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INVASION NOTE

Generic ecological impact assessment of alien species (GEIAA): the third generation of assessments in Norway

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Abstract The generic ecological impact assessment of alien species (GEIAA) is described. It comprises a set of criteria and an assessment procedure. The set of criteria consists of three criteria that quantify invasion potential, and six criteria that capture the ecological effects of alien species. The threshold values for all criteria are numerically defined, rendering the set of criteria fully quantitative. Genericity is ensured by using criteria that are applicable to all taxonomic groups and in all habitats. In being generic, quantitative, ecological and normatively neutral, the criteria were inspired by the international Red List criteria. Capturing both invasion potential and effect, GEIAA can be regarded as a full ecological impact assessment. The assessment procedure contains guidelines on documentation, the collection of background information, the handling of uncertainty, and quality assurance. GEIAA represents the second revision, and thus the third generation, of assessment methodology in Norway. It has recently been used to carry out more than 2500 impact assessments of alien species in Norway and Sweden.

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Introduction

The signatory states of the Convention on Biological Diversity have committed themselves to "Prevent[-ing] the introduction of, control[ling] or eradicate[ing] those alien species which threaten ecosystems, habitats or species" (CBD, Article 8 [h]). As a step towards fulfilling this obligation, the Norwegian government has decided to carry out ecological impact assessments of alien species on a regular basis. The body responsible for these assessments is the Norwegian Biodiversity Information Centre (NBIC). So far, three such rounds of assessments of alien species have been carried out in Norway, and the methodology used has been improved each time, based on the experience collected. The first assessment was purely qualitative in nature, and covered 217 selected alien species (Gederaas et al. 2007). The second assessment used a completely new set of criteria, which was semi-quantitative (Sandvik et al. 2013). It was used to assess 1383 alien species (Gederaas et al. 2013). The third impact assessment, which has been completed in 2018, covered 1532 taxa, including all alien species (within certain delimitations) known to occur in Norway (H. Sandvik et al. in prep.). The aim of this paper is to describe the method used in the third assessment, the generic ecological impact assessment of alien species (GEIAA). GEIAA is a revised version of the method that was used in the previous assessment (Sandvik et al. 2013). Due to the revision, GEIAA's criteria are now quantitative throughout. With 1532 impact assessments in Norway and an additional 1033 impact assessments in Sweden (Strand et al. 2018), GEIAA is among the most widely applied alien species assessment schemes.

GEIAA's set of criteria

The core of GEIAA is the set of criteria, based on which species can be assigned to five ecological impact categories from 'no known impact' to 'severe impact'. Three criteria (A–C) are used to assess invasion potential, while the remaining six criteria (D–I) capture the ecological effect of species. For each species, all nine criteria are to be assessed, assigning scores between 1 and 4.

Threshold values for the criteria are summarised in Tables 1, 2 and 3. Some key terms, which are given in small capitals in the following criteria definitions, are explained in Box 1. The rationale behind each criterion and the differences between GEIAA and the previous set of criteria are outlined in Online Resource 1.

Overall impact

Ecological impact is here defined as the product of invasion potential and ecological effect. For this reason, the impact of alien species on nature can best be captured using a two-dimensional figure (Fig. 1), where impact is indicated by the species' position along two axes—the invasion axis (criteria A–C) and the effect axis (criteria D–I). On each axis separately, the relevant criteria are combined in accordance with the one-out–all-out principle. In other words, the maximum score of the six effect criteria determines the placement along the effect axis; and the maximum score of the three invasion criteria determines the placement along the invasion axis (with the reservation that criteria A and B are coupled by means of auxiliary conditions, cf. Table 1 and Table A2 in Online Resource 1).

The four subcategories along each axis provide the basis for 16 possible combinations of invasion potential and ecological effects (Fig. 1). The position of a species in Fig. 1 illustrates the (risk of) impact that a species exerts on nature. The position determines, in turn, which of the five impact categories the species is placed in:

- severe impact (SE),
- high impact (HI),
- potentially high impact (PH),
- low impact (LO) or
- no known impact (NK).

Species that are excluded from assessments, e.g., because they are not alien species or do not fulfil the historical, geographic, ecological or taxonomic DELIMITATIONS (see Box 1 and H. Sandvik et al. in prep.), are referred to as 'not risk-assessed' (NR). For reasons

Table 1 Criteria, scores and threshold values for the classification of the invasion potential of alien species

Score for invasion potential	A *Median* population lifetime	B *Expansion speed*	C Colonisation of ecosystems (%)
1	< 10 years	< *50* m/a	< 5
2	≥ 10 years [*and B ≥ 2*][a]	≥ *50* m/a	≥ 5
3	≥ *60* years [and B ≥ 2][a]	≥ *160* m/a [and A ≥ 2][a]	≥ 10
4	≥ *650* years [and B ≥ 3][b]	≥ *500* m/a [and A ≥ 3][a]	≥ 20

All criteria are to be evaluated, and the highest score obtained by any of the criteria A–C determines the placement along the invasion axis (Fig. 1). Changes compared to the 2012 criteria are italicised. Terms in small capitals are defined in Box 1 [Due to auxiliary conditions (in square brackets), criteria A and B are dependent on each other (see notes and Table A2 in Online Resource 1)]

NB! The auxiliary conditions do not apply to species that have ecological effects despite not being established

[a] If the auxiliary condition is not fulfilled, the score is to be reduced by one

[b] *If the auxiliary condition is not fulfilled, the score is defined as the score of criterion B increased by one*

Table 2 Criteria, scores and threshold values for the classification of the ecological effect of alien species, criteria D–G

Score for ecological effect	D Documented or likely effect on	E	F	G
	Native species		ecosystems	
	threatened/keystone	Other	threatened/rare	Other (%)
1	unlikely	weak	unlikely	< 5
2	*Weak and Local*	moderate[a]	> *0%*	≥ 5
3	weak *and large-scale*	local displacement	≥ *2%*	≥ 10
4	moderate[a] or displacement	large-scale displacement	≥ 5%	≥ 20

All criteria are to be evaluated, and the highest score obtained by any of the criteria D–I determines the placement along the effect axis (Fig. 1). Changes compared to the 2012 criteria are italicised. Terms in small capitals are defined in Box 1

[a] *If the effect is moderate and local, the score is to be reduced by one*

Table 3 Criteria, scores and threshold values for the classification of the ecological effect of alien species, criteria H and I

Score for ecological effect	H Documented or likely transmission of	I
	Genetic material	Parasites or pathogens[b]
1	unlikely	unlikely
2	*Locally to native species*	Prevalence increases with moderate effect[a]
3	*Large-scale* to native species	Existing parasite to novel host[a]
4	To threatened or keystone species[a]	Existing parasite to novel threatened or keystone host[a], or of a novel alien parasite

All criteria are to be evaluated, and the highest score obtained by any of the criteria D–I determines the placement along the effect axis (Fig. 1). Changes compared to the 2012 criteria are italicised. Terms in small capitals are defined in Box 1

[a] *If the effect is merely local, the score is to be reduced by one*

[b] *The score of the host must not exceed the parasite's overall score for ecological effect*

Box 1 Definitions of key terms

AOO (area of occupancy) 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; IUCN 2017)

Delimitation any condition that must be met by a species (in addition to being alien) to be assessed (relevant delimitations may be historical, geographical, ecological and/or taxonomic; for use in Norway, delimitations follow H. Sandvik et al. in prep.)

Displacement reduction of a native species's AOO or EOO by at least 1% through INTERACTIONS with an alien species

Ecosystem all organisms within a more or less uniform and delimitable area, the total environment they live in and are adapted to, and the processes that regulate the relationships between the organisms and the environment, including human activity (for use in Norway, definitions of ecosystems follow Halvorsen et al. 2016)

EOO (extent of occurrence) the area of the smallest convex polygon that can be drawn to encompass all occurrences of the species (IUCN 2017)

Expansion speed the annual increase in the AOO of the species, measured in metres per year (H. Sandvik in prep.)

Heavily modified ECOSYSTEM characterised by a high intensity of anthropogenic disturbance, often brought about by interferences that have changed the structure and/or other features of the system so strongly that the resulting ecosystem and biotic relationships are disrupted or absent (Halvorsen et al. 2016)

Interaction competition, herbivory, predation, parasitism, allelopathy and indirect effects (e.g., apparent competition) with/of/on native species

Introgression transfer of genetic material from the gene pool of the alien species to the gene pool of at least one native species (mere hybridisation without subsequent backcrossing does not fulfil this definition)

Keystone species a species that, despite being relatively rare (in terms of biomass), can have a large effect on the abundance, distribution or diversity of other species (based on Power et al. 1996; for applications of this definition, see Valls et al. 2015)

Large-scale effect that affects (or will most likely affect) at least 5% of the population size or AOO or EOO of a native species

Local effect that affects (and that most likely will remain constrained to) less than 5% of the population size and AOO and EOO of a native species

Median population lifetime: the time when it is 50% likely that the population in the assessment area has gone extinct due to natural factors alone (cf. Table A1 in Online Resource 1)

Moderate effect that results (or will most likely result) in a reduction of at least 15% in the population size of at least 1 native subpopulation over a 10-year period, but without DISPLACING any native species (a population decline of 15% per decade corresponds to a reduction in carrying capacity of 15% per decade or in the annual multiplicative growth rate of 2%)

Rare an ECOSYSTEM that is near threatened (NT) because of a low number of occurrences (i.e., according to criterion 2 or 3 for the red-listing of ecosystems; Lindgaard and Henriksen 2011)

Substantial state change in an ECOSYSTEM that corresponds to at least one well-defined (countable) level or to more than one-third of the levels defined for the environmental variable concerned (Halvorsen et al. 2016), or to that number of levels more than the state change would have been in the absence of the species

Threatened a species or ECOSYSTEM that is listed as vulnerable (VU), endangered (EN) or critically endangered (CR) according to the appropriate Red List (in the case of Norway, Lindgaard and Henriksen 2011; Henriksen and Hilmo 2015)

Unlikely an effect that has an expected likelihood of less than 25% for being above the lowest threshold of its criterion (Tables 2, 3)

Weak effect whose negative consequences on the population size of native species will be less than MODERATE

that are detailed in Online Resource 1 (§ 1.1), GEIAA does not have a category for 'data deficiency'.

Criteria A–C: invasion potential

Invasion processes can be split into two phases, which form the basis for one criterion each: establishment and expansion. A third criterion relates to the area of ecosystems that is colonised.

A: *Population lifetime* The higher the MEDIAN POPULATION LIFETIME of an alien species, the higher the species scores on the invasion axis (Table 1).

B: *Expansion speed* The higher the EXPANSION SPEED of an alien species, the higher the species scores on the invasion axis (Table 1).

C: *Colonisation of ecosystems* The larger the area of an ECOSYSTEM colonised by an alien species, the higher the species scores on the invasion axis (Table 1).

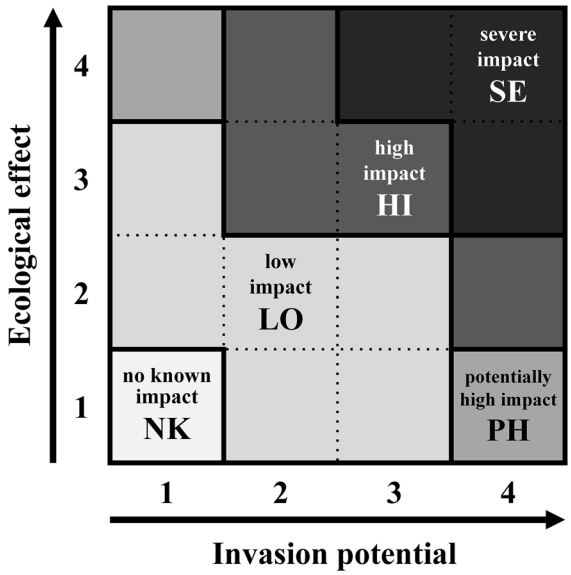

Fig. 1 Impact matrix. During impact assessment, a score between 1 and 4 is assigned to the invasion potential and to the ecological effect of a given species (using the numerical thresholds described in Tables 1, 2 and 3, Box 1). The ecological impact of an alien species increases with increasing invasion potential (*x*-axis, criteria A–C) and with increasing ecological effect (*y*-axis, criteria D–I), and it is classified into five impact categories (NK, LO, PH, HI, SE)

Criteria D–I: ecological effect

Alien species are classified along the effect axis (Fig. 1) according to their negative effects upon nature. The six criteria measure ecological and genetic effects on native species as well as effects on ecosystems.

D: *Interactions with threatened or keystone species* The stronger the negative ecological INTERACTIONS an alien species has with THREATENED or KEYSTONE SPECIES, the higher the alien species scores on the effect axis (Table 2).

E: *Interactions with other native species* The stronger the negative ecological INTERACTIONS an alien species has with other native species (that are neither THREATENED nor KEYSTONE), the higher the alien species scores on the effect axis (Table 2).

F: *Changes in threatened or rare ecosystems* The larger the area of THREATENED or RARE ECOSYSTEMS undergoing SUBSTANTIAL change due to an alien species, the higher the species scores on the effect axis (Table 2).

G: *Changes in other ecosystems* The larger the area of other ECOSYSTEMS (that are neither THREATENED nor RARE nor HEAVILY MODIFIED) undergoing SUBSTANTIAL change due to an alien species, the higher the species scores on the effect axis (Table 2).

H: *Genetic contamination* The larger the likelihood and consequence of an alien species genetically contaminating native species by INTROGRESSION, the higher the alien species scores on the effect axis (Table 3).

I: *Transmission of parasites* The larger the likelihood and consequences of an alien species acting as a vector for parasites (including pathogens such as bacteria or viruses) to native hosts, the higher the alien species scores on the effect axis (Table 3).

GEIAA's assessment procedure

In addition to the set of criteria described above, GEIAA contains guidelines on the procedure of assessment. Assessments are carried out by experts in a purpose-made web application, the Alien Species Database. This application has two interfaces: an assessment interface and a public interface. The assessments and all documentation are registered in the assessment interface (for an English test version, see http://efab.artsdatabanken.no/fab/efab/), which is only accessible to the assessors, facilitates standardisation across assessors and provides a way of archiving all data. After completion of assessments and quality assurance, the results are made available in the public interface (for Norwegian assessments, see https://artsdatabanken.no/fremmedartslista2018).

GEIAA's assessment procedure includes instructions on the following four aspects (for details, see Online Resource 1):

- *Time frame* All assessments are to be based on historical and current effects. Assessments of criteria C–I should also consider effects that, based

on documented evidence, can be expected to occur within 50 years into the future.

- *Documentation* A criterion is not regarded as met unless documentation is available. In addition to the documentation regarding the nine criteria, further information is archived in the Alien Species Database, including species characteristics, distribution history and pathways of introduction and spread (Table A3 in Online Resource 1). Documentation may consist of scientific publications, but also of the assessors' own observations or judgements and other unpublished data or analyses, provided the latter are uploaded to the Alien Species Database.
- *Uncertainty* Uncertainty is reported in terms of interquartile ranges (equivalent to 50% confidence intervals).
- *Quality assurance* Assessments are to be carried out by expert panels rather than single assessors. Assessors receive training from NBIC, and NBIC checks whether assessments have been following the guidelines. Before finalising assessments, the preliminary results are circulated for public comment.

Discussion

GEIAA is a (1) generic (2) ecological (3) impact assessment of alien species based on a (4) quantitative set of criteria. These four characteristics merit elaboration:

(1) GEIAA is *generic* in the sense that it is applicable to all living taxonomic groups, irrespective of phylogenetic position, habitat or status. This is corroborated by the fact that it has been used in Norway to assess 1460 species and 72 sub-specific taxa belonging to all major eukaryotic groups ('algae', animals, fungi, plants); occurring in marine, freshwater and terrestrial habitats; leading sessile, vagile or parasitic lives; and including both established alien species and door-knockers (H. Sandvik et al. in prep.). So far, it has not been applied to unicellular organisms or viruses, but GEIAA would presumably be applicable in those cases, too, since it worked well with pathogens such as oomycetes. Genericity is attained by avoiding taxon-specific or taxon-dependent criteria, such as population size, fecundity or dispersal distance. Instead, GEIAA uses parameters that are directly comparable (e.g., population viability, AOO, species interactions).

(2) GEIAA assesses *ecological* effects in the sense that anthropocentric effects of alien species are deliberately excluded from the set of criteria. Direct or indirect, positive or negative, effects upon human health, ecosystem services, economy, aesthetics etc. are regarded as anthropocentric in this context, as is the feasibility of management measures. Information available on such effects is collected as part of the assessment procedure and made available to stakeholders and the public together with the ecological results (cf. Table A3e in Online Resource 1), but it does not affect the impact score. This is because the aim of GEIAA is a purely ecological and normatively neutral impact assessment, in analogy to the Red List, which is based on ecological criteria alone. The weighting of ecological (e.g., conservation) concerns against economic and other anthropocentric issues is a decision of a normative or political rather than a scientific nature, and it should therefore be taken by management authorities. GEIAA is meant to provide the *ecological* background knowledge needed by the authorities for making informed decisions on alien species management.

(3) GEIAA defines (ecological) *impact* as the product of invasion potential and (ecological) effect. This definition is based on the understanding that impact is proportional to the area invaded, to the density attained, and to the per-capita effects exerted (Parker et al. 1999). As the area colonised often will be unknown and increasing, area is replaced by a species's invasion potential. Population density and per-capita effect can be combined into a measure of per-locality ecological effect. These two factors must be multiplied, and not added together, if the ecological impact is to be quantified (cf. Branquart 2009; D'hont et al. 2015). A species will thus have a small impact whenever one of the factors is small. This is the rationale for using a two-dimensional impact matrix (Fig. 1). The concept of impact underlying GEIAA

differs from some other assessment schemes (e.g., EICAT, GISS; Hawkins et al. 2015; Nentwig et al. 2016), which do not explicitly incorporate the spatial component (area invaded), so that their "impact" is equivalent to our concept of (per-locality) ecological effect. In Jeschke et al.'s (2014) framework, our definition of impact is unidirectional (by excluding positive effects), normatively neutral (by excluding human values), quantitative (see below), ecological (see above); and its spatial, temporal, taxonomic and functional scales cover impacts of the entire alien population in the assessment area within 50 years, and on all multicellular taxa at all organisational levels (gene to ecosystem).

(4) GEIAA is a fully *quantitative* set of criteria in the sense that all thresholds for all criteria are numerically defined (Tables 1, 2 and 3, Box 1). Although the need for quantitative assessments is widely recognised (Lodge et al. 2006), the majority of assessment schemes is still qualitative (Verbrugge et al. 2010). Quantitative sets of criteria have several advantages over qualitative ones, including a higher degree of repeatability, testability and transparency (Tversky and Kahneman 1974; Burgman 2001; McCarthy et al. 2004). In a comparison of twelve impact assessment schemes, GEIAA obtained the highest repeatability (i.e., the lowest coefficient of variation of species scorings across assessors; González-Moreno et al. 2019), which is likely due to its quantitative nature.

GEIAA meets the 14 minimum standards that have been developed for the assessment of alien species (Roy et al. 2018; for details, see Online Resource 1, § 3). The method is currently used in Norway (where it constitutes the third generation of assessments) and in Sweden, but the principles and criteria are applicable in any country or region. In line with its generic nature, GEIAA has been used to carry out more than 2500 impact assessments of alien species in all major taxa and habitats (Strand et al. 2018; H. Sandvik et al. in prep.).

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Author contributions LG was administratively responsible and HaS scientifically responsible for the revision process. AGF, HH, TLM, TR and OS were members of the scientific advisory panel that revised the set of criteria. HaS, OH and LG revised the assessment procedure with input from RE, HH and HeS. HeS designed and developed the Alien Species Database. HaS wrote the paper with input from the remaining authors.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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