce indoors or in cultivation.)

Regionally alien species: A species that is not alien to Norway, but that has been introduced to novel areas within Norway after 1800.

TABLE 1 Criteria and impact categories used by the Generic Ecological Impact Assessment of Alien Species (GEIAA; Sandvik et al., 2019b)

Criteria	
A	Population lifetime (population viability, likelihood of long-term establishment)
B	Expansion speed (rate at which the area of occupancy increases; Sandvik, 2020)
C	Colonisation of ecosystems (proportion of area colonised)
D	Effects on threatened or keystone species (negative interactions with species)
E	Effects on other native species (negative interactions with species)
F	Effects on threatened or rare ecosystems (substantial changes to environmental variables)
G	Effects on other ecosystems (substantial changes to environmental variables)
H	Genetic contamination (transfer of genetic material by introgression)
I	Transmission of parasites (vector for pathogens)
Ecological impact categories	
NR	Not risk-assessed
NK	No known impact
LO	Low impact
PH	Potentially high impact
HI	High impact
SE	Severe impact

Note. Criteria A–C determine the invasion potential and criteria D–I determine the ecological effect of an alien species, corresponding to the *x*- and *y*-axis, respectively, of the impact matrix (Figure 1). See Appendix A in the Supporting Information for further details on GEIAA.

specialised web application (see Appendix A in the Supporting Information). NBIC was responsible for quality control, ensuring that the assessment guidelines (Sandvik, Gederaas, & Hilmo, 2017) were followed in a coherent and reproducible way. These assessments were then opened for peer review and comments in early 2018. This resulted in 174 comments from governmental agencies, research institutions, individual researchers, non-governmental organisations and the public. When finalising the assessments, the expert committees considered all comments and incorporated relevant feedback. The Alien Species List was published on June 5, 2018 and is available as a fully searchable online-only database (NBIC, 2018).

2.3 | Additional information

The data recorded for each species covered the documentation necessary to score the nine criteria, as well as other information that might be relevant for management authorities and other end users of the assessments (see Appendix A in the Supporting Information). The latter information included the biogeographic distribution of each species; the pathways of entry (into the country), introduction (into Norwegian nature) and spread (within Norwegian nature) following a standardised categorisation (CBD, 2014; Hulme et al., 2008); the current known, assumed total and projected future *area of occupancy* (defined in Box 1); the ecosystems colonised and affected; and the importance of geographic variation and climate change for the scoring it had received (for a complete list of parameters recorded, see Sandvik et al., 2019b).

2.4 | Statistical analysis

All data used and referred to are available in an open dataset (Sandvik et al., 2020). Analyses were carried out in the **R** environment (**R** Core Team, 2017). To take multiple testing and the exploratory nature of our analyses into account, we applied a (statistical) significance level of $\alpha = .0005$, corresponding to Bonferroni correction for 100 tests (this paper contains a total of 89 tests). Correlations are only regarded as (biologically) significant if $R^2 > .1$. Unless stated otherwise, figures are reported as mean ± standard error.

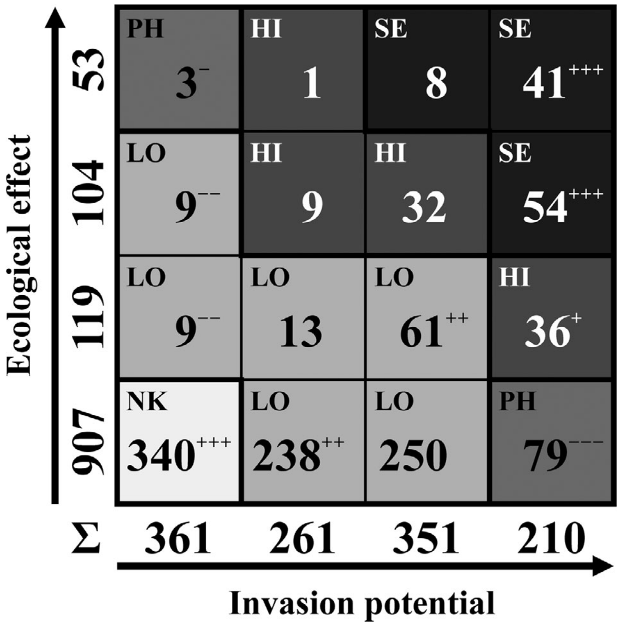

FIGURE 1 Impact matrix with numbers of alien species in each cell, column and row. The scores on invasion potential and on ecological effect (both vary from 1 to 4) determine the placement of a species. Sixteen possible score combinations are translated into five impact categories (NK = no known, LO = low, PH = potentially high, HI = high, SE = severe impact; see Appendix A in the Supporting Information). Species numbers are based on the set of species that reproduce in and are alien to mainland Norway (N = 1,183). Plus/minus signs indicate whether a number in a cell is higher/lower than expected by chance alone (based on Pearson's χ^2 tests; 1 sign, $\chi^2 > 12$; 2 signs, $\chi^2 > 24$; 3 signs, $\chi^2 > 84$; for detailed statistics, see Table B1 in Appendix B in the Supporting Information)

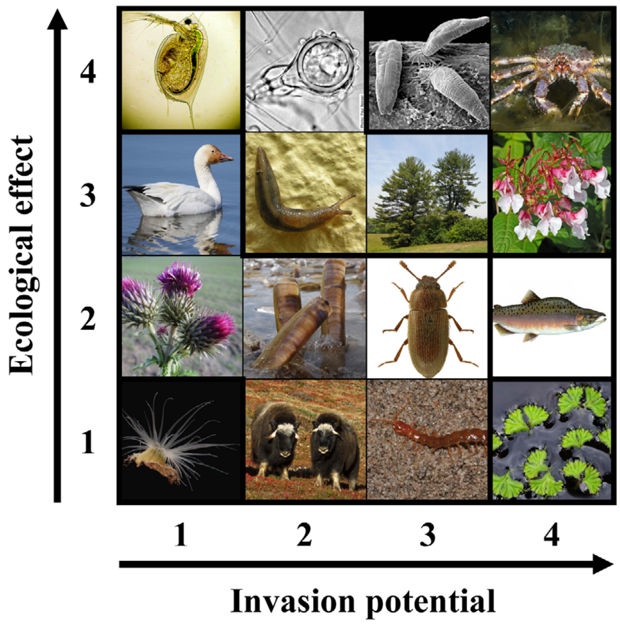

FIGURE 2 Impact matrix with illustrations. For each cell of the matrix (cf. Figure 1), one species is shown that has been assessed to have the respective combination of invasion potential and ecological effect. For species names and credits, see Appendix E in the Supporting Information

Frequency distributions of scores were compared using contingency tables. In particular, we compared, for different subsets of the data, the frequency of species in the HI plus SE categories (see Table 1) against the remaining species. Detailed statistics are provided in Appendix B in the Supporting Information.

3 | RESULTS

A total of 3,104 species were considered for impact assessment. Of these, 1,585 were excluded by our delimitations or were determined not to be alien after all. For the remaining 1,519 species, 1,532 impact assessments were carried out, namely 1,485 for mainland Norway and 47 for Svalbard, of which 13 species received separate assessments for both Svalbard and mainland Norway. The assessments fell into four classes:

- 1,199 assessments of alien species fulfilling all four delimitations (1,183 in the mainland, 16 on Svalbard, of which three where assessed for both areas);
- 319 assessments of door-knockers;
- 12 regionally alien species and
- two alien species with distance effects (*Drosophila suzukii*, *Vicia sativa* ssp. *segetalis*).

Analyses of the latter two groupings are not presented in this article. Door-knockers are analysed in Appendix C in the Supporting Information. The following five sections summarise the characteristics of the 1183 risk-assessed alien species that are reproducing in mainland Norway, whereas the final section is concerned with the assessments for Svalbard and Jan Mayen.

3.1 | Impact categories and criteria

All five impact categories were represented among the 1,183 alien species reproducing in mainland Norway, with "low impact" being the most frequent category (Table 2(a)). Figure 1 shows how the species were distributed across the impact matrix. Although the species were rather uniformly distributed across the four scores for invasion potential, the number of species decreased with increasing scores for ecological effect. Cells on or directly below the diagonal from the lower left to the upper right contained more species, and the cells furthest away from this diagonal contained fewer species, than expected by chance (Figure 1; Table B1 in Appendix B in the Supporting Information).

The placement of species in the impact matrix (Figures 1 and 2) was determined by the criterion or criteria with the highest score on each of the two axes (see Table 1 and Appendix A in the Supporting Information for criteria). Among the 181 species with high or severe impact, their placement on the invasion axis was predominantly determined by the combination of criteria A and B, whereas criterion C determined placement for only five species (3%). The placement of these 181 species on the effect axis was mainly determined by their ecological effects on native species, that is, by criteria D (58%) and E (28%), followed by

TABLE 2 Distribution of reproducing alien species in mainland Norway across impact categories

	N	NK (no known impact)	LO (low impact)	PH (potentially high impact)	HI (high impact)	SE (severe impact)
(a) Total	1,183	340 (28.7%)	580 (49.0%)	82 (6.9%)	78 (6.6%)	103 (8.7%)
(b) Taxonomy[a]						
Plants	896	319 (36%)	403 (45%)	46 (5%)	54 (6%)	74 (8%)
Non-marine invertebrates	147	12 (8%)	95 (65%)	24 (16%)	8 (5%)	8 (5%)
Fungi	79	8 (10%)	57 (72%)	4 (5%)	7 (9%)	3 (4%)
Marine invertebrates	26	1 (4%)	11 (42%)	4 (15%)	2 (8%)	8 (31%)
Vertebrates	25	0	12 (48%)	1 (4%)	7 (28%)	5 (20%)
Algae	10	0	2	3	0	5
(c) Continents/oceans of origin						
Europe	719	221 (31%)	357 (50%)	46 (6%)	45 (6%)	50 (7%)
Asia	610	185 (30%)	294 (48%)	38 (6%)	44 (7%)	49 (8%)
North America	281	66 (23%)	153 (54%)	20 (7%)	19 (7%)	23 (8%)
Africa	167	61 (37%)	79 (47%)	8 (5%)	10 (6%)	9 (5%)
South America	61	12 (20%)	37 (61%)	8 (13%)	3 (5%)	1 (2%)
Oceania	45	5 (11%)	31 (69%)	4 (9%)	3 (7%)	2 (4%)
Pacific Ocean	22	1 (5%)	4 (18%)	3 (14%)	4 (18%)	10 (45%)
Atlantic Ocean	16	0	8	5	0	3
(d) Pathways of introduction						
Escape	657	185 (28%)	331 (50%)	29 (4%)	52 (8%)	60 (9%)
Contaminants	434	127 (29%)	212 (49%)	46 (11%)	23 (5%)	26 (6%)
Stowaways	230	62 (27%)	89 (39%)	36 (16%)	14 (6%)	29 (13%)
Release	89	27 (30%)	26 (29%)	3 (3%)	14 (16%)	19 (21%)
Unaided	86	10 (12%)	44 (51%)	15 (17%)	7 (8%)	10 (12%)
(e) Habitats colonised						
Open lowlands	910	215 (24%)	487 (54%)	69 (8%)	59 (6%)	80 (9%)
Urban environments	628	173 (28%)	313 (50%)	41 (7%)	41 (7%)	60 (10%)
Woodlands	479	67 (14%)	276 (58%)	29 (6%)	48 (10%)	59 (12%)
Wetlands	76	10 (13%)	25 (33%)	5 (7%)	13 (17%)	23 (30%)
Marine/coastal habitats	73	2 (3%)	26 (36%)	11 (15%)	11 (15%)	23 (32%)
Parasitic lifestyle	51	5 (10%)	26 (51%)	8 (16%)	5 (10%)	7 (14%)
Lakes and rivers	39	1 (3%)	18 (46%)	3 (8%)	7 (18%)	10 (26%)
Mountains	6	1	3	1	0	1

Note. Rows within sections (c)–(e) are not mutually exclusive sets of species. Percentages are provided only if $N > 20$; decimals only if $N > 1{,}000$. Statistics are provided in Table B2 (Appendix B in the Supporting Information).

[a]Note that some groups are not strictly taxonomically defined, as "fungi" comprise Asco-, Basidio- and Oomycota; whereas "algae" comprise Chloro-, Phaeo- and Rhodophyta. "Plants" are here defined as Embryophyta (i.e. land plants).

criteria F (22%), H (17%), I (3%) and/or G (2%; percentages are non-exclusive, as two criteria may obtain equally high scores).

Across species, the scores for criteria A–G were positively correlated with each other (Figure B1 in Appendix B in the Supporting Information). The strongest correlation ($R^2 = .47$) was found between the two criteria concerned with ecosystems (with their colonisation and transformation, respectively, i.e. C:G). Other strong correlations involved the criteria measuring effects on threatened nature (D:F, $R^2 = .31$), the two main aspects of invasion potential (A:B, $R^2 = .28$), and the criteria measuring species effects (D:E, $R^2 = .17$). Two further pairs of criteria (B:E and E:F) reached $R^2 > .10$.

The uncertainty attached to a score was quantified by assessing the interquartile range for each criterion for each species. In most of the cases, uncertainty did not affect the outcome of the assessments, that is, the interquartile ranges did not intersect with the threshold values between scores. Uncertainty affected the placement on the invasion axis (criteria A–C) for 25%, and the placement on the effect axis (criteria D–I) for 14% of the species. For 21% of the species, the final impact category was uncertain: for 9% impact might have been higher than assessed, for 11% lower than assessed, and for 1% uncertainty extended both ways.

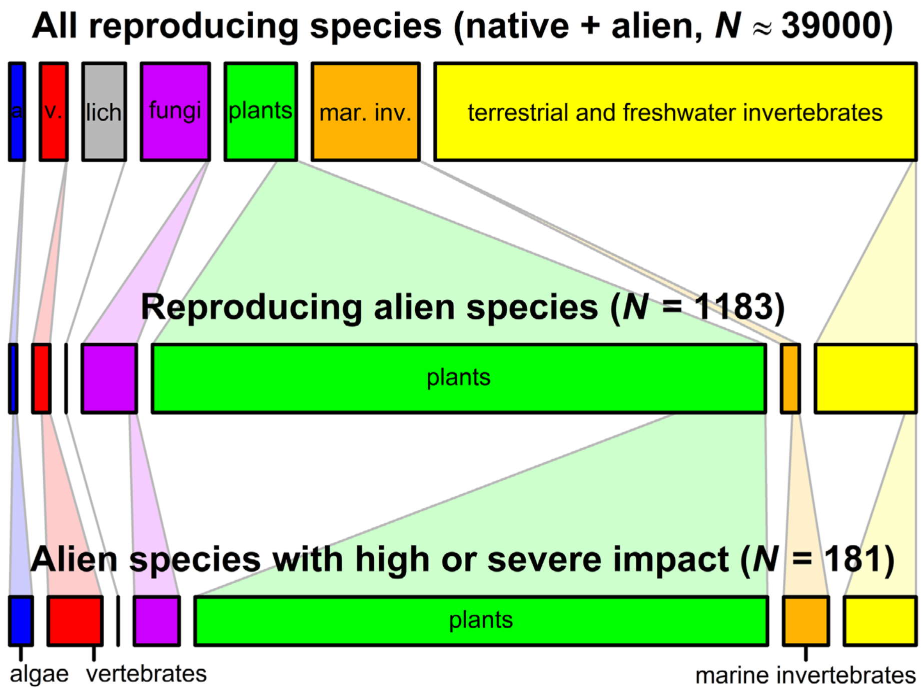

FIGURE 3 Relative frequency of different groups of alien species in Norway. The middle row shows how groups of alien species are represented among the set of all reproducing species (including native ones; top). The bottom row shows how alien species with the two highest ecological impact categories are represented among the set of reproducing alien species. (lich., lichens; no alien lichens have been recorded.)

3.2 | Taxonomy, origin and history

Table 2(b) shows the distribution of impact categories across taxonomic (and ecological) groups of species (cf. Figure 2). Vertebrates were significantly overrepresented in the two highest impact categories (HI+SE; see Table 1), compared to all other taxa combined (Table B2 in Appendix B in the Supporting Information; see Figure 3). Alien species were not a taxonomically representative sample of all species (native + alien) that reproduce in the wild (Figure 3). Plants were grossly overrepresented among alien species, with risk-assessed alien species constituting roughly a quarter of the Norwegian flora, whereas invertebrates were underrepresented, with risk-assessed alien species constituting less than 1% of the Norwegian invertebrate fauna.

Alien species originated from all continents, although species of European origin were the most frequent (Table 2(c)). Among species introduced from the Pacific Ocean, there was a higher proportion with high or severe impact than expected from chance (Table B2 in Appendix B in the Supporting Information). None of the other areas of origin were over- or underrepresented among species with high or severe impact. The average number of continents (and/or oceans) in which an alien species is native was 1.6 and did not differ between impact categories (Wilcoxon's rank sum test, $N = 1{,}182$, $W = 94{,}028$, $p = .35$). On the other hand, the number of currently inhabited continents/oceans was higher for HI+SE species (3.3±0.1) than the remainder (2.9±0.1; $N = 1{,}179$, $W = 69{,}969$, $p < 10^{-6}$).

The dates of first observation in Norway have been recorded for 1,173 of the species (Figure 4). From 1800 to 2017, the frequency of new observations per year increased approximately exponentially over time, and reached a level of 10.2±1.0 species per year in 2017 (linear regression of the log-transformed number of records per year + 1, estimate $[7.9 \pm 0.7] \cdot 10^{-3}$, $F_{1;216} = 132.0$, $R^2 = .379$, $p < 10^{-23}$; a linear increase obtained $R^2 = .319$). On average, species with high or

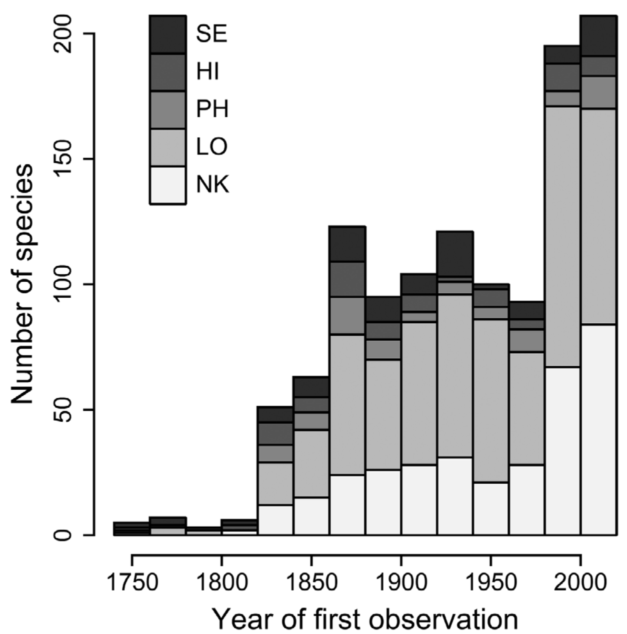

FIGURE 4 Distribution of years of first observation of reproducing alien species in Norway ($N = 1{,}173$). Grey tones indicate ecological impact (severe, high, potentially high, low, no known impact). Bars comprise 20 years, except for the last one (2001–2017)

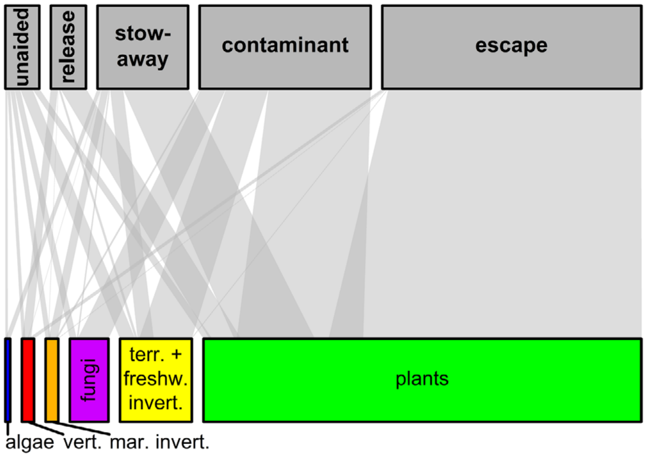

FIGURE 5 Distribution of introduction pathways for reproducing alien species in Norway according to taxonomic groups. A species can have more than one introduction pathway, which is why pathways may overlap ($N = 1{,}147$ species and 1,496 species-pathways; the graph is somewhat simplified in that the overlap area may not be correct for a specific pair of pathways, whereas the total overlap area is)

severe impact had been recorded earlier (median year 1908, interquartile range 1865–1978, $N = 181$) than the remaining species (1947, 1896–1995, $N = 992$; $W = 112{,}067$, $p < 10^{-6}$).

3.3 | Pathways of introduction

Relevant pathways of introduction to Norway were recorded for almost all species ($N = 1{,}147$ species, 1,496 species-pathways), and escape from containment was the most common pathway (Table 2(d)). Species that had been released intentionally were overrepresented in the SE and HI categories, compared to all other pathways combined (Table B2 in Appendix B in the Supporting Information).

The most frequent pathway subcategories were escape from horticulture (46%), escape from other ornamental purposes (21%), contamination of seeds (15%), ballast water or ballast sand (13%), habitat material (10%), plants (6%), vehicles (5%) and timber import (5%; percentages are non-exclusive because species can be introduced along more than one pathway). The remaining pathway subcategories were relevant for less than 5% of the species. The above numbers are dominated by plants, whereas most marine organisms were introduced with ballast water (44%), fungi as parasites on plants (58%) and non-marine animals with habitat material (25%). The highest proportion of species with high or severe impact was found in the vehicle subcategory (28%) among stowaways, in the ornamental subcategory (25%) among escapees and in the habitat material subcategory (14%) among contaminants.

There were large taxonomic differences in the relative importance of pathways (Figure 5). Although escape was the predominant introduction pathways for plants, most non-marine invertebrates and fungi were introduced as contaminants, marine organisms largely as stowaways and most vertebrates had been released intentionally. A higher-than-proportional fraction of non-marine invertebrates had spread unaidedly from neighbouring countries where they were also alien.

3.4 | Habitat and climate

Species with high or severe impacts were overrepresented among alien species reported from wetlands, from marine and coastal habitats and from lakes and rivers (Table 2(e) and Table B2 in Appendix B in the Supporting Information). In open lowlands, in contrast, species with high or severe impacts were underrepresented.

Eight ecosystems were affected by more than 10 alien species (Table 3), in the sense that the species caused substantial changes in these ecosystems. Also, one critically endangered ecosystem was affected (namely hay fen margins), although only by two species.

Assessments took projected future climate change during the 50 years from 2017 to 2066 into account. The experts judged that, in the absence of climate change, 150 species (13%) would have had a lower score for invasion potential. Likewise, for 53 species (5%) the ecological effect score was considered to depend on climate change.

3.5 | Area of occupancy

The median area of occupancy of alien species in Norway was 144 km^2, with an interquartile range from 30 to 800 km^2, and 95% of the areas lying between 4 and 16,000 km^2 (Figure 6; for comparison, the total area of mainland Norway is 324,000 km^2). The species with the largest areas of occupancy were American mink *Neovison vison* (240,000 km^2), the beetle *Atomaria lewisi* (180,000 km^2), red king crab *Paralithodes camtschaticus* (98,000 km^2), the beetle *Cartodere nodifer* (90,000 km^2), red-berried elder *Sambucus racemosa* (88,000 km^2), garden lupin *Lupinus polyphyllus* (78,000 km^2) and pineappleweed *Lepidotheca suaveolens* (78,000 km^2). These estimates were based on the known areas of occupancy, multiplied by *dark figures* (defined in Box 1).

Area of occupancy was positively correlated with the scores of all criteria, except I. The highest correlations were found for criteria A ($R^2 = .42$) and B ($R^2 = .33$), whereas area of occupancy explained less than 10% of the variance in the remaining criteria (Table B3 in Appendix B in the Supporting Information).

3.6 | Svalbard and Jan Mayen

Of the 47 alien species that were risk-assessed for Svalbard, 16 were already reproducing, whereas 31 were door-knockers. Twelve of the species were classified as NK, 31 as LO, one as PH, one as HI (the amphipod *Ischyrocerus commensalis*, door-knocker) and two as SE (snow crab *Chionoecetes opilio*, reproducing; and red king crab *P. camtschaticus*, door-knocker). The 16 alien species reproducing on Svalbard included 14 flowering plants, one crustacean and one mammal. The only alien species known to reproduce on Jan Mayen, common sorrel *Rumex acetosa*, had no known impact.

TABLE 3 Norwegian ecosystems undergoing substantial changes due to alien species

Ecosystem	Red List category	N	Score for effect on ecosystem 1	2	3	4
Open lime-rich shallow-soil lowland systems in the boreonemoral zone	Vulnerable	73	26	29	16	2
Forests	–	50	39	9	2	0
Semi-natural grasslands	–	39	32	7	0	0
Alluvial forests	–	23	23	0	0	0
Coastal heaths	Endangered	19	2	5	7	5
Open alluvial systems	–	17	15	2	0	0
Shallow stable seabeds	–	16	15	1	0	0
Southern fixed dunes	Endangered	12	1	3	5	3

Note. All ecosystems affected by more than 10 alien species are listed. Red List categories of ecosystems follow Lindgaard and Henriksen (2011). Scores are for criteria F and G.

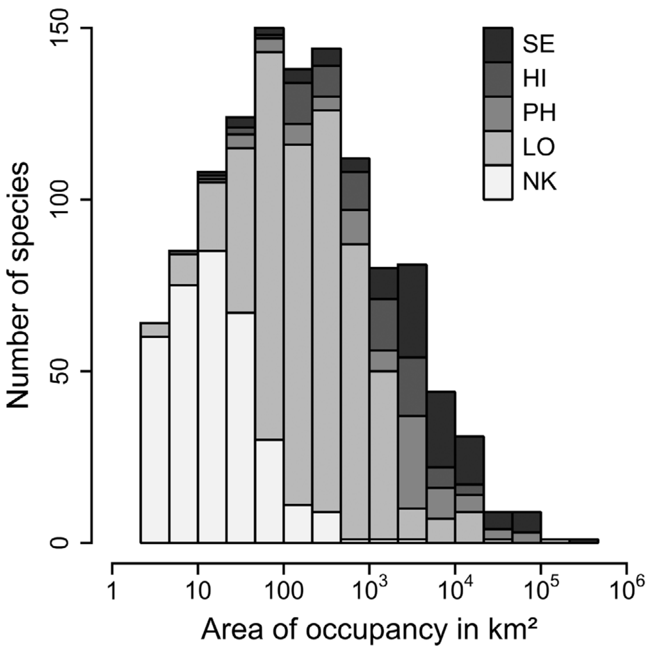

FIGURE 6 Distribution of areas of occupancy of reproducing alien species in Norway ($N = 1,183$). Grey tones indicate ecological impact (severe, high, potentially high, low, no known impact). Note that the *x*-axis is logarithmic

4 | DISCUSSION

Preventing and halting the invasion of alien species is an urgent and global challenge. However, costs for eradication may be considerable and are likely to increase in the future (Hoffmann & Broadhurst, 2016; Jardine & Sanchirico, 2018). It is therefore not realistic, and arguably not even necessary, to eradicate all alien species. Instead, management authorities need a scientific basis for prioritising their efforts. Because alien species are not *by definition* harmful (e.g. Davis et al., 2011), the Norwegian impact assessments classify alien species according to their actual and potential ecological impacts.

In this study, we present the first quantitative impact assessment of all alien species in a country, within the delimitations outlined above. By applying the same set of criteria to all species, the method (GEIAA) ensures that the impact categories are comparable across widely different taxonomic groups and ecosystems (see Figure 2). This enables a transparent prioritisation of management efforts, largely independent of expert opinion (see also Nentwig, Bacher, Kumschick, Pyšek, & Vilà, 2018). Furthermore, by using quantitative criteria, the GEIAA assessments are testable and have a high repeatability (González-Moreno et al., 2019). In Sweden, the same method has been used to assess 1,033 species (Strand, Aronsson, & Svensson, 2018). If other countries follow the example of Norway and Sweden to carry out taxonomically exhaustive impact assessment of alien species using quantitative criteria, this would allow for international compilations and comparisons of the assessment results.

As we demonstrate here, most (78%) alien species in Norway have no known impact (NK) or a low impact (LO) on native biota and ecosystems. It is possible, though, that some species end up in these categories due to poor knowledge. On average, impact seems to increase with the number of years an alien species has been in the country (Figure 4). This may be due to the presence of lag effects, that is, species need some time (years to decades) to adapt to their new environment, before they exhibit their full invasion potential and ecological effect (Aikio, Duncan, & Hulme, 2010; Whitney & Gabler, 2008; Witte, Buschbaum, van Beusekom, & Reise, 2010). Biased research interest may also contribute to a delay in the reporting of relevant impacts. In both cases, this would mean that a categorisation of alien species based on their current impact may underestimate their true potential for harm, even if impacts reported from the rest of the world are taken into account, as was done here (see Appendix A in the Supporting Information).

An additional 7% of the species were categorised as having potentially high (PH) impact. This category contains species that received the maximum score on the invasion or the effect axis, combined with a minimum score on the other axis (see Figure 1). Although PH species are not currently categorised as having high impact, unforeseen changes in their invasiveness or effect may render these species problematic in the future, for example, due to climate change or changes in land-use, plastic or evolutionary responses or due to novel ecological interactions as the alien species encounter new native biota.

TABLE 4 "The 103 worst": alien species reproducing in mainland Norway that were risk-assessed as having a severe impact (SE) on Norwegian nature

Higher taxon	*N*	Species
Tracheophyta	73	*Bunias orientalis* (Turkish warty-cabbage), *Cytisus scoparius* (common broom), *Elodea canadensis* (American waterweed), *Lupinus polyphyllus* (garden lupin), *Petasites hybridus* (butterbur), *Picea sitchensis* (Sitka spruce), *Reynoutria japonica* (Japanese knotweed), *Rosa rugosa* (beach rose), *Tsuga heterophylla* (western hemlock), *Vinca minor* (dwarf periwinkle) and 63 others
Crustacea	4	*Caprella mutica* (Japanese skeleton shrimp), *Homarus americanus* (American lobster), *Pacifastacus leniusculus* (signal crayfish) and *Paralithodes camtschaticus* (red king crab)
Mollusca	3	*Arion vulgaris* (Spanish slug), *Crassostrea gigas* (Pacific oyster) and *Potamopyrgus antipodarum* (New Zealand mud snail)
Nematoda	3	*Angiostrongylus vasorum* (French heartworm), *Anguillicoloides crassus* and *Meloidogyne hapla* (northern root-knot nematode)
Rhodophyta	3	*Bonnemaisonia hamifera*, *Dasysiphonia japonica* and *Gracilaria vermiculophylla*
Amphibia	2	*Pelophylax esculentus* (edible frog) and *Pelophylax lessonae lessonae* (continental pool frog)
Mammalia	2	*Lepus europaeus* (European hare) and *Neovison vison* (American mink)
Oomycota	2	*Aphanomyces astaci* (crayfish plague) and *Phytophthora ramorum* (sudden oak death)
Annelida	1	*Marenzelleria viridis*
Ascomycota	1	*Hymenoscyphus fraxineus* (ash dieback)
Aves	1	*Branta canadensis* (Canada goose)
Bryophyta	1	*Campylopus introflexus* (heath star moss)
Bryozoa	1	*Tricellaria inopinata*
Chelicerata	1	*Opilio canestrinii*
Chlorophyta	1	*Codium fragile* (green sea fingers)
Ctenophora	1	*Mnemiopsis leidyi* (sea walnut)
Insecta	1	*Harmonia axyridis* (harlequin ladybeetle)
Monogenea	1	*Gyrodactylus salaris*
Phaeophyta	1	*Sargassum muticum* (Japanese wireweed)

Note. For vascular plants, only a selection of species is provided; for the complete list, see Sandvik et al. (2020).

A change in the limiting category for the impact assessment of these species could lead to rapid changes in impact. The characteristics of "$PH_{(lower\ right)}$" and "$PH_{(upper\ left)}$" species (referring to the corners of the impact matrix, see Figure 1) will generally be very different, however. For example, many of the former species have been in the country for a long time and have not exhibited any detrimental effects, despite being widespread. The latter group, which only includes three species (namely, willow-leaved cotoneaster *Cotoneaster salicifolius*, the water flea *Daphnia ambigua*, water pineapple *Stratiotes aloides*), has opposite characteristics: albeit not being invasive, these species have a huge ecological effect, and if their expansion ability were to increase, for example, due to a changing climate, their impact would become massive. It may therefore be warranted to reassess these species on a regular basis to detect such changes.

The remaining 15% of the alien species reproducing in Norway were assessed to be in the two highest impact categories (HI and SE). Incidentally, the number of species with severe impacts was close to 100, as in IUCN's list of "100 of the worst" invasives globally (Luque et al., 2014; cf. Nentwig et al., 2018). Building on this parallelism, a summary of "the 103 worst" alien species in Norway is given in Table 4 and compared with IUCN's list in Appendix D in the Supporting Information. A corresponding summary of the 24 door-knocker species with severe impact is provided in Table C4 (Appendix C in the Supporting Information). For the latter species, it would be especially rewarding to consider management measures to prevent establishment (Keller, Lodge, & Finnoff, 2007; Leung et al., 2002).

The 103 worst alien species are rather unevenly distributed taxonomically (Table4). The main reason is that plants dominate among alien species in Norway (Table2; see Sandvik et al., 2019a). A further factor is that many alien plants and vertebrates have been imported (and partly also released) intentionally, meaning that there has been a likely pre-selection of species that cope with Norwegian climate. Finally, one has to expect a certain reporting bias in favour of larger and more visible organisms.

The impact categories do not have any immediate legal implications in Norway. For example, a species is not automatically banned for use or enlisted for eradication even if it has been classified as having a severe impact, although the responsible authorities may decide its ban or eradication *based on* this impact assessment. In this, the impact categories function analogously to IUCN's (2012b) Red List categories (vulnerable, endangered, critically endangered, etc.), namely as the ecological foundation for evidence-based management.

The impact categories and the placement of species in the impact matrix can thus guide authorities in prioritising alien species to be managed: other things being equal (which they rarely are, however), management *priorities* are likely to be in the order

SE > HI > $PH_{(upper\ left)}$ > $PH_{(lower\ right)}$ > LO > NK (see Figure 1, and Table 1 for abbreviations). The additional information collected can help to design and target appropriate management *measures*, for example, prevention, eradication, containment, control or monitoring. These measures are emphasised by the Convention of Biodiversity (CBD 2010) and the European Union (EU 2014) as important strategies to combat alien species.

Prevention, early detection and rapid response are much more cost efficient than measures later in the invasion process (Essl et al., 2015; Hulme et al., 2008; Leung et al., 2002). To this end, establishing surveillance systems with watch lists of prioritised species are important measures. The present assessments of door-knocker species (Appendix C in the Supporting Information), and especially knowledge of their *introduction pathways* (CBD 2014), are essential for designing effective policies against these species.

Eradication is an option available for species that still have rather low *areas of occupancy*, especially when they have an increased invasion potential under future climate conditions. The expansion of several alien species in Norway is facilitated by climate change (Gjershaug, Rusch, Åström, & Qvenild, 2009), which would aggravate their impact (Bellard, Jeschke, Leroy, & Mace, 2018).

For the remaining species, authorities may want to prioritise *containment* and/or *control* measures. For alien species whose areas of occupancy already cover thousands of square kilometres, one might have to prioritise further, namely by focusing management efforts on specific areas or ecosystems where their impacts are particularly negative, and on pathways where certain changes in practice may suffice to prevent further expansion.

Our results can thus guide management authorities in two ways. First, the use of quantitative and generic assessment criteria facilitates the prioritisation of management resources across species. Second, the background information collected for each species can be a help for designing appropriate management measures.

AUTHOR CONTRIBUTIONS

LG was project leader and organised the impact assessments. HSa, OH and LG prepared the assessment guidelines with input from RE, HHe and VV. Assessments were carried out by RE, PAÅ, HHe, OP, PAP, HSols, VV, KBW (vascular plants); FØ, SÅ, HE, AE, ØG, BAH (terrestrial invertebrates); HSolh, BN, LS, VT (fungi); TF, BG, AJ, EO, JS (marine invertebrates); EF, AF, TH, KN, RW (fishes); VH, SF, KS, HSt (algae); HHa, ISH, EK, CM, BY (flatworms and nematodes); HCP, JES, POS (mammals); BGS, JOG (birds); DD (amphibians and reptiles); GK, SIJ, TCJ (freshwater invertebrates) and KH (bryophytes). RE, FØ, HSolh, TF, EF, VH, HHa, HCP, BGS, DD and GK headed the respective expert committees. OH and LG assisted the expert committees in their work. OH, LG and HSa carried out quality control. HSa, OH and SH analysed the data. HSa wrote the article; all authors commented on and approved the manuscript.

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DATA AVAILABILITY

Data available from the Dryad Digital Repository at https://doi.org/10.5061/dryad.8sf7m0cjc (Sandvik et al., 2020).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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