

Cumulative impacts from co-occurring non-native species

Gaute Velle, Anders Bryn, Kyrre Kausrud, Lawrence R. Kirkendall, Martin Malmstrøm, Brett K. Sandercock, Paul Ragnar Berg, Kjetil Hindar, Johanna Järnegren, Erlend B. Nilsen, Eva B. Thorstad and Anders Nielsen

Scientific Opinion of the Panel on Biodiversity of the Norwegian Scientific Committee for Food and Environment

This report examines how co-occurring non-native species can interact to create cumulative impacts on ecosystems. Non-native species may interact in additive, antagonistic, or synergistic ways. Through literature review, we found theoretical foundations and empirical examples showing that such interactions often occur. Synergistic interactions are of particular concern. Certain ecosystems appear particularly susceptible, including agricultural landscapes, urban environments, riparian systems, shipping-influenced marine areas, and islands with naïve fauna. We conclude that cumulative effects are ecologically important, and that it would be beneficial to incorporate multispecies interactions into risk assessments of non-native species in Norway.

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Cover photos: Non-native species with ecological assessments of high (HI) or severe risk (SE) on the Norwegian Alien Species List (Artsdatabanken 2023). Top row (L-R): *i*) Japanese knotweed *Reynoutria japonica* SE (credit: Bibliothèque de l'Université Laval), *ii*) signal crayfish *Pacifastacus leniusculus* SE (credit: Nervurax Fishing), *iii*) pink salmon *Oncorhynchus gorbuscha* SE (credit: Totti), *iv*) Egyptian goose *Alopochen aegyptiaca* SE (credit: Andreas Trepte), and *v*) Spanish slug *Arion vulgaris* SE (credit: Syrio). Bottom row (L-R): *vi*) Wild boar *Sus scrofa* HI (credit: Byrdyak), *vii*) Canada goose *Branta canadensis* HI (credit: Michal Klajban), *viii*) Asian lady beetle *Harmonia axyridis* SE (credit: URSchmidt), *ix*) American mink *Neogale vison* SE (credit: Patrick Reijnders), and *x*) giant hogweed *Heracleum mantegazzianum* SE (credit: Micheal Ely). Public domain photos sourced from Wikimedia Commons (*i-viii* and *x*) or OpenVerse (*ix*) and adapted for reuse under the terms of Creative Commons licenses CCO 1.0 (*ii*), CC BY-SA 2.0 (*x*), CC BY-SA 2.5 (*iv*), CC BY-SA 3.0 (*ix*) or CC BY-SA 4.0 (*i, iii, v-viii*).

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Preparation of the opinion

The Norwegian Scientific Committee for Food and Environment (Vitenskapskomiteen for mat og miljø, VKM) appointed a project group to draft the opinion. The project group consisted of five VKM members and one VKM staff member. Two external referees reviewed the draft and provided comments, and the project group revised the draft accordingly. An approval group from the Panel on Biodiversity assessed and approved the final opinion, after which the project group made final edits in line with the Panel's comments.

Authors of the opinion

The authors have contributed to the opinion in a way that fulfils the authorship principles of VKM (VKM 2023). The principles reflect the collaborative nature of the work, and the authors have contributed as members of the project group or as other members of the VKM Panel on Biodiversity.

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Competence of VKM experts

Persons working for VKM, either as appointed members of the Committee or as external experts, do this by virtue of their scientific expertise, not as representatives for their employers or third-party interests. The Civil Services Act instructions on legal competence apply for all work prepared by VKM.

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Summary

Background

The number and impact of non-native species is increasing in ecosystems worldwide due to climate change, global trade, and human land use. Traditional environmental risk assessments evaluate each non-native species separately, but ecosystems may contain multiple non-native species whose interactions can amplify or suppress their ecological impacts. The net cumulative effects of interacting non-native species could be additive, antagonistic, or synergistic, with synergistic impacts representing the greatest concern.

The Norwegian legislation (Nature Diversity Act Section 10) requires assessing overall environmental pressure, yet current Norwegian environmental risk assessment frameworks and practices remain largely based on single-species assessments. In this report, we conduct a literature review of cumulative impacts of co-occurring non-native species. Based on our findings, we assess whether cumulative impacts should be integrated into risk assessments for non-native species. Finally, we explore how cumulative effects and species interactions could be incorporated into such assessments, using the Environmental Impact Classification for Alien Taxa (EICAT) framework from the International Union for Conservation of Nature (IUCN) as a foundation.

Methods

The project team conducted targeted literature searches to identify the theoretical foundations for multispecies interactions, empirical case studies demonstrating additive, antagonistic, and synergistic effects and case studies that are relevant to Norwegian ecosystems. The review focused on key mechanisms, impact pathways, and ecological contexts where cumulative effects are likely. The team examined how EICAT's 12 impact mechanisms can be expanded to include interactions among non-native species.

Results

We found examples of additive, antagonistic, and synergistic interactions when multiple non-native species interact. Interactions can occur through direct mechanisms (competition, predation, hybridization, mutualisms, commensalism, and pathogens) or indirect mechanisms (habitat modification, altered nutrient levels, interaction networks, and fluxes of organic matter, nutrients, and energy across ecosystems). Many mechanisms can operate simultaneously.

Ecosystems especially prone to cumulative impacts include (i) cultivated fields, hay meadows and grazed pastures, (ii) urban areas, grey spaces and transport or infrastructure corridors, (iii) riparian zones and regulated rivers, (iv) ports, estuaries, and other shipping exposed marine areas and (v) islands with naïve fauna. In Norway, likely hotspots for cumulative impacts include coasts with oysters and tunicates, regulated waterways with invasive plants and crustaceans, and freshwater systems containing invasive fishes, mammals, crayfish, and riparian plants. Species that can especially facilitate synergistic interactions include those that increase the establishment success rate, abundance, or per-capita impact of other non-native species, such as of predators, pathogens, ecosystem engineers or mutualists. We found that the EICAT/EICAT+ - framework can incorporate cumulative effects by evaluating how multiple invaders jointly influence the same mechanism or assessment endpoint. We also define a set of potential assessment endpoints, which are measurable response variables against which

adverse effects in risk assessments are evaluated and that represent conservation and management targets.

Uncertainties

Several uncertainties create challenges for assessment of cumulative effects. Data limitations are a key concern because few empirical studies have quantified ecological interactions among invasive species in Norway. Limited long-term monitoring makes it difficult to detect possible nonlinear or lagged effects, and interaction strength is often dependent on the context of habitat, climate, or co-stressors, complicating predictions. In addition, quantification of effects is often uncertain because synergistic and antagonistic interactions are difficult to measure without controlled experiments or structured models, and effects may change over time as the environmental context changes. Many of the mechanisms that underly the EICAT categories, such as indirect effects or ecosystem engineering, require system-specific and species-specific data that are rarely available. Future species introductions and effects of future climate change introduce uncertainty about potential new combinations of invaders, and probability of co-occurrence will depend on dynamic changes in trade patterns, climate suitability, and human behavior.

Conclusions

VKM finds that cumulative effects among non-native species are ecologically important, common, and should be considered in environmental risk assessments. VKM's single-species framework can be expanded to include multispecies dynamics by:

- incorporating interactions among co-occurring species directly into EICAT assessments.
- evaluating additive, antagonistic, and synergistic scenarios for introduced non-native species that co-occur.
- using explicit pathway to harm models with defined assessment endpoints.
- using a qualitative approach as a default, until better data are available from field experiments based on strong experimental designs.
- including both short-term and long-term climate perspectives.

Additive, antagonistic, and synergistic effects among non-native species occur globally and are likely to affect Norwegian ecosystems, particularly where multiple invaders co-occur in human-influenced environments.

The report recommends that mandates for forthcoming VKM risk assessments, including evaluations of single or multiple species, should require assessment of potential cumulative effects. High-risk ecosystems should receive prioritized attention, particularly areas where many non-native species are already established.

Sammendrag på norsk

Bakgrunn

Klimaendringer, global handel og menneskelig arealbruk gjør at fremmede arter etablerer seg i miljøer hvor de ikke opprinnelig hører hjemme. Disse ikke-naturlig forekommende artene konkurrerer med lokale arter om ressurser, kan innføre sykdommer og endrer ofte den lokale næringskjeden.

Tradisjonelt vurderes risikoen av hver art enkeltvis, men det er ofte flere ikke-naturlig forekommende arter til stede i samme økosystem. Samspillet artene imellom kan da forsterke eller dempe påvirkningen på lokalt biologisk mangfold.

De samlede effektene kan være additive (summen av effekten fra enkeltartene), antagonistiske (artene svekker hverandre) eller synergistiske (artene forsterker hverandre). Synergistiske effekter representerer den største bekymringen.

Norsk lovgivning (naturmangfoldloven § 10) krever vurdering av samlet miljøbelastning, men nåværende systemer fokuserer hovedsakelig på enkeltarter. Denne rapporten utforsker derfor hvordan kumulative effekter og samspill mellom arter kan innlemmes i fremtidige risikovurderinger, med IUCNs EICAT-rammeverk (Environmental Impact Classification for Alien Taxa) som faglig utgangspunkt.

Metoder

Prosjektgruppen foretok målrettede litteratursøk for å finne hvordan ikke-naturlig forekommende arter samspiller. Den vurderte både norske og internasjonale studier som dokumenterer additive, antagonistiske og synergistiske effekter. Gjennomgangen var rettet mot sentrale mekanismer, påvirkningsforløp og økologiske kontekster hvor kumulative effekter er sannsynlige. Videre undersøkte gruppen hvordan de tolv påvirkningsmekanismene i EICAT-rammeverket kunne utvides til å inkludere samspill mellom arter, for å bedre evaluere de økologiske effektene av fremmede arter.

Resultater

Vi fant eksempler på alle tre kategorier av samspill. Samspillene kan skje direkte (konkurransen, predasjon, hybridisering, mutualisme, kommensalisme og smittestoffer) eller indirekte (habitatendring, endrede trofiske nivåer, koblinger i næringsnett, samt flyt av organisk materiale, næringsstoffer og energi mellom økosystemer). Flere mekanismer kan virke samtidig. Noen områder er særlig utsatt for kumulative samspillseffekter mellom ikke-naturlig forekommende arter:

- (i) dyrkede områder, slåttemarker og beitemarker
- (ii) urbane områder, «grå» arealer og transport- og infrastrukturkorridorer
- (iii) kantsoner langs vassdrag og regulerte elver
- (iv) havner, estuarier og andre marine områder med mye skipsfart
- (v) øyer

I Norge er det sannsynlig at kysthabitater med fremmede arter av østers og sekkedyr, regulerte vassdrag med fremmede planter og krepsdyr, samt ferskvannssystemer med fremmede arter av fisk, kreps og mink er spesielt utsatt for kumulative effekter.

Sannsynligheten for at en art inngår i et synergistisk samspill med en annen, er særlig stor dersom arten øker sannsynligheten for at andre arter etablerer seg, eller påvirker tetthet og/eller økologisk effekt hos andre ikke-naturlig forekommende arter. Dette gjelder for eksempel rovdyr, smittebærere, arter som endrer habitatet fysisk og arter i gjensidig nyttesymbiose.

Vi ser at slike kumulative effekter kan evalueres innenfor EICAT/EICAT+ -rammeverket som kan tilpasses til å beskrive hvordan flere ikke-naturlig forekommende arter kan virke gjennom den samme mekanismen. I tillegg definerer vi et sett med mulige endepunkter, det vil si målbare responsvariabler som kan brukes til å evaluere negative effekter i risikovurderinger og som kan representere bevarings- og forvaltningsmål.

Usikkerheter

Flere usikkerhetsfaktorer begrenser vurderingen av kumulative effekter. Datamangel er en sentral utfordring, siden få empiriske studier har kvantifisert økologiske samspill mellom ikke-naturlig forekommende arter i Norge, og fordi en vurdering av kumulative effekter krever data fra økosystemene og artene som skal vurderes.

Mangelfull langtidsovervåking gjør det vanskelig å avdekke effekter som ikke er lineære, eller som først opptrer lenge etter at en art har etablert seg. I tillegg er styrken i samspillene ofte kontekstavhengig, den påvirkes av habitat, klima og andre miljøpåvirkninger.

Det er også betydelig usikkerhet knyttet til kvantifisering av effekter, fordi synergistiske og antagonistiske samspill er vanskelige å påvise uten kontrollerte eksperimenter eller detaljerte modeller, og fordi effektene kan endres over tid, i takt med klimaendringer, nye ikke-naturlig forekommende arter som introduseres og andre miljøpåvirkninger.

Konklusjon

Additive, antagonistiske og synergistiske effekter av ikke-naturlig forekommende arter er en global utfordring som også vil påvirke norsk natur, spesielt i områder hvor flere ikke-naturlig forekommende arter lever tett sammen og er påvirket av menneskelig aktivitet. Disse kumulative effektene er viktige for økosystemene og bør vurderes når man analyserer risikoen av fremmede arter.

VKMs nåværende rammeverk for vurdering av enkeltarter kan utvides til å omfatte samspill mellom ikke-naturlig forekommende arter ved å:

- integrere interaksjonsmekanismer direkte i EICAT
- evaluere additive, antagonistiske og synergistiske scenarier for arter som forekommer sammen
- bruke eksplisitte «pathway to harm»-modeller med klart definerte endepunkter
- benytte kvalitative tilnærminger som standard inntil bedre data foreligger, for eksempel fra feltstudier og eksperimenter
- inkludere både kortsiktige og langsiktige klimaperspektiver

Vi anbefaler at fremtidige risikovurderinger vurderer de mulige samlede effektene av ikke-naturlig forekommende arter, både for enkeltarter og flere arter samlet. Vi mener også at økosystemer med høy risiko, særlig der mange ikke-naturlig forekommende arter allerede finnes, bør prioriteres i dette arbeidet.

Background as provided by the VKM Panel on Biodiversity

Environmental risk assessments for non-native species traditionally focus on single species. Each species is evaluated in isolation for its likelihood of establishment, spread, and potential impacts on native biodiversity. However, a single-species approach can overlook the possibility of interactions with other non-native species that co-occur within the same ecosystem or area. When multiple non-native species are present, their ecological interactions can potentially lead to combined effects that would otherwise not be captured by a traditional single-species environmental risk assessment. A focus on single non-native species without interactions has the potential to under-, or overestimate biodiversity outcomes and lead to unintended consequences for management actions.

Assessing the effects of multiple non-native species is particularly relevant in an era of rapid environmental change due to land use and land cover change, shifts in species distributions associated with climate warming, as well as interactions between the climate system and ongoing land conversions. A growing number of non-native species have become established in many ecosystems, and the rate of increase has been accelerating. The ecological rationale for a multi-species perspective is thus strong. The cumulative impacts of multiple invaders can be *additive* with each species contributing independently to a greater total stress on native species or ecosystem functions. The greater risk is that the impacts might also be *synergistic*, where two or more invasive species actively facilitate one other, resulting in a total impact that is greater than the sum of their individual effects. A third possibility is that the cumulative impacts might be *antagonistic* if competition, predation, parasitism or other interactions between two invaders limits their densities or ecosystem impacts. There are gradual transitions between these categories of impact, and with more than two non-native species, several effects can occur simultaneously.

Hence, the net ecological outcome of multiple invaders is not always the sum of independent effects (Howarth 1985, Simberloff and von Holle 1999). Failing to factor in such interactions may lead to over- or underestimation of serious risks if there are synergistic or antagonistic effects. Unrecognized, such effects could in turn result in misleading understanding of ecosystem impacts and misallocation of management actions. Removing one non-native species without accounting for its interactions with others can backfire when single-species control efforts accidentally release a second non-native species from competition, predation, or other interactions. Similarly, the addition of one seemingly innocuous species can unleash the invasive potential of currently harmless non-native plants, for example if the new species can pollinate or disperse seeds of the existing non-native species. Synergistic effects can be especially strong in the case of non-native invasive species that are so-called ecosystem engineers: invasive species whose presence or activities significantly alter the physical or chemical environment in a way favorable to other invasives (Crooks 2002, Rilov et al. 2023).

In light of these issues, it is potentially advantageous to establish an improved risk assessment framework that incorporates multi-species dynamics and interactions. Norwegian law emphasizes a holistic view in the Nature Diversity Act (19 June 2009 No.100) Relating to the Management of Biological, Geological and Landscape Diversity stating that “An impact on an ecosystem shall be assessed in light of the combined pressure to which the ecosystem is or will be subjected” (our translation of §10). In other words, the combined influence of multiple factors on an ecosystem should be considered, rather than considering each factor in isolation. However, management frameworks in Norway currently perform single species risk assessments, including the national Alien Species List produced by the Norwegian Biodiversity Information Center and risk assessments for non-native species conducted by VKM for the

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Norwegian Environment Agency. Our current project on multi-species risk assessments has the potential to aid both VKM and other institutions that perform environmental risk assessments in Norway. In a first step (this report), VKM will lay the ground by performing a literature review on multi-species perspectives in environmental risk assessments. If the review concludes that assessing cumulative effects is beneficial, VKM will in a next step (a coming report) test a multi-species approach using case studies.

Terms of reference as provided by the VKM Panel on Biodiversity

- a) To describe the three possible interaction categories that are relevant to assess:
 - a. Additive
 - b. Synergistic
 - c. Antagonistic

Literature searches shall be carried out to identify examples that illustrate the different interactions. Furthermore, potential examples for non-native species in Norway shall be identified.

- b) Based on the literature review, to assess whether it is possible to quantify the effect, or whether it is sufficient to identify the potential interspecific interactions and the category to which they are likely to belong, and on that basis conduct a qualitative assessment.
- c) To include an assessment of what constitutes an appropriate time frame (including a climate change perspective) for evaluating potential cumulative effects. The starting point shall be the Norwegian Environment Agency's current practice for VKM mandates: existing climate, "in a climate change perspective 10 years into the future and further in a long-term climate perspective".
- d) To assess whether cumulative effects can be incorporated into the existing environmental risk assessment methodology used in VKM. The project shall be based on the IUCN EICAT (Environmental Impact Classification for Alien Taxa) categories and specifically assess whether category 12 (indirect impacts via species interactions) is adequate for such evaluations.
- e) As a subsidiary aim, to specify which assessments should be carried out for different types of assignments, and to propose how this can be incorporated into the standardized terms of reference for single species and species complexes that are currently being developed.

Comments on terminology as used in this report

Additive effect	The net effect on native biodiversity is the sum of the effects of the individual invasive species (Section 3.2).
Antagonistic effect	Net effect on native biodiversity is less than the sum of the individual invasive species. Can occur when invasive species cancel out effects of other invasive species, to some extent (Section 3.3).
Assessment endpoint	In risk assessments of non-native species, assessment endpoints are measurable ecosystem attributes that may be affected by the non-native species. In a management context, these are conservation (or restoration) targets for a desirable aspect such as native species richness, recruitment, decomposition, or nutrient retention (Section 4.1).
Biotic resistance	Biotic resistance refers to the ability of a community to resist invasion of non-native species (Section 3.7).
Climate debt/credit lag phase	A lag between current climate conditions and a species' distribution. It reflects that the species has not yet shifted, adapted, or declined enough to match the new climate. The species shows delayed range shifts, reduced recruitment, or increasing stress before a full response becomes apparent (Section 4.4).
Cumulative effects	The net effects of two or more potentially interacting non-native species on native biodiversity. Depending on the context, <i>effects</i> can include individual fitness, population fitness, population density, species reproductive rate, community structure, community composition, species richness, or ecosystem functions (such as ecosystem services) (Section 3). Cumulative effects covers additive, antagonistic, and synergistic effects (see above).
Direct vs indirect effect	<i>Direct effects</i> are the immediate impacts on individuals or populations that one species has on another. (We use effects and impacts synonymously in this report.) Interactions producing direct effects include competition, predation, herbivory, mutualism, parasitism, diseases, and hybridization. Effects of one species on a second species are indirect when they are mediated by interactions with a third species or via effects of one species on the biotic, physical or chemical environment of the second species (Section 3.1).
Ecosystem engineers	Species are referred to as ecosystem engineers when their activities have such large effects on the physical or chemical environment that their introduction profoundly changes what sorts of species can exist in their environs (Section 3.8.2).
Facilitative interaction	In a facilitative interaction between two species, one species positively affects the survivorship, growth or reproductive rate of the other species (see also <i>synergistic</i> and Section 3.4).
Functional trait	A functional trait is any measurable characteristic of a species that influences how it interacts with its environment or with other species. Examples for plants include leaf size, growth rate, flowering time, whereas examples for animals include body size, feeding mechanism, reproductive strategy (Section 3.8.2).
Impact	Impacts are the realized change in a valued ecological attribute caused by one or more invasive species such as reduced native abundance, altered community composition, degraded habitat structure, or changed ecosystem function (see also assessment endpoint).
Invasive species	A non-native species that establishes, spreads, and causes ecological, economic, or health-related harm. The definition therefore includes both successful establishment/spread and negative impact.

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Invasion debt, lag phase	<i>invasion debt</i> is used in connection with the time lags that often occur between the establishment of a non-native species and the time in the future when it becomes invasive and has an impact. When first successfully established in a region, many non-native species may cause little to no ecological damage; but they have invasion debt if they become harmful in the future. The period between establishment and becoming harmful is referred to as the <i>lag phase</i> : a period of quiescence for an established non-native species before it becomes widespread and invasive (Section 4.4).
Invasional meltdown	Describes a positive feedback spiral where non-native species modify the biotic or abiotic environment in ways that make further invasion easier, leading to a reinforcing or accelerating increase in the number of established non-native species that can lead to changes in ecosystem state (Section 3.7).
Hazard	A source of potential harm due to a non-native species (or its traits/mechanisms) that could cause negative impacts if exposure occurs (e.g., a predator, pathogen, ecosystem engineer). Hazard does not imply impact has occurred, only that it is possible.
Non-native species	A species that has been introduced, intentionally or unintentionally, by human activity outside its natural past or present distribution range.
Pathway to harm	The sequence of steps a non-native species must go through before it can have an impact on native ecosystems. The sequence may include a progression of steps from transport via introduction to development of a self-sustaining population, before potential impacts occur. Management action may be more feasible at early steps in the pathway (Section 4.3).
Pressure	The agent or process that can cause an impact, often expressed as the intensity of influence exerted by non-native species due to predation rate, grazing intensity, propagule pressure, disease transmission pressure, or other factors. In practice, “pressure” is what acts on the system.
Risk	The likelihood and magnitude of harm to an endpoint over a specified place and time frame, given exposure and system vulnerability as a function of probability × consequence. The conceptual chain is Hazard → (exposure/pathway) → Pressure → Stress → Impact. Risk summarizes probability and consequence across that chain.
Stress	The state of strain experienced by organisms, populations, or ecosystems due to energetic or physiological stress, reduced growth or reproduction, or decreased demographic performance. Stress is often an intermediate step between pressure and impact.
Synergistic effects	The net effect is greater than the sum of effects of individual invasive species. The species amplify the effects of other species (Section 3.4).

1 Introduction

1.1 Background on non-native and invasive species

Biological dispersal of organisms into new regions has occurred repeatedly on Earth, with geological events and climatic conditions driving the creation of new corridors and barriers to movement. Natural events have included the formation of land bridges between continents or new passages linking ocean basins and facilitated dispersal via active movement or passive transport (Marshall et al. 1982, McKeon et al. 2016, Jiang et al. 2019). Ecological interactions among species that have not been in previous contact have disrupted ecological systems and shaped the formation of new species assemblages and ecosystems. Modern human activities have amplified dispersal processes by transporting species over great distances and into new habitats in larger numbers and at a higher frequency than might be expected from natural processes (Ricciardi 2007, IPBES 2023). In addition, human activities have heavily impacted natural ecosystems through habitat loss and degradation, climate change, and pollution (Haase et al. 2023), which in turn determines which non-native species can establish and their potential ecological effects. The transport and introductions of non-native organisms have been shaped by economic development and social change (IPBES 2023), where global trade volume in 2024 was about 4500% of levels in 1950 and the number of international tourist trips over 5500% (World Trade Organization 2019; 2025).

Non-native species include organisms that have been moved beyond their native geographic ranges into areas where they do not naturally occur (Blackburn et al. 2014, Vilizzi et al. 2026). An invasive species is a non-native species that establishes, spreads, and causes ecological or economic consequences (Richardson et al. 2000b, Vilizzi et al. 2026). Many potentially invasive species are unlikely to be successful at all stages of the invasion. It has been proposed that roughly a tenth of species transported outside their native range are released or escape into the wild. About 10% of these species manage to establish self-sustaining populations, and in turn, approximately 10% of the established non-native species become invasive (Williamson and Brown 1986, Jeschke and Strayer 2005, Jeschke 2008). This rule of thumb has been referred to as 'the Tens rule' (Jeschke et al. 2012).

Invasive species are a major threat to global biodiversity (IPBES 2019, 2023), but it remains poorly understood how multiple invasive species interact and their consequences for native species and natural ecosystem processes (Bellard et al. 2016). A better understanding of species interactions can be critical for risk assessments and for optimizing management and conservation actions. Assessing the cumulative effects of multiple non-native species on natural ecosystems is highly relevant in an era of ongoing changes in species distributions, rapid changes in land use, and ecological feedbacks associated with climate change. A growing number of non-native species have already gained a foothold in new ecosystems, and global analyses show that both their numbers and the rate of spread have increased markedly in recent decades with no evidence for saturation (Seebens et al. 2017, Pyšek et al. 2020, IPBES 2023). Moreover, joint introductions of multiple non-native species that are co-adapted may affect settlement and establishment in new environments (Prior et al. 2015, Le Roux et al. 2017).

The cumulative impacts of multiple non-native species can produce several outcomes for native biodiversity. Impacts may be positive if the non-native species provide food or habitat resources, pollination, seed dispersal, or other ecosystem services, neutral if there are no detectable effect, or negative if introduced species reduce native biodiversity (Vimercati et al. 2022). When effects are negative and more than one non-native species is involved, cumulative outcomes can range from *additive* to *antagonistic* to *synergistic* (Figure 1).

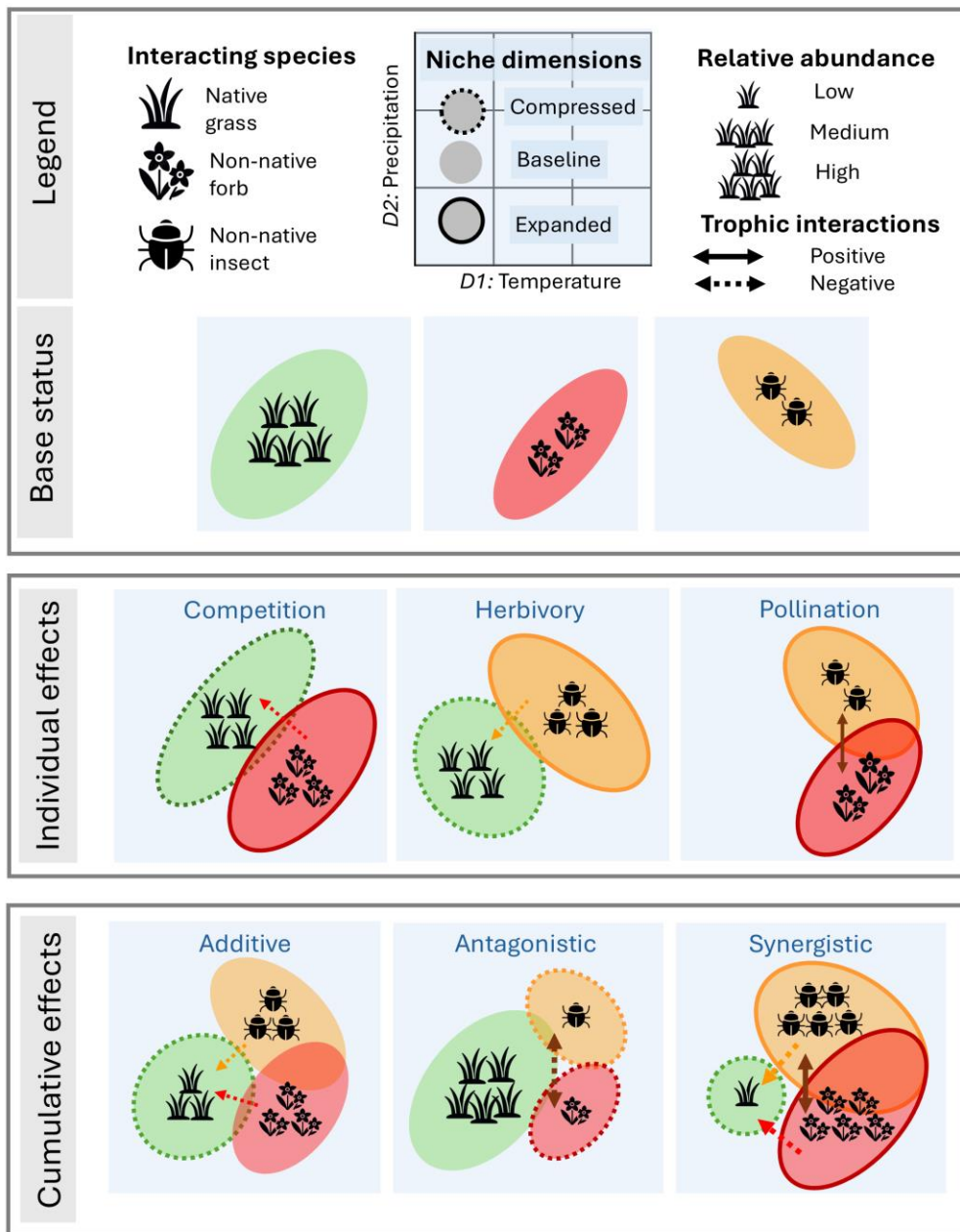


Figure 1. Possible outcomes of multiple non-native species interacting with a native species. **Top:** Responses among interacting species could include changes in niche dimensions or relative abundance from a baseline status due to positive or negative trophic interactions. **Middle:** Non-native species introduced to a new habitat can expand niches or increase population numbers, leading to niche compression or reduced abundance for native species. Positive interactions have reciprocal benefits for non-native species. **Bottom:** Cumulative effects can be *additive* if the niche space or populations of native species are further reduced by addition of multiple non-native species. Alternatively, cumulative impacts may be *antagonistic* if native species are only weakly or not affected because strong ecological interactions constrain the non-native species. In the worst-case scenario, *synergistic* interactions due to mutualisms or facilitation among non-native species could lead to greater impacts on niche space or population numbers of native species.

Ecological interactions among non-native species may be weak or effectively neutral, in which case cumulative impacts are more likely to be *additive*, with each species contributing independently to an increased total pressure on native species or ecosystem functions (Kuebbing and Nuñez 2015, Braga et al. 2019). The cumulative impacts of non-native species could be *antagonistic* if strong ecological interactions through competition, predation, or parasitism reduce densities of non-native species and hence reduce the consequences for native biodiversity. More harm can arise if the cumulative impacts of multiple non-native species are *synergistic* because facilitation or mutualistic interactions benefit non-native species so that their negative impacts on native biodiversity are greater than the sum of effects for individual species (Folt et al. 1999, Crego et al. 2016). In the worst case, positive interactions among non-native species can lead to an invasional meltdown where an ecosystem changes from historic conditions to a new state dominated by non-native organisms (Simberloff and von Holle 1999, Simberloff 2006, Jeschke et al. 2012, Braga et al. 2018, Weir et al. 2024, Ricciardi and Simberloff 2025).

A multi-species perspective may improve the quality of risk assessments for non-native species because the net ecological outcome of several non-native species may be different from the sum of effects for the individual species (Howarth 1985, Simberloff and von Holle 1999). Failing to consider potential interactions among non-native species could result in unnecessary allocation of resources if the net effects are positive or if antagonistic effects nullify the negative impacts on native species. Conversely, the removal of one species may be insufficient if synergistic effects magnify the cumulative effects of multiple non-native species (Kuebbing et al. 2014).

Removal of one non-native species without accounting for potential ecological interactions can have unintended consequences when single-species control efforts accidentally release a second non-native species from competition or predation. For example, targeted removals of the introduced red fox (*Vulpes vulpes*) in south-eastern Australia led to substantially higher densities of invasive feral cats (*Felis catus*), consistent with mesopredator release after control of a dominant non-native predator and release of a subordinate non-native predator from suppression (Rees et al. 2023). Secondary invasion responses have also been documented in plant management. For example, management of invasive *Tamarix* with biocontrol defoliation and mechanical removal from riparian systems in the United States was frequently followed by persistent secondary invasions of other non-native weeds (González et al. 2017). Disease-mediated interactions can likewise magnify cumulative impacts, for example when invasive grey squirrels (*Sciurus carolinensis*) in the UK act as reservoirs for squirrelpox virus and accelerate declines of native red squirrels (*S. vulgaris*, Rushton et al. 2005). An introduced mosquito vector (*Culex quinquefasciatus*) and introduced avian malaria (*Plasmodium relictum*) have negatively affected native birds in Hawaii, including the amakihi (*Hemignathus virens*, Woodworth et al. 2005). Similarly, addition of one seemingly innocuous non-native insect can unleash the invasive potential of currently harmless non-native plants via enhanced pollination or seed dispersal (Traveset and Richardson 2014), or an introduced plant species can monopolize the pollinator community and reduce the pollination, and consequently reproduction, or a native plant species (Bjerknes et al. 2007).

Synergistic effects can be especially strong in the case of non-native invasive species that are *ecosystem engineers* with activities that significantly alter physical or chemical environments and improve conditions for other invasive species (Crooks 2002, Rilov et al. 2023), or have indirect effects on other trophic levels (Preston et al. 2012). Moreover, even if the total density of multiple invasive species is simply the sum of what they would have achieved alone, negative effects on native biodiversity may still be synergistic if the net density of invasive species exceeds a threshold (or tipping point) and ecosystem functions break down (Panetta and Gooden 2017, O'Loughlin et al. 2021).

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The foundation for assessing the effects of non-invasive species is rooted in both theoretical and practical research. The concept of "competitive exclusion" is especially important. Darwin (1859) incorporated the process into his natural selection, while Grinnell (1904) articulated it as: "Two species of approximately the same food habits are not likely to remain long evenly balanced in numbers in the same region. One will crowd out the other..." (page 377). The foundation for assessing effects of non-native species has received extensive development in risk assessment frameworks. The Generic Ecological Impact Assessment of Alien Species (GEIAA) was developed by the Norwegian Biodiversity Information Centre (Sandvik et al. 2019, NBIC 2022). GEIAA uses a quantitative framework to assess invasion potential and ecological effects. The Environmental Impact Classification for Alien Taxa (EICAT), managed by the International Union for Conservation of Nature (IUCN) (www.iucngisd.org), includes 12 mechanisms by which invasive species impact native biodiversity (IUCN 2020, Box 1). The EICAT mechanisms cover direct and indirect impacts, and species are ranked based on the magnitude of changes to natural ecosystems, extinctions of native species, and socioeconomic factors. Five impact categories are ranked from Minimal Concern (MC), Minor (MN), Moderate (MO), Major (MR), and Massive (MV). The last three categories of impacts are collectively deemed to be Harmful and such non-native species can be classified as invasive.

Box 1. Environmental Impact Classification for Alien Taxa (EICAT) includes 12 mechanisms by which invasive species can impact native biodiversity and habitats (Blackburn et al. 2014, Hawkins et al. 2015, IUCN 2020).

1. **Competition:** Competes with native species for resources such as food, space, light, or breeding sites and cause displacement or population declines.
2. **Predation:** Non-native species are at higher trophic levels and depredate native organisms.
3. **Hybridization:** Non-native organisms interbreed with native species, causing genetic introgression.
4. **Transmission of disease:** Non-native species acts a host or vector that affects transmission of disease agents to native species.
5. **Parasitism:** Parasites or pathogens that negatively affect performance or population size of native species.
6. **Poisoning / toxicity:** Non-native species releases chemicals that have toxic, allergenic, or allelopathic effects on native organisms.
7. **Biofouling or direct physical disturbance:** Physically covers, smothers, tramples, or disturbs native organisms.
8. **Grazing / herbivory / browsing:** Consumes native plants or algae.
9. **Chemical impact on ecosystem:** Alters nutrient cycling, pH, oxygen, or other chemical properties.
10. **Physical impact on ecosystem:** Changes physical conditions such as hydrology, sedimentation, turbidity, light or fire regimes.
11. **Structural impact on ecosystem:** Modifies ecosystem features related to architecture or habitat complexity. Major changes caused by organisms that are ecosystem engineers.
12. **Indirect impacts through interactions with other species:** Alters food webs or community structure through indirect impacts on pollination or seed dispersal, or by modification of commensal, apparent competition, mutualism or other trophic interactions.

EICAT+ is an extension of the original framework that includes a broader set of assessment endpoints beyond native biodiversity. EICAT is restricted to environmental impacts on native species, whereas EICAT+ includes assessment of impacts on ecosystem services, human well-being, socio-economic values, and potentially positive impacts (IUCN 2020, Bacher et al. 2018, Vimercati et al. 2022). For VKM assessments with a mandate focused specifically on biodiversity impacts, EICAT provides a scientifically robust and internationally harmonized framework. Where mandates also include evaluations of ecosystem services, food production, or human health considerations (e.g., under a One Health perspective), an EICAT+-type extension may be more appropriate. In this report, we have not differentiated between EICAT and EICAT+. Note, however, that of the two, only EICAT+ incorporates positive biodiversity impacts.

Norwegian law emphasizes a holistic view (Nature Diversity Act LOV-2009-06-19-100) in Management of Biological, Geological and Landscape Diversity: “An impact on an ecosystem shall be assessed in light of the combined pressure to which the ecosystem is or will be subjected.” (our translation from § 10). Thus, the combined influence of all factors should be considered together, rather than each factor in isolation. Current risk assessments in Norway are on a species-by-species basis, such as risk assessments for the Norwegian alien species list conducted by the Norwegian Biodiversity Information Center (Artsdatabanken 2023), and various risk assessments for non-native species conducted by VKM for the Norwegian Environment Agency (Järnegren et al. 2023, Velle et al. 2024, Kirkendall et al. 2025). Developing a unified theory and methodology on cumulative effects will improve our ability to address emerging ecological challenges. This review highlights the potential for incorporating the cumulative effects of non-native species into environmental risk assessments. We synthesize observational and experimental evidence on alternative cumulative outcomes, drawing on case studies across different taxa, mechanisms, and regions.

2 Methodology and data

2.1 Literature search and selection

The authors conducted literature searches to identify relevant articles and case studies to address the key questions outlined in the Terms of Reference provided to the VKM Panel on Biodiversity. The primary purpose was to evaluate the potential need to expand existing frameworks for risk assessments from a single species perspective to consider the possible consequences of interactions among multiple species of non-natives. We did not attempt to complete a systematic review of the large and growing literature on non-native and invasive species. We used focal searches to identify the key papers that provided a theoretical foundation for the possible outcomes of interactions among non-native species, examples of the different types of ecological interactions and mechanisms that affect pathways to harm, and then we compiled selected case studies from different regions of the globe with specific examples that were particularly relevant for environmental conditions in Norway.

Before starting the searches, the project group discussed the questions and scope of the report and agreed on a flexible strategy for search terms and keywords. The terms were then combined using Boolean operators to build effective search strings. To identify explanations and examples of cumulative impacts, we used combinations of keywords such as:

- (“multiple” OR “multiple invaders” OR “co-invasion” OR “co-occurring”) AND (“invasive” OR “non-native” OR “alien” OR “invasion”) AND (“species” OR “organism” OR “taxa”) AND (“cumulative” OR “accumulative” OR “combined” OR “additive” OR “synergistic” OR “antagonistic”) AND (“effects” OR “impacts”)

Searches were run both with and without “Norway”, and both with and without methodological terms such as (“framework” OR “method” OR “protocol” OR “assessment”). Our primary database was Google Scholar, and we also used Web of Science to locate recent articles that cited key papers. We used peer-reviewed publications and reports as our main sources of information and did not include grey literature.

3 Cumulative impacts

3.1 Direct versus indirect effects

To understand interactions among co-occurring non-native species, it is important to distinguish between *direct* and *indirect effects*. Understanding the role of direct and indirect can help clarify how invasive species may alter recipient systems and provide better options for management interventions. Direct effects include the ecological interactions that are expected from trophic ecology, disease dynamics, or hybridization. Indirect effects work through secondary changes caused by environmental change or modification of interaction networks. Direct effects are easier to evaluate in a risk assessment because the functional traits of a non-native species are often known, and the impact of hybridization can be assessed by patterns of phylogenetic relatedness compared to native species.

Direct effects act on individuals or populations via three groups of mechanisms:

1. Trophic interactions: competition, predation, and herbivory (EICAT mechanism 1, 2 and 8).

Trophic interactions are well-established as ecological mechanisms that can change fecundity, growth, survival, and niche occupancy of native or non-native species (Jackson 2015).

2. Pathogens, parasites, and toxicity (EICAT mechanism 4, 5, and 6). Non-native species can serve as vectors or hosts for novel pathogens or parasites, alter host–pathogen dynamics among co-occurring species (Roy et al. 2013) or cause toxicity.

3. Hybridization (EICAT mechanism 3). Crosses between non-natives (or with native organisms) can produce hybrid genotypes with higher invasion potential. Hybridization can increase the genetic variation that natural selection acts on, or it can create novel genotypes that are particularly invasive (Vilà et al. 2000, Buhk and Thielsch 2015, Gaskin 2016, Fournier and Aron 2021). It can also cause genetic contamination of native species and loss of local adaptation (Rueness et al. 2017, Lennox et al. 2021).

Indirect effects are mediated through underlying drivers, typically environmental changes in the chemical, physical or structural properties of key habitats, or through indirect interactions with vectors, mutualists, competitors, predators, and prey. Indirect pathways often propagate across levels of organization from population to community to ecosystem, so that small initial stress can be magnified into large ecological responses. Identifying potential pathways is important for assigning impacts in the EICAT system and for predicting responses where one invasive species affects the environment for other invasive species, for example by acting as an ecosystem engineer (Simberloff and von Holle 1999, Ricciardi 2001, Crooks 2002, Traveset and Richardson 2014, IUCN 2021). Climate warming, altered precipitation patterns, and the dynamics of extreme events can reconfigure indirect effects by expanding phenological overlap, shifting mutualist availability, or crossing abiotic thresholds (Hof et al. 2012, Blois et al. 2013). For example, longer growing seasons or heat waves can lead to increased resource availability or expand a window for biofouling that favors establishment of an ecosystem engineer, that in turn facilitates other non-native species. The most relevant indirect effects for multiple non-native species include three additional groups of mechanisms (EICAT mechanisms 6-7 and 9-12):

4. Chemical-physical changes to the environment (EICAT mechanisms 6, 7, 9, and 10) can reinforce invasion impacts. In lakes, filter-feeders like invasive zebra mussels remove phytoplankton, which increases light penetration and favors light-limited macrophytes, such as the non-native Eurasian watermilfoil. Primary production then shifts toward the benthos and can fuel the growth of nuisance benthic algae like *Cladophora*. Trophic shifts reshuffle oxygen dynamics and food-web pathways, altering fish habitat, spawning substrates, and prey availability (Skubinna et al. 1995, Crane et al. 2020). On land, nitrogen-fixing plants increase

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soil nitrates, making it easier for other plants to invade (Wang et al. 2015, O’Loughlin and Green 2017), whereas invasive grasses raise fuel loads and change fire regimes in ways that further promote grass dominance (Setterfield et al. 2013). Similarly, release of allelopathic chemicals or biofouling of natural substrates may favor or hinder settlement of other non-native organisms. Chemical and physical changes can also lead to *cross-ecosystem linkages*. Non-native species that couple ecosystems (riparian to stream, coastal to marine) can transfer subsidies (propagules, nutrients) that amplify indirect routes of effect (Hodgson and Halpern 2019). For example, pink salmon (*Oncorhynchus gorbuscha*) are an invasive species in the North Atlantic. The species has a semelparous life-history strategy and migratory fish die after spawning in rivers, thus bringing inputs of marine nutrients that influence both freshwater and riparian species (Hindar et al. 2020).

5. **Structural modification of the environment (EICAT mechanisms 11)** can moderate indirect interactions among non-native and native species. Invasive species can be ecosystem engineers that add or transform physical structures, which can shift carrying capacities, refuge availability, resource availability, and settlement surfaces (Rilov et al. 2023). Dense Pacific oyster reefs or mussel beds convert soft to hard substrate, increasing settlement opportunities for other sessile non-natives and restructuring benthic communities (Dolmer et al. 2014). In river systems, non-native crustaceans or aquatic mammals can affect the presence of macrophytes or woody debris, thereby altering hydraulics and sediment dynamics, with cascading effects on the ecosystem (Velle et al. 2021). In temperate woodlands, non-native earthworms can change many physical and biological soil properties and be vectors of seeds, leading to major changes in associated communities of plants and soil organisms, and favor establishment of non-native plants over indigenous species (Babu Ojha and Devkota 2014, Clause et al. 2015, Le Bayon et al. 2017, Zhang et al. 2025).

6. **Alteration of interaction networks (EICAT mechanisms 12)** can include indirect interactions among species that are mutualists, enemies, or vectors. Non-native pollinators and frugivores can accelerate the spread of non-native plants (Richardson et al. 2000a, Traveset and Richardson 2014). In the process of *apparent competition*, a non-invasive species can indirectly harm a native species if both species share a common community of predators, pathogens or parasites, and the non-native species acts as a reservoir that effectively sustains higher enemy pressure on the native species. Indirect effects can also arise via trophic cascades (including mesopredator release), when a non-native species suppresses a top predator and thereby increases the abundance or impact of a predator one trophic level down, ultimately increasing stress on native prey (Caujapé-Castells et al. 2010, Ripple et al. 2016). A non-native species can also facilitate other non-native organisms during transport and introduction. For example, marine organisms that tolerate antifouling paints may provide a substrate or refuge for other non-native species, enhancing the potential for human-mediated spread via shipping traffic (Floerl et al. 2004).

3.2 Additive effects

Additive effects arise when each non-native species contributes to the total impact but without influencing one another’s performance. If several non-native species use different resources or occupy different niches, the species may coexist without interacting. An additive outcome implies that co-occurring non-native species have neutral interactions without either positive or negative effects on each other. In such cases, the combined effect on the ecosystem is then the sum of the independent impacts for each non-native species (Jackson 2015).

An additive scenario is the simplest to assess and manage since risk assessments can be completed separately for each non-native species. The assumption would be that the potential harm to an ecosystem is the aggregated total across stresses from all individual species. Still,

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the extra step involved in adding impacts across multiple invaders that co-occur is not often used in environmental risk assessments for single species. The additional step may appear straightforward, but evaluations of added ecological stress can be challenging when assigning a standardized hazard characterization rating, such as ranking the magnitude of biodiversity impacts on an ordinal scale from minimal to massive.

3.2.1 Examples of additive effects

Additive effects have been well-documented in ecological studies (Ahmad et al. 2025, Jackson et al. 2015). In grasslands, the cumulative cover of multiple invasive plant species can scale proportionally with the number of invaders, producing a near-linear increase in competitive suppression and displacement of native species (Hejda et al. 2009, Brandt et al. 2023). Kuebbing et al. (2014, 2016) experimentally manipulated two invasive shrubs in the southeastern USA (*Ligustrum sinense* and *Lonicera maackii*) and found that co-invasion had additive impacts where the combined effects on native plant communities were approximated by the sum of the effects for the individual species. For marine and coastal habitats, invasive seaweed and filter-feeding bivalves each reduced native biodiversity independently, with their cumulative impact being additive (Thomsen et al. 2011). In rivers and wetlands, invasive crayfish and non-native predatory fish often act in parallel. For example, the non-native crayfish (*Procambarus clarkii*) reduces biomass of benthic invertebrates whereas non-native salmonids may reduce the recruitment of native fish. Each non-native species can affect different components of the food web, and the combined effect approximates their sum (Rodríguez et al. 2005).

Additive impacts can propagate to indirect and ecosystem-level responses. In the Brazilian cerrado, experimental removal of two invasive grasses (*Melinis minutiflora* and *Urochloa decumbens*) revealed that the plants have additive effects on several soil properties, even though other response variables showed synergistic behaviour (Zenni et al. 2020). This underscores that the degree of additivity can depend upon which effects are measured. In North American lakes, the combined presence of zebra mussels (*Dreissena polymorpha*) filtering phytoplankton and invasive macrophytes reducing native plant cover led to overall habitat alteration that could largely be explained additively (Strayer 2010). Here, the cumulative impact of mussels and macrophytes on light availability, habitat structure and energy flow produced cumulative ecosystem changes that were broadly consistent with the sum of their individual contributions.

3.3 Antagonistic effects

Negative interactions among co-occurring non-native species can reduce the abundance or demographic performance of one or more of them, leading to *antagonistic effects*. In some cases, the interactions have been described as inhibitory or competitive effects (Kuebbing et al. 2013). An antagonistic effect arises when the combined impact of multiple non-native species is less than the sum of the impacts of each individual species. Negative interactions can arise from competition, predation, herbivory, or disease dynamics among the non-native species and underline the biotic resistance hypothesis (Section 3.7). The net consequence is that the ecological impacts arising from multiple non-native species on native biodiversity or natural ecosystems is reduced in comparison to the situation where additive effects are present.

3.3.1 Examples of direct antagonistic effects

Antagonistic effects among non-natives that dampen impacts on native communities are common (Ahmad et al. 2025). In eastern US forests, the invasive grasses *Microstegium vimineum* and *Oplismenus undulatifolius* produced largely redundant effects on native plant richness and soil properties, and their combined impact was not greater than that of either species alone (Tekiel and Barney 2017), possibly because *O. undulatifolius* is a weak competitor (Kepner and Beauchamp 2020). Similarly, a field experiment showed that two invasive grasses *Bothriochloa bladhii* and *B. ischaemum* inhibited each other's growth when planted together (Schmidt et al. 2007). In ant communities in Hong Kong, co-invasion by multiple non-native species reduced native ant species and functional-trait diversity less than single-species invasions because the invaders competed (Hu et al. 2025). American bullfrog (*Lithobates catesbeiana*) and red swamp crayfish (*Procambarus clarkii*) are invasive in many aquatic habitats. When the two species co-occur, such as in China, impacts of bullfrogs on native anurans can be reduced where crayfish densities are high because crayfish prey on bullfrog eggs and tadpoles (Liu et al. 2018). In Japanese ponds, the invasive American bullfrog depresses populations of the native wrinkled frog (*Glandirana rugosa*), but the negative effect is weaker if the non-native common carp (*Cyprinus carpio*) is present. Carp preferentially prey on bullfrog tadpoles, reducing bullfrog abundance and thereby dampening impacts on native frogs (Atobe et al. 2014).

3.3.2 Examples of indirect antagonistic effects

Antagonistic effects can also arise through indirect interactions. In abandoned fields in Poland, negative effects on native plant diversity were strongest where single invasive species dominated, whereas co-occurrence of goldenrod (*Solidago canadensis*) and Persian walnut (*Juglans regia*) reduced overall impact because walnut canopy and litter alter light and soil conditions, reducing the density and dominance of goldenrod (Lenda et al. 2019). Co-invasion of grasslands in China by two invasive forbs (*Solidago canadensis* and *Erigeron annuus*) led to allelopathy or release of biochemicals that affect the growth, germination, or survival of other native plants, and reduced the performance of the invader *A. annuus* (Wang et al. 2020).

Work on mesopredator release indicates that removing a dominant species can free a second invader to increase in abundance and impact. Such indirect antagonistic interactions mean that management actions aimed at one invader can backfire if the role of that species in suppressing other invaders is not recognized beforehand. Experimental removals have revealed strong trophic interactions among a guild of four invasive mammals in the forests of New Zealand, where the community of invasive mammals includes a predatory stout (*Mustela erminea*), two omnivorous rodents (ship rat, *Rattus rattus* and house mouse, *Mus musculus*) and an herbivore (Australian brushtail possum, *Trichosurus vulpecula*). Removing possums led to competitive release of rats, whereas removing rats released mice, reflecting strong antagonistic interactions among the different invasive species (Ruscoe et al. 2011). Removing a native predator can also release an invasive species, such as culling of the native Eurasian otter (*Lutra lutra*) in Norway that may cause an increase in invasive American mink (*Neogale vison*, Hanssen et al. 2026).

3.4 Synergistic effects

Synergistic interactions occur when invasive species mutually reinforce each other, leading to a combined impact that is greater than the sum of the individual effects (Folt et al. 1999, Simberloff and von Holle 1999). The dynamics of synergistic impacts may be complex and differ over the ranges where the species occur. Positive interactions among non-native species are the basis of *the invasional meltdown hypothesis* because they increase abundance or demographic performance and therefore increase the magnitude of negative effects (Section 3.7). For synergistic effects, one species may alter the environment in a way that makes it more favorable for another, or directly assist the co-invader by providing food, shelter or habitats, or by enhancing indirect interactions among non-native organisms. Positive feedback represents major challenges for management intervention since non-native species might be relatively benign in isolation yet highly invasive and destructive when in certain combinations. Assessing and managing ecosystems that have been invaded by multiple non-natives therefore requires careful planning and coordinated action (Ruscoe et al. 2011). For example, control of zebra mussels might monitor their direct impacts on benthic habitats in freshwater systems but also include measures to prevent facilitation of other non-native species of aquatic weeds. Synergistic effects represent the worst-case scenario because the net cumulative effects of multiple non-native species will be greater than either additive or antagonistic effects.

3.4.1 Examples of direct synergistic effects

Synergistic effects among invasive species are numerous, especially through direct positive interactions, such as mutualisms, habitat creation, and trophic subsidies. Mutualistic interactions among invasive plants, pollinators, or seed dispersers are well documented (Simberloff and Von Holle 1999). For instance, an ornamental fig tree (*Ficus macrocarpa*) became invasive in several regions after the introduction of a co-evolved species of fig wasp (*Parapristina verticellata*), that acts as a pollinator. Together, the fig and wasp spread rapidly and transform forest structure by strangling native host trees and shading out competing vegetation. Similarly, generalist species of invasive frugivores can greatly accelerate the spread of non-native plants. For example, common lantana (*Lantana camara*) is an invasive shrub with fruits dispersed by invasive birds in Hawaii (Smith 1984). At least 19 non-native plant species are dispersed by non-native populations of European blackbirds (*Turdus merula*) in Australia and New Zealand (Carr 1993, Williams and Karl 1996). Another common mechanism is trophic subsidies, where one invasive species provides key food for another. Honeydew-producing species of aphids, mealybugs and scale insects can meet most of the energetic needs of invasive ants, as shown by associations between non-native mealybugs (*Antonina graminis*) and fire ants (*Solenopsis invicta*) in the southeastern USA (Helms and Vinson 2002).

Positive interactions also occur through ecosystem engineering and creation of refuge habitats. The invasive American beaver (*Castor canadensis*) has transformed forests into wetlands in South America, which are then favoured by introduced muskrats (*Ondatra zibethicus*), while muskrats in turn provide a key prey resource sustaining non-native populations of American mink (Crego et al. 2016). In marine habitats, the bryozoan *Watersipora subtorquata* can colonize ship hulls with toxic coatings of antifouling chemicals and create a refuge substrate for fouling organisms that would otherwise be repelled (Floerl et al. 2004). In coastal ports of Norway, Pacific oysters (*Crassostrea gigas* SE, very high risk as a non-native species in Norway; Mortensen et al. 2023a) often co-occur with other non-native species, including Japanese skeleton shrimp (*Caprella mutica* SE; Mortensen et al. 2023b), bay

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barnacle (*Amphibalanus improvisus* PH, potentially high risk; Glenner et al. 2023), and a tunicate (*Styela clava* PH; Husa et al. 2023a). Oyster shells can create synergy because they are often overgrown by algae, hydroids and small mussels, which provide a hard substrate that facilitates dense assemblages and likely promotes settlement of other non-natives (Critchley 1983, Dolmer et al. 2014, Espelien 2020). Similarly, the invasive Japanese seaweed (*Sargassum muticum* SE, Husa et al. 2023b) is found along the coast of Norway, and can host rich faunal assemblages with over 100 taxa recorded (Sjøtun et al. 2021). The seaweed likely facilitates secondary invasions through habitat and rafting opportunities, as occurred for the non-native skeleton shrimp elsewhere in Europe (Ashton et al. 2006).

3.4.2 Examples of indirect synergistic effects

Beyond these direct interactions, indirect and cascading effects can substantially amplify impacts on native ecosystems, especially by priming the system for establishment and spread of other non-native species. In the North American Great Lakes, invasion by zebra mussels facilitated a subsequent expansion by non-native Eurasian watermilfoil (*Myriophyllum spicatum*). By filtering out phytoplankton, zebra mussels increased water clarity and light penetration, allowing watermilfoil to colonize deeper waters and expand its range (Skubinna et al. 1995). Expansion of milfoil directly displaced native macrophytes, reducing their species richness, and triggered a cascade of indirect effects: energy flow shifted toward the lakebed, promoting nuisance benthic algae, such as *Cladophora*, altering oxygen dynamics near the bottom and restructuring invertebrate communities. The ecological changes affected fish populations through modified habitat structure with denser plant beds that altered spawning and nursery areas, and changes in food resources that included declines in pelagic prey and greater reliance on benthic prey. The net result was a clear-water state dominated by invasive weeds and mussels, with a cascade of severe effects on native macrophyte and fish communities that far exceeded the expected impact of either invader alone (Zhu et al. 2006). In the sea, indirect synergistic effects can occur when a habitat-building invasive species, such as oysters, create hard substrate that increases available settlement surfaces for other non-native species. When several non-native species recruit to the newly created habitat, the oyster reefs effectively boost their establishment and local abundance, so the combined impact of oysters plus associated fouling invaders becomes greater than what might be expected from each species alone (Skubinna et al. 1995, Dolmer et al. 2014).

3.5 The EICAT mechanisms in a multi-species context

The framework for Environmental Impact Classification for Alien Taxa (EICAT) includes 12 impact mechanisms that are used to evaluate the potential effects of a non-native species (Section 3.2 of IUCN 2021, Box 1). To translate potential interactions into specific impact pathways, we have expanded the EICAT framework in three ways. First, we used literature searches to identify relevant case studies where multiple non-native species have combined impacts on native biodiversity via the same 12 impact mechanisms. Second, we propose a range of systems where a multi-species perspective would be relevant to risk assessments for native biodiversity in Norway. Lastly, we review the available evidence for different types of ecological outcomes, including additive, antagonistic and synergistic effects (Table 1). It should however be noted that there is currently no standardized and evidence-based system to classify potentially *positive* impacts and interactions from alien taxa on various assessment endpoints (see box 3). But considering the rapidly changing nature of many current species assemblages due to climate change and other disturbances, one may need to consider that

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some alien species are taking over an ecosystem role from native species that find themselves poorly adapted to new climate conditions. Alien species can also positively affect biodiversity, for instance through food and habitat provisioning or dispersal facilitation (Bacher et al. 2025, Goodenough 2010, Shackleton et al. 2019, Vimercati et al. 2022). Thus, when considering the net impact of alien species and their interactions, we get a biased result if we only consider potentially negative effects on the assessment endpoints. Especially since Norway is in a region experiencing climate change significantly faster than global average, it seems natural to fill this gap by systematically taking this into account, for instance by employing the EICAT+ modification proposed by Vimercati et al. 2022. EICAT+ uses 5 semiquantitative scenarios to categorize positive impacts and underlying mechanisms and can be applied to alien taxa at different spatial and organizational scales. Thus, application of EICAT+ or similar approach could be considered to provide unbiased decision support.

Table 1. Case studies that illustrate the direct and indirect mechanisms that underly ecological interactions among multiple species of non-native plants, fungi and animals. The 12 mechanisms are based on the framework of the Environmental Impact Classification for Alien Taxa (EICAT), but are expanded here to illustrate ecological interactions among co-occurring species of non-native taxa that could impact native biodiversity through the same or different mechanisms (IUCN 2021). Risk assessments for non-native species were compiled from Norway’s Alien Species List (Artsdatabanken 2023) where NR = not assessed, LO = low risk, PH = potential high risk, HI = high risk and SE = severe risk.

Mechanisms (EICAT category)	Global examples of interactions among multiple non-native species	Risk of interactions among non-native species co-occurring in Norway
Competition (1). Competition for resources affects interactions among non-native species	<ul style="list-style-type: none"> Establishment of non-native willow shrubs and aphids provide habitat and food resources for non-native yellowjacket wasps (Masciocchi et al. 2022) 	<ul style="list-style-type: none"> Competitive interactions among non-native and naturalized populations of vendace (<i>Coregonus albula</i>, SE), Arctic char (<i>Salvelinus alpinus</i>) and brown trout (<i>Salmo trutta</i>) determine foodweb structure in the littoral and pelagic zones of lakes where the species co-occur (Bøhn et al. 2008)
Predation (2). Trophic interactions among non-native taxa affect the population dynamics of prey and predators	<ul style="list-style-type: none"> Non-native crayfish depredate invasive zebra mussels (zu Ermgasset et al. 2011) and provide a food source for non-native American mink (Melero et al. 2014) Eradication of invasive cats can lead to mesopredator release of non-native populations of rodents or rabbits (Courchamp et al. 1999b, Bergstrom et al. 2009a) 	<ul style="list-style-type: none"> Signal crayfish (<i>Pacifastacus leniusculus</i>, SE), pink salmon (<i>Oncorhynchus gorbuscha</i>, SE), rainbow trout (<i>Oncorhynchus mykiss</i>, HI), American mink (<i>Neogale vison</i>, SE) are non-native species in freshwater habitats in Norway. Trophic interactions could lead to synergistic effects that favor establishment or spread of invasive taxa
Hybridization (3). Hybrid crosses between non-native species have a greater invasive risk	<ul style="list-style-type: none"> Hybrids between different species of non-native plants can have more aggressive growth and rapid range expansion (Vilà et al. 2000, Buhk and Theilsch 2015) 	<ul style="list-style-type: none"> Three taxa of Japanese knotweed (<i>Reynoutria</i> spp., SE) co-occur in Norway and currently spread via clonal reproduction. Climate warming may favor sexual reproduction and spread of invasive hybrids (Holm et al. 2018)
Pathogens (4). Presence of multiple non-native species impacts disease transmission	<ul style="list-style-type: none"> Norway and black rats (<i>Rattus</i> spp.) share high diversities of zoonotic pathogens (Roy et al. 2023) Overabundant white-tailed deer preferentially use areas dominated by invasive honeysuckle which increases human exposure to tick-borne bacterial pathogens (<i>Ehrlichia</i> spp., Allan et al. 2010) 	<ul style="list-style-type: none"> Non-native species of plants such as annual ragweed (<i>Ambrosia artemisiifolia</i>, LO) and black cherry (<i>Prunus serotina</i>, HI) are vectors for >25 species of pathogens which could be shared with other non-native plants (Najberek et al. 2022)

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<p>Parasites (5). Presence of multiple non-native species changes parasite transmission</p>	<ul style="list-style-type: none"> ● Disease dynamics among non-native taxa of avian malaria, avian pox, mosquitoes and birds have negatively impacted native species of island birds in Hawaii (Samuel et al. 2018) 	<ul style="list-style-type: none"> ● <i>Echinococcus multilocularis</i> (SE) is a parasitic tapeworm that with a complex life-cycle that includes canids as a definitive host. The parasite has been detected in raccoon dogs (<i>Nyctereutes procyonoides</i>, SE), golden jackals (<i>Canis aureus</i>) and other non-native canids in Sweden (Robertson et al. 2024)
<p>Poisoning (6). Non-native taxa interact to create toxic environmental effects</p>	<ul style="list-style-type: none"> ● Non-native species of grass are adapted to the chemotypes of co-occurring species of herbaceous plants (Ehlers and Thompson 2004) 	<ul style="list-style-type: none"> ● Garden lupins (<i>Lupinus polyphyllus</i>, SE) are a highly invasive species known to have allelopathic impacts on other plants. Chemical leachates from lupins could have antagonistic effects on seed germination and establishment of other non-native taxa
<p>Biofouling (7). Non-native taxa interact to accumulate on a surface or cause direct physical disturbance</p>	<ul style="list-style-type: none"> ● Establishment of invasive Pacific oysters (<i>Crassostrea gigas</i>) favors settlement of other invasive species of sessile marine invertebrates (Firth et al. 2021) 	<ul style="list-style-type: none"> ● The non-native carpet tunicate <i>Didemnum vexillum</i> (SE) causes biofouling in marine habitats that provides a suitable substrate for establishment of other invasive taxa (Järnegren et al. 2023)
<p>Herbivory (8). Grazing or browsing by non-native species favors other non-native species</p>	<ul style="list-style-type: none"> ● Disturbance from rooting by feral hogs facilitates plant growth in an invasive clonal plant (Oldfield and Evans 2016). Wild boars also disperse seeds of exotic plants from agricultural lands into native plant communities in conservation areas (Dovrat et al. 2012) ● Foraging behavior of non-native Canada geese favours co-invasion of non-native species of annual grasses (Best and Arcese 2009) 	<ul style="list-style-type: none"> ● Wild boars (<i>Sus scrofa</i>, HI) are a non-native species occurring in agricultural lands in southern Norway and rooting activity could facilitate establishment of non-native plants (Rivrud et al. 2024) ● Canada geese (<i>Branta canadensis</i>, HI) are a non-native species with high invasion potential in Norway and their grazing activity may affect establishment of non-native plants in natural areas (Solvang et al. 2023)
<p>Chemical (9). Non-native taxa interact to affect pH, water quality, or nutrient conditions</p>	<ul style="list-style-type: none"> ● Establishment of non-native species of N-fixing plants causes soil nitrification that favors secondary invasion by other non-native species (O’Loughlin and Green 2017) ● Zebra mussels affect water quality by filter-feeding on phytoplankton and enhancing nutrient cycling which favors establishment by non-native species of aquatic plants (Skubinna et al. 1995, Crane et al. 2020) 	<ul style="list-style-type: none"> ● Non-native Canada goldenrod (<i>Solidago canadensis</i>, SE) forms large clonal colonies up to 2 meters in height that can change soil properties by increasing C/N ratios, which could favor other non-native plants (Królak 2021)

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<p>Physical (10). Non-native taxa interact to change the light conditions, fire frequency, or disturbance regimes</p>	<ul style="list-style-type: none"> ● Invasion of non-native grasses increases fuel loads and changes fire regimes to conditions that favor other invasive species (Setterfield et al. 2013) 	<ul style="list-style-type: none"> ● Heathlands in coastal Norway have been invaded by native juniper and non-native Sitka spruce (<i>Picea sitchensis</i>, SE) which has increased the likelihood for severe wildland fires (Gjedrem and Log 2020)
<p>Structural changes (11). Non-native species interact to affect the complexity or architecture of habitat structure</p>	<ul style="list-style-type: none"> ● Invasive cordgrass creates suitable habitat conditions for a non-native species of songbird (Ma et al. 2014) ● Invasive zebra mussels provided a substrate that has facilitated invasion by the hydroid <i>Cordylophora caspia</i> (Rilov et al. 2023) ● Introduced beavers (<i>Castor canadensis</i>) create suitable habitats for non-native populations of rainbow trout (<i>Oncorhynchus mykiss</i>, Arismendi et al. 2020) and muskrats (<i>Ondatra zibethicus</i>, Crego et al. 2016) 	<ul style="list-style-type: none"> ● A risk assessment for two non-native species of mitten crabs (<i>Eriocheir</i> spp., LO to SE) identified structural changes on ecosystems as a likely factor with a potential for moderate impacts (Velle et al. 2024)
<p>Indirect impacts (12). Non-native species interact through pollination or seed dispersal</p>	<ul style="list-style-type: none"> ● Establishment of non-native plants creates new conditions for invasive insects that are pollinators (Bertelsmeier et al. 2024). ● Establishment of non-native insects can also increase the spread of invasive plants that require ants for seed dispersal (Prior et al. 2015). ● Introduced common carp (<i>Cyprinus carpio</i>) can disperse seeds of Russian olive (<i>Elaeagnus angustifolia</i>), an invasive riparian shrub (Heinrich et al. 2021, Cheek et al. 2024) ● Spread of an introduced shrub (<i>Lantana camara</i>) in Hawaii is accelerated by generalist species of non-native birds which disperse the seeds (Smith 1984) ● Exotic mammals disperse non-native fungi that in turn promote invasion by non-native trees (Nuñez et al. 2013, Wood et al. 2015) 	<ul style="list-style-type: none"> ● Domestic honey bees (<i>Apis mellifera</i>, NR) are regularly used as pollinators for agricultural fruit production in Norway (Norwegian Ministries 2018). Beekeeping poses a low risk to most populations of wild pollinating insects in Norway, except for a few wild bees that depend on a limited number of plant species for nectar resources (Nielsen et al. 2024)

3.6 Studies of cumulative effects in controlled settings

The cumulative effects of multiple non-native species have been investigated under controlled field conditions with a variety of study protocols. Experimental studies have used treatments with different combinations of non-native plants in greenhouse experiments (Ehlers and Thompson 2004, Sun et al. 2024), field plots (Flory and Bauer 2014, Oschirin and Reynolds 2019), or reciprocal transplant designs (Torres et al. 2022). Interactions have also been tested in mesocosm experiments (Adams et al. 2003, Johnson et al. 2009, Glon et al. 2017, Crone et al. 2023). Manipulative field experiments based on before–after/control–impact (BACI) designs are relatively rare (Wonham et al. 2005), and field experiments involving deliberate introductions of invasive species are generally not an option for ethical reasons. Introductions are nevertheless assessed for genetically modified organisms, and there is a long history of moving supposedly useful species to non-native habitats for biocontrol of other invasive species (Messing and Wright 2006). On the other hand, much can be learned from eradication efforts where one or more invasive species have been deliberately removed from natural systems (Zavaleta et al. 2001, Ballari et al. 2016). Manipulative approaches have been complemented by long-term observational studies of plots or lakes that vary in the occurrence or density of non-native species (Jäger et al. 2009, Allan et al. 2010, Lenda et al. 2019, Larkin et al. 2020). Together with compilations of global data (Liu et al. 2018) and meta-analyses that synthesize effects across multiple tests (Ahmad et al. 2025, Jackson 2015), observational studies have provided additional insights into the consequences of non-native species and their interactions. The current evidence base includes a growing number of examples for cumulative effects of invasive species on native biodiversity and natural ecosystems worldwide (IPBES 2023). Quantification of the ecological impacts of non-native species across taxa has received much attention in Norway (Nielsen et al. 2016, Sandvik et al. 2020). However, multispecies frameworks have not been applied in assessments on non-native species in Norway, implying a lack of information on additive, antagonistic, or synergistic effects.

3.7 Biotic resistance and invasional meltdown

Two mutually non-exclusive hypotheses predict possible effects of multiple invasive species on natural ecosystems: the biotic resistance model and the invasional meltdown model. The *biotic resistance model* proposes that species-rich, well-functioning communities should be more resistant to invasion because resident species collectively reduce resource availability, and increase competitive, predatory, or pathogenic pressure on newcomers (Elton 1958). As native diversity and biomass increase, niche space is more completely occupied, leaving fewer opportunities for non-native species to become established or spread. The model has been supported and refined by subsequent syntheses and meta-analyses showing that resident competitors, consumers, and pathogens can reduce the performance of non-native species and limit their establishment (Byers and Noonburg 2003, Levine et al. 2004, Jeschke et al. 2012).

The *invasional meltdown model* posits that non-native species can facilitate one another, leading to an accelerating accumulation of invasive species and escalating ecological impacts (Simberloff and Von Holle 1999, IPBES 2023). The “meltdown” occurs as a result of a positive feedback spiral: an increase in introduced species destabilizes an ecosystem, making it even easier to invade (Weir et al. 2024). Under this framework, invasive species can have positive interactions, such as mutualisms, habitat modification, trophic subsidies, or enemy release,

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which in turn promote the establishment and spread of subsequent invasive species. According to IPBES (2023), biodiversity loss can reduce the resilience of ecosystems to invasive species, with subsequent feedback facilitating the establishment and spread of other invasive species. Evidence from selected ecosystems, including the temperate grasslands of the western US, the Great Lakes region of North America, and oceanic islands, such as Hawaii, have been interpreted as consistent with invasional meltdown. Syntheses have discussed the diversity of mechanisms by which co-occurring invaders can generate synergistic effects (Simberloff and von Holle 1999, von Holle 2011, Ricciardi and Simberloff 2025).

The biotic resistance hypothesis describes a general continuum in which the susceptibility of the community to invasion varies as a function of its diversity and associated resistance. The invasional meltdown hypothesis proposes a specific mechanism at the low-resistance end of that continuum where established invasive species in invasion-prone ecosystems can facilitate additional invaders and amplify their impacts. In actual ecosystems, antagonistic and facilitative interactions are both likely to occur simultaneously, and the net effect will depend on the underlying mechanisms for possible impacts and the environmental context (Ricciardi and Simberloff 2025). In two meta-analyses of studies with co-occurring species of invasive animals, the average effects of ecological interactions among invasive species were negative so that the impacts on native species were either additive or weakly antagonistic (Jackson 2015, Ahmad et al. 2025). The patterns differed somewhat among marine, freshwater, and terrestrial systems. The frequency of different types of interaction effects varied significantly with response variables and study design, but also with ecological organization, ecosystems, and continents, indicating that ecological factors also play an important role in shaping co-invasion interaction effects. However, another review of experimental studies evaluated evidence for the invasional meltdown hypothesis and five other invasion hypotheses. Here, the invasional meltdown hypothesis received the strongest overall support with 77% of tests showing evidence of invasive-invasive facilitation with synergistic effects (Jeschke et al. 2012).

3.8 Are cumulative impacts more likely for some ecosystems or species?

The likelihood that multiple non-native species will interact and produce cumulative impacts is not uniform across ecosystems or taxa. Instead, the potential for antagonistic or synergistic effects depends on a combination of environmental context, invasion history with how many and which invaders are already present, and the functional traits of the focal non-native species, particularly their position in interaction networks and the extent to which they modify the abiotic environment. Habitat serves as an important mediator of trophic interactions, such as predation (Lennox et al. 2025). Several reviews have emphasized that the ecological impacts of invasive species are strongly context-dependent, including the extent to which multiple invasive species interact to dampen or amplify each other's effects (Ricciardi et al. 2013). The invasional meltdown hypothesis predicts that the probability of synergistic multi-species effects increases as communities accumulate non-native species and different pathways of interaction (Simberloff and von Holle 1999). Groups of non-native species that are likely to be introduced through the same pathway, such as organisms associated with ballast water, soil or animal fodder, may be more likely to have positive interactions if they share similar life-history traits, such as vegetative reproduction, high reproductive rates with propagules with high dispersal ability, or resistance to allelopathy.

3.8.1 Ecosystems prone to cumulative impacts

Human-altered habitats tend to host more non-native species and experience higher propagule pressure than relatively intact systems (IPBES 2023), suggesting a greater opportunity for multi-species interactions in disturbed habitats. A global analysis of risks from non-native species shows that human-modified landscapes are disproportionately exposed to invasions because of high disturbance and high connectivity caused by humans, which in turn increases the likelihood that multiple non-native species co-occur (Gallardo et al. 2024). Agricultural fields and pastures often have the highest species richness and abundance of non-native species because tilling and grazing disturb soils, fertilization creates a nutrient-rich environment, transport of seeds and animal fodder acts as a pathway for introductions, and native species were removed during habitat conversion to agricultural production (Nater and Eriksen 2025). Similarly, urban and peri-urban systems, transport corridors and other disturbed habitats often support higher richness and abundance of non-native species than adjacent, less transformed habitats (Gaertner et al. 2017, Sandercock et al. 2023). Analogously, invasive tree species are more abundant and more frequently present in secondary forests than in primary forests (Murali et al. 2025). More generally, human use of forests increases the richness and abundance of non-native plant species (Fine 2002, Mungi et al. 2021).

Rivers, lakes, and wetlands near human settlements are susceptible to non-native species when there are active dispersal pathways along shipping and waterways, recurring disturbance due to floods, land use, or water regulation, or extended connectivity along hydropower water tunnels or fish ladders (Mologni et al. 2023). For example, the Great Lakes of North America harbour dozens of non-native species and may be reaching the point of invasional meltdown (Ricciardi and MacIsaac 2000). Here, facilitative interactions among invasive species are more frequent than competitive interactions, supporting that a community with many non-native taxa becomes increasingly susceptible to invasion and synergistic effects (Ricciardi 2001). However, note that an invasional meltdown in the Great Lakes has been debated (DeVanna et al. 2011, Box 2). Multiple non-native species also frequently co-exist in rivers (Mologni et al. 2023, Hindar et al. 2020), and especially along regulated rivers in Norway (Pulg et al. 2024).

Box 2. Alternative interpretation of invasional meltdown in the Laurentian Great Lakes

The Laurentian Great Lakes are frequently cited as a textbook example of invasional meltdown, where multiple non-native species interact in ways that mutually reinforce their impacts (Ricciardi 2001). However, DeVanna et al. (2021) propose an alternative hypothesis: rather than a cascading network of mutually facilitating invaders, much of the observed community change may be driven by general facilitation by zebra and quagga mussels (*Dreissena* spp). According to this view, the non-native mussels act as powerful ecosystem engineers that alter nutrient cycling, water clarity, benthic-pelagic coupling, and substrate availability. The suite of physical and chemical modifications can incidentally benefit a wide range of other species, both native and non-native, without requiring specific positive interactions among invaders. In this framework, community shifts reflect a broad environmental restructuring initiated by a dominant invasive species, rather than reciprocal facilitation among multiple alien taxa. The concept is that apparent synergies among non-native species may arise from a shared response to ecosystem modification by a single strong driver, rather than from direct positive interactions among the invaders themselves.

Marine and coastal ecosystems are connected by shipping and drifting plastic waste (Bastesen et al. 2021) so that estuaries and ports are exposed to high propagule pressure and numerous non-native species, which have led to a boost in invasions (Johnston et al. 2022). In the western United States, the arrival of the invasive European green crab (*Carcinus maenas*) triggered a rapid expansion of the non-native eastern gem clam (*Gemma gemma*), that had previously remained scarce for almost five decades. The expansion appears to be driven by an indirect facilitative or synergistic effect in which predation by the crab on native bivalves has reduced competition for the non-native bivalve (Grosholz 2005).

Island ecosystems are historically prone to dramatic multi-invader interactions. The isolation and ecological naiveté of island biota mean that invasive species of predators and herbivores can have outsized effects. When multiple non-native species arrive, they often interact in unexpected ways. On some islands, an invasive prey can sustain high densities of an invasive predator, thereby intensifying impact on native prey. An example of such hyperpredation includes feral cats and European rabbits (*Oryctolagus cuniculus*). Feral cats depredate native birds, but their population is bolstered by abundant invasive rabbits, leading to higher cat densities and increase predation on native species (Courchamp et al. 2000). The synergistic impacts of cats and rabbits together are worse than the sum of the impacts from each species alone. Camera trap surveys on Madeira Island in Portugal show that cats overlap strongly in activity with introduced rabbits and rodents rather than with native prey, suggesting that non-native prey are subsidizing populations of cats, thereby exacerbating cat predation on native birds (Abrahams et al. 2025). Other island studies have documented other ecological cascades of undesirable effects, such as invasive goats altering vegetation and thereby aiding invasive rats, or pigs disturbing soil and helping to spread invasive plants (Caujapé-Castells et al. 2010).

Relatively intact and remote ecosystems with fewer introductions, such as Arctic or alpine regions or pristine tropical forests, are less likely to host interactions among co-occurring invasive species due to lower numbers of invaders. The potential for cumulative effects in such regions will likely grow as climate change and human trade introduce more non-native species (Nummi 1996, Sandvik et al. 2020). In Norway, boreal forests historically had relatively few non-native species and with limited potential for cumulative effects. However, the number of non-native species is increasing in boreal forests, such as Sitka spruce (*Picea sitchensis*, Øyen and Nygaard 2020), American mink (Wildhagen 1956), raccoon dogs (*Nyctereutes procyonoides*, Kauhala and Kowalczyk 2011), wild boar (*Sus scrofa*, Skjerve et al. 2018), domestic cats (Nilsen et al. 2023), pink salmon (Hindar et al. 2020), and riparian plants (Pulg et al. 2024). The community change raises the possibility of future increases in the occurrence of cumulative effects from non-native species in remote areas of Norway.

3.8.2 Types of species involved in cumulative impacts

Synergistic effects are most likely when at least one non-native species is a facilitator and increases the establishment success, abundance, or per-capita impact of other non-native species by altering the environment or biotic interactions (Crooks 2002, Crego et al. 2016). Facilitators tend to have strong top-down effects, modify habitat structure or physical or chemical conditions, or weaken native resistance so that joint impacts exceed additivity (Crooks 2002, Ehrenfeld 2010, Ricciardi and Simberloff 2025). Certain characteristics of non-native species make interactive effects more likely or ecologically potent:

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Predators. Invasive predators often drive top-down effects, and outcomes can be complex when multiple predators establish (Ballari et al. 2016). They may additively increase predation on native prey or interact with one predator suppressing or facilitating another. Invasive predators may also reduce native biotic resistance by suppressing native competitors or the prey. Island hyperpredation illustrates one form of predator - prey facilitation (Section 3.8.1).

Pathogens. The combination of an invasive host and an invasive pathogen can produce a greater impact than either organism would alone. The introduced North American grey squirrel (*Sciurus carolinensis*) in Europe outcompetes native red squirrel (*S. vulgaris*), but also carries the squirrelpox virus, which is relatively harmless to grey squirrels but lethal to red squirrels. The symptoms caused by the co-introduced virus have a synergistic effect with ecological competition from the grey squirrel, accelerating the decline of the native red squirrel (Tompkins et al. 2003). Likewise, the invasive American signal crayfish (*Pacifastacus leniusculus*) spreads the crayfish plague pathogen *Aphanomyces astaci* which rapidly kills the native noble crayfish (*Astacus astacus*) in Scandinavia, including Norway (Velle et al. 2021). Spread of pathogens may also occur when reintroducing a locally extinct native species that introduce hitchhiking invasive organisms carried with the donor population (Velle et al. 2025).

Ecosystem engineers. Non-native species that modify the resource availability, disturbance regimes, or physical or chemical habitat, may facilitate additional invasions. Invasive nitrogen-fixing plants, like garden lupins in Norway, enrich soils and can enable invasive herbs that thrive on high nitrogen soils (Maron and Connors 1996). Foraging disturbance of large herbivores, such as wild boar in Norway (Skjerve et al. 2018), can promote the long-term population maintenance of ruderal and other non-native plants by creating bare ground and fragmenting vegetation cover (Oldfield and Evans 2016). Similarly, non-native earthworms promote plant invasion by ingesting seeds and modifying soil properties (Clause et al. 2015). Other examples are mentioned above, like increased water clarity caused by zebra mussels, crabs that dig (Velle et al. 2021; 2024) or oysters that create hard substrate.

Mutualists: Some of the most striking synergistic invasions involve mutualistic relationships. Non-native species that provide services to one another can greatly boost each other's spread and impact. Classic examples are invasive insect pollinators and invasive plants. For instance, the introduced honeybee (*Apis mellifera*) in North America preferentially pollinates invasive yellow star-thistles (*Centaurea solstitialis*), increasing seed set and spread of the weeds (Barthell et al. 2001). Invasive Argentine ants (*Linepithema humile*) form mutualisms with invasive scale insects and aphids, protecting them from predators in exchange for honeydew. The association leads to population explosions of sap-feeding insects that harm native plants, while the ants also displace native ant species (Holway et al. 2002, Daane et al. 2007, Grover et al. 2008). Interestingly, an invasion by a seed-dispersing ant (*Myrmica rubra*) promoted recruitment of a co-introduced non-native plant (Prior et al. 2015). In marine systems, host-symbiont mutualisms can strongly promote biological invasions. The spread of an Indo-Pacific algal symbiont (*Symbiodinium trenchii*) into Caribbean corals has increased coral thermal tolerance and facilitated persistence under extreme warming (Pettay et al. 2015). Similarly, invasive zooxanthellate jellyfish, such as *Cassiopea andromeda* and *Phyllorhiza punctata*, rely on mutualistic dinoflagellate algae, an important trait for their establishment and range expansion in the Mediterranean (Cillari et al. 2022, Dall'Olio et al. 2022). Co-invasions of hosts and mutualists can allow both partners to occupy environments they could not successfully exploit alone (Aizen and Torres 2024, Martignoni et al. 2025).

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4 Considerations when assessing non-native species

4.1 Assessment endpoints

A widely used framework for ecological risk assessment follows a structured problem-formulation process (USEPA 1992). The framework typically starts with a concern about potential or observed ecological harm, and then defines the scope of the assessment by identifying the stressors of interest, the ecosystems or receptors at risk, and the relevant exposure pathways and potential effects. The next step is identification of appropriate endpoints where *assessment endpoints* are broadly defined as the environmental values to be protected, and *measurement endpoints* are ecological characteristics that are related to the assessment endpoints (USEPA 1992). In risk assessments for non-native species, the assessment endpoints are the measurable indicators of ecosystem state or ecosystem services that may be affected by the non-native species (Ehrenfeld 2010). In a management context, the assessment endpoints are typically framed as conservation targets defined through international agreements or conventions, national biodiversity laws, or state regulations. Many potential assessment endpoints can be considered (Box 3), but they are rarely specified in risk assessments beyond overarching goals.

Different invasive species can act through a variety of mechanisms (Box 1). However, the mechanisms and their cumulative effects can impact the same assessment endpoint, such as reduced recruitment of native fish, loss of submerged vegetation, or increased water turbidity. Well-established assessment endpoints allow resource managers to integrate effects even when the underlying mechanisms differ. Assessment endpoints can help make the cumulative effects explicit and prevent mixing incomparable outcomes. Clear and measurable endpoints also make it possible to identify thresholds where a small additional stress can trigger disproportionate change or switches to a new ecosystem state.

Box 3. Potential assessment endpoints and their attributes. A practical way to frame endpoints is by structure or composition of the community (endpoints 1-3), functions and processes (endpoints 4-6), biotic interactions (endpoints 7-8), environmental changes (endpoints 9-10) or services to humans (endpoint 10-11). See also USEPA (1992).

1) Biodiversity and community composition. Use these when focusing on the impact on natural biodiversity. Possible metrics include:

- a. Native species richness
- b. Richness of red-listed species
- c. Diversity indices (Shannon, Simpson indices)
- d. Beta diversity or turnover measuring community changes across sites or time
- e. Genetic diversity; measures of introgression, hybridization, or effective population size
- f. Community composition, often the deviations from a pre-disturbance assemblage

2) Population status of focal native species. Use these when focusing on the impact on viable populations, densities, or biomass of target species.

- a. Abundance, density, biomass, or catch-per-unit-effort
- b. Demography or reproductive success: measures of recruitment based on young-of-year or age ratios, fecundity and survival
- c. Growth and condition: length-at-age, weight - length or body condition
- d. Size or age structure where truncation can indicate predation or competition
- e. Spatial configuration or species distributions, such as population fragmentation or range contractions

3) Ecosystem functions and processes. Use these when focusing on ecosystem functioning, and for cumulative effects when focusing on multiple stressors that may push processes to thresholds that potentially lead to changes in ecosystem state.

- a. Measures of primary production, such as biomass, chlorophyll-a, macrophyte growth, or gross primary productivity
- b. Ecosystem metabolism based on ecosystem respiration or net ecosystem production. Measurements estimating the balance between gross primary production as the carbon produced by organisms versus net carbon gain or loss due to organismal use
- c. Decomposition rates measured by leaf litter breakdown, or cotton-strip assays
- d. Nutrient cycling or retention based on uptake lengths, denitrification potential, sediment - water fluxes
- e. Bioturbation or sediment resuspension rates

4) Functional composition and food-web structure. Use these when focusing on shifts that may occur without changes in species richness. Beta diversity will inevitably also change when functional composition and food-web structure are altered.

- a. Biomass or abundance of different functional groups, such as relative abundance of grazers, shredders and predators in freshwater habitats
- b. Functional diversity based on trait richness
- c. Trophic structure: predator - prey ratios, measures of trophic level for organisms in a food web based on stable isotopes of carbon and nitrogen
- d. Energy pathway indicators for reliance on benthic versus pelagic habitats, or community size
- e. Stability, resilience, and "tipping point" indicators, keystone species
- f. Changes in functional genes, such as markers in the microbial community associated with nitrification and denitrification

5) Behavioural and physiological stress of native species. Useful when density remains stable but individual performance is impacted.

- a. Stress indicators, such as body condition, stress hormones, or immune function
- b. Changes in habitat use, activity patterns, vigilance, foraging behaviour, or migration behaviour
- c. Changes in resource allocation. For example, trees that are browsed allocate more to growth, or more to roots, or more to reproduction.

Box 3. Continued.

6) Species interactions and interaction strength. Use these when invasive species is likely to affect native species primarily through biotic interactions.

- Predation rate or grazing pressure on key taxa based on losses to nest predation or intensity of herbivory
- Competition intensity observed by resource depletion, space occupancy, interference rates, or patterns of aggressive behaviour
- Mutualism disruption affecting pollination success, seed set, or mycorrhizal dependence

7) Disease and parasite dynamics. Use when the invasive species can introduce, amplify, or redistribute pathogens and parasites.

- (1) Pathogen prevalence in native populations
- (2) Parasite load, infection intensity and frequency
- (3) Spillover or spillback where disease burden increases for native species because invasives act as a reservoir
- (4) Changes in vector abundance if a non-native is a vector or creates habitat for a vector

8) Habitat extent, quality, and structural complexity. Use these when invasive species alter physical habitat due to engineering, bioturbation, vegetation displacement.

- Habitat extent based on areal coverage of key habitats
- Structural complexity, such as changes in canopy height and density, substrate heterogeneity, or availability of refugia
- Fragmentation and other changes in connectivity measured by patch size, edge:area ratios, or corridor continuity
- Microhabitat quality metrics including fine-sediment cover, shelter density, or sediment stability
- Niche availability, such as access to suitable substrates for spawning or nesting, or nursery habitats for juvenile life-stages

9) Physico-chemical condition of an environment. Often best treated as intermediate response variables linking invasive mechanisms to biological outcomes.

- a) Water and soil quality indexed by nutrients (nitrogen, phosphorous), turbidity or clarity, oxygen regime, pH, conductivity, or dissolved organic carbon
- b) Light availability measured by Secchi depth, or photosynthetically active radiation
- c) Temperature or air humidity regime if invasive species influences microclimate
- d) Frequency or severity of harmful algal blooms or
- e) Greenhouse gas fluxes (CO₂/CH₄/N₂O) in systems where invasive species alter carbon or nitrogen cycling
- f) Hydrological and geomorphic processes, such as rates of bank erosion or accumulation of sediments caused by activity of non-native crabs
- g) Resilience to changes in stress or disturbance regimes from for example fire, floods, drought, avalanches, landslides, icing or storms

10) Ecosystem services. Use these when the conservation target explicitly includes services, or economic targets, or when this is important for management or humans.

10. Provisioning: fishery yield, harvestable biomass, or forage availability
11. Regulating: water purification by nutrient retention for clarity, shoreline/bank stabilization, or flood attenuation/ protection
12. Supporting: habitat provision for harvested species, proxies for soil formation, or pollination support in terrestrial habitats
13. Cultural: recreation quality (perceived naturalness) or existence of iconic species/habitats

11. Ecosystem disservice. Use these when the target includes negative effects on humans.

- (i) Fouling and clogging of filters, pipes, or hydropower intakes
- (ii) Pollen, toxic blooms or other allergens, plants, or biting bugs that sting or irritate
- (iii) Pest outbreaks (bark beetles, potato blight, geometrid moth outbreaks, pine shoot blight)
- (iv) Aesthetic nuisance, like surface scums or excessive cover of macrophytes

4.2 Environmental targets in legislatives in Norway

Risk assessments of non-native species conducted by the Norwegian Biodiversity Information Centre and VKM focus on evaluating the risk of negative impacts on biodiversity in Norway. Although “biodiversity” is not always explicitly defined in mandates, the concept is firmly anchored in Norwegian legislation and policy. Across constitutional, environmental, marine, freshwater, and land-use frameworks, Norwegian law establishes clear objectives to safeguard ecosystems, species, genetic variation, ecological processes, and long-term ecosystem productivity.

At the highest level, Norwegian environmental governance is guided by the principle that nature’s productivity and diversity shall be safeguarded for future generations. The overarching principle is operationalized through sectoral legislation covering terrestrial, freshwater, marine, and polar environments. Together, the different frameworks define the conservation and management targets that risk assessments must implicitly or explicitly consider, including viable populations of native species, maintenance of ecosystem structure and function, protection of ecological processes, prevention of significant adverse effects from invasive species, and the achievement of good ecological status in aquatic environments (Box 4).

In this context, cumulative effects from multiple non-native species are directly relevant. Legal frameworks emphasize non-deterioration, long-term sustainability, risk-reduction based on a precautionary approach, ecosystem-based management, and assessing combined pressures. Risk assessments that address cumulative impacts therefore contribute to fulfilling existing national obligations to maintain biodiversity, ecological integrity, and ecosystem services under increasing pressure from climate change, land use, pollution, and biological invasions.

Box 4. Legal basis for protecting biodiversity in Norway.

Constitutional foundation

Section 112 of the Norwegian Constitution states that natural resources shall be managed in a way that safeguards their productivity and diversity for future generations. This establishes a long-term and intergenerational obligation to protect biodiversity.

Nature Diversity Act (*Naturmangfoldloven*)

The Nature Diversity Act defines biodiversity as encompassing ecosystems, species, and genetic variation. The objectives it sets are:

- Ecosystems shall be maintained within their natural ranges,
- Species shall occur in viable populations within their natural ranges,
- Ecological processes and functional areas shall be safeguarded.

The Act also establishes that the introduction or release of non-native species must not cause significant adverse effects on native biodiversity

Regulations relating to alien organisms (*Forskrift om fremmede organismer*)

This regulation operationalizes prevention and control of non-native species. Its purpose is to prevent the import, release, and spread of non-native organisms that may have adverse impacts on biodiversity. It applies to mainland Norway, freshwater, territorial waters, and Jan Mayen (but not Svalbard).

Svalbard Environmental Protection Act (*Svalbardmiljøloven*)

Sections §26–27 specify requirements for permits for import, release, or cultivation of species that are non-native to Svalbard.

Water Framework Directive (*Vannforskriften*)

Norway's implementation of the EU Water Framework Directive sets environmental objectives for rivers, lakes, coastal waters, wetlands, and groundwater. It requires that the status of water bodies must not decline (non-deterioration principle) and that they should achieve at least good ecological status and good chemical status. Ecological status is assessed relative to type-specific reference conditions using biological quality elements.

Marine and terrestrial frameworks

Marine conservation targets are anchored in the Marine Resources Act (*Havressurslova*) and associated management plans, emphasizing ecosystem structure, functioning, productivity, diversity, precaution, and ecosystem-based management.

Terrestrial protection is further supported by:

- The Planning and Building Act (*Plan- og bygningsloven*): sustainable land-use planning
- The Forestry Act (*Skogbrukslova*) and Regulation promoting sustainable forestry (*Forskrift om berekraftig skogbruk*); biodiversity safeguards in forests
- The Pollution Control Act (*Forurensningsloven*): protect the outdoor environment against pollution
- The National Land Act (*Jordloven*): promoting environmentally sound, long-term land use

National Biodiversity Strategy

Norway's National Biodiversity Strategy and Action Plan (*Bærekraftig bruk og bevaring av natur*, Meld. St. 35 [2023–2024]) implements the Kunming–Montreal Global Biodiversity Framework. Non-native species are identified as a major pressure, with targets to prevent introductions, reduce establishment rates, manage pathways, and control or eradicate invasive species. National risk assessments, including the Norwegian Alien Species List (Artsdatabanken 2023), are central tools for achieving these objectives

4.3 Pathway to harm

Hazards in risk assessments includes the potential harm that a non-native species can cause to native biodiversity and the likelihood that the harm will occur. A “Pathway to harm” section in a risk assessment may improve the accuracy of the likelihood estimation. A pathway to harm identifies the sequence of steps that may lead to harm, each with its own intrinsic probability. The sequence may include a progression of steps from transport via introduction to development of a self-sustaining population (Figures 2 and 3).

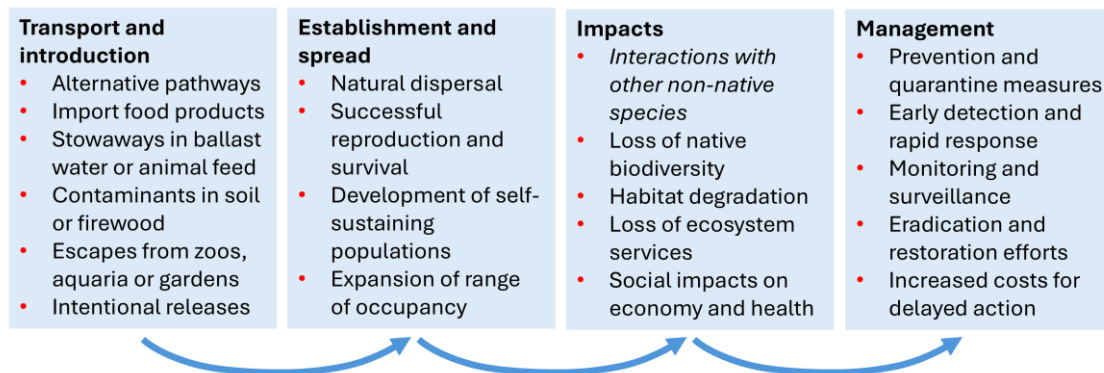


Figure 2. The stages of invasion include four general categories of steps that non-native species pass before becoming a hazard. The categories include initial stages of transport and introduction, establishment and spread in new areas, potential impacts on native biodiversity and natural ecosystems, which then lead to management action. Improved risk assessments based on a multi-species perspective also include the potential role of ecological interactions with other non-native species.



Figure 3. An example of a pathway to harm from a recent VKM risk assessment of non-native species of crabs (Velle et al. 2024). For crabs to realize their potential threat, there must first be an initial demand for import of the species in Norway. Juvenile or adult crabs must survive transport from abroad and handling in Norway before either being deliberately released or escaping into natural habitats. Except for pathogens and parasites, which can be transmitted from a single, or even dead individual, most hazards require that the species become established to pose a threat to native biodiversity.

A pathway-based approach provides important information when assessing cumulative impacts. Cumulative impacts can arise when multiple non-native species (i) share or overlap in

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pathways, such as the same introduction routes, recipient habitats, or establishment bottlenecks, thereby increasing combined propagule pressure, or (ii) alter each other's pathway probabilities through facilitation, habitat modification, or other interactions. By making the steps explicit, assessors can evaluate whether likelihoods will be independent (additive) or interactive (antagonistic or synergistic), and can compare alternative scenarios, such as species A alone, species B alone, and A + B together. The approach further strengthens the link between risk assessments and risk-reducing measures since mitigation can be targeted to the specific pathway steps where cumulative effects are most likely to occur, such as the points of entry, handling and containment, or a common habitat of establishment.

Non-native species are easy to recognize when transported long distances out of their native range and into introduced areas, particularly in association with anthropogenic activities, such as import as a food product, stowaways in ballast water or animal feed, contaminants in untreated soil or wood products, as organisms in the aquaria or pet trade, or from intentional releases, such as for biocontrol agents. Non-native species can also arrive from natural dispersal processes and range expansions into new areas and be associated with climate change, land use conversion or other processes that favor establishment. In the case of species that are hard to detect or identify, it may be difficult to determine whether first detections are a species that has been present but overlooked versus a species that has newly arrived (Sandercock et al. 2023). A last category of non-native species includes organisms that may be native to a country but can still cause ecological problems due to introductions to new regions. Examples of regionally invasive species in Norway include bulbous rush (*Juncus bulbosus*), northern pike (*Esox lucius*), and European minnows (*Phoxinus phoxinus*, Hesthagen and Sandlund 2019, Velle et al. 2022).

4.4 Time frame for evaluating effects

A central decision in risk assessment is the time frame over which potential cumulative impacts are evaluated. In VKM mandates, the Norwegian Environment Agency ask for assessments “in a climate change perspective 10 years into the future”, and “further in a long-term climate perspective” (Kirkendall et al. 2025). Both are directly applicable to cumulative effects, because both establishment probabilities and interaction strength can change through time as environmental constraints, phenology, disturbance regimes, and habitat suitability change. Over longer time frames, mechanisms linked to the intrinsic dynamics of the species itself also become increasingly important, including spatial spread into novel habitats and frequency- or density-dependent processes, such as population growth.

An introduced species may persist in a habitat without noticeable spread or harm, but later expand rapidly and have major effects. The concept of *invasion debt* has been used to describe the long lag phases exhibited by some non-native species with the implications that introductions today may have major impacts in the future (Jackson and Sax 2010, Dullinger et al. 2013). Long generation time tends to increase invasion debt by slowing demographic buildup, spread, and adaptation. Short generation time tends to reduce invasion debt. However, even short generation organisms can show long lags if other environmental constraints are important, such as Allee effects at low densities, dispersal barriers, detection bias, or climate thresholds (Hulme et al. 2020). A study of more than 5700 species of invasive plants found that about one third had latency periods, with an average of about 40 years before explosive growth (Robeck et al. 2024). Self-fertilizing species were less likely to experience lags, suggesting that mode of reproduction may limit fecundity. An extreme case in

the study was the sycamore maple (*Acer pseudoplatanus*) in the United Kingdom, which was first recorded in 1613 and began spreading invasively after 320 years. Such lags are also seen among animals. The Australasian barnacle (*Austrominius modestus*) persisted at low densities in Scotland for decades before increasing dramatically (Gallagher et al. 2015). The main driver of the delays appears to be that the species are held in check by abiotic conditions but spread after climate and environmental conditions become favorable (Davenport 2015, Robeck et al. 2024). In addition, invasion debt may occur when non-native species arrive and cause synergistic effects with already established non-native species (Essl et al. 2011). The European Environment Agency states that “Cumulative impacts include a time dimension, since they should calculate the impact on environmental resources resulting from changes brought about by past, present and reasonably foreseeable future actions” (Malogni et al. 2023, page 2).

More frequent extreme events and disturbances from storms, fires, and floods can shift species distributions and facilitate invasions by weakening competitively strong native species and disrupting ecosystem stability (Kausrud et al. 2022). Changes in temperature and precipitation and the frequency of extreme events can modify phenological overlap, mutualist availability, and abiotic constraints, thereby altering whether interactions are additive, antagonistic or synergistic (Hof et al. 2012, Blois et al. 2013). The conclusion is that assessments should treat multi-species interactions as a developing risk over time rather than an exceptional case.

5 Methodological considerations

5.1 Strengths of single-species approaches

Environmental risk assessments for non-native species have usually focused on single species. Each species is evaluated in isolation for the different stages in the pathway to harm, including the likelihood of establishment, spread, and potential impacts on native biodiversity (Vilizzi et al. 2021, Velle et al. 2024). The single-species approach has advantages because it allows for an in-depth analysis of species-specific traits, evaluations of the match to envelopes of environmental conditions, and potential impacts on assessment endpoints. A single-species approach can also provide clear management recommendations that are feasible to implement. Focusing on one species at a time has been viewed as an effective strategy in conservation (Brandt et al. 2023), and the approach is widely used in research and for risk assessments (Bradley et al. 2019, Sandvik et al. 2019, Velle et al. 2021, 2024).

It is also more straightforward to assess single species than accounting for cumulative impacts from multiple non-native species. In practice, cumulative impacts can only be evaluated when specific ecosystems are assessed, or when likely interactions among co-occurring species are already suspected. Otherwise, it would require a tremendous effort to consider all potential combinations of non-native species. For example, with roughly 2000 species on Norway's Alien Species List (Artsdatabanken 2023), there are about 2 million possible species pairs. Although many potential interactions can be ruled out because species do not co-occur, identifying which co-occurring pairs are most in need of assessment remains complex and typically requires ecological hypothesis testing and/or prior empirical observations.

Many legal and policy frameworks are structured around individual non-native species, which makes the single-species risk assessment a practical and straightforward tool for decision-makers. Examples in Norway include the Norwegian Biodiversity Information Center, regulations for import of non-native organisms, quarantine protocols for plants and animals, and legislation for protection of species of conservation concern. By concentrating on a single non-native species, risk assessors can draw on well-established protocols, such as the Risk Assessment scheme of the Non-native Species Secretariat in Great Britain (NNS 2025, see also Roy et al. 2013), the Aquatic Species Invasiveness Screening Kit (Vilizzi et al. 2021), or the Generic Ecological Impact Assessment of Alien Species (GEIAA; Sandvik et al. 2019, NBIC 2022). Standardized protocols help with production of scientific predictions about that species' likelihood of establishment and impact, and with a given confidence. A targeted focus helps prioritize the worst potential invaders, ensuring that available management resources are allocated to the species deemed most harmful under controlled assumptions.

5.2 Perils of single-species approaches

Non-native species do not exist in isolation after they have been introduced to an ecosystem, suggesting that risk assessments for single species may have major limitations if the broader ecological context is ignored. Single-species approaches consider risks arising from interactions with native species but usually overlooks the potential for interactions among co-occurring non-native species (Caut et al. 2009, Kuebbing et al. 2013, Jackson 2015). Interactions among multiple species could be the result of simultaneous introductions of non-native organisms. Alternatively, introductions of new organisms to a local fauna or flora can significantly change the impacts of the non-native organisms that are already present in the system but have not

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yet become invasive (Simberloff and von Holle 1999, Richardson et al. 2000a, Ricciardi 2001, Kuebbing et al. 2013, Mologni et al. 2023).

Management of invasive species may have unintended consequences if one invader suppresses another. In such cases, removal could release the second invader from top-down control, thereby allowing it to thrive and cause additional harm (Ruscoe et al. 2011, Brandt et al. 2023). It is therefore advantageous to evaluate the likelihood of secondary release when planning eradication or control of non-native species. Where this likelihood is non-trivial, management actions could include paired interventions or staged controls, combined with monitoring to detect and respond to potential secondary releases (Ruscoe et al. 2011, Brandt et al. 2023). Multi-species risk assessments improve on the single species approaches by considering potential for different types of antagonistic or synergistic effects, exploring a wider range of possible outcomes for native biodiversity and natural ecosystems, and improving management recommendations to make better use of available resources (Kuebbing et al. 2013, Jackson 2015).

Mesopredator release is a classic example of the unintended consequences that can arise in the single-species approach. Oceanic islands often support endemic species of plants and animals that are vulnerable to introductions of non-native species. In island systems with multiple species of invasive vertebrates, removal of a dominant predator or competitor can trigger population increases in other co-occurring non-native species (Courchamp et al. 1999a, Ruscoe et al. 2011). Feral cats were eradicated to protect native seabirds on Macquarie Island, Tasmania. Removal of cats led to increased populations of rabbits and rodents that consumed about 40% of the island's vegetation, which caused extreme erosion and a worsening crisis (Bergstrom et al. 2009a, 2009b). Alternative explanations for the increase in rabbits and rodents on Macquarie Island have also been suggested (Box 5), highlighting the complexity of managing disturbed ecosystems with multiple invaders.

Box 5. Removal programs for invasive vertebrates in island ecosystems

The Macquarie Island cat - rabbit - vegetation story is a textbook example of unintended consequences in an eradication program. Feral cats were removed to protect seabirds, and then rabbit numbers exploded, which led to extensive vegetation loss and erosion. Bergstrom et al. (2009a) concluded that cats maintained top-down control on rabbit numbers. The interpretation was challenged by Dowding et al. (2009) who argued that increases in rabbits could not be attributed to cat removal alone, but instead reflected a combination of reduced land use, attenuation of the Myxoma virus, abundant forage after decades of vegetation recovery, release from cat predation and climate variability. The authors noted that high rabbit numbers and vegetation damage had occurred previously, and that rabbit numbers declined again in the absence of both cats and Myxoma releases. In response, Bergstrom et al. (2009b) analyzed how variation in Myxoma virus releases and the presence or absence of cats were related to two different estimates of rabbit abundance. Their reanalysis indicated that Myxoma releases had a statistically detectable, but relatively weak effect on the lower rabbit numbers but no significant effect on higher numbers. Instead, presence or absence of cats remained a strong and highly significant predictor of rabbit numbers for both population estimates. In this case, the joint assessments for multiple non-native species lead to improved insights.

Eradication programs can be highly effective for restoration of island ecosystems (Towns and Broome 2003, Snow et al. 2025), but may be more likely to be successful if multi-trophic

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perspectives are included in planning of eradication efforts (Caut et al. 2009), and if multiple non-native species are targeted for simultaneous removals (Ballari et al. 2016, Masters et al. 2018).

5.3 Defining additive, antagonistic, and synergistic

When assessing cumulative impacts caused by non-native species, the terms additive, antagonistic, and synergistic should be defined. The terms form a continuum, rather than separate states. Conceptually, additivity is the boundary between antagonism and synergy, and can be defined relative to an additive expectation (Crain et al. 2008, Darling and Côté 2008, Piggot et al. 2015). Additivity then needs to be given an explicit criterion or value. In ecological data, however, perfect equality to additive is unlikely because of measurement error, environmental variation, and context dependence. A practical definition of these terms requires:

- (1) Specifying a null model (most commonly additivity, but sometimes multiplicative or other nulls depending on the response scale). Non-additivity is inferred if a statistical test rejects an additive null model. Tests may be possible in experiments including many replicates and large samples, but are less feasible in natural observational studies (Folt et al. 1999, Piggot et al. 2015).
- (2) Defining how far the observed cumulative effect must deviate from the null to be classified as synergistic or antagonistic. Synergy and antagonism can be defined using a pre-specified quantitative threshold such as: synergistic if the joint effect is $\geq 10\%$ greater than additive or antagonistic if $\leq 10\%$ lower. The approach is often preferable in risk assessments because it can be applied even when data is insufficient for formal statistical testing. Specifying numerical thresholds makes the assessment transparent, comparable, and testable in the sense that new data can confirm or revise the classification, even when expert judgement is needed to assign likely effect sizes (Darling and Côté 2008, Sandvik 2023).

A realistic workflow can be to:

- (i) define the assessment endpoint and an effect metric such as change from a state without disturbance (Section 4.1),
- (ii) compute the additive expectation from the effects of a single non-native species,
- (iii) quantify the deviation of the observed or expected joint effect from expected, and
- (iv) classify the interaction using an agreed threshold (e.g., $\pm 10\%$) chosen to reflect management relevance and/or observational uncertainty.

5.4 Methods for assessing cumulative effects

Most environmental risk tools are designed for single-species assessments. Multi-species effects based on interactions, co-occurrence, and shared pathways can be combined in some of the methods to give a multi-species, or species assemblage view. Cumulative assessments can either be quantitative, semi-quantitative or qualitative. To quantify cumulative effects, we typically need: (i) a defined assessment endpoint, (ii) a null expectation for combined effects of multiple non-native species (usually additivity), and (iii) data that allows estimation whether the cumulative impacts deviate from levels predicted by the null hypothesis. The broader literature on multiple stressors emphasizes that combined effects are often not reliably predictable from single-stressor effects without either mechanism-based assumptions or data

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across stressor combinations (Pirootta et al. 2022). Estimation is most feasible in discrete, well-studied systems, such as field experiments, observational models using gradients of invasion intensity, or evidence synthesis and databases (Section 3.6). Understanding how impacts accumulate with additional invasions remains a key gap, even though multiple invaders with modest risk can collectively generate substantial harm (Brock and Bernard 2025). Even in systems with expected synergistic effects that could lead to invasional meltdown, community- and ecosystem level consequences are rarely tested, largely because interaction pathways are complex and difficult to study at large spatial scales (Ricciardi and Simberloff 2025). The challenges suggest that qualitative frameworks that predict cumulative outcomes from best available evidence are preferred (Mologni et al. 2023).

The alternative methods that are currently available for handling multi-species effects can be divided into four broad categories: (i) spatial cumulative-impact tools, (ii) mechanism-based scoring frameworks, (iii) network and dynamical food-web models, and (iv) community-level statistical modeling.

5.4.1 *Spatial cumulative-impact tools*

Cumulative impacts of invasive alien species (CIMPAL) is a standardized, map-based method that estimates and visualizes the cumulative impact of multiple non-native species by combining (i) species distribution layers, (ii) habitat or biotope maps, and (iii) literature-derived impact scores that are weighted by the strength of evidence (Katsanevakis et al. 2016). Impacts are then summed with an additive model across species - habitat pairs to produce raster maps of impact hotspots, along with lists that can rank species, habitats, and sites for management. CIMPAL is semi-quantitative since the impact and evidence are typically encoded as scored weights rather than measured effect sizes. The method was originally developed and implemented for the Mediterranean Sea, and has since been applied more broadly to other marine, freshwater, and terrestrial habitats, and is available via LifeWatch/JRC workflows (<https://metadatalogue.lifewatch.eu/srv/eng/catalog.search#/home>) that output GIS-ready products including GeoTIFF vulnerability/impact layers. In practice, CIMPAL supports screening and prioritization but not modeling of mechanistic interactions, thereby helping 'target surveillance and control where cumulative impacts are expected to be highest.

Cumulative-effects assessment (CEA) is a framework for estimating how multiple stressors and actions over time combine to affect ecosystem components (Stelzenmüller et al. 2018). CEA has six elements: (i) definition of scope for ecosystems components, spatial/ temporal boundaries, scenarios, (ii) inventory of stressors from non-native species, land use, nutrients, hydromorphology, or climate change, and then builds stressor – pathway - receptor linkages, (iii) quantification of exposure × sensitivity using datasets, thresholds, or exposure response functions (or by matrix scoring, Bayesian networks, or index models), (iv) aggregation of effects across multiple stressors, allowing classification of additive, antagonistic, or synergistic effects, (v) mapping of hotspots and risk, such as probability of exceeding an ecological threshold or tipping point, with comparison of management scenarios, and (vi) adding uncertainty and set up of monitoring or adaptive management. For non-native species, CEA treats each invader along with its vectors or habitat modifications as a stressor layer, combines them with other stressors, and ranks places or pathways for action. The method is useful for assemblage-level prioritization across multiple species rather than species-by-species assessment.

5.4.2 Mechanism-based scoring frameworks

Environmental impact classification for alien taxa (EICAT) is a standardized system for evidence-based scoring of impacts caused by non-native species (IUCN 2020). The three steps for each species are: (i) evaluation with respect to 12 impact mechanisms (see Box 1), (ii) assignment of an impact severity category ranging from Minimal, Minor, Moderate, Major, to Massive (plus Data Deficient/Not Evaluated), and (iii) recording of an evidence confidence (low/medium/high) with supporting references. Severity categories are defined by the level of harm posed on individuals, populations, communities or ecosystems, which makes results comparable across taxa and regions. Use of the EICAT system to assess multi-species impacts is discussed in Section 5.6.

Generic impact scoring system (GISS) scores each non-native species across a set of impact categories based on environmental, socio-economic or health factors on a scale from zero to five where zero equals no evidence of impact and five equals very high (Nentwig et al. 2016). The impact categories cover direct and indirect effects such as predation, competition, hybridization, disease/parasites, herbivory, biofouling/physical disturbance, and ecosystem-level changes. Each score is evidence-based and with separate assessments of confidence for each category. To use the GISS method for a multi-invader assessment, first the scope is defined for sites/ habitats/ pathways and alternative GISS categories, and then each non-native species is scored per impact category with cited evidence and a confidence tag. The scores are converted to a per-species impact, combined with species occurrence data, and pooled across species to rank sites, mechanisms, and pathways. Co-occurring non-native species acting on the same mediator could be flagged and multipliers for antagonistic or synergistic interactions could be applied where evidence supports interactions that differ from additive effects.

Generic ecological impact assessment of alien species (GEIAA) is a quantitative, criteria-based framework developed for risk assessment of non-native species in Norway (and also used in Sweden), implemented by the Norwegian Biodiversity Information Centre (Sandvik et al. 2019, NBIC 2022). GEIAA defines ecological impact as the product of invasion potential and ecological effect, placing each species in a two-dimensional impact matrix. Invasion potential is scored from one to four from three criteria, while ecological effect is scored from one to four from six criteria. The maximum criterion score determines the axis position, and the resulting matrix position assigns the species to one of five impact categories ranging from no known impact, low, potentially high, high, to severe. Because GEIAA scores invasion potential and ecological effect on separate axes, it can support multi-species summaries by aggregating species' positions in the matrix for a given site, habitat, or pathway. The approach makes it straightforward to distinguish assemblages dominated by high-effect invasive species (management priority) from those dominated by high spread potential invasive species (surveillance/containment priority), without implying that GEIAA itself quantifies non-additive interactions.

5.4.3 Network and food-web modelling

Ecopath with ecosim/ecospace software tools + ecological network analysis can be used to simulate direct and indirect trophic pathways to quantify how one or several non-native species change biomass flows, and assess combined effects (Keramidas et al. 2023). Modeling can also be conducted under alternative scenarios of climate warming or harvest levels.

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Bayesian networks can integrate multiple invaders, co-stressors, and mediators such as habitat structure into a causal graph to estimate cumulative effects and propagate uncertainty. The method is well suited when sources of evidence are based on field data combined with expert judgment (Kaikkonen et al. 2020).

Structural equation modeling is a method that can partition direct vs. indirect pathways and test whether multiple invaders act antagonistically or synergistically via shared mediators (Schweiger et al. 2016). Examples include models of freshwater ecosystems with complex links among water quality, invasive species, macrophytes, and invertebrates.

5.4.4 Community-level modelling

Joint Species Distribution Models (JSDMs) can be used to model many species jointly by treating species as a random effect so that community-level hyperparameters are calculated for a combined pool of common and rare species (Sandercock et al. 2025). Joint modeling can correct for problems of imperfect detection and yields improved estimates for overall measures of species richness and diversity. The method can also incorporate potential species interactions and forecast community change under multiple non-native species. A variety of packages are available in R for modeling of multiple species, including an updated scalable version of JSDM, the sjSDM package (Pichler and Hartig 2021).

5.5 Semi-quantitative assessment of cumulative effects

A semi-quantitative method that combines the best available quantitative evidence with structured expert judgement can provide a transparent basis for evaluating which cumulative outcomes are most plausible (Côté et al. 2016, Katsanevakis et al. 2016, Dey and Koops 2021, Pirota et al. 2022). The method can move beyond a qualitative description of potential interactions, support prioritization across species and settings, and explicitly represent uncertainty through evidence grading and scenario analysis (Box 6). The output is a decision-support index for comparative assessments, such as ranking hotspots or evaluating species combinations, but is not a mechanistic estimate of effect size. A semi-quantitative approach builds a cumulative-effects score from two components:

- *Baseline*: the expected cumulative impact assuming species impacts are additive relative to a set assessment endpoint, based on the magnitude of impact from each species and its likelihood of being present in the assessed setting.
- *Interaction adjustment*: a structured accounting of pairwise interspecific interactions that may dampen (antagonistic) or amplify (synergistic) effects from the null expectation of additivity, conditional on the likelihood of co-occurrence and the plausibility of an ecological mechanism.

Last, positive interactions can cause ecosystems to become more easily invaded and modified, thereby resulting in an accumulation of invasive species and impacts. Thus, it is particularly valuable to identify and flag high-scoring pairs for which the available knowledge base includes evidence of mutualism, facilitation or similar interactions (Ricciardi and Simberloff 2025).

Box 6. Example of a semi-quantitative assessment. A riparian corridor can host multiple co-occurring non-native species, with substantial potential for non-additive outcomes (Kuebbing et al. 2013, Brandt et al. 2023). For each focal riparian setting, we would then:

1. Assign each non-native species an ordinal impact class, aligned where possible with established impacts from single-species assessments and its likelihood of occurring in the setting. Together, these scores define an additive baseline.
2. Build a pairwise interaction matrix in which each species pair is scored for:
 - a) Likelihood of co-occurrence within the riparian unit
 - b) A plausible interaction mechanism (e.g., facilitation via habitat modification, altered disturbance regimes, shared dispersal vectors, trophic mediation, or competitive suppression)
 - c) The expected interaction category relative to an additive null expectation (synergistic, antagonistic, or unknown; see Section 5.3)

The cumulative score is then calculated as the additive baseline plus an interaction adjustment. Results can be reported under alternative scenarios, such as additive-only, plausible synergy, and an upper plausible bound.

5.6 A qualitative framework using EICAT

Additive effects can be approximated in EICAT by adding the sum of single effects from co-occurring invasive species. It is also possible to incorporate synergistic and antagonistic effects under the EICAT mechanisms, although we lack a protocol on how to assess such effects. When VKM conducts single-species risk assessments, the EICAT mechanisms of interactions with already established non-native species have been included in some assessments. A multi-species approach was for example used in a risk assessment for the potential impacts of Northern Cardinal (*Cardinalis cardinalis*) in Norway (Kirkendall et al. 2023). Here, VKM performed a qualitative (expert opinion) assessment on the potential negative effects of increased seed dispersal of the non-native red elderberry (*Sambucus racemosa racemosa*), should Northern Cardinals establish. However, when multiple non-native species are assessed together (in one assignment), VKM has not evaluated potential interactions between these species, and the accumulated effects on the environment. Cumulative effects can be assessed either qualitatively, semi-qualitatively, or quantitatively, with the latter requiring substantially more data and insight into the potentially effected ecosystem. However, such data is rarely available. A baseline approach can be to conduct a qualitative analysis using the EICAT framework. Here, we suggest a nine-step protocol for assessing direct and indirect effects caused by multiple non-native species.

A realistic workflow can be to: (i) define the endpoint and an effect metric (e.g., change from the no disturbance situation), (ii) compute the additive expectation from the effects of a single non-native species, (iii) quantify the deviation of the observed/expected joint effect from that expectation, and (iv) classify the interaction using an agreed threshold (e.g., $\pm 10\%$) chosen to reflect management relevance and/or observational uncertainty. A protocol can be:

1. Perform a standard single species risk assessment, using the EICAT mechanisms as basis.
2. Perform a screening by documenting co-occurrence likelihood of non-native species (either new or already established) in the environment. Likelihood can be ranked on a 5-point scale: Very unlikely, Unlikely, Moderately, Likely and Very likely.

3. For each non-native species assemblage that at least have a moderate likelihood of co-occurring, specify potential EICAT mechanisms caused by interactions between the non-native species that co-occur.
4. For direct effects (EICAT mechanisms for competition, predation, herbivory, pathogens, parasites, toxicity, and hybridisation; Section 3.1), set the relevant assessment endpoint and effect metric (Section 4.1).
5. For indirect effects (EICAT mechanisms for transmission of disease, bio-fouling or other physical disturbance, chemical impact on ecosystem, physical impact on ecosystem, structural impact on ecosystem, indirect impacts through interactions with other species, Section 3.1), determine the likely pathway:
 - a. habitat or structural modifications caused by ecosystem engineers
 - b. resource fluxes and abiotic feedback with species that influence light availability, water clarity or access to nutrients
 - c. interaction-network alterations with species that are mutualists, apparent competitors or vectors for parasites and pathogens
 - d. cross-ecosystem linkages with species that couple ecosystems or transfer subsidies
6. Use additivity as a null model (Section 5.3), set a threshold deviation to define synergistic effects (e.g., +10 %) and antagonistic effects (e.g., -10 %).
7. Score the likelihood of direct or indirect mechanisms. Information from literature reviews with observations of multi-species interactions (e.g., Jackson 2015, Jeschke et al. 2012) could be combined with expert judgement. Likelihood can be ranked on a 5-point scale from Very unlikely, Unlikely, Moderately, Likely, to Very likely.
8. Compare alternative scenarios for baseline, non-native species A only, species B only, versus the combination of species A+B.
9. Describe the level of confidence with which these assessments were made (Low, Medium, High) based on both the level of information available on the subject, the relevance of that information, and to what degree expert judgment was used.

As two additional non-obligative steps, it is possible to:

10. Pinpoint cumulative effects or rankings of species under threat, sites, habitats, pathways, or nature types. Then, add the EICAT scores for the object of interest. Simple visuals such as stacked bars or heatmaps can be used to summarize how many impacts there are and how serious they are.
11. Assess invasion debt, using the four components (after Robertson et al. 2016):
 - (i) the number of species not yet introduced but likely to be introduced in the future given current levels of introduction or propagule pressure
 - (ii) the established non-native species
 - (iii) the potential increase in area invaded by established species and new non-natives
 - (iv) the potential increase in impacts

6 Implications

6.1 Implications for environmental risk assessments

6.1.1 *Assessing cumulative effects*

Our review of cumulative impacts, considerations, and assessment methods in Section 5 leads to several recommendations for potentially improving environmental risk assessments for non-native species. We recommend expanding risk assessments to evaluate potential interactions with new introductions or co-occurrence with established species of non-native organisms. A multi-species perspective will facilitate cumulative impact assessments that include identifying whether the focal species is likely to influence the establishment or impact of other non-native species based on different trophic roles, such as being a pollinator, habitat modifier, or role as a prey or host species that could sustain another predator or parasite. Also, species that are predators, ecosystem engineers, generalist mutualists, or disease carriers should be given extra attention for potential synergistic effects. Incorporating such scenarios will better capture the cumulative impact risk. It follows that risk frameworks explicitly weigh invasive traits linked to facilitation or strong interactions.

Risk assessments should also consider the vulnerability of certain habitats to multiple non-native species. If a species is likely to establish in agricultural, urban, riparian, coastal port or island ecosystems, the assessment should note that many non-native species are already established and thrive in these environments, raising the probability of cumulative impacts. Existing data from previous field experiments or long-term monitoring can be used to help disentangle whether co-occurring species of non-native organisms are likely to have additive, antagonistic, or synergistic effects. A long-term goal for support of risk assessments would be to develop checklists with problematic pairs or groups of invasive species where effects on native biodiversity are known to be particularly damaging.

6.1.2 *Using quantitative or qualitative methods*

Robust quantification of cumulative effects requires: (i) clearly defined assessment endpoints, (ii) an explicit null expectation based on additivity or another hypothesis, and (iii) datasets that contain sufficient information on co-occurrence or abundance to estimate departures from the null expectation due to antagonistic or synergistic effects. In practice, such requirements are only met in factorial experiments based on manipulations of conditions in field plots or mesocosms, or through extensive multi-site monitoring that supports statistical models with interaction terms. Tools exist for experimental and observational studies for mapping of spatial overlap and quantification of cumulative impacts. However, the tools often rely on aggregated evidence and are less able to estimate mechanistic interaction effects directly. Even so, adopting explicit quantitative criteria or thresholds for what constitutes a non-additive effect can reduce interpretive uncertainty by making assessments transparent and testable, even when quantitative data are limited (Sandvik 2023). In Norway, the main remaining uncertainty in quantitative risk assessment of cumulative effects therefore often stems from insufficient data on co-occurrence, abundance, and interactions, rather than from the use of quantitative definitions per se.

Due to knowledge gaps on cumulative effects and future invasion debt, the evidence base for understanding potential impacts of multiple non-native species remains uneven and varies markedly among regions and different ecosystems. Nevertheless, a default risk assessment based on *qualitative screening* can still identify plausible interspecific interactions, classify them as additive, antagonistic or synergistic, and assess cumulative impacts using a transparent qualitative framework. A qualitative approach is acceptable provided it is explicit about (a) the likelihood of co-occurrence based on information on propagule pressure, shared pathways, or hotspot environments, (b) the hypothesized mechanisms driving non-additive outcomes, (c) evidence strength, and (d) uncertainties in the evidence base. Where the decision context demands greater resolution, or where available data and resources allow, the default qualitative approach can be upgraded to a *semi-quantitative* or *quantitative* assessment. A stepwise assessment approach can be:

Level 1: Qualitative screening. A default approach based on identification of where co-occurrence for non-native species is likely, description of candidate mechanisms, and assignment of interaction categories with evidence strength and uncertainty.

Level 2: Semi-quantitative scoring. A suitable approach when prioritization is needed. The evaluation is based on a structured ecological interaction matrix with weighted scoring, where scores are based on combining per-species impact classes with co-occurrence probability and numerically defined mechanism plausibility, and by using scenario analysis (Box 6). To make the approach transparent and testable, “mechanism plausibility” can be operationalized using effect-size thresholds for departures from additivity, such as synergy if the joint effect is $\geq 10\%$ greater than the additive expectation or antagonism if $\leq 10\%$ lower, even when formal statistical testing is not feasible due to limited data. Where empirical data are lacking, threshold-based scores can be elicited through expert judgement to be testable and comparable across assessments (Sandvik 2023).

Level 3: Quantitative screening. An approach that can be used when justified by available data and a need to make decisions. Steps include application of factorial studies, robust observational models, or carefully parameterized cumulative-impact mapping for a limited number of high-priority species combinations and assessment endpoints.

6.1.3 Time frame

Cumulative-effect assessments should explicitly state the temporal horizon and justify the chosen period in relation to potential invasion debt of the species involved and in relation to projected environmental change driven by climate and other human pressures. Environmental drivers can change rapidly, but communities may require years to decades to respond through demographic change, dispersal, and adaptation. As a result, two non-native species that have not yet encountered each other may come into contact as their ranges expand, potentially producing cumulative effects. Time lags and the speed at which a species can build populations and exert measurable effects depend on its life history, generation time, dispersal capacity, and propagule pressure. About one third of plants species exhibit such lag phases, and of these the average lag phase is 40 years (Robeck et al. 2024). Assessments should also acknowledge that “present climate” is itself a moving target. Climate baselines (e.g., climate normals) are typically estimated from historical multi-year windows and may lag current conditions. In practice, there can therefore be two offsetting delays, one in the environmental baseline used to define “current” conditions and another in ecosystem responses.

VKM therefore recommends that assessments explicitly consider species specific time lags and two time horizons in addition to the present: (1) a near-term perspective of about 10 years, consistent with shorter invasion lags and the Norwegian Environment Agency's mandate to capture near-future climate change, and (2) a mid-term perspective of at least 40 years, which better reflects more substantial climatic change and delayed ecological responses. Using both a near-term and a mid-term horizon aligns with common climate projection time frames such as the IPCC RCP/SSP reporting periods. IPCC also reports projections for five to seven decades until the late century (2081–2100), but uncertainty in ecological risk assessment is typically much greater for longer time horizons because the spread and impacts of non-native species are strongly influenced by stochastic events, and it is difficult to predict human activities that will influence land use and dispersal corridors.

6.2 Implications for management

6.2.1 Handling cumulative impacts

For management purpose of non-native species with cumulative impacts, it may be advantageous to target removal or control measures to the entire complex of invasive species rather than single species. Removing one target species from a community of non-native species may not yield the desired recovery if the impacts of the other species increase after a management intervention. Hence, assessments of the potential likelihood of release from competitive or trophic interactions should be evaluated before attempting to remove a non-native species. If the likelihood of secondary increase and undesirable consequences is assessed to be at least moderate, an adaptive management strategy based on paired interventions or a combination of staggered removals with ongoing monitoring can be used to investigate whether the target species is suppressing other non-native species in the system (Ruscoe et al. 2011, Brandt et al. 2023).

Management actions can also be targeted to match the underlying mechanisms for cumulative impacts and different steps in the pathway to harm. It is advisable to target direct effects with population-focused measures based on removal or containment. In contrast, indirect effects can be targeted with context-focused measures, such as limiting available settlement surfaces, managing fuel loads (grasses, trees), or keeping turbidity within natural ranges to disrupt vectors. Where one non-native species facilitates others, management can focus on control of the pathway with interventions, such as biofouling hygiene or substrate management, instead of attempting to control individual species (Floerl et al. 2004, Setterfield et al. 2013, Dolmer et al. 2014, O'Loughlin and Green 2017). In the field, proxy indicators for habitat conditions, such as percent hard substrate in marine habitats, Secchi depth in freshwater, or nitrate levels in soils, may be needed to determine the underlying mechanisms and pathways to harm (Kissling et al. 2012, Hodgson and Halpern 2019).

Risk assessments of cumulative effects provide an essential foundation for integrated management actions that will break positive feedback loops, such as simultaneous control of an invasive plant and its associated pollinator, or joint removal of a prey species along with its main predator. Regulators might also decide that a particular combination of non-native species is likely to be especially harmful.

Future impacts from invasive species may arise from species being introduced now, as well as from established species that have not yet spread or expressed their full impact due to time

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lags. Consideration of the possibility of invasion debt will help to clarify whether risks are near-term management priorities or longer-term, climate-dependent concerns. By incorporating the perspective of potential invasion debt, assessments can avoid a narrow focus based on current conditions and support more proactive management over longer horizons. Control measures can then be implemented before cumulative effects fully develop, thereby preventing a latent non-native species from expanding in a new climatic window, or encountering another non-native species that would allow it to become invasive.

6.2.2 Ecosystem approach

It is advisable to evaluate whether the ecosystem threatened by an invasive species is already under pressure from other human-induced stressors at local and regional scales. Vulnerable or red-listed ecosystems may warrant a lower threshold for conservation concern. Where ecosystems are already degraded by land-use change (Haase et al. 2022), human-induced or animal-induced pollution (Côté et al. 2010, Stenberg et al. 2022), climate change (Fossheim et al. 2015), or the establishment of other non-native species (Sandvik et al. 2020), they may appear resilient to the addition of a single invader. However, they may become far less resilient when two or more non-native species are introduced and establish, particularly when their impacts are likely to be synergistic. In heavily stressed systems, even additive effects can be sufficient to push the ecosystem beyond a tipping point and trigger major ecosystem shifts. Once multiple non-native species begin interacting, control measures also tend to become much harder to implement. An example is California grasslands where native perennial grasses were replaced by exotic annual grasses and forbs, which resulted in altered nutrient cycles and fire regimes (Seabloom et al. 2003).

6.2.3 Defined conservation targets and the pathway to harm

From a management perspective, clearly defined conservation targets translate broad biodiversity goals into operational units that can be monitored, evaluated, and acted upon. They help prioritize what risks matter most, and whether these involve endpoints desirable to protect. Assessment endpoints, or conservation targets, also support the selection of measures that are proportional to expected consequences, and they improve accountability by providing a basis for evaluating whether interventions are effective over time and for communicating decisions transparently.

A pathway-to-harm framework is valuable because it decomposes the risk into a sequence of steps, each with a separate probability of occurring spanning from introduction, release or escape, establishment, spread, and impacts (Figures 2 and 3). For cumulative impacts, identifying overlapping pathways shared by multiple non-native species can reveal phases where risks are likely to accumulate. Examples include shared transport routes or points of entry, common recipient habitats such as garden-waste depots, and situations in which synergistic effects are plausible because one species increases the likelihood or magnitude of impacts caused by another. By identifying the most influential bottlenecks in these pathways, management authorities can target resources where intervention is likely to be most effective and use principles of Early Detection and Rapid Response (Reaser et al. 2020).

7 Conclusions with answers to the terms of reference

We conclude our VKM report on the cumulative effects of non-native species with final conclusions addressing each of the five goals outlined in the Terms of Reference (ToR) from the VKM. The original text from the Terms of Reference is reported with a *grey background*.

7.1 ToR 1

To describe the three possible interaction categories that are relevant to assess:

- a) Additive
- b) Synergistic
- c) Antagonistic

Literature searches shall be carried out to identify examples that illustrate the different interactions. Furthermore, potential examples for non-native species in Norway shall be identified.

Cumulative effects from two or more non-native species can be grouped into three possible outcomes: *additive effects*, where each species contributes independently to total pressure; *synergistic effects* such as facilitation or mutualisms that amplify the negative impacts of non-native species above the sum of single-species effects, or *antagonistic effects*, where negative interactions between invaders, such as competition or predation, reduce niche space or abundance of non-native species and reduce impacts on native species. Synergistic interactions represent a worst-case scenario because the species can mutually amplify ecological impacts on the local community. Synergistic effects can be especially pronounced when an invasive species alters physical or chemical conditions in ways that benefit other non-native species via ecosystem engineering, habitat modification, or related indirect pathways. Antagonistic effects are also common in empirical studies and most often arise from direct interactions between species, such as predation, competition, or parasitism. With antagonistic interactions, the overall impact on native species is lower than anticipated since the non-native species constrain each other. In practice, there are gradual transitions among the three outcomes, and more than one mechanism can occur simultaneously when multiple non-native species co-occur. The overall outcome depends on the balance of mechanisms, context, and the chosen assessment end point.

There are many examples for all three interactions in global ecosystems. Potential examples of cumulative effects also exist for a range on non-native species in Norway, for example involving garden lupin, carpet tunicate, wild boar, or Canada goose. However, few studies in Norway have explicitly addressed cumulative effects. In Norway, there are habitats exposed to high propagule pressure and frequent co-occurrence where multiple non-native taxa commonly overlap, and where additive, synergistic, and antagonistic outcomes are likely to occur. Examples include agricultural fields, ports, estuaries, riparian corridors, depots for garden waste, and other human-impacted environments.

7.2 ToR 2

Based on the literature review, to assess whether it is possible to quantify the effect, or whether it is sufficient to identify the potential interspecific interactions and the category to which they are likely to belong, and on that basis conduct a qualitative assessment.

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VKM concludes that quantifying the cumulative effects from multiple non-native species is normally not possible, since the data necessary to do so generally will not be available for many pairs of interacting species. It is sufficient and better to identify plausible interspecific interactions, classify cumulative interactions as additive, synergistic, antagonistic, and then conduct a transparent risk assessment based on qualitative evaluations or semi-quantitative classification into risk classes.

A qualitative approach is acceptable provided the assessment is explicit about (a) the likelihood of co-occurrence based on propagule pressure, shared pathways, or hotspot environments, (b) the hypothesized mechanisms driving non-additive outcomes, (c) evidence strength, and (d) uncertainties in the knowledge base.

7.3 ToR 3

To include an assessment of what constitutes an appropriate time frame (including a climate perspective) for evaluating potential cumulative effects. The starting point shall be the Norwegian Environment Agency's current practice for VKM mandates: existing climate, "in a climate change perspective 10 years into the future and further in a long-term climate perspective".

VKM concludes that assessments of potential cumulative effects must apply a sufficiently long time horizon and evaluate both the current climate, a climate-change perspective from ten years into the future, and a longer-term climate perspective of at least four decades. Two future time horizons are consistent with guidelines from the Norwegian Environment Agency and ensure that both slow processes and current effects are captured. It is a common finding that newly established populations of non-native species can exhibit time lags before becoming invasive and causing an impact. The ultimate expansion and concurrent ecological effects can be species-specific and depend on life history, generation time, dispersal capacity, and propagule pressure. Effects can occur when climatic or other human-induced environmental conditions change or when further non-native species arrive that interact with the established non-native species. At a global scale, the number of non-native species continues to increase without signs of saturation, indicating that stress on ecosystems and cumulative effects from non-native species may become substantially greater in the coming decades. A warming may enable more species to establish and generate cumulative effects.

7.4 ToR 4

To assess whether cumulative effects can be incorporated into the existing environmental risk assessment methodology used in VKM. The project shall be based on the IUCN EICAT (Environmental Impact Classification for Alien Taxa) categories and specifically assess whether category 12 is adequate for such evaluations.

Cumulative effects can be incorporated into the existing VKM framework for environmental risk assessments by expanding the EICAT/ EICAT+ framework from a single-species to a multi-species perspective. EICAT provides 12 mechanisms spanning both direct and indirect effects, and we propose explicitly mapping how multiple non-native species may be combined via the same mechanisms and pathways, including direct ecological effects and indirect effects mediated through environmental change or interaction networks. We identified a range of case studies worldwide and in Norway that demonstrate that a multi-species perspective is relevant to all of the 12 EICAT mechanisms.

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EICAT does not “calculate synergy” per se, but a pragmatic way forward is to include more than one non-native species in the risk assessment to evaluate whether combined impacts are most plausibly additive, synergistic, or antagonistic, and how relevant are the mechanisms, assessment endpoints, and spatial contexts. The current EICAT criteria explicitly include the potential impacts of non-native organisms on native biodiversity. Under an expanded framing, EICAT’s 12 mechanisms covering indirect impacts through interactions with other species becomes particularly relevant, but the key improvement is to ensure that potential interactions among non-native species are also systematically considered and that the causal pathways are made explicit.

Core elements include: (1) specifying relevant EICAT mechanisms for each focal non-native species including mechanisms arising from interactions among non-native species, (2) distinguishing direct versus indirect pathways and identifying plausible pathway types including habitat or structural modification, resource or abiotic feedbacks, network alterations involving mutualists and vectors, as well as cross-ecosystem linkages, (3) mapping impact metrics such as population decline, community reassembly, or altered ecosystem function, (4) scoring magnitude on VKM’s existing severity scale, (5) scoring likelihood using literature plus expert judgement, (6) comparing scenarios for baseline conditions, species A only, species B only, or the combination of A+B, (7) assess invasion debt, and (8) documenting confidence.

To strengthen likelihood assessments and the connection to mitigation, VKM recommends using an explicit “Pathway to harm” framework based on identification of a consecutive sequence of steps that each have its own intrinsic probability starting with transport and introduction, then establishment and spread, and leading to realized and specified impacts, so that risk-reducing measures can be targeted to specific steps where harm could be prevented or reduced.

7.5 ToR 5

As a subsidiary aim, to specify which assessments should be carried out for different types of assignments, and to propose how this can be incorporated into the standardised terms of reference for single species and species complexes that are currently being developed.

VKM concludes that the scope of cumulative effect assessments should be tailored to the type of assignment, and that standardized mandate formulations should be updated to include a multi-species perspective. For the single-species risk assessments that are used for import permits and similar purposes, we recommend inclusion of a qualitative review of the species’ potential interactions with other non-native species in the relevant environment. Consideration of interactions implies that assessors can identify whether the species may affect, or be affected by, other established non-native species. If the new species may act as a pollinator, seed disperser, predator, or prey resource for another non-native species, the ecological relationships could generate cumulative impacts. For larger assignments based on assessments of multiple species, a more comprehensive cumulative assessment should be carried out. Multi-species evaluations could include scenario analyses comparing a baseline with and without specific combinations of non-native species, or modelling or experimental studies where available knowledge indicates likely ecological interactions.

Regardless of the type of assignment, environments that are likely to be invasion-prone should receive particular attention. If a non-native species is expected to establish in a habitat that already supports many non-native species, such as agricultural fields, urban areas,

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watercourses, coastal waters, or islands, the requirement for a more thorough cumulative effect assessment should be strengthened.

The panel proposes that VKM's new standardized mandates for both single and multiple species should explicitly include a point on cumulative effects. For example, a mandate for a single-species assessment could require that one "assesses the species' potential interactions with other non-native species and possible combined effects on biodiversity". Similarly, mandates for multi-species assessments could include a dedicated subpoint on analyzing interacting effects among the species. Consideration of cumulative effects would then become an integrated part of relevant risk assignments, which would capture scenarios where risks from single species of non-native species can accumulate and push an ecosystem beyond a tolerance threshold. A multi-species approach will benefit management interventions by identifying vulnerable native species and ecosystems at risk, by assessing harmful combinations of invasive species, and by guiding the implementation of preventive measures at an early stage to ensure protection of natural resources in Norway.

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