Department of Biology, Ecology and Evolution

University of Fribourg (Switzerland)

Impacts of alien species

THESIS

presented to the Faculty of Science and Medicine of the University of Fribourg (Switzerland) in consideration for the award of the academic grade of *Doctor of Philosophy in Biology*

by

Lara Volery

citizen of Switzerland

Thesis no: 5525

UNIPRINT, FRIBOURG 2022

Accepted by the Faculty of Science and Medicine of the University of Fribourg (Switzerland) upon the recommendation of

- Prof. Sven Bacher (supervisor, University of Fribourg)
- Prof. Daniel Wegmann (internal expert, University of Fribourg)
- Prof. Jonathan Jeschke (external expert, Freie Universität Berlin)
- Prof. Helen Elizabeth Roy (external expert, UK Centre for Ecology & Hydrology)
- Prof. Louis-Félix Bersier (president of the jury, University of Fribourg)

Fribourg, the 17th of September 2021

Prof. Sven Bacher	Prof. Gregor Rainer
Supervisor	Dean
....	....

Summary

Alien species are species accidentally or intentionally translocated by human activities, such as trade or tourism, to new areas where they do not occur naturally. With globalization, the number of established alien species worldwide is in constant augmentation and is expected to massively increase in the next decades, as overall biosecurity policies do not seem efficient enough to halt or slow their invasion. Alien species are widely recognized as one of the major drivers of the current biodiversity loss; their environmental impacts are diverse as they can occur through a wide range of mechanisms and affect different native taxa in all environments. Quantifying and comparing impacts across alien taxa is essential for effectively prioritizing the most harmful aliens for management, and for improving our understanding of impacts to develop models predicting their future impacts. However, expressing their diverse impacts in standardized metrics across alien taxa and environments is very challenging.

The International Union for Conservation of Nature (IUCN) Environmental Impact Classification for Alien Taxa (EICAT) framework provides a generic tool which compares the environmental impacts of alien species using five semi-quantitative scenarios, based on their impacts on native populations. Because impacts of alien species are usually measured by comparing snapshot estimates between invaded and uninvaded states, EICAT primarily relies on punctual impacts and does not discriminate between stable, increasing or decreasing impacts. This information is, however, crucial for management and for developing predictive models.

This thesis comprises four chapters. Chapter 1 presents a conceptual framework to account for temporal dynamics when quantifying impacts of alien species: it provides two impact metrics, one measuring impact magnitude and one measuring the rate of change in impacts. Our framework readily allows for comparisons of alien species' impacts across time, taxa, and regions, as well as with impacts caused by other stressors, such as climate change or pollution. Chapter 2 aims at improving our mechanistic understanding of impacts by providing a classification for impact mechanisms of alien species, which shows that many indirect mechanisms have been overlooked in existing studies. This chapter is expected to be particularly useful for management, as understanding the mechanisms of impacts can help to develop alternative measures to mitigate impacts when alien eradication is not feasible or wanted.

Chapters 3 and 4 focus on the application of EICAT. In Chapter 3, we explain the rationales behind the revisions that were brought to the initial EICAT guidelines after an IUCN-wide consultation process; this is to ensure consistency in EICAT assessments and to improve the understanding of the framework. Finally, in Chapter 4, we used the EICAT framework to classify and compare the environmental impacts caused by alien ungulates, a widely introduced group. We found that alien ungulates caused significant impacts: all species, except one, were found to cause at least one decline in a native population, and

eight species caused at least one native local extinction. We then developed a method for measuring the risk of each species to cause native population declines or extinctions, to compare alien species by accounting for context-dependency in their impacts.

Based on these findings, I propose to revise the IUCN EICAT framework to integrate temporal dynamics of impacts and to better describe their mechanisms. Such modifications will likely improve the relevance and usefulness of EICAT for conservation purposes; it would also make the framework more informative for future investigation of context-dependency in impacts and would thereby facilitate the development of predictive models for the impacts of alien species. Although mainly conceptual, this work also has practical implications regarding impact measurements, prioritization of alien species for management, and the development of new management strategies.

Résumé

On appelle ‘espèces exotiques’ les espèces qui ont été transportées accidentellement ou volontairement, par les activités humaines telles que le commerce ou le tourisme dans des régions où elles n’apparaissent pas naturellement. Avec la globalisation, le nombre d’espèces exotiques n’a cessé d’augmenter jusqu’à présent. Les politiques de biosécurité ne semblant pas assez efficaces pour freiner leur invasion, ce nombre va encore augmenter massivement dans les décennies à venir. Les espèces exotiques sont une des causes principales de la perte global de biodiversité qui est en cours : leurs impacts environnementaux sont très variés, puisqu’ils peuvent être causés par beaucoup de mécanismes différents, et affecter de nombreuses espèces indigènes dans tous types d’environnements. Afin de prioritiser efficacement les espèces exotiques les plus néfastes pour la biodiversité et de pouvoir développer des modèles pour prédire leurs futurs impacts, il est essential de quantifier et comparer leurs impacts. Cependant, trouver des mesures standardisées qui quantifient ces impacts extrêmement variés, causés par de nombreuses espèces exotiques dans de nombreux environnements, est très complexe.

La classification EICAT (*Environmental Impact Classification for Alien Taxa*) de l’Union Internationale pour la Conservation de la Nature (UICN) offre une méthode qui compare les impacts environnementaux des espèces exotiques en les classant dans cinq scénarios semi-quantitatifs, en fonction de leurs impacts sur les espèces indigènes. Puisque les impacts des espèces exotiques sont généralement quantifiés en comparant des mesures prises à un moment précis dans des sites envahis par l’espèce exotique et non-envahis, EICAT ne se base que sur des mesures ponctuelles d’impacts et ne différencie pas les impacts stables des impacts croissants ou décroissants. La variation temporelle de l’impact est pourtant une information cruciale pour la gestion des espèces exotiques et pour mieux comprendre leurs impacts.

Cette thèse comprend quatre chapitres. Le Chapitre 1 présente un cadre conceptuel pour quantifier les impacts des espèces exotiques en prenant en compte leur variation temporelle : nous y proposons deux mesures d’impacts, une pour la magnitude d’impact (à un moment précis), et une pour le taux de variation (temporelle) de l’impact. Ces mesures permettent de comparer les impacts entre espèces exotiques et entre habitats impactés, et de comparer les impacts des espèces exotiques aux impacts causés par d’autres facteurs environnementaux, tels que le changement climatique ou la pollution. Le Chapitre 2 a pour but d’améliorer la compréhension des mécanismes d’interactions entre les espèces exotiques et indigènes, en offrant une nouvelle classification de ces mécanismes et en démontrant que beaucoup de mécanismes indirects ont été ignorés jusqu’ici. Ce chapitre est destiné à être particulièrement utile à la gestion des espèces exotiques, car il devrait permettre de développer des mesures alternatives à l’éradication des espèces exotiques, dans les cas où cette dernière n’est pas faisable ou désirée par la société.

Les Chapitres 3 et 4 concernent l'application de la classification EICAT. Le Chapitre 3 décrit les raisons qui ont amené à la révision de la classification EICAT, après un processus de consultation de l'UICN. Le but de ce chapitre est d'assurer la cohérence de la classification EICAT et d'en améliorer la compréhension. Enfin, le Chapitre 4 utilise EICAT pour classer et comparer les impacts environnementaux causés par les ongulés exotiques, un groupe extensivement introduit dans le monde entier. À part une, toutes les espèces d'ongulés ont causé au moins un déclin local d'une espèce indigène dans leurs nouveaux environnements, et huit espèces ont causé au moins une extinction locale. Ces résultats nous ont permis de développer une méthode pour mesurer le risque de chaque espèce de causer un déclin ou une extinction locale d'une espèce indigène.

Finalement, sur la base de ce travail, je suggère de modifier la classification EICAT de l'UICN afin d'y intégrer la variation temporelle des impacts et de mieux décrire les différentes interactions entre espèces exotiques et indigènes. Ces modifications pourraient améliorer la pertinence et l'utilité d'EICAT pour la gestion des espèces exotiques et la préservation de la biodiversité. De plus, la classification pourrait alors contenir des informations cruciales pour mener des analyses sur comment et pourquoi les impacts des espèces exotiques varient d'un contexte à un autre, et ainsi faciliter le développement de modèles prédictifs. Bien qu'essentiellement conceptuel, ce travail a aussi des implications pratiques, car il aborde les mesures d'impacts, la priorisation des espèces exotiques pour leur gestion, et le développement de nouvelles stratégies pour leur gestion.

Contents

General introduction

Biological invasions: Past, present, and future trends

Alien species (also frequently referred to as 'exotic', 'introduced', 'non-native', or 'non-indigenous' species) are defined as species translocated by human activities beyond the biogeographical barriers delimiting their native range, to regions where they could not disperse without human assistance (Jeschke *et al.* 2014; Essl *et al.* 2018). The long history of human-mediated species introductions started many millennia ago when humans migrated from Africa to the rest of the world and transported non-domesticated species along with them, intentionally or accidentally (Crees & Turvey 2015). Examples of ancient introductions include the dingo (*Canis lupus dingo*) to Australia c. 5000 years ago and (probably) the island fox (*Urocyon littoralis*) to the California Channel Islands c. 6500 years ago (Crees & Turvey 2015).

The number of alien species has increased since the middle of the fifteenth century, after the discovery of the Americas by Europeans in the year 1492 and the subsequent European colonial extension and globalization of trade networks. Many species were intentionally introduced by European colonists, for aesthetic reasons (e.g. birds [Long 1981] and plants [Kleunen *et al.* 2018]) or as new sources of food or opportunities for recreation (e.g. game animals [Long 2003]).

During the last 200 years, the intensification of trade and transport led to a continuous increase in the rate of biological invasions; 37% of all first records (i.e. year of the first detection of an alien species which later became established in a region) were reported between 1970 and 2014, and first record rates are still increasing, without showing sign of saturation (Seebens *et al.* 2017). Along with this increase, the risks posed by biological invasions became more apparent, resulting in regulations aiming to limit species introductions (McGeoch *et al.* 2010). For instance, intentional introductions have now been mostly forbidden, leading to declining rates of invasion by mammals and fishes in the last decades, as these taxa were mainly associated with intentional introductions (Hulme *et al.* 2008; Seebens *et al.* 2017). However, new drivers or pathways of biological invasions have emerged; examples include the creation of new corridors (e.g. due to the disappearance of the ice sheet), the massive release of plastics in the oceans which facilitates the transport of species across oceans, and the constant and global increase in trade and tourism (Pyšek *et al.* 2020a). This has led to the incorporation of new source pools of potential alien species, that have kept the emergence rate of new alien species at high levels, even though the formerly important source pools have been depleted: one-quarter of first records during 2000–2005 were of species not already recorded as alien elsewhere (Seebens *et al.* 2018). These unintentional pathways of introduction are mainly associated with invertebrates, algae, fungi and micro-organisms and their prevention is challenging (Hulme *et al.* 2008; Saul *et al.* 2017). The intensification of other anthropogenic stressors such as climate change, land-use change, and the presence of other alien species, has also facilitated the establishment of alien species because degraded habitats are less resistant to invasions (Pyšek *et al.* 2020a). As a result, thousands of species have been introduced to new areas and have established viable populations, leading to important rearrangements of the local biota. North America and Europe have the highest numbers of established alien species with more than 50,000 alien species in the United States (Pimentel *et al.* 2005) and about 14,000 alien species in Europe (https://easin.jrc.ec.europa.eu/easin, accessed in May 2021).

The current regulations against biological invasions have proven not efficient enough to halt or slow the increasing numbers of alien species (Seebens *et al.* 2017). Invasion risk is being modified through the expanding transportation networks, technological advances, and the intensification of global environmental change and of human activities in the Arctic (Ricciardi *et al.* 2017). Sardain *et al.* (2019) forecasted global maritime traffic to increase by 240–1,209% by 2050 and that this increase would lead to a drastic rise (3- to 20- fold) of invasion risk in middle-income countries with growing economies, particularly in Northeast Asia. Applying a business-as-usual approach, Seebens *et al.* (2021) predicted that the number of alien species per continent will increase by 36% on average from 2005 to 2050. When considering continents and taxonomic groups, particularly strong increases are predicted for Europe, temperate Asia, North and South America and invertebrates, respectively. In Europe alone, 2,500 new alien species are predicted to arrive by 2050.

Negative impacts of alien species

Species translocations have resulted in numerous changes in the recipient environments, termed 'impacts'. Although alien species can cause positive impacts (Vimercati *et al.* 2020), many have caused severe negative impacts to the environment, human society, or both.

Alien species are widely recognized as one of the five major drivers of the ongoing global biodiversity loss, along with land- or sea-use change, overexploitation, climate change, and pollution (Sala 2000; Butchart *et al.* 2010; IPBES 2019). They rank as the second (after overexploitation) most common driver of global extinctions since the year 1500 (Bellard *et al.* 2016a), and have been the main driver of global declines in amphibians as well as an important driver of the extinction risk of birds and mammals (McGeoch *et al.* 2010). Among the ~5,000 vertebrate species threatened worldwide, 27% are threatened by alien species; one-quarter of all threatened amphibian and bird species are currently estimated to be threatened by alien species (Bellard *et al.* 2016b).

Alien species can impact biodiversity through different mechanisms. For instance, the impact of alien predatory species has been particularly devastating on islands, where the lack of eco-evolutionary processes with alien predators (or with any predators in some cases) has resulted in prey naivety of insular species (Anton *et al.* 2020). Consequently, alien predatory species have led to the decline or extinction of many endemic species on islands (Blackburn 2004; Medina *et al.* 2011). Alien mammalian predators have contributed to 58% of extinctions for birds, mammals, and reptiles and threaten another ~600 native species with extinction, mainly on islands (Doherty *et al.* 2016). Predation by the unintentionally introduced brown tree snake (*Boiga irregularis*) on Guam (Mariana Islands) led to the extirpation of 11, and the severe decline of six, resident native bird species (Wiles *et al.* 2003). Severe impacts on biodiversity have also occurred due to alien pathogens or vectors of pathogens; the alien chytrid fungus (*Batrachochytrium dendrobatidis*), which is probably vectored by alien amphibians, is the main driver of the global decline in amphibians (Bellard *et al.* 2016b). Alien species can also affect the genetic integrity of native species through hybridization. In Ireland, the extensive hybridization between the Asian sika deer (*Cervus nippon*) and the native Red deer (*Cervus elaphus*) has contributed to the decline of the pure red deer and probably even to its extinction in some places (Smith *et al.* 2014). Alien species can substantially modify ecosystem structure or functioning by altering water flow, nutrient cycling, disturbance regimes, or habitat complexity or heterogeneity (Crooks 2002; Gaertner *et al.* 2014; Emery-Butcher *et al.* 2020). Such profound ecosystem modifications usually result in a wide range of cascading effects, often impacting and modifying the entire recipient community. Finally, alien species can interact with other anthropogenic stressors such as climate change, land-use change, or pollution (Bellard *et al.* 2016b), and magnify their impacts, resulting in synergistic interactions (Ricciardi *et al.* 2020). Experts in biological invasions expect moderate (20-30%) increases in biological invasions to results in major impacts to biodiversity in most socioecological contexts, with transport, climate change, and socio-economic changes highly influencing impacts (Essl *et al.* 2020).

Alien species also cause substantial impacts on society. They affect many ecosystem services, from decreased productivity of crops, livestock, aquaculture, fishery, or forestry, to water quality, or pollination services (Vilà & Hulme 2017; Bacher *et al.* 2018). Furthermore, alien species affect public health. For instance, alien mosquitoes, crustaceans, fishes, or amphibians are vectors of human disease, alien plants and insects have allergenic properties, and alien fishes and amphibians can be poisonous or venomous to humans (Schindler *et al.* 2015; Mazza & Tricarico 2018). Well known examples of alien species affecting human health include the tiger mosquito (*Aedes albopictus*), a vector of various viruses, the poisonous lionfish (*Pterois volitans* and *P. miles*), and the allergenic ambrosia (*Ambrosia artemisiifolia*). Other examples of socio-economic impacts include those to infrastructure, ecotourism, and through decreased public well-being, for instance, by changing recreational activities or cultural and spiritual practices (Vilà & Hulme 2017; Bacher *et al.* 2018). Altogether, the total economic costs caused by alien species between 1970–2017, including damage, control and repair costs, has been estimated at US$1.288 trillion, and show a consistent threefold increase per decade, with no sign of slowing down (Diagne *et al.* 2021). For comparison, the annual global estimates of the economic costs of alien species in 2017 exceed the gross domestic product of 50 out of 54 countries on the African continent in 2017 (Diagne *et al.* 2021). However, many of these impacts on human well-being are difficult to quantify with monetary losses and other methods to quantify such impacts have been developed (Bacher *et al.* 2018).

Comparing the impacts of alien species

The Ten's rule has been proposed by Williamson & Fitter (1996) and posits that only 10% of all introduced species establish, and subsequently 10% of these cause significant impacts. Although these proportions are largely underestimated regarding many taxonomic groups and their validity has received little support (Jeschke 2008; Lapointe *et al.* 2012), they show that not all alien species cause significant impacts. Therefore, the limited resources available for alien species' management need to be effectively allocated. Identifying and prioritizing alien species based on their impacts is a focal area of much research (Roy *et al.* 2014, 2015). To do so, it is necessary to describe and express the very different mechanisms and magnitudes of impacts using comparable metrics (Parker *et al.* 1999; Nentwig *et al.* 2010a; Blackburn *et al.* 2014).

The challenges of comparing the impacts of alien species

Comparing the impacts of alien species is challenging. Firstly, this is due to the highly varied nature of impacts. As previously discussed, impacts can affect very different aspects of the invaded environments, from biodiversity to ecosystem functioning and services, human health and well-being, and the economy. These aspects can each be expressed using many different metrics; for instance, impacts on biodiversity can be described in countless ways, like impacts on the performance of native individuals, the size of native populations, the species richness or alpha/beta diversity of a community, or on the genetic integrity of native individuals (Blackburn *et al.* 2014). Consequently, invasion biologists focus on different taxa occupying different environments, at various spatial and temporal scales, and by using diverse metrics, techniques, terms and even definitions (Jeschke *et al.* 2014).

Second, impacts are context-dependent (Thomsen *et al.* 2011; Ricciardi *et al.* 2013; Kumschick *et al.* 2015b; Pyšek *et al.* 2020b; Ricciardi *et al.* 2020): the same species might cause different types and magnitudes of impacts when introduced under different contexts. The impact of a particular alien species not only depends on the traits of this species, but also on the abiotic and socio-economic characteristics of the recipient environment, and its biotic community (Thomsen *et al.* 2011; Kumschick *et al.* 2015b; Pyšek *et al.* 2020b). Thus, summarizing the overall impact of an alien species for comparison is complex.

Invasion science (i.e. the discipline studying alien species) must also deal with very different perceptions of impacts and alien species, and therefore, conflicting interests (García-Llorente *et al.* 2008; Kumschick *et al.* 2012; Leung *et al.* 2012; Shackleton *et al.* 2019; Vimercati *et al.* 2020). The different individuals or stakeholders in the society have different value systems (Shackleton *et al.* 2019). Thus, alien species are often perceived contradictorily: the same impact can be perceived as beneficial or detrimental, or the same alien species can affect two variables in opposed ways, both of importance according to different points of view.

Finally, impacts caused by alien species vary over time, for multiple reasons (Strayer *et al.* 2006; Strayer 2012). They might increase after some time if the alien adapts and becomes more efficient (Mooney & Cleland 2001) or starts interacting with another stressor (e.g. Laverty *et al.* 2017; Smith *et al.* 2017; Alexander & Levine 2019). Alternatively, alien populations may also follow 'boom-bust' dynamics, when introduced populations initially undergo a successful phase during which their abundance reaches high levels (boom-phase) and then stabilize at lower levels (bust-phase) (Simberloff & Gibbons 2004; Strayer *et al.* 2017). Because the impact magnitude of an alien species is linked to its abundance (Parker *et al.* 1999; Sofaer *et al.* 2018; Bradley *et al.* 2019; Strayer *et al.* 2019; Strayer 2020), impacts are likely to follow these boom-bust dynamics (e.g. Flory *et al.* 2017). The effect of the alien species may also decrease over time because of behavioral, phenotypic, or genotypic adaptation of the affected individuals (Carthey & Banks 2016; Leger & Goergen 2017; Anton *et al.* 2020; Langkilde *et al.* 2017 for a review). Although it is acknowledged that impacts can change over time, temporal variation is usually ignored. Impacts of alien species are most commonly quantified by comparing ecological variables between invaded and uninvaded states (Strayer *et al.* 2006; D'Antonio *et al.* 2017; Crystal-Ornelas & Lockwood 2020; Ricciardi *et al.* 2020). Consequently, comparisons of alien species' impacts are usually restricted to punctual comparisons (i.e. impact at a time) and rarely consider how impacts change over time.

The Environmental Impact Classification of Alien Taxa - EICAT

A wide range of different frameworks or schemes has been proposed for comparing the impacts of alien species (Hulme *et al.* 2013). These differ in their focus, with some concentrating only on negative impacts while others include positive impacts, some considering the different perceptions of impacts and alien species while others focus on one value system, and some only focusing on environmental impacts and others also considering socio-economic impacts (Jeschke *et al.* 2014). Generally, most of these schemes rely on expert judgments and hence lack objectivity and transparency (Essl *et al.* 2011).

Additionally, most of these frameworks have been limited in their application to only a few specific taxa (Leung *et al.* 2012; D'hondt *et al.* 2015).

To fulfill the need for a generic, evidence-based, and transparent classification system to compare the negative ecological impacts of alien species, the Environmental Impact Classification for Alien Taxa (EICAT) was developed (Blackburn *et al.* 2014; Hawkins *et al.* 2015). EICAT is based on the Generic Impact Scoring-System (GISS), a scoring system that compares the impacts of alien animal species (Nentwig *et al.* 2010a). EICAT was designed to share analogous properties with the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Mace *et al.* 2008). The framework classifies alien species' impacts in standardized terms across taxa and recipient environments, by using native species as the focal variable (Blackburn *et al.* 2014; Hawkins *et al.* 2015). Impacts are classified into one of five impact magnitudes, from 'Minimal Concern' to 'Massive', depending on the level of organization of the native species that is affected (decreased performance of individuals, population decline, or local extinction), and can occur via one of 12 impact mechanisms. For consistency, EICAT only relies on documented impacts; expert appreciations or opinions, which are prone to subjective judgment, are not considered. For each alien species, all documented negative impacts on native species are classified into one of the five impact magnitudes. Alien species are then classified and compared based on the highest impact magnitude they have ever reached ('Maximum recorded impact'), to highlight those with the potential of causing severe impacts (Hawkins *et al.* 2015). Importantly, EICAT is not predictive by itself as it cannot be used alone to predict how impacts will evolve over time or to predict the impacts of new alien species with no impact history, but it can be used to test hypotheses and look for patterns in impacts and thereby provide predictive information (Blackburn *et al.* 2014; Kumschick *et al.* 2020). EICAT is increasingly used and has already been implemented to classify impacts of alien birds (Evans *et al.* 2016), amphibians (Kumschick *et al.* 2017), marine fishes (Galanidi *et al.* 2018), bamboos (Canavan *et al.* 2019b), gastropods (Kesner & Kumschick 2018), terrestrial invertebrates (Nelufule *et al.* 2020), and feral mammals (Hagen & Kumschick 2018).

To capture the temporal variation of impacts, EICAT proposes a dual assessment for each alien species, where both the Maximum Recorded Impact (i.e. the highest level of impact documented for the taxa) and the 'Current Impact' (i.e. the current highest level of impact documented for the taxa) are assessed (Hawkins *et al.* 2015). The Current Impact aims at tracking changes in impact magnitude, either due to a real evolution in the impact (e.g. as invasion proceeds or management reduces the impact) or to new evidence of pre-existing impacts. It is not considered in the final assessment of the species, where only the Maximum Recorded Impact is reported. Because EICAT mainly relies on punctual impact reports (Crystal-Ornelas & Lockwood 2020; Ricciardi *et al.* 2020), it is not designed to record individual trends in impacts. Therefore, increasing, stable or decreasing impacts cannot be discriminated, even in the rare cases where this information would be available. Such information, however, is crucial for management.

EICAT purposely excludes societal judgment regarding the value of aliens; it aims at informing the decision-making process, which can then include such judgments. In 2020, EICAT was officially adopted by the IUCN as its formal classification system to assess the impacts of alien species. A classification aligning with—and complementary to—EICAT was recently developed for classifying impacts of alien species on the society and economy, the Socio-Economic Impact Classification for Alien Taxa (SEICAT; Bacher *et al.* 2018), which categorizes impacts on the different constituents of human well-being and highlights the potential consequences of alien species on society.

Definitions

Alien species

Because the geographic distributions of species are being extensively re-modeled by different anthropogenic drivers such as climate change, land-use change, or pollution, it is becoming increasingly difficult to evaluate whether a species is native or alien to a region (Essl *et al.* 2018). For instance, many species are now expanding their ranges to adjacent territories which became favorable as a result of global warming (Essl *et al.* 2019). Furthermore, archaeobiota (i.e. species introduced before 1492) are usually considered as native local biota and sometimes targeted by conservation interventions (Essl *et al.* 2018). Therefore, a new set of criteria have recently been proposed for discriminating between native or alien species (Essl *et al.* 2018): to qualify as an alien, a species must have crossed biogeographical barriers assisted by humans, have been introduced after the year 1492 and, if introduced due to indirect human assistance (i.e. without physical movement of propagules or individuals), it must have been through direct mediation such as the construction of corridors or the creation of artificial ecosystems. This latter criterion purposely excludes species naturally expanding their range in response to human-induced change, e.g. climate or land-use change, due to the substantial difference in the mechanism underlying the two colonization processes and to the debatable status of the naturally expanding species (i.e. should they be managed or protected?). Such species have been termed ‘neonatives’ (Essl *et al.* 2019). Finally, an alien species must be able to survive without human assistance (as opposed to captive or cultivated alien species).

A widely used term in invasion science is ‘invasive alien species’ (IAS), which can designate either alien species spreading rapidly and over long distances after introduction, or alien species which negatively impact the environment or human society (Pyšek *et al.* 2020a). All alien species are considered here, regardless of their impact or spread.

Impact

This work focuses on ecological impacts of alien species, which are characterized here by a decrease (negative impact) or increase (positive impact) of an ecological variable of interest in response to an alien species (Ricciardi *et al.* 2013). This definition ignores human value systems and includes no judgment on whether the changes (increases or decreases) should be considered beneficial or detrimental for the environment or society (Vimercati *et al.* 2020).

Thesis scope

Questions

Several questions arise from the previous sections, which will be addressed in this thesis:

- What are the consequences of the current practice for quantifying impacts (i.e. punctual comparisons) on our understanding of the impacts caused by alien species and on management?
- How can we consider temporal variation in the impacts of alien species when quantifying impacts?
- The impacts of alien species are increasingly influenced by other anthropogenic stressors: how do such interactions occur, and can we quantify them, to better predict the future impacts of alien species under global changes?
- How can we summarize the overall impact of an alien species across its invaded range?
- EICAT compares individual impacts of alien species and is used to flag alien species which have caused, at least once, severe impact magnitudes; but is this the most relevant way of summarizing the alien species' overall impact or should the context-dependency of impacts be considered?
- Has the application of EICAT to varied taxonomic groups proven its pertinence and suitability across impact mechanisms, alien taxa, and environments?
- Is the current way proposed by EICAT to capture temporal variation of impact ('Current Impact') adequate?

Layout

This thesis is structured as four standalone chapters, either already published or intended for publication. The first two chapters discuss conceptual aspects around alien species' impacts: the temporal dynamic and indirect mechanisms of impacts. The following two chapters focus on the EICAT framework and its application.

Chapter 1 proposes a conceptual framework to account for temporal dynamics when quantifying alien species' impacts. Currently, impacts are mainly measured by comparing snapshot estimates between invaded and uninvaded states. Ignoring temporal dynamics of the system does not only overlook temporal variation in impacts but may also bias their quantification, thereby hampering our understanding and future prediction of impacts. To address this, we propose a framework to quantify impacts by contrasting the trajectory of an ecological variable in the presence of an alien with the forecasted trajectory in the absence of the alien. The focal ecological variable can, for instance, be the abundance of a native population; our framework can thus be seen as an extension of EICAT. The proposed metrics readily allow for comparisons of alien species' impacts across taxa and regions, as well as with impacts caused by other stressors. Accurately quantifying impacts and capturing their temporal variation is crucial for management.

Chapter 2 proposes a classification for indirect mechanisms of impacts caused by alien species. Understanding the mechanisms underlying impacts is not required in impact quantification (Chapter 1); it is in contrast crucial to adequately mitigate impacts. To mitigate impacts, efforts have so far mainly been invested in the eradication of alien populations. However, the eradication or control of alien populations is often not feasible or desired by all members of a local community, some of whom may profit from the alien's presence. Finding alternative mitigation measures, which focus on managing the impact rather than the alien itself, is therefore becoming a necessity for slowing biodiversity loss caused by alien species. This cannot be achieved without a mechanistic understanding of how impacts occur. Indirect impact mechanisms (as opposed to direct impact mechanisms, e.g. predation, herbivory, or hybridization) are chains of events in which the alien species does not directly interact with the impacted native species but affects the native species by modifying another factor of the environment (e.g. another alien population, or water composition). In EICAT, indirect mechanisms include 'transmission of disease', 'chemical, physical, or structural impact on ecosystem', 'competition' and 'interaction with another alien species'. However, other indirect mechanisms exist and have been overlooked; this follows a general tendency regarding indirect mechanisms of alien species, which are generally less well understood and studied. Therefore, we provide a straightforward and interpretable classification of indirect mechanisms, which captures their complexity. This classification will be useful in efforts to mitigate the negative impacts of alien species because it can be used to identify alternative management strategies to alien eradication or control.

Chapter 3 (published in *NeoBiota*, 2020) explains revisions to the EICAT framework and guidelines, based on an IUCN-wide consultation process. Since EICAT was adopted by the IUCN, new standard (Appendix 1) and guideline documents (Appendix 2) have been developed, which profited from the experience gained during the application of the framework to several taxa and which were refined where needed. Our aim in explaining the revision process was to ensure consistency of EICAT assessments and to improve the understanding of the framework.

Chapter 4 (published in *Global Change Biology*, 2021) analyzes the risks of alien ungulates to cause environmental impacts. Currently, EICAT only compares alien species based on their highest impact, thereby ignoring variation in impact magnitudes across invaded environments. This means an alien species that consistently causes high impacts to native species across environmental contexts is classified the same as another alien species that only occasionally causes high impacts. In this chapter, we used information on the variation in impact magnitudes of assessed alien species to estimate their risks to cause high impacts if introduced to a novel environment. We demonstrate the usefulness of this approach by classifying the global impacts of alien ungulates. Ungulates have been widely introduced around the world for farming and hunting purposes making them an ideal study group for investigating variation in impacts.

Published chapters were slightly modified for avoiding repetition where possible, or for consistency in terminology between chapters.

I also contributed, as co-author, to other scientific publications which are not part of this thesis but still included (as Appendixes), as they contribute to addressing the general questions of this thesis. These are:

- The IUCN EICAT Standards (IUCN 2020a; Appendix 1) and Guidelines (IUCN 2020b; Appendix 2), which are the official IUCN documents for the EICAT framework, adapted from the work by Hawkins *et al.* (2015);
- Probert *et al.* (NeoBiota, 2020; Appendix 3), which identify the main sources of uncertainty and biases in EICAT assessments, to increase consistency in the way uncertainty is evaluated in EICAT;
- Vimercati *et al.* (NeoBiota, 2020; Appendix 4), which discusses the importance of studying, evaluating, and considering the positive impacts of alien species to provide more complete information for management;

- Probert *et al*. (submitted; Appendix 5), which identifies the sources and extent of uncertainty in citizen science projects addressing different research questions on alien species, and discusses how to reduce uncertainty through appropriate study designs, depending on the question.

Chapter 1 — Temporal Dynamics of Alien Species' Impacts

Lara Volery[1], Daniel Wegmann[1,2*], Sven Bacher[1*]

[1]Department of Biology, University of Fribourg, Chemin du Musée 10, CH-1700 Fribourg, Switzerland. [2]Swiss Institute of Bioinformatics, Chemin du Musée 10, CH-1700 Fribourg, Switzerland.

[*]These authors contributed equally to this work

Abstract

Alien populations keep establishing at alarming rates and often have highly detrimental impacts on recipient environments. Quantifying the magnitude of their impact is essential for prioritization and management and is commonly done by comparing ecological variables between invaded and uninvaded states. Such estimates are highly uncertain and often biased because they ignore the temporal dynamics of the system. This has hampered the understanding and prediction of impacts, and hence management. To address this, we propose a conceptual framework that quantifies alien species' impacts through their effect on the trajectory of an impacted variable, for instance the abundance of a native population. This framework can be readily applied in practice and provides critical information to prioritize alien species.

1.1 Impact quantification in ecology

The number of established alien species has been increasing for the last centuries (Seebens *et al.* 2017) and is predicted to increase in the next decades (Seebens *et al.* 2021). Alien species cause varied environmental and societal changes in invaded environments (MEA 2005; Bellard *et al.* 2016a; Nentwig *et al.* 2018; Shackleton *et al.* 2018; IPBES 2019; Pyšek *et al.* 2020a; Diagne *et al.* 2021), which are referred to as **impacts** (see Glossary). To understand and predict these changes and to optimize the management of alien species, it is crucial to accurately quantify their impacts.

Evidence is accumulating that the current practice of punctual impact quantification is error-prone and that the temporal dynamics of the studied systems (e.g. natural variability, long-term temporal trajectories) must be accounted for (e.g. Wolkovich *et al.* 2014; McCain *et al.* 2016; Christie *et al.* 2019; Ryo *et al.* 2019; Büntgen *et al.* 2020; Jackson *et al.* 2021; Wauchope *et al.* 2021). Considering temporal dynamics when quantifying impacts, for instance, revealed that driver-response relationships are not necessarily constant but may vary over time (Ryo *et al.* 2019). In invasion science, however, alien species' impacts are still mainly measured by comparing **snapshots** of the situation with ('invaded state') and without the alien ('uninvaded state'; e.g. before introduction, (Simberloff *et al.* 2013; Kumschick *et al.* 2015b; Gallardo *et al.* 2016; Crystal-Ornelas & Lockwood 2020; Ricciardi *et al.* 2020). Such comparisons implicitly assume that the **impacted variable** (e.g. a native population) follow **stationary** trajectories and show little variability, both in the uninvaded and invaded states. When these assumptions are not met, impacts can be misinterpreted (Christie *et al.* 2019; Wauchope *et al.* 2021). In addition, such comparisons do not capture temporal variation in alien species' impacts themselves, which provide crucial information for management. Temporal variation is also not considered in popular impact frameworks (e.g. Baker *et al.* 2008; Brunel *et al.* 2010; Essl *et al.* 2011; Dick *et al.* 2014; D'hondt *et al.* 2015; Bacher *et al.* 2018; Roy *et al.* 2018, 2019), including the Environmental Impact Classification for Alien Taxa (EICAT; Blackburn *et al.* 2014; Appendix 1), which has recently been adopted by the IUCN as its official classification system for alien species. As these issues may have led to a distorted understanding of alien species' impacts, we here propose a conceptual framework to accurately quantify the impacts of alien species under dynamic conditions and discuss how this can be done in practice.

Glossary

Abundance: By abundance we refer to the number of individuals of a particular species at a particular site or in a particular region. Because of large age-dependent mortality and large numbers of offspring in many species (e.g. seedlings in plants; larvae in fish), usually the number of reproducing individuals is counted (Appendix 1).

Impact: An impact is characterized here by a decrease (negative) or increase (positive) of a variable of interest caused by a driver such as an alien species. This definition ignores human value systems and includes no judgement on whether this decrease should be considered beneficial or detrimental.

Impacted variable: A dynamic and measurable characteristic of the environment (e.g. native species abundances [Blackburn *et al.* 2014; Appendix 1], biodiversity indicators, water quality) or human society (e.g. human well-being [Bacher *et al.* 2018], economy [Diagne *et al.* 2021a]) used as an indicator of their state.

Snapshots: Measurements taken at single time points as opposed to repeatedly taken over long-term periods (time-series).

Stationary: The trajectory of a variable (e.g. abundance) that shows no temporal variation.

1.2 Why should we stop quantifying alien species' impacts by comparing snapshots?

1.2.1 Impact mis-quantification

Ignoring temporal dynamics in impact assessments can lead to mis-quantification. Consider an alien population affecting the temporal trajectory of a native population (Fig. 1). A classic measure of impact is obtained by comparing snapshots of the **abundance** of the native population before and after the alien introduction. While this measure may be meaningful if the native population was stationary (Fig. 1A), it is problematic if the native population followed a temporal trend independently of the presence of the alien species (Fig. 1B-F). This is likely a common situation as alien species frequently co-occur and interact with other anthropogenic stressors like climate change, harvesting, habitat loss or pollution (Bellard *et al.* 2016b; Russell *et al.* 2017; Geary *et al.* 2019; Pyšek *et al.* 2020a). In such cases, simply comparing snapshots of abundances before and after an alien introduction may lead to biased impact estimates in terms of their magnitude and potentially even in their sign. In case the native population was already decreasing in absence of the alien, for instance, the impact would be overestimated (Fig. 1B). In case it was increasing, the impact might even be wrongly inferred as positive (Fig. 1C,D). Similarly, a positive impact could be wrongly inferred as negative if the native was heading towards extinction (Fig. 1E). In addition, stochastic (natural variability) and deterministic processes (biotic interactions) can lead to fluctuating abundances; ignoring this variability by measuring snapshots can result in inaccurate assumptions about the native population's baseline state and on the effect of the alien (Fig. 1F), as was argued for other stressors (McCain *et al.* 2016; White 2019; Büntgen *et al.* 2020; Didham *et al.* 2020).

1.2.2 Lack of understanding of impacts' temporal variation

Some of the above issues can be mitigated by comparing snapshots from invaded to snapshots from uninvaded control sites (Christie *et al.* 2019). But such comparisons would still not shed light on the temporal dynamics of impacts themselves (Wauchope *et al.* 2021), which is indispensable to understand how and why impacts evolve over time and across taxa and contexts, for which data is currently scarce.

The few studies that investigated temporal variation in impacts of alien species have identified three distinct patterns of trends in negative impacts (Strayer 2012): The first pattern shows monotonously increasing impact magnitudes until they either reach the maximally possible impact (e.g. by leading to a local extinction, Fig. 1A,B), or level off at a lower value (e.g. Fig. 1C). The second pattern shows boom-bust dynamics, in which impacts decrease after an initial, acute phase. This pattern can occur because of accumulation of alien's enemies (Simberloff & Gibbons 2004; Strayer *et al.* 2017), or behavioral, phenotypic or genotypic adaptation of the native (Carthey & Banks 2016; Langkilde *et al.* 2017; Leger & Goergen 2017; Anton *et al.* 2020). The third pattern shows abrupt instead of continuous changes (Strayer 2012), e.g. when alien populations interact with rare events such as wildfires and suddenly become dominant (e.g. D'Antonio *et al.* 2017; Klinger & Brooks 2017), or experience mass mortality (e.g. Leuven *et al.* 2014). The relative frequency of these patterns is not known, however, and neither are the timescales at which these dynamics are at play, despite their relevance for predictions (Strayer 2012). While adaptation of native species to the alien can sometimes be rapid due to phenotypic plasticity, other evolutionary processes can last over many generations (Saul & Jeschke 2015).

Discriminating between stable, increasing, or decreasing temporal trends in impacts would also inform decisions on if and when management interventions are relevant, and how to avoid unnecessary costs and efforts. Impacts that decrease over time, for example, may not require urgent management, even if they are currently at a high level. By contrast, impacts that are currently at a low level, but increasing, may call for management to prevent high impacts in the future.

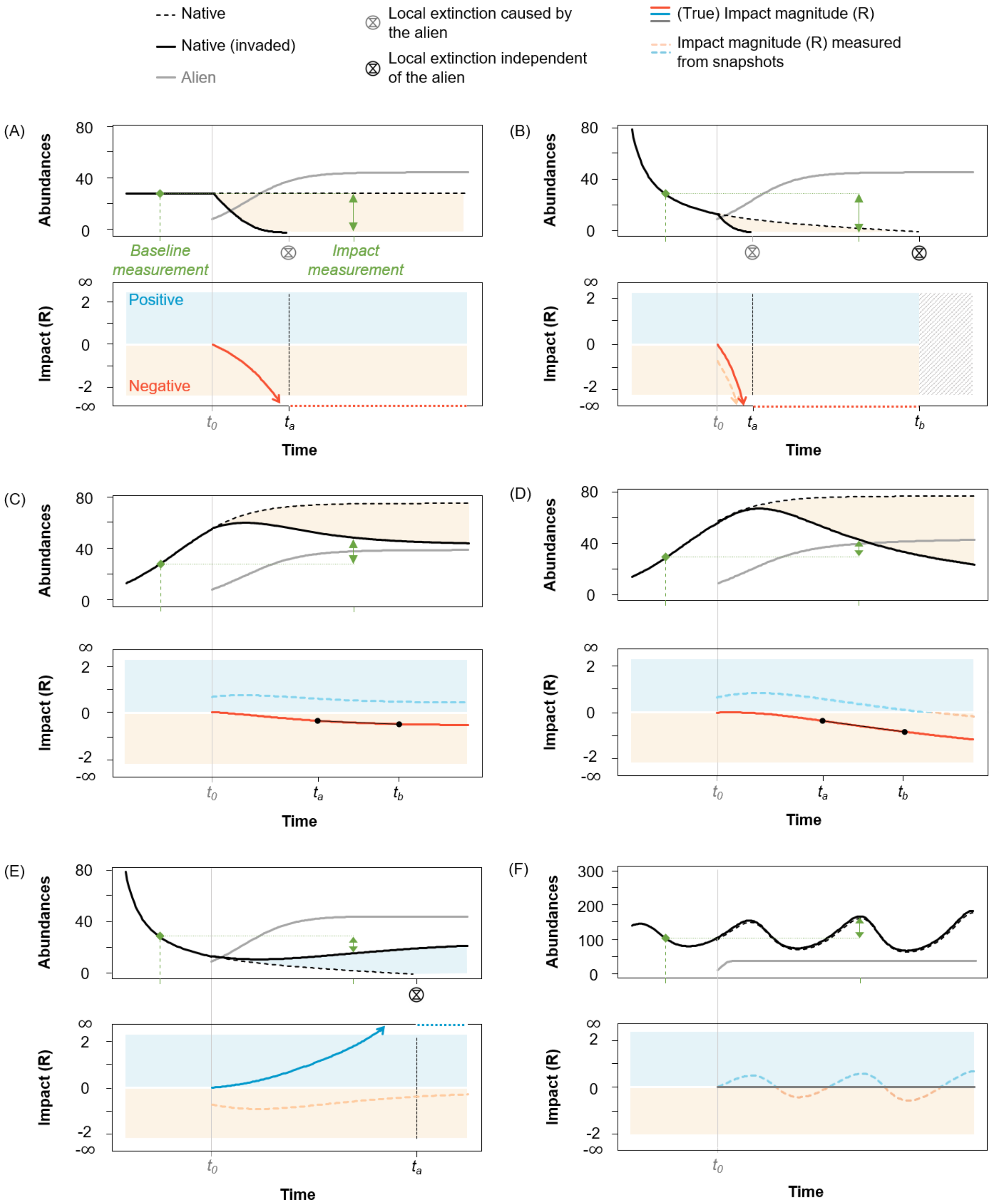


Figure 1. Impacts of alien populations on native populations. Top panels show trajectories of the abundance of native and alien species (introduced at t_0) with shades representing the absolute loss (orange; A,B,C,D) or gain (blue; E) of the native due to the alien. Bottom panels show alien's temporal impacts *vs* those calculated from snapshots. From snapshots, impact is only correctly quantified when the native's trajectory is stationary (A); however, impacts are overestimated when the native was decreasing independently of the alien (B); a positive impact is wrongly inferred when the native was increasing independently of the alien (C & D) and a negative impact is wrongly inferred when the alien prevents the extinction of the native (E). When the native's trajectory is cyclical (e.g. prey-predator oscillations) but the alien has no impact (F), a positive or negative impact may be wrongly inferred, depending on when the snapshots were taken. In (A) and (B), the alien causes a local extinction of the native at time t_a: the aliens' impact magnitude reaches -∞. At time t_a in (E), the alien prevents the local extinction of the native: its impact magnitude reaches +∞. At time t_b in (B), the native would have gone extinct independently of the alien: quantifying the alien's impact is not meaningful afterwards (shaded grey area). In (C) and (D), the alien causes the same impact at time t_a, but the rate of change between t_b and t_a, $\rho(t_a, t_b)$, is larger in (D)

1.3 Quantifying alien species' impacts and their temporal variation

1.3.1 Quantifying impacts

Alien impacts are often quantified through caused changes in the abundance of a native population, a strategy recommended by the IUCN (see Appendix I) and a case we adopt here for illustration. To quantify such an impact properly, the trajectory of the native population in the invaded state must be compared with its trajectory in the uninvaded state. For the impact $R(t)$ at time t, we propose the relative measure

$$R(t) = \log \frac{N^*(t)}{N(t)},$$

of the abundance of the native population in the absence ($N(t)$) and presence ($N^*(t)$) of the alien introduced at t_0 (Fig. 1). Before the introduction of the alien ($t \leq t_0$), we define $N^*(t) = N(t)$, in which case there is no impact ($R(t) = 0$).

A negative impact ($R(t) < 0$) denotes a decrease of the native population due to the alien (Fig. 1A-C), and reaches $R(t) = -\infty$ if the alien causes the extinction of the native population (Fig. 1A,B). Similarly, a positive impact ($R(t) > 0$) denotes an increase of the native population due to the alien, and reaches $R(t) = +\infty$ if the alien prevents the extinction of the native population (Fig. 1D). Note that the alien continues to cause an impact even after it led to a local extinction (Fig. 1A,B), but that the impact is not defined once the native species would have gone extinct in the absence of the alien, i.e. for reasons unrelated to the alien (Fig. 1B).

Importantly, the measure $R(t)$ can be calculated regardless of the mechanism of interaction between alien and native (e.g. predation, hybridization, etc.; Blackburn *et al.* 2014; Appendix 1). Further, the measure, while presented in terms of population abundances, is readily applied to other impacted variables such as biodiversity indicators (e.g. local species richness, evenness, diversity, Red List Index) or impacts on abiotic characteristics of the environment (e.g. nitrogen content, frequency of fire events, nutrient availability, water quality), human well-being (Bacher *et al.* 2018) or the economy (Diagne *et al.* 2021). However, depending on the variable or indicator of interest, one would need to carefully reflect on the interpretation of the sign of the impact (e.g. is a positive impact on soil nitrogen beneficial or detrimental to e.g. local biodiversity? [Vimercati *et al.* 2020]).

1.3.2 Quantifying impact dynamics

To quantify the temporal dynamics of impacts, we propose a second metric, $\rho(t_1, t_2)$, which quantifies the average rate of change in $R(t)$ between two time points t_1 and t_2 and is given by

$$\rho(t_1, t_2) = \frac{1}{t_2 - t_1} \log \frac{N^*(t_2)N(t_1)}{N^*(t_1)N(t_2)}.$$

Here, $\rho(t_1, t_2) = 0$ indicates a constant (negative or positive) impact over time, while $\rho(t_1, t_2) < 0$ indicates either that the magnitude of a negative impact is increasing, or that a positive impact is decreasing, and vice-versa for $\rho(t_1, t_2) > 0$. This metric is particularly useful for the prioritization of management actions: two alien populations causing impacts of the same magnitude ($R_1(t) = R_2(t)$) may warrant different management actions if their impacts differ in their dynamics ($\rho_1(t_1, t_2) \neq \rho_2(t_1, t_2)$, e.g. Fig. 1C,D). Rapidly increasing impacts (e.g. Fig. 1D), for instance, may be prioritized over stable impacts (e.g. Fig. 1C).

1.3.3 Interactions among multiple stressors

The $R(t)$ and $\rho(t_1, t_2)$ measures can also be used to compare impact magnitudes and dynamics caused by different stressors. Under our definition, two alien populations leading to the same relative reduction of a native population, for instance, cause impacts of the same magnitude ($R_1(t) = R_2(t)$), regardless of the initial native abundances. If multiple stressors act simultaneously, the measures allow to quantify their joint impact by comparing the abundance in the presence of all stressors with that in their absence. To quantify the individual impact of one out of several stressors, two strategies can be used (Box 1): To compare the relative importance of stressors, the abundance of the native in the presence of a single stressor should be compared against the abundance in the absence of all stressors. To prioritize stressors for management, however, the abundance of the native in the presence of all stressors should be compared against that in the presence of all but the stressor in question. These two measures are identical if the interaction between multiple stressors is additive, in which case the total impact equates the sum of individual impacts (Fig. 2A), but differs if the interaction is synergistic or antagonistic, in which case the total impact is larger or smaller than the sum of individual impacts, respectively (Fig. 2B,C) (Piggott *et al.* 2015; Côté *et al.* 2016; Birk *et al.* 2020; Braga *et al.* 2020; Jackson *et al.* 2021).

Importantly, interactions may also be subject to temporal dynamics and change in both strength (e.g. increasing synergistic effect in Fig. 2B, or decreasing antagonistic effect in Fig. 2C) and type (e.g. antagonistic becomes synergistic; Fig. 2D) (Garnier *et al.* 2017; Romero *et al.* 2019). This can happen because the dynamics of multiple stressors are rarely synchronized (Ryo *et al.* 2019; Jackson *et al.* 2021), or because populations adapt to the co-occurrence of stressors, which decreased their combined effect and leads to antagonistic interactions over time (e.g. Romero *et al.* 2019). However, studies rarely capture this variation, and thus overlook important features of interactions between multiple stressors that can shed light on their evolution (Garnier *et al.* 2017; Jackson *et al.* 2021). Understanding the mechanisms of interactions is also informative for management actions (Didham *et al.* 2007; Geary *et al.* 2019): If a synergistic interaction evolves towards an additive rather than an antagonistic one, for instance, suggests that the interaction should be targeted directly by management actions (e.g. Fig. 2B).

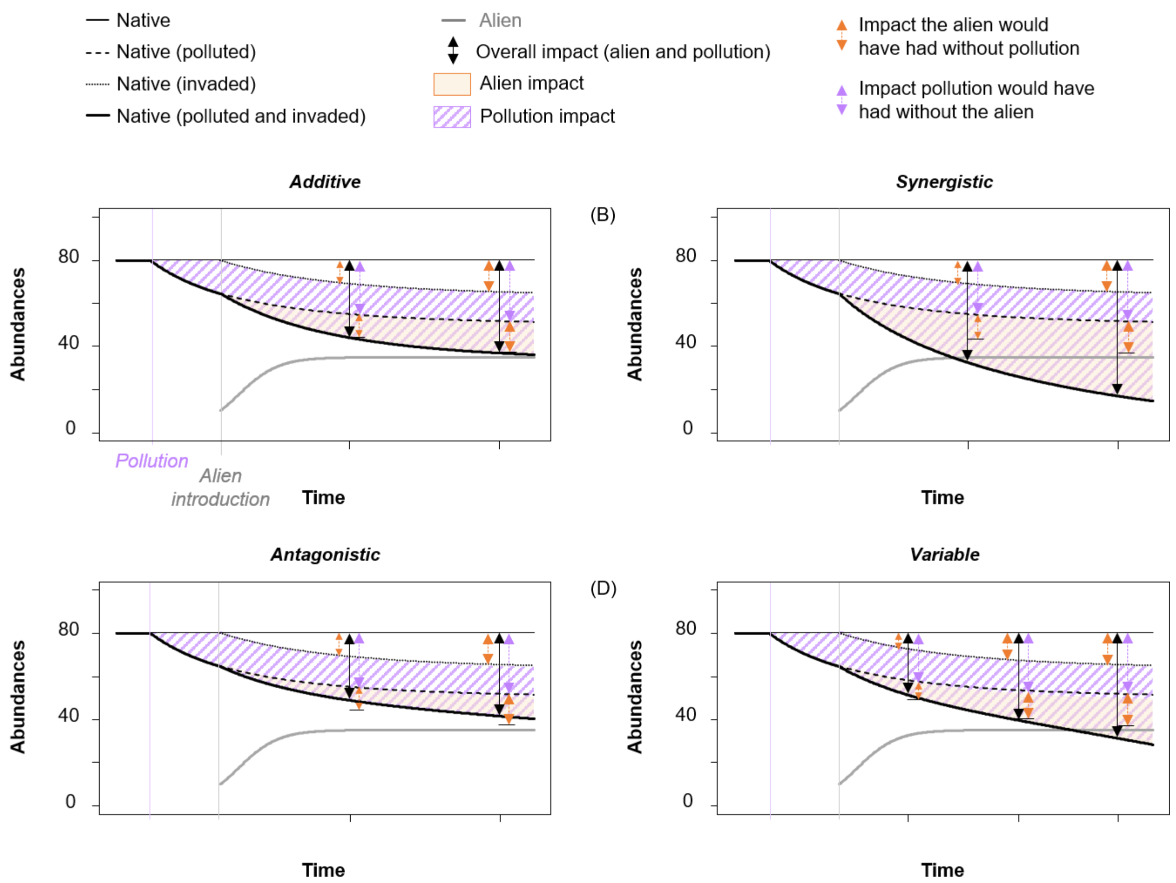


Figure 2. Types of interactions between multiple stressors (e.g. an alien species and pollution). When the joint pressure of the alien and pollution (black arrow) equates the sum of their individual pressures in absence of the other stressor (orange and violet arrows), the interaction is additive (A); when it is larger, the interaction is synergistic (B); and when it is smaller, the interaction is antagonistic (C). The strength of the interaction can change over time: for instance, the synergistic and antagonistic effect between the two stressors increases over time in (B) and decreases in (C). Interaction type can also change over time: e.g. in (D), the interaction is first antagonistic, then additive, and finally synergistic. For simplicity, we assumed that the impact dynamics of both stressors are similar: however, disturbances can have different shapes (e.g. continuous *vs* discrete events), evolve over very different time scales, occur at different frequencies, etc. (Ryo *et al.* 2019; Jackson *et al.* 2021).

Box 1: ***Case study - Zebra mussels' impact in North American lakes***

The role of the introduced Zebra mussel (*Dreissena polymorpha*) in native freshwater mussel extinctions in North America is debated (Gurevitch & Padilla 2004a, b; Ricciardi 2004). Ricciardi (Ricciardi 2004) argues that Zebra mussel introductions should be considered as major driver of native mussel extinctions in lakes, as they greatly accelerated these extinctions. Gurevitch & Padilla (2004b) oppose this view and argue that Zebra mussels are not a major driver of extinctions, as these would have happened anyway in a near future (because of pollution, habitat destruction, harvesting, etc.) and could not have been avoided by managing the alien alone.

This well-known controversy illustrates well how accounting for temporal trends in the impacted variable can aid in interpreting the roles of multiple, interacting stressors, which is critical for the management of such scenarios (Ricciardi *et al.* 2020), and brings quantitative terminology to the debate. To rank stressors by their importance, their individual impacts can be compared, e.g. based on their respective impact in the absence of the other stressor(s), or on whether or not each stressor would have caused a local extinction on their own and on the time needed to cause an extinction (Fig. I). To identify the most effective management strategy, however, what matters is how much the overall impact can be reduced by removing one of multiple stressors. Consider the hypothetical scenarios represented in Fig. I: while native mussels can be more effectively preserved in Scenario (A) by reducing the impact of pollution rather than of the Zebra mussel, this is not the case under Scenario (B), in which the impacts of both stressors would need to be reduced.

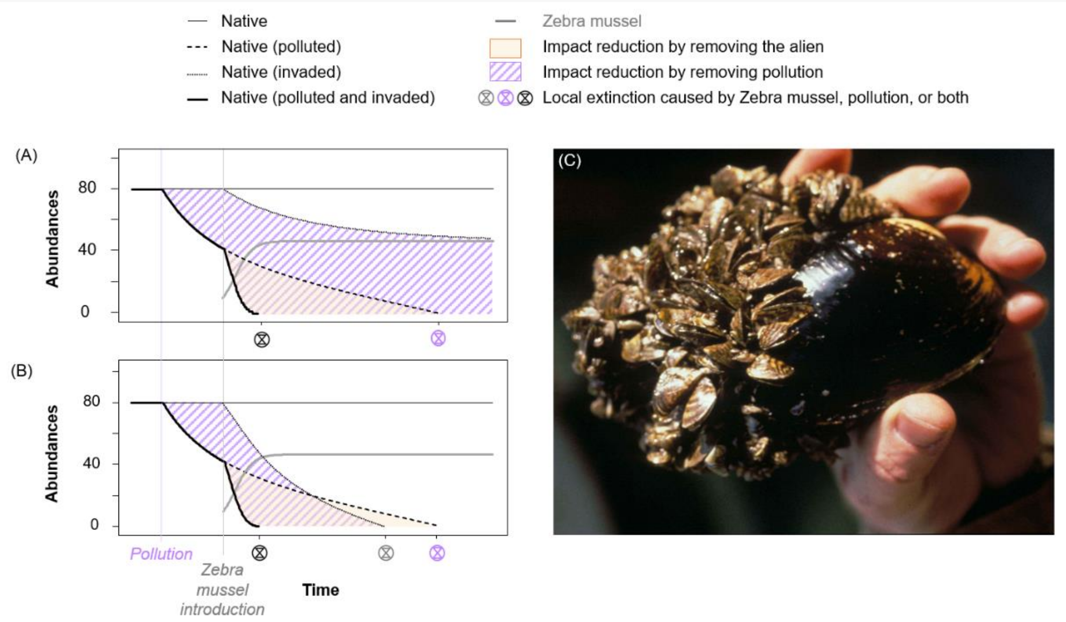


Figure I. Hypothetical scenarios of interaction between the alien Zebra mussel and pollution. While both scenarios show the same total impact of both stressors, they differ in the relative impacts of the two stressors. In (A), pollution plays a dominant role leading to a local extinction because, contrary to the Zebra mussel, it would also have led to an extinction alone (in absence of the Zebra mussel). In (B), both stressors play dominant roles: Zebra mussel and pollution would both have caused an extinction alone, but it would have taken less time to the Zebra mussel to cause it than to pollution. (C) Zebra mussels biofouling on a native mussel (http://www.public-domain-image.com).

1.4 How to estimate alien species' impacts and their evolution over time in practice?

To estimate impacts under the framework proposed above, the trajectory of the variable of interest (e.g. the abundance of a native species) must be compared in the presence and absence of the alien. While the former can be directly measured, the latter must be estimated, either by extrapolating from measurements prior to the introduction of the alien, from populations in a similar context but at uninvaded sites, or from a combination of both. These setups are similar to the designs classically used to quantify the impact of alien species (Kumschick *et al.* 2015b; Crystal-Ornelas & Lockwood 2020), namely the Before-After (BA), Control-Impact (CI) or combined Before-After-Control-Impact (BACI) designs (Christie *et al.* 2019; Wauchope *et al.* 2021), but used here to model the temporal trajectory of the native species in the absence of the alien. Such forecasted trajectories are likely associated with uncertainties from multiple sources: First, any forecast requires a statistical model and hence relies on specific assumptions (e.g. exponential change). Second, once the alien was introduced, there exist no measurements of the native in absence of the alien, which results in increased uncertainty through time (Fig. 3A; Oliver & Roy, 2015). And third, trajectories often exhibit substantial, inherent stochasticity not well characterized by covariates (Fig. 3B; Connors *et al.* 2014; d'Eon-Eggertson *et al.* 2015; McCain *et al.* 2016; Fox *et al.* 2019; White 2019; Didham *et al.* 2020).

Uncertainty stemming from the former two sources may be reduced, either by increasing survey efforts such that more realistic models can be learned (Oliver & Roy 2015; Fox *et al.* 2019; White 2019), or through BACI designs in which regional effects such as specific weather conditions affecting all populations can be captured (Christie *et al.* 2019; Wauchope *et al.* 2021). However, substantial uncertainty will likely remain, particularly in cases with high natural variability in abundances.

To deal with this uncertainty, we recommend three steps in impact quantification: First, the uncertainty associated with the forecasted trajectories should be accounted for when quantifying impacts and be reflected in the uncertainty associated with impacts (e.g. Fig. 3). This applies equally to any additional uncertainty that stems from measuring the impact variable in the presence of the alien (e.g. measurement error, e.g. Didham *et al.* 2020). Second, we recommend quantifying impacts jointly from multiple sites or populations, if the research question permits, and thus to spread the survey effort across multiple sites. By aggregating information across sites, shared impacts can be quantified at much higher accuracy than for any site individually, particularly in case of high variability in the native abundance (Christie *et al.* 2019). This equally applies when investigating context-dependency of impacts: although between-sites differences are important for such research questions, replicating measures for each context variable of interest improves the quality and relevance of the findings. Third, we recommend focusing on probabilistic statements rather than impact estimates themselves whenever possible (see also Appendix 5). Even if impact estimates are associated with high uncertainty, it may for instance still be possible to confidently conclude that there is a negative impact ($R(t) < 0$), in many cases already shortly after the alien introduction (Fig. 3). Similarly, two species may be ranked based on the probability that $R_1(t) < R_2(t)$ rather than their impact point estimates.

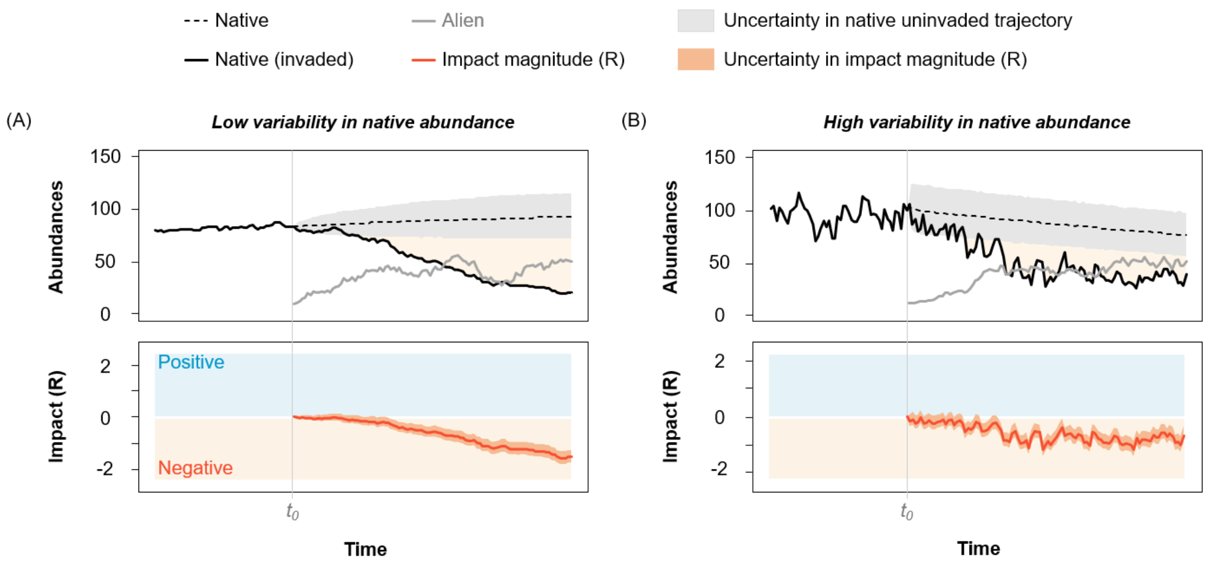


Figure 3. Uncertainty in estimations of alien species' impacts. This figure illustrates two of the main sources of uncertainty in impact estimations: that the native trajectory in the uninvaded state cannot be measured after the alien introduction at t_0, and that substantial variability renders trajectory forecasts difficult (here done solely from data prior to t_0). When variability in native abundance is low (A), uncertainty in the native trajectory in the uninvaded state is small just after t_0, but increases over time. When variability in native abundance is high (B), uncertainty is already large just after t_0, but does not increase much. In real impact studies, the statistical model chosen to forecast the native trajectory in the uninvaded state might not be suitable, which would result in increased uncertainty. Furthermore, uncertainty would likely also exist in the native trajectory in the invaded state, for instance because of measurement error.

1.5 Concluding remarks

The necessity to account for temporal dynamics when quantifying impacts has been recognized in other areas of ecology (De Palma *et al.* 2018; Chevalier *et al.* 2019; Christie *et al.* 2019; Ryo *et al.* 2019; Büntgen *et al.* 2020; Jackson *et al.* 2021; Wauchope *et al.* 2021), and the impacts of alien species are no exception. The quantification of impacts of alien species therefore needs to shift from simple before-after or other two-point comparisons to the comparison of long-term temporal trends and modelling studies, for which we introduce a coherent conceptual framework that can also be generally applied to compare ecological impacts. Most of our current knowledge about alien species' impacts relies on comparisons of point estimates, but such estimates contain unknown biases that may distort our understanding of impacts. It is critical to address the challenges of accurately measuring impacts (see **Outstanding Questions**) to improve our understanding and to better predict future impacts of invasions and other drivers of global change.

Outstanding Questions

- What are the most efficient strategies to quantify impacts under temporally dynamic conditions, i.e. which survey strategies and models should be used under which conditions?
- How are modelling uncertainties best incorporated into and reflected in impact estimates?
- What are the most relevant indicators to quantify the full impact of alien species on the environment and the human well-being, and can these indicators be generalized across taxa and geographic scales?
- How can the rapidly growing large-scale biodiversity data sets assembled by citizen science projects and remote sensing be used to quantify alien species' impacts?
- How can temporal impact measures be incorporated in existing impact frameworks such as EICAT?

Author contributions

All authors designed the study, Lara Volery performed modelling work with help of Daniel Wegmann, Lara Volery prepared the first draft, all authors contributed substantially to revisions.

Chapter 2 — A Classification of Indirect Mechanisms of Impacts of Alien Species

Lara Volery[1], Sabrina Kumschick[2,3], Anna Frances Probert[1], Giovanni Vimercati[1], Sven Bacher[1]

[1]Department of Biology, University of Fribourg, Chemin du Musée 10, CH-1700 Fribourg, Switzerland. [2]Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa. [3]South African National Biodiversity Institute, Kirstenbosch National Botanical Gardens, Claremont 7735, South Africa.

Abstract

Alien species often cause ecological impacts in their recipient environments, which need to be mitigated in order to halt the resulting biodiversity loss. For efficient management of these impacts, it is necessary to gain a mechanistic understanding of how they occur. Compared to direct impact mechanisms, indirect impact mechanisms are less well studied and understood, owing to their complexity and variety. We provide a comprehensive tool for classifying the direct and indirect mechanisms through which alien species negatively and positively impact native species, across alien taxa and types of impacts, and which can also be used when alien species synergistically or antagonistically interact with other stressors. This work aims to assist the planning of conservation strategies: by classifying their positive indirect impacts, it informs on the risks of alien eradication on non-target species, by classifying their negative indirect impacts, it informs on options for alternatives to alien eradication, and, by classifying their interactions with other stressors, it informs on the most efficient way to mitigate impacts of alien species in a context of global change.

2.1 Introduction

Human-mediated translocations of species to new regions has led, together with other anthropogenic changes, to a global redistribution of fauna and flora (Seebens *et al.* 2017; Essl *et al.* 2019; Pyšek *et al.* 2020a). About 4% of the world's flora has established alien populations in at least one region (Pyšek *et al.* 2020a), and present policies against biological invasions have been ineffective to halt or slow the increasing number of alien species (Seebens *et al.* 2017). Once introduced, alien species can cause all sorts of **impacts** (see Glossary) on the environment, from structural changes to local communities and modification of ecosystem functioning, to the local extinctions of native populations or the loss of their genetic integrity (Blackburn *et al.* 2014; Pyšek *et al.* 2020a). Alien species also cause **positive** impacts like provision of surrogate food, refugia, or habitat resources, prevention of erosion, or improvement of water quality (Ewel & Putz 2004; Rodriguez 2006; Chiba 2010), although such impacts have received less attention compared to their **negative** environmental impacts (Vimercati *et al.* 2020).

To mitigate the negative effects of alien species, efforts are invested in the eradication of populations, or, when eradication is not feasible, their long-term management (i.e. containment, suppression, or complete reproductive removal) (Robertson *et al.* 2020; García-Díaz *et al.* 2021). However, the eradication or control of alien species is often not feasible for various reasons, although usually due to logistical constraints or ethical concerns arising from opposing values (Cowan & Warburton 2011; Keitt *et al.* 2011; Rytwinski *et al.* 2019; Hulme 2020). In addition, alien eradication or control might not help to reduce the impact (Courchamp *et al.* 2003). Finding alternative mitigation measures, which focus on managing the impact rather than the alien itself, is therefore becoming a necessity for slowing biodiversity loss caused by alien species (Dunham *et al.* 2020; García-Díaz *et al.* 2021). Possible alternative mitigation measures are numerous and varied (García-Díaz *et al.* 2021). For instance, manipulating habitats to provide refugia or safe breeding sites against alien predators is an approach that has been adopted for protecting native amphibians and small mammals (Stokes *et al.* 2004; Falaschi *et al.* 2020). In other examples, artificial nesting sites have been used to decrease competition with alien species (Tomasevic & Marzluff 2017; Hernández-Brito *et al.* 2018) or barriers have been displayed in streams to prevent the upstream dispersal of freshwater aliens (Manfrin *et al.* 2019). However, to identify appropriate alternative management options, which would target the impact instead of the alien, it is essential to understand how negative impacts occur, i.e., what are the underlying mechanisms. On the other hand, when eradication is necessary and judged feasible, understanding the mechanisms through which alien species positively interact with native populations may prevent undesirable consequences of their eradication (Zavaleta *et al.* 2001; Courchamp *et al.* 2003; Bergstrom *et al.* 2009; Caut *et al.* 2009). A common example of such undesirable consequences is the meso-predator release, where the eradication of an alien top predator leads to a burst in a meso-predator, causing important declines or extinction in native prey species (Crooks & Soulé 1999; Rayner *et al.* 2007; Ballari *et al.* 2016).

Mechanisms of impacts are broadly classified as either direct or indirect. While **direct mechanisms** occur between two *actors* (i.e. the alien population and a native population) and do not require the presence of a third actor—or **mediator**—for happening (such as another native or alien population, or an abiotic characteristic of the recipient environment), **indirect mechanisms** only occur in the presence of a mediator. Indirect mechanisms are characterized by a modification, caused by an alien population, of an interaction between a mediator and the native population of interest. Examples include exploitative competition, transmission of disease, **hyperpredation**, or change in disturbance regimes. As with direct mechanisms, indirect mechanisms can result in major impacts on invaded ecosystems (Vilà *et al.* 2011; Gaertner *et al.* 2014). When the alien indirectly causes negative impacts and its eradication or control is impractical or impossible, developing management strategies which target the mediator, its effect, or the effect of the alien on the mediator, could also result in impact mitigation. For instance, in a scenario of hyperpredation, controlling the alien prey population (i.e. the mediator), or providing refugia to the native prey against the predator, are alternatives to alien eradication.

Alien species might also interact with other co-occurring anthropogenic stressors, for instance if the mediator of an **indirect impact** caused by an alien species is another stressor (e.g. climate change, pollution, land-use change, etc.). Similarly, the alien species can itself be the mediator in an indirect impact caused by another stressor. For instance, climate warming (e.g. Smith *et al.* 2017; Hulme 2020) and other anthropogenic disturbances (e.g. Crooks *et al.* 2011; Early *et al.* 2016) often favor alien populations and thus increase their impacts, thereby indirectly impacting native biodiversity (through the alien mediator). Identifying and understanding the underlying mechanisms of stressor interactions also provides critical information to management. For instance, it can help to highlight cases where mitigating only one of the interacting stressors would not be sufficient (Didham *et al.* 2007; Foster *et al.* 2016), or in contrary, cases where impact mitigation can be achieved by targeting only one of the stressors, or its effect, and can hence avoid redundancies in management strategies and offer a broader range of possible management strategies (Chadés *et al.* 2015; Geary *et al.* 2019). Finally, improving our understanding of how interactions between stressors occur will help improve predictions as to how climate change will modify existing interactions in the future (Ricciardi *et al.* 2020).

While direct mechanisms can usually be observed in nature, indirect mechanisms are more subtle and difficult to demonstrate and identify; they are hence often overlooked or ignored in impact studies (Levine *et al.* 2003). In addition, as indirect mechanisms are highly varied and complex, reviews and classifications have focused only on specific categories of mechanisms (e.g. Crooks 2002; Rodriguez 2006; White *et al.* 2006; Gaertner *et al.* 2014) or specific alien taxa (e.g. Levine *et al.* 2003; Stout &

Morales 2009; McGeoch *et al.* 2015). Consequently, indirect mechanisms are less well understood compared to direct mechanisms. This is supported by the fact that they are poorly captured or classified by existing frameworks (McGeoch *et al.* 2015; Chapter 3).

We propose a comprehensive, systematic, and straightforward classification of direct and indirect mechanisms through which alien species cause ecological impacts, which breaks down the chain of events through which indirect impacts occur and identifies and categorizes the different actors at play. This classification also aims to capture the complexity and variety of indirect impact mechanisms, across different categories. By offering a mechanistic understanding of indirect impacts, this work can help to identify alternative management strategies to alien eradication or help identify the potential undesirable side-effects of their eradication. We thus expect this classification to be useful to mitigate negative impacts of alien species or, when necessary, to efficiently plan eradication strategies to prevent their undesirable consequences.

Glossary

Abiotic indirect impact: Category of *indirect impacts* in which the *mediator* is an *abiotic condition or resource*, or a disturbance.

Abiotic resource: Substance or element in the environment necessary for population survival or reproduction (e.g. mineral nutrients, nesting sites, refuges, radiation) which can be consumed or used by a population and whose availability to other populations can thereby be reduced.

Abiotic condition: Chemical, physical, or structural characteristic of the environment (e.g. temperature, pH, salinity, soil structure) which cannot be consumed or used by living organisms.

Abundance: The number of reproducing individuals of a species at a site or in a region.

Biotic indirect impact: Category of *indirect impacts* in which the *mediator* is biotic, i.e. another (alien or native) population.

Cascading effects: A succession of events or interactions in which the effect of the alien on a *mediator* has follow-up effects: here, we define cascading effects as *indirect impacts* involving at least two intermediate steps, or *mediators*.

Direct impact: *Impacts* caused through *direct mechanisms*.

Direct (impact) mechanisms: Mechanisms of *impacts* involving only two actors (e.g. the alien and the impacted native population).

Dynamic (of a population): The change in the intrinsic growth rate of a population per unit of time (for simplicity, immigration to- and emigration from- other populations are not considered).

Dynamic (of an abiotic factor): The cycle of abiotic factors per unit of time, such as the duration, frequency, or extent of a disturbance, the regime of an *abiotic condition* (e.g. water current, pH or temperature regimes), and the cycling (e.g. Nitrogen cycling) or amount of an *abiotic resource*.

Facilitation: An increase—caused by a driver of interest (e.g. an alien species)—in the (*negative* or *positive*) *impact* of a *mediator* on a variable of interest (e.g. a native population); this increase can be caused either by an increase in the *dynamic* or in the *per capita effect* of the *mediator*.

Hyperpredation: Scenario in which an alien prey leads to an increase in a top predator population and thus to an increased predation by the top predator on native prey species (e.g. Roemer *et al.* 2001; Caudera *et al.* 2021).

Impact: Changes (increase or decrease) in a response variable of interest (e.g. the *dynamic* of a native population) caused by a driver of interest (e.g. an alien species).

Indirect impact: *Impacts* caused through *indirect mechanisms.*

Indirect (impact) mechanisms: Mechanisms of *impacts* involving more than two actors: the presence of a *mediator* is required for the *impact* to happen.

Mediator: Intermediate actor in an *indirect impact*, which can be either biotic (i.e. an alien or native population) or abiotic (e.g. *abiotic resource*, *abiotic condition*, disturbance) and whose presence is necessary for the *indirect impact* to occur.

Negative impact: A decrease in the variable of interest. This definition excludes judgment on whether or not this decrease should be considered beneficial or detrimental (Vimercati *et al.* 2020).

Per capita effect: The effect of one 'unit' of a driver on the impacted variable of interest per unit of time (e.g. change caused by one alien individual in the number of reproducing native individuals per unit of time).

Positive impact: An increase in the variable of interest. This definition excludes judgment on whether or not this increase should be considered beneficial or detrimental (Vimercati *et al.* 2020).

Suppression: A decrease—caused by a driver of interest (e.g. an alien species)—in the (*negative* or *positive*) *impact* of a *mediator* on a variable of interest (e.g. a native population); this decrease can be caused either by a decrease in the *dynamic* or in the *per capita effect* of the *mediator*.

2.2 A classification for direct and indirect mechanisms of impacts

For the purpose of this classification, we focus on the impacts caused by alien species to native species (Blackburn *et al.* 2014; Appendix 1). Although alien species can also cause other types of environmental impacts, for instance, to community composition, ecosystem functioning, disturbance regimes or abiotic characteristics (e.g. Crooks 2002; Linders *et al.* 2019), such impacts are likely to either lead to changes in native biodiversity or result from changes in native biodiversity. Therefore, focusing on native biodiversity captures a variety of environmental impacts (Blackburn *et al.* 2014).

Because indirect impact mechanisms are a combination of direct mechanisms, we first discuss direct mechanisms.

2.2.1 Direct mechanisms of impacts

Impacts (*I*) of alien species depend on the alien range (*R*), **abundance** (*A*), and **per capita effect** (*E*; also called 'interaction strength') (*I* = *R* x *A* x *E*; Parker *et al.* 1999). For simplicity, we focus here on local impacts (i.e. at a specific location) on native populations: an impact is defined by a change, due to an alien population, in the **dynamic of a native population**, and therefore depends on the alien's per capita effect and abundance (Fig. 1).

Impacts between an alien and a native population are direct when no mediator is needed for the interaction to happen (Fig. 1; (Wootton 2002).

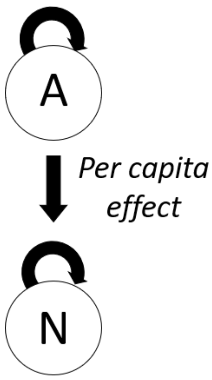


Figure 1. Direct interaction between an alien population (A) and a native population (N), at a point in time. The circular arrows indicate the dynamics of the alien and native populations, while the straight arrow indicate the per capita effect.

Based on an existing classification of the negative impacts of alien species and their mechanisms of impacts (Blackburn *et al.* 2014; Hawkins *et al.* 2015; Appendix 1), we identified the negative and positive mechanisms through which an alien population causes **direct impacts** on the dynamic of a native population (i.e. native individuals' survival and/or reproduction):

Negative direct mechanisms:

- Trophic consumption (e.g. predation, herbivory, parasitism);
- Hybridization;
- Toxicity;
- Direct physical disturbance (e.g. bio-fouling, trampling, rooting, fighting/aggression, etc.);
- Physiological stress induced by (visual, chemical, acoustic) cues of alien predators or by previous experience (memory). Exposure to predators can induce a sustained and long-lasting physiological stress (involving predator avoidance behavior, which is comparable to chronic stress in humans) in individuals of the species that is preyed upon, which can affect birth and long-term survival ('ecology of fear'; Clinchy *et al.* 2013). It should be noted that food shortage, for instance, also induces physiological stress; however, food shortage is an indirect mechanism (decrease in resource quantity or access; see *Indirect mechanisms of impacts*) and is therefore not captured by the direct mechanism described here.

Positive direct mechanisms:

- Provision of resources necessary to survive, grow and reproduce:
    - Trophic resources (e.g. alien prey or plants, alien producing fecal material which is used as food source)
    - Non-trophic resources:
        - Nesting or reproduction sites (e.g. alien tree)
        - Substrate for growing (e.g. alien coral)
        - Vector of propagules (e.g. alien pollinator);
- Herbivory: Herbivory might lead to vegetative (growth is stimulated) or reproductive (reproduction or flowering is stimulated) overcompensation in the attacked plant individuals (Garcia & Eubanks 2019);
- Physiological stress induced by the presence of alien predators leading to overcompensation (for instance, the presence of parasitoid wasps can accelerate mating in *Drosophila* [Ebrahim *et al.* 2021]; note that this example concerns two native species).

Importantly, such interactions occur at the individual level before they affect the dynamic of the native population. An alien population can hence interact with a native population through different mechanisms. For instance, an alien predatory population can negatively impact a native prey population through predation (i.e. the consumption of prey), the physiological stress induced by the predator presence, and/or chronic physical challenges due to foraging impairment (Clinchy *et al.* 2013). On the contrary, an alien herbivore can negatively impact native plant individuals through browsing and grazing, but this can have a positive impact on their native plant conspecifics, e.g. if they are released from intra-specific competition (density-dependent population growth). This could potentially result in overcompensation at the plant population level and to an overall positive impact on the population. Because management usually targets impacts occurring at the level of native populations (and not individuals), we focus here only on the mechanism(s) affecting the dynamic of the native population.

2.2.2 Indirect mechanisms of impacts

Indirect mechanisms are characterized by a modification, caused by an alien population, of an interaction between a mediator and the native population of interest (Strauss 1991; Crooks 2002; Wootton 2002; White *et al.* 2006; Fig. 2). They can occur through many different ways, which we summarize as follows:

2.2.2.1 Facilitation vs suppression

Alien species can generally either:

- *i)* **facilitate** a negative impact of a mediator on a native population's dynamic (Fig. 2A and 2B);
- *ii)* **suppress** a positive impact (Fig. 2C and 2D);
- *iii)* facilitate a positive impact (Fig. 2E and 2F); or
- *iv)* suppress a negative impact (Fig. 2G and 2H).

Scenarios *i)* and *ii)* result in (indirect) negative impacts of the alien population on the native population of interest (+/- or -/+), whereas scenarios *iii)* and *iv)* result in (indirect) positive impacts of the alien population on the native population of interest (+/+ or -/-) (Fig. 2).

2.2.2.2 Interaction chain vs interaction modification impacts

The four scenarios can each result from a change in the mediator dynamic ('interaction chain effect'; Fig. 2A, C, E, and G) or per capita effect ('interaction modification effect'; Fig. 2B, D, F, and H) (Wootton 1993, 2002; Didham *et al.* 2007; Geary *et al.* 2019). For instance, changes in the per capita effect of the mediator—i.e. its efficiency to cause the impact—can result from changes in its mode of action, functional response, or visibility, or in the resistance, behavior, or visibility of the native population, or, if the mediator acts as a resource, in its quality (Wootton 2002). Nelson *et al.* (2010) found that the alien toxic cane toad (*Bufo marinus*) in Australia has induced toad-aversion in native predators, which have shifted their feeding behavior to feed less on native frogs and more on other taxa, such as insects. Thus, the cane toad has a positive indirect impact on the native frogs and a negative indirect impact on other native taxa through interaction modification effects. In some cases, the alien species might cause indirect impacts through both interaction chain and modification effects (Wootton 2002).

2.2.2.3 Biotic vs Abiotic indirect impacts

The indirect impacts represented in Fig. 2 can be further divided into **biotic or abiotic indirect impacts**, depending on whether the mediator of the interaction is another population or an abiotic factor, respectively.

Biotic indirect impact

Biotic indirect impacts involve at least three species and describe how a third species modifies an interaction between two species (Strauss 1991). Here, the alien is the third species modifying an interaction between two species (a mediator [M] and the impacted native species [N]; Fig. 2). Because the previously listed direct mechanisms through which alien species can impact native populations are not alien-native specific but also describe native-native interactions, the modified interaction (i.e. between M and N) could occur between two native species (M and N= natives), or between another alien species and a native species (M= alien, N= native; White *et al.* 2006).

White *et al.* (2006) wrote a comprehensive review of biotic indirect impacts and provided many real-life examples of such impacts. The authors highlighted the most documented types of biotic indirect impacts, which include: apparent competition, indirect mutualism/commensalism, exploitative competition (when resources are biotic), and trophic cascades. These different indirect impacts can be classified into the different scenarios of Fig. 2:

> *Apparent competition:* A (native/alien) consumer (the mediator: a predator, herbivore, or parasite/pathogen) becomes more abundant (Fig. 2A), or more efficient (Fig. 2B) at consuming a native species in the presence of the alien species. Examples of apparent competition include the vectoring of parasite/pathogen by the alien (which results in an increased abundance in the parasite/pathogen; Fig. 2A) and hyper-predation (i.e. the increase in the abundance of a predator caused by the presence of an alien prey, which leads to an increased predation by the predator on native prey; Fig. 2A).

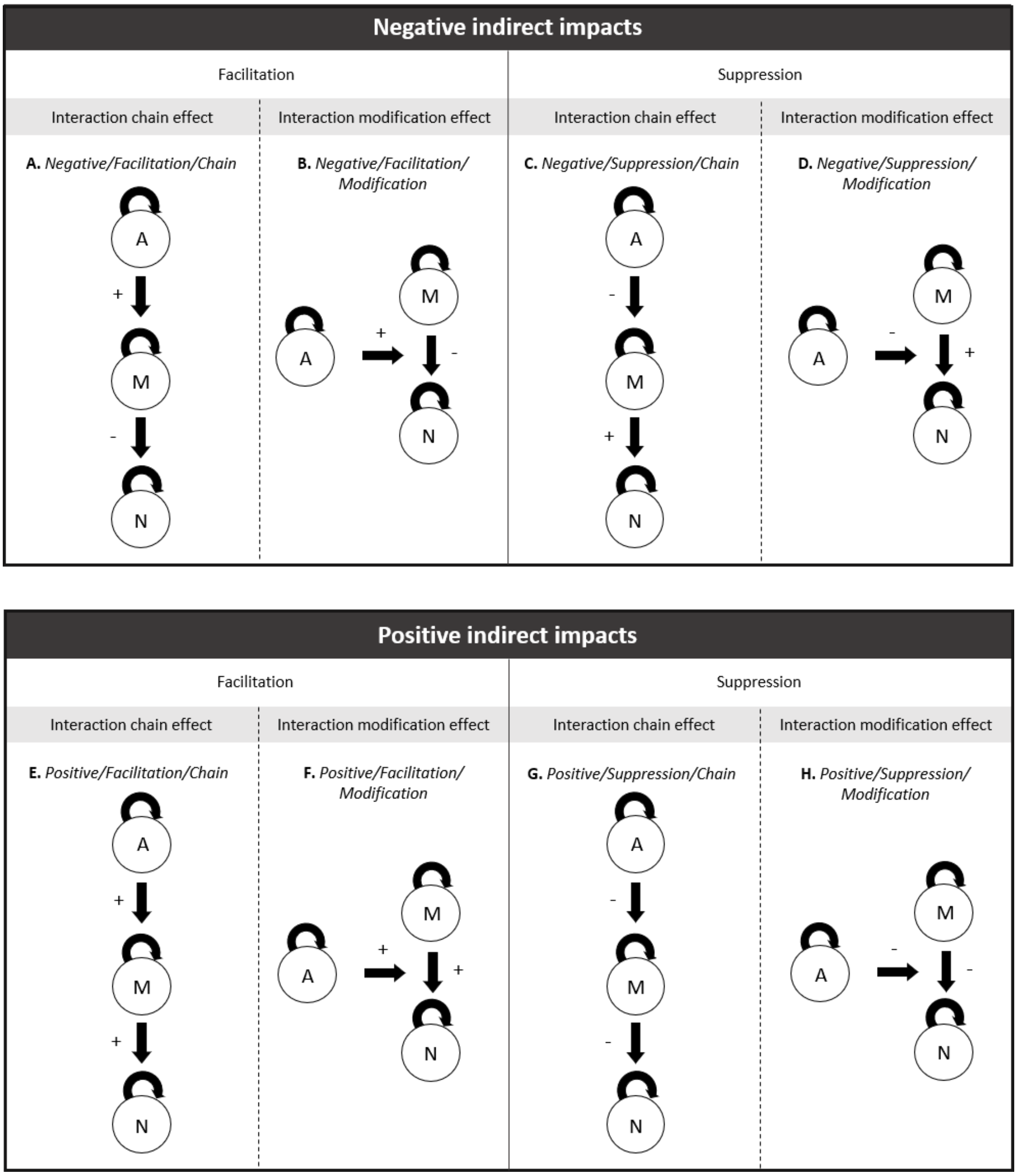


Figure 2. Possible ways in which indirect impacts can occur. In A) and B), the alien (A) facilitates (plus sign) the negative impact (minus sign) caused by the mediator (M) on the dynamic (circular arrow) of the native population (N), resulting in an indirect negative impact on the native population (+/-). The alien facilitates the negative impact either by A) increasing the dynamic (circular arrow) of the alien ('interaction chain effect') or B) increasing the per capita effect (straight arrow) of the alien ('interaction modification effect'). In C) and D), the alien suppresses the positive impact caused by the mediator on the dynamic of the native population (through chain or modification effect, respectively), resulting in an indirect positive impact on the native population (-/+). In D) and E), the alien facilitates the positive impact caused by the mediator on the dynamic of the native population (through chain or modification effect, respectively), resulting in an indirect positive impact on the native population (+/+). Finally, in F) and G), the alien suppresses the negative impact caused by the mediator on the dynamic of the native population (through chain or modification effect, respectively), resulting in an indirect positive impact on the native population (-/-). In each graph, the mediator can either be biotic (another alien or native population) or abiotic (e.g. an abiotic condition of the environment, abiotic resource, or a natural disturbance).

Exploitative competition (biotic resource): The alien and native species compete for a limited resource: the alien leads to a decrease in the resource (Fig. 2C).

Interference competition (biotic resource): The alien and native species compete for a limited resource: the alien aggressively or physically defends its access to the resource, at the expense of its native competitor (Fig. 2D).

Indirect mutualism/commensalism: The alien decreases or suppresses a consumer (predator, herbivore or parasite) (Fig. 2G), or decreases or suppresses its per capita effect, for instance through prey switching/consumer satiation mechanisms (Fig. 2H) or the provision of refugia to native populations (Fig. 2H). The alien can also benefit native populations by increasing the abundance (Fig. 2E) or per capita effect (Fig. 2F) of a mediator positively impacting the native population; Ewel & Putz (2004) and Rodriguez (2006) reviewed several real-life examples of indirect (biotic) positive impacts caused by alien species.

Trophic cascade: An alien consumer is introduced and feeds on an intermediate consumer, thereby benefiting the native populations at lower trophic levels that were consumed by the intermediate consumer (Fig. 2G). Similarly, an alien resource could increase the abundance of a (native/alien) intermediate consumer by providing a new food source, which could in turn benefit a native top consumer feeding on the intermediate consumer (Fig. 2E).

These examples of indirect mechanisms mainly describe scenarios in which the mediator provides resources to, or consumes, the native species; other types of indirect mechanisms have been overlooked by existing reviews or frameworks. For instance, an alien may increase the abundance or spread of a (native or alien) population, which negatively impacts native populations through hybridization, toxicity, or direct physical disturbance (Fig. 2A).

Abiotic indirect impacts

Here, we define 'abiotic indirect impacts' as impacts in which the alien modifies an interaction between an abiotic mediator and the native species of interest (Fig. 2). While predation, herbivory, parasitism, and hybridization can only occur between two populations, the other identified direct mechanisms can also occur between abiotic mediators and native populations. For instance, **abiotic resources**, such as water, light, or oxygen directly benefit native populations, whereas natural disturbances, like fire events or extreme temperatures directly negatively affect them (through direct physical disturbance, or physiological stress respectively). Vitousek (1990) and later Crooks (2002) identified the main mechanisms of abiotic indirect impacts and reviewed many real-life examples (see also Levine *et al.* (2003) and Gaertner *et al.* (2014) for more real-life examples of abiotic indirect impacts of alien plants;

Emery-Butcher *et al.* (2020) for a review of impacts of invasive ecosystem engineers in freshwaters; Ewel & Putz (2004) and Rodriguez (2006), for examples of positive impacts of alien species through habitat modification).

Exploitative competition (abiotic resource): The alien and native species use the same limited abiotic resource (e.g. Nitrogen, minerals, water, radiation, O_2, CO_2, nesting or reproduction sites (physical structures), living space/territory, etc.) and the alien reduces its amount or quantity for the native (Fig. 2C).

Change in nutrient resources: The alien changes the amount, quantity, or cycling (**'dynamic'**) of an abiotic resource (Nitrogen, minerals, water, radiation, O_2, CO_2) (Figs. 2E and 2C) or its quality/access (Figs. 2F and 2D). As opposed to exploitative competition, the alien does not cause these changes by consuming the resource.

Change in physical resources: The alien increases or reduces the amount or quantity of an abiotic resource (nesting or reproduction sites, living space/territory, etc.) (Figs. 2E and 2C) or its quality/access (Figs. 2F and 2D). As opposed to exploitative competition, the alien does not cause these changes by consuming the resource.

Change in disturbance regimes: The alien increases or decreases the duration, frequency or extent of disturbances affecting the native species, such as fire and wind events, droughts, or floods (Figs. 2A or 2G). The alien might also increase or decrease the effect of the natural disturbances on the native species (Figs. 2B and 2H). For instance, the alien can push native individuals closer to their tolerance limit (e.g. by grazing on a native plant or by parasitizing a native host), thereby rendering them more vulnerable to natural disturbances.

Changes in abiotic condition of the habitat: The alien modifies an **abiotic condition** of the habitat, such as pH, current velocity, sediment deposition, humidity, soil structure, salinity, or temperature. Each abiotic characteristic of the habitat presents an optimum value for the native species, and a suitable range around this value. In natural conditions, the abiotic conditions of the environment fall within this suitable range (otherwise, the resident native species would not be present at the location). The addition of the alien population to the system can cause a deviation to less or more suitable conditions for the native populations, either by increasing or decreasing the values. The deviation from suitable to less suitable abiotic conditions causes a negative indirect impact on the native populations, and the deviation from less to more suitable conditions causes a positive indirect impact (Figs. 2A, C, D, G). Although it is likely that many changes in abiotic conditions cannot be described by simple increases or decreases (e.g. changes in the temperature regime are usually more complex to describe), the direction (negative or positive) of the overall indirect impact, and its mediator, can still be identified.

Change in habitat type: The alien might also change the type of habitat as a whole, and by doing so, modify a combination of different resources and/or abiotic conditions necessary for the native to occupy a location, including, for example, living space, biotic resources, reproduction sites, nutrients, etc. (which can be, for simplicity, combined into the resource '(suitable) habitat'; Figs. 2C or 2E). Example of changes in habitat type include the appearance of a forest where there was none initially or the disappearance of a pond. These indirect impacts can hence be a combination of biotic and abiotic indirect impacts.

Species creating, destroying or modifying the physical state of habitats and thereby modulating the availability of biotic or abiotic resources to other species are often called ecosystem engineers (Jones *et al.* 1994; Crooks 2002; Emery-Butcher *et al.* 2020). Several of the above indirect (biotic and abiotic) mechanisms can be considered as ecosystem engineering (Figs. 2A, C, E, G), when they occur through a modification of a physical characteristic of the habitat (e.g. a change in the structure of a forest or the construction of a dam in a river).

2.2.3 Cascading effects: the different levels of complexity of indirect impacts

Our classification can be repeated multiple times to also capture the full chain of events of **cascading effects** (e.g. Fig. 3A). Let us take the example of an alien increasing the population size of a species competing with the native population of interest. This can be represented in many ways, either with the complete chain of events (Fig. 3A: M_1= the resource both N and its competitor are competing for, M_2= the competitor), or with simplified chains of events (Fig. 3B: M= the competitor of N; or Fig. 3C: M= the resource both N and its competitor are competing for).

These classifications are all correct; however, depending on the purpose, we suggest classifying cascading effects as in Figs. 3B (simplified classification) or 3C (complete classification), in which the last interaction (between $M_{(1)}$ and N) is always direct. This first ensures that the same mechanism cannot be classified differently (e.g. Fig. 3B *vs* 3C). Second, we argue that identifying the 'primary' mediator and its direct mechanism of impact is most relevant for management purposes, as it highlights the critical step (which is facilitated or suppressed) for the native species of interest.

Cascading effects can involve many mediators; each of them can either be biotic or abiotic and can interact through interaction chain or modification effects. Therefore, even if the simplified classification is either biotic or abiotic or through interaction chain or modification effect, the full cascading effect might be a combination of the two.

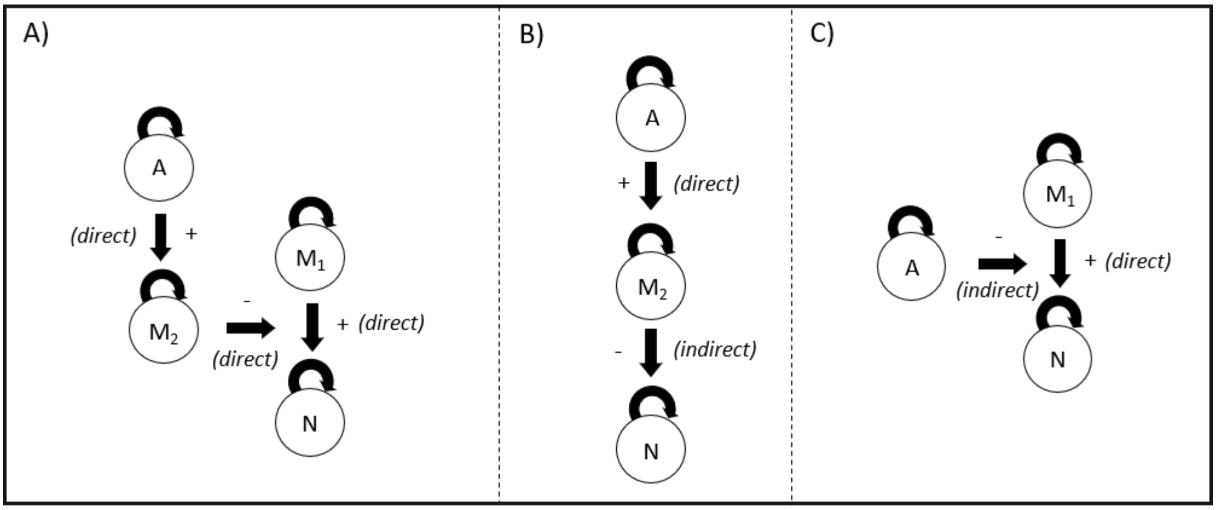


Figure 3. Possible classifications of a cascading effect. In A), the complete cascading effect is represented: the alien (A) has a direct impact on a mediator (M_2), which itself modifies the direct impact of another mediator (M_1) on the native population of interest (N). The same cascading effect is simplified in B) and C). In B) the interaction between the alien and the mediator (M_2) is direct, while the interaction between the mediator (M_2) and the native population is indirect (M_1 is not represented); the contrary is true in C).

2.2.4 Indirect impacts and stressors interaction

Alien species often co-occur and interact with other drivers of anthropogenic environmental change, like climate change, pollution, over-exploitation, or land-use change, leading to additive, antagonistic, or synergistic effects on the variable of interest (Didham *et al.* 2007; Côté *et al.* 2016; Geary *et al.* 2019; Burgess *et al.* 2021; Chapter 1). The mechanisms underlying these interactions can also be captured with our classification.

Let us take the example of an alien population interacting with climate change to impact a native population. In an additive interaction, the alien population and climate change do not interfere with each other, meaning that none of them influences the interaction of the other stressor with the native population (Chapter 1). Concretely, this means that neither the alien population nor climate change has—in addition to its individual impact—an indirect impact through the other stressor (Didham *et al.* 2007; Geary *et al.* 2019). In contrary, synergistic or antagonistic interactions occur when at least one stressor interferes with the other one to increase or respectively decrease its impact on the native population, resulting in the magnification of their respective impacts compared to what they would cause in absence of the other stressor (Chapter 1). Under a mechanistic perspective, this means that at least one stressor has an indirect impact on the native population through the other stressor (i.e. which plays the role of the mediator of the indirect impact), in addition to its individual impact (Didham *et al.* 2007;

Geary *et al.* 2019). The alien can thus either cause an indirect impact through the other stressor (Fig. 2) or be the mediator of an indirect impact caused by another stressor.

Although it is unrealistic for alien species to modify the 'dynamic' (extent) of anthropogenic stressors like climate change, or land-use change, some alien plants have been used to restore soils and waters because they can accumulate and sequester pollution (Ewel & Putz 2004). Examples where alien species influence the per capita effect of such stressors (Fig. 2B, D, F, H) are also difficult to find, but would for instance include alien plants decreasing the negative impact of climate change by providing alternative food sources, when native plants are slower to adapt.

On the other hand, stressors like climate change, pollution, or land-use change often facilitate alien species establishment and increase (Crooks *et al.* 2011; Vilà & Ibáñez 2011; Diez *et al.* 2012; Early *et al.* 2016; Russell *et al.* 2017; Bellard *et al.* 2018). Such stressors have also been reported to modify the per capita effect of alien species; for example, gradual climate change decreasing competitive abilities of native populations by pushing them closer to their tolerance limit (Diez *et al.* 2012), increasing predation rates of alien populations by shifting conditions towards their physiological optima (Iacarella *et al.* 2015), or increasing the phenological overlap between native and alien plant populations (Alexander & Levine 2019; Giejsztowt *et al.* 2020).

2.3 Discussion

2.3.1 How can our classification aid management?

A detailed understanding of the mechanisms through which alien species modify—and interact with—their recipient environment is necessary for adequately planning management strategies. For instance, assuming that the alien is the driver of an impact when it actually only profits from a change in the environment (which itself causes the observed impact) leads to an inefficient mitigation of the impact (Didham *et al.* 2007). Indirect impacts of alien species can occur through a multitude of mechanisms, but they are generally less well understood compared to direct mechanisms. This work provides a tool for classifying the indirect mechanisms through which alien species negatively and positively impact native species. By doing so, it aims at assisting the planning of conservation strategies, by informing on options for alternatives to alien eradication, on the risks of alien eradication on non-target species when eradication is the best option, and on the way multiple stressors interact.

Depending on the type of indirect impact mechanisms, different options of management actions can be considered. For instance, under the scenario where an alien species heightens the negative impacts of enemies on a native species (Figs. 2A or 2B), these impacts may be mitigated by targeting the enemy (i.e. biotic mediator) or its effect. Under the scenario where an alien species reduces the availability or quality of a resource (Figs. 2C or 2D), these impacts may be mitigated by providing alternative resources (e.g. the creation of artificial refuges or nesting sites). Negative impacts occurring through changes in abiotic conditions could be artificially mitigated; for example, maintaining alien vegetation at low foliar density could benefit native ectotherms by mitigating the changes in thermal regimes caused by dense alien plants (Carter *et al.* 2015). Finally, while interaction chain effects can be mitigated by targeting the dynamic of the mediator (or the effect of the alien on its dynamic), the effect of the alien on the mediator-native interaction should be targeted in interaction modification effects (Wootton 2002; Didham *et al.* 2007; Foster *et al.* 2016). In the cases of long cascading effects, the simplified classification (Fig. 3C) might be sufficient to identify mitigation actions; However, if more alternative management options need to be determined, understanding the complete chain of events offers more possibilities (Fig. 3A).

On the other hand, when alien species perform unexpected functions in their recipient environments that indirectly profit native species, their eradication or control might lead to undesirable consequences on non-target species (Courchamp *et al.* 2003; Bergstrom *et al.* 2009; Kopf *et al.* 2017). The eradication of cats on the sub-Antarctic Macquarie Island led to a dramatic increase in the rabbit population, resulting in large-scale effects to the whole island ecosystem and significant additional expenses from required conservation actions (Bergstrom *et al.* 2009). Thus, a good understanding of the system is necessary before planning alien eradications or controls so that the potential consequences of alien management can be accounted for. By capturing positive indirect impacts of alien species, our classification could also be used to identify situations in which strategies to prevent undesirable consequences of alien eradication would be needed, and to plan such strategies. Prior to planning an eradication campaign of black rats (*Rattus rattus*) on Surprise Island (New Caledonia), Caut *et al.* (2009) investigated the potential chain effects of this eradication on mice (*Mus musculus*), the only competitor of rats on the island. The authors developed a mathematical model to assess the risk of a burst in the mice population if only rats were eradicated (Caut *et al.* 2007), and concluded that both populations would need to be managed simultaneously, as the release of the rat competitor would have led to a dramatic increase in the mice population. Such approaches should be more frequently adopted as they can prevent such dramatic consequences.

Lastly, we showed that our classification can also be used to address the mechanisms underlying synergistic and antagonistic interactions between alien species and other anthropogenic stressors. Understanding the mechanisms of such interactions is key for efficiently managing their effects, as threats increasingly co-occur (Didham *et al.* 2007; Chadés *et al.* 2015; Geary *et al.* 2019; Ricciardi *et al.* 2020). Accounting for redundancies between management strategies across threats can substantially reduce the costs of conservation by achieving the same result than simple cost-effectiveness approaches adopted for each threat independently (Chadés *et al.* 2015). For instance, if possible, targeting only the distal threat of a threat network could result in the mitigation of all the proximal threats, and might be more efficient in terms of costs and efforts (Geary *et al.* 2019). In western North America, the warming of the streams due to human activity degrades water quality and facilitates the invasion of the alien Smallmouth Bass (*Micropterus dolomieu*), a species sensitive to cool water; thus, restoring lost riparian vegetation could help managing thermal regimes of streams and simultaneously reduce the impact of the Smallmouth Bass (Dunham *et al.* 2020). In contrary, when stressors interact through an interaction modification effect, managing only one stressor might not be efficient to decrease an impact (Didham *et al.* 2007; Foster *et al.* 2016).

It is likely that biological processes between alien species and their recipient environments are too rich and complex to all be captured within one simple classification. Although we acknowledge that some indirect impacts on native species will probably not be classifiable with our classification, we were able to classify all well-known indirect mechanisms, as well as many usually overlooked ones. Furthermore, this classification could be extended and adapted to other types of impacts, caused by other stressors.

2.3.2 Predicting indirect impacts

Improving our understanding of impacts of alien species and of how they occur is essential to be able to predict impacts. Predicting impacts will help prevent risky introductions or manage introduced populations likely to cause important impacts early in the invasion process. Furthermore, understanding how other stressors influence these impacts will allow a better consideration of their effects under current global changes in which stressors are continuing to co-occur (Bellard *et al.* 2018; Ricciardi *et al.* 2020), and has become the focus of much current research (Laender 2018; Schäfer & Piggott 2018; Bruder *et al.* 2019; Jackson *et al.* 2021).

As indirect impacts always occur in the presence of at least one mediator, they can be expected to be less predictable than direct ones, although some indirect impacts might be easier to predict than others. For instance, unlike interaction modification effects, interaction chain effects only require knowledge on the different direct interactions involved (Wootton 1993, 2002). The relatively lower interest in studies for indirect impact mechanisms (Levine *et al.* 2003; White *et al.* 2006), has hence hampered our ability to look for patterns and generalities and to make predictions for such interactions. However, there has been a growing interest in the indirect impact mechanisms of alien species particularly in context of analytical methods like structural equation modeling (Hoyle 1995), which allow the detection of interactions within complex systems (e.g. Linders *et al.* 2019; Boscutti *et al.* 2020). Furthermore, the use of networks or webs of interactions between the species residing in an invaded environment (Frost *et al.* 2019) or between the stressors at play (Geary *et al.* 2019) help to capture the complexity of the system. Such approaches are, therefore, likely to be important in the development of new tools to predict impacts of alien species (Frost *et al.* 2019).

2.4 Conclusion

The eradication or control of alien species is often unfeasible or unwanted, meaning that alternative solutions must be found to mitigate their negative impacts on biodiversity. Alternatives are increasingly being developed and proposed (Woodhams *et al.* 2011; Dunham *et al.* 2020; Falaschi *et al.* 2020; García-Díaz *et al.* 2021) but they can only be found when the mechanisms underlying impacts are well understood. We argue that the lack of understanding of the varied and often subtle ways through which alien species indirectly interact with their recipient environments has hampered progresses to develop such alternatives. As each direct impact can lead to several indirect and cascading effects, it can be expected that indirect impacts occur much more frequently than direct impacts; it is thus necessary to improve our understanding of their mechanisms, for broadening the options for management. This work provides a simple tool which breaks down indirect impact mechanisms to show their complexity and variety. Reviews and classifications have so far focused only on specific categories of mechanisms or taxa. Here, we aimed at summarizing this knowledge about indirect impact mechanisms into one classification. Biological invasions are generally overlooked in conservation planning and need to be more thoroughly considered (Mačić *et al.* 2018); thus, simple and straightforward frameworks will hopefully facilitate the integration of biological invasions in such planning.

Author contributions

Lara Volery and Sven Bacher conceived the study, Lara Volery prepared the first draft, all authors commented, provided critical feedback, and contributed substantially to the development of the conceptual framework and to the writing of the manuscript.

Chapter 3 — Improving the Environmental Impact Classification for Alien Taxa (EICAT): a summary of revisions to the framework and guidelines*

Lara Volery[1], Tim M. Blackburn[2,3], Sandro Bertolino[4], Thomas Evans[5,6], Piero Genovesi[7], Sabrina Kumschick[8,9], Helen E. Roy[10], Kevin G. Smith[11], and Sven Bacher[1]

[1]Department of Biology, Unit Ecology & Evolution, University of Fribourg, Chemin du Musée 10, 1700 Fribourg, Switzerland. [2]Department of Genetics, Evolution & Environment, Centre for Biodiversity & Environment Research, Darwin Building, UCL, Gower Street, London WC1E 6BT, UK. [3]Institute of Zoology, Zoological Society of London, Regent's Park, London NW1 4RY, UK. [4]Department of Life Sciences and Systems Biology, University of Turin, Turin, Italy. [5]Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587 Berlin, Germany. [6]Freie Universität Berlin, Department of Biology, Chemistry, Pharmacy, Institute of Biology, Königin-Luise-Str. 1-3, 14195 Berlin, Germany. [7]ISPRA, Institute for Environmental Protection and Research and Chair IUCN SSC Invasive Species Specialist Group, Via Vitaliano Brancati 48, 00144 Rome, Italy. [8]Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa. [9]South African National Biodiversity Institute, Kirstenbosch National Botanical Gardens, Claremont 7735, South Africa. [10]UK Centre for Ecology and Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, UK. [11]Global Species Programme, IUCN, Pembroke St, Cambridge CB2 3QZ, UK.

Abstract

The Environmental Impact Classification for Alien Taxa (EICAT) classifies the impacts caused by alien species in their introduced range in standardized terms across taxa and recipient environments. Impacts are classified into one of five levels of severity, from Minimal Concern to Massive, via one of 12 impact mechanisms. Here, we explain revisions based on an IUCN-wide consultation process to the previously published EICAT framework and guidelines, to clarify why these changes were necessary. These changes mainly concern: the distinction between the two highest levels of impact severity (Major and Massive impacts), the scenarios of the five levels of severity for the hybridization and disease transmission mechanisms, the broadening of existing impact mechanisms to capture overlooked mechanisms, the Current (Maximum) Impact, and the way uncertainty of individual impact assessments is evaluated. Our aim in explaining this revision process is to ensure consistency of EICAT assessments, by improving the understanding of the framework.

* Please note that in this chapter, we talk about alien 'taxon' instead of 'species', for consistency with the terminology used in the EICAT framework.

3.1 Introduction

The Environmental Impact Classification for Alien Taxa (EICAT: (Blackburn *et al.* 2014; Hawkins *et al.* 2015; Appendix 1,2) has been developed to quantify variation in the severity and type of environmental impacts generated by alien species. Semi-quantitative scenarios are used to categorize impacts caused by alien taxa on native species into one of five levels of severity – Minimal Concern (**MC**), Minor (**MN**), Moderate (**MO**), Major (**MR**), Massive (**MV**) (Fig. 1) – via one of 12 EICAT impact mechanisms: (1) Competition, (2) Predation, (3) Hybridization, (4) Transmission of diseases to native species, (5) Parasitism, (6) Poisoning / toxicity, (7) Biofouling or other direct physical disturbance, (8) Grazing / herbivory / browsing, (9, 10, 11) Chemical, physical, or structural impact on ecosystem, (12) Indirect impacts through interaction with other species (see Table 1 in Appendix 1: Criteria used to classify alien taxa by EICAT Impact Category). Non-native species residing in the recipient environment can be negatively affected by the alien taxon as well, but EICAT only classifies impacts on the native biota. This classification system facilitates comparisons between impacts generated by alien species across geographic regions and taxonomic groups. (Hawkins *et al.* 2015) provided guidelines for the application of the framework inspired by the IUCN Red List of Threatened Species (IUCN 2012, 2019).

EICAT has been used to undertake assessments of the environmental impacts of alien birds (Evans et al. 2016), amphibians (Kumschick *et al.* 2017), bamboos (Canavan *et al.* 2019b), marine fishes (Galanidi *et al.* 2018), feral mammals (Hagen & Kumschick 2018) and gastropods (Kesner & Kumschick 2018), among others. Whilst these assessments demonstrated that EICAT can be effectively used to quantify and categorise the environmental impacts of alien species from different taxonomic groups, they also highlighted that aspects of the existing guidelines require refinement in order to improve the assessment process. In 2020, EICAT was officially adopted as the IUCN standard for classifying alien species in terms of their environmental impact. A new standard classification of the impact of invasive alien taxa (Appendix 1), as well as new guidelines for using this standard classification (Appendix 2) have been developed based on an IUCN-wide consultation process to solve the problematic aspects and improve the process: these documents update and replace the existing guidance documentation (Hawkins *et al.* 2015).

Here, we have explained the major changes made to the previous EICAT guidance and the reasons for these changes, so that the revision process is transparent. By detailing the reasoning behind the changes, we also aim to improve the general understanding of the framework, which is likely to result in an increased consistency in its use by different assessors. Therefore, while this guidance will be particularly useful to assessors already familiar with EICAT, we would also recommend it to assessors intending to use EICAT for the first time.

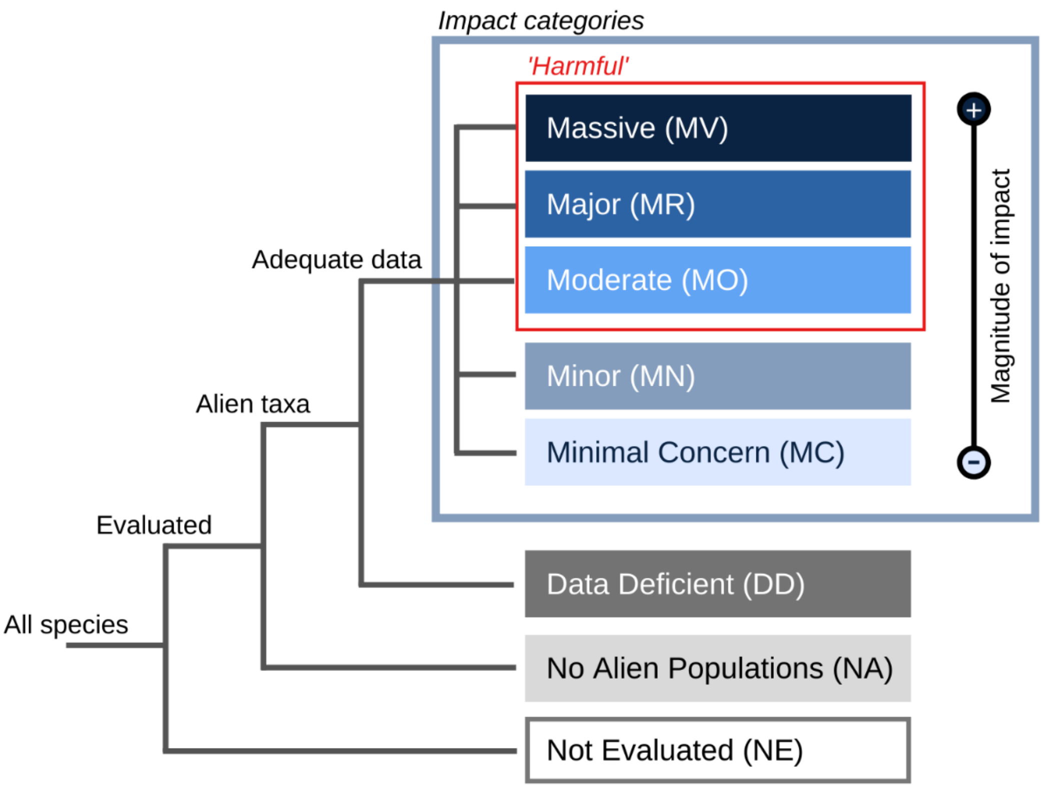


Figure 1. The different EICAT categories and the relationship between them. Reproduced from Appendix 1 (IUCN EICAT Categories and Criteria; with permission from IUCN).

3.2 Definitions

3.2.1 'Fitness' has been replaced by 'Performance'

In the description of the **MN** impact magnitude and throughout, the term 'fitness' has been replaced by the term 'performance'. As fitness is usually defined as the number of descendants provided by an individual to the next generations, changes in the individual fitness lead per definition to changes in native population sizes (**MO** impact) (Krimbas 2004; Hunt & Hodgson 2010). This is problematic, as in EICAT, **MN** impacts explicitly do not involve population level impacts. Performance, on the contrary, does not necessarily relate to offspring production and therefore does not imply **MO** impacts: it includes changes in the individual growth, reproduction, fecundity, survival, defense, immunocompetence, etc. **MN** impacts (i.e. impacts on the individual performance) can lead to population level impacts (**MO**, **MR** and **MV** impacts), but do not necessarily do so.

3.2.2 Population, sub-population, local population

The three most severe EICAT impact categories (**MO**, **MR** and **MV**) involve population level impacts to native taxon (causing declining populations of native taxon (**MO** impacts), or reversible and irreversible population extinctions [**MR** and **MV** impacts, respectively]). To reflect the severe nature of these impacts and to assist efficient communication of high impacts, **MO**, **MR** and **MV** impacts have been grouped together under the term ‘harmful’ (Fig. 1). This follows a similar approach adopted by the IUCN Red List of Threatened Species (https://www.iucnredlist.org/), where native species in the three of the Red List categories (Vulnerable (**VU**), Endangered (**EN**) and Critically Endangered (**CR**)) are grouped under the term ‘threatened’. The terms ‘population’, ‘local population’, ‘sub-population’ and ‘global population’ are widely used terms which might not always be understood in the same way (Wells & Richmond 1995): to avoid any confusion on what is meant in EICAT by ‘population level impacts’, these different terms have been clearly defined in the revised guidance.

Revised guidance

The relationship between a global population, a sub-population and a local population has been clarified (Appendix 1):

- A global population includes all individuals of a taxon
- A sub-population is a geographically or otherwise distinct group in the global population of a taxon
- A local population is a group of individuals within a sub-population of a taxon

Sub-populations are largely isolated from each other, whereas local populations within a sub-population are connected by frequent movements of individuals (Fig. 2). For EICAT assessments, population decline and extinction should be evaluated at least at the level of a local population (but can also happen at higher levels, such as sub-population or global population levels).

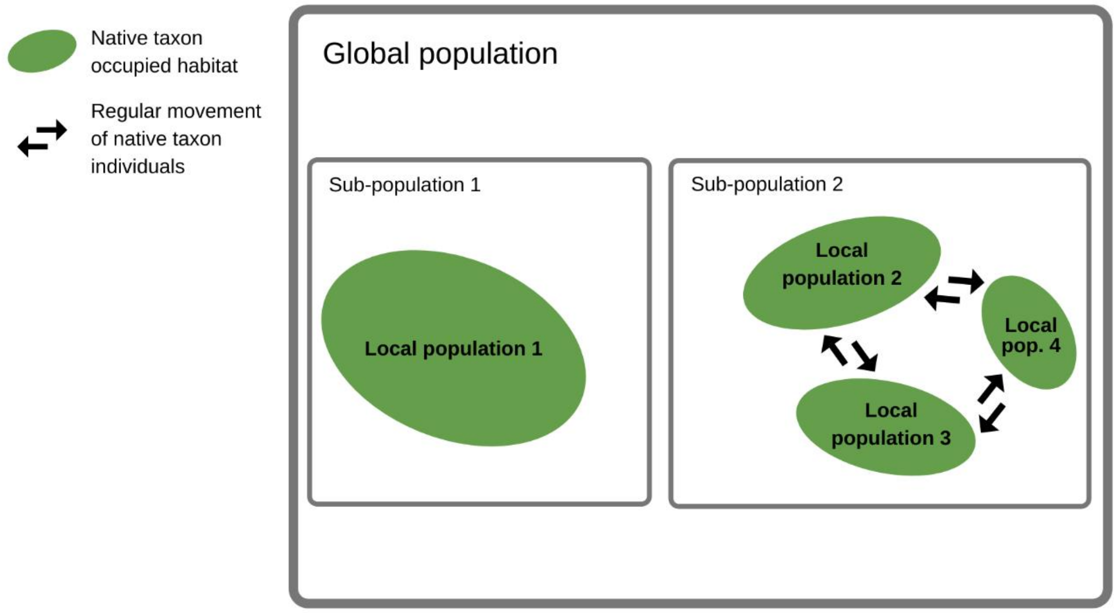


Figure 2. The relationship between a global population, sub-population and local population for the purposes of EICAT assessments. The global population includes all individuals of a taxon, a sub-population is a geographically or otherwise distinct group in the population, and a local population is a group of individuals within a sub-population. In this example, local population 1 includes all individuals within sub-population 1. Local populations 2, 3 and 4 are connected by frequent natural immigration, whereas sub-populations 1 and 2 are largely isolated from each other. Reproduced from Appendix 1 (IUCN EICAT Categories and Criteria; with permission for IUCN).

To show impacts at the native population level (**MO**, **MR** or **MV**), studies should understand the structure and dynamics of the populations being considered through the assessment. The individuals comprising a local population are often spatially grouped into smaller units (termed patches, aggregates, clusters, herds, etc.), which are naturally dynamic (i.e. appearance of new patches and disappearance or expansion of existing patches; Hanski 1994). Impact studies and EICAT assessors should be careful not to consider individual patches as local populations when evaluating the magnitude of the impact caused by the alien taxon. Studies should also ideally have attempted to understand the natural dynamics of the native local populations, to avoid incorrectly interpreting changes due to natural variation as impacts of the alien taxon (e.g. Schooley & Branch 2009; Hanski *et al.* 2017); the guidelines of the IUCN Red List of Threatened Species (IUCN 2012, 2019) provide examples of different population dynamics, such as extreme fluctuations or severely fragmented populations).

Observations or experiments are sometimes carried out on native local 'populations' that are not reproducing (e.g. common garden experiments for plants or mesocosm experiments). In EICAT, impacts can be reported at the population level (**MO**, **MR** or **MV**) only when observations or experiments are carried out on native self-sustaining populations. Ideally, changes in native population dynamics should have been happening over several generations to conclude population level impacts (**MO**, **MR** or **MV**): for instance, to confidently detecting population level impacts, it might not be sufficient to observe fewer native plant individuals in the same generation, as these losses could be compensated for by seedling recruitment. Therefore, in the cases of non-self-sustaining native populations, one can only infer impacts on individual performance (**MN**).

3.3 Impact Categories

3.3.1 Determining whether an impact is Major (MR) or Massive (MV) under EICAT

Determining whether the impact of an alien taxon on a native taxon is **MR** or **MV** under EICAT is established by assessing whether the impact is reversible. Both **MR** and **MV** impacts result in native taxon extinctions: a local population extinction that is reversible is classified as an **MR** impact, whilst an irreversible local population extinction is an **MV** impact. Under the previous EICAT guidance, the assessor is required to determine whether the impact of the alien taxon is likely to be reversible through management actions (for example by considering the logistics associated with extirpating or eradicating the alien taxon, re-introducing the native taxon and / or restoring native habitats). In cases where the effort or cost required to reverse the changes caused by the alien taxon were beyond capabilities, the impact would be judged irreversible (i.e. it would be assessed as an **MV** impact), even if in theory it might be possible to re-establish the native local population.

Determining whether management actions are likely to enable the native taxon to re-colonise the area is an unrealistic demand of the assessor. This is very difficult to establish in an EICAT assessment procedure and is usually not discussed in the original impact reports used in the EICAT process: it would inevitably introduce new causes of uncertainty and subjectivity.

Revised guidance

The requirement to evaluate the reversibility of a native taxon extirpation through management actions has been removed from the guidance documentation. To determine whether an impact is **MR** or **MV**, the assessor must instead apply the hypothetical scenario which assumes that the alien taxon is eradicated from the location where it caused the extinction of a native local population, regardless of whether this eradication is feasible or if the native taxon could be re-established with additional effort:

- A local population extinction is reversible (an **MR** impact) if the native taxon would most likely return to the community from which it was extirpated within 10 years or 3 generations of the native taxon, whichever is longer, under either of the following conditions; (1) naturally (e.g. individuals migrating from another local population (of the same sub-population) recolonising the area), or (2) assisted by human re-introductions, either intentionally or unintentionally, but only where the re-introductions were occurring at a similar rate before the alien taxon led to the native taxon local population extinction, and the re-introductions are not for conservation purposes. Examples for the second condition include cases where individuals of a native mussel are frequently (unintentionally) transported via boats to the place where the local population of this native mussel went extinct, or cases where a native fish is periodically (and intentionally) restocked for fishing in the lake where the local population of this fish went extinct. Therefore, re-introductions assisted by humans that were not already in place at the time the alien taxon led to the local population extinction and would require extra effort (e.g. re-introductions from captivity or from other areas) are not considered as reversible changes.

- A local population extinction is irreversible (an **MV** impact) if the native taxon is not likely to return to the community within 10 years or 3 generations of the native taxon, whichever is longer, without additional human assistance that was not already in place at the time the alien taxon led to the local population extinction. Local extinctions are irreversible when there is no propagule influx of the native taxon (e.g. global extinction, disconnection of the local population), or when the alien population changes the environment, making it unsuitable for the native taxon.

Local extinctions which, under the previous guidance, were considered irreversible (**MV**) because of practical constraints or inability to either eradicate the alien or restore the native habitats, should be re-classified as **MR** impacts, if it is possible for the native taxon to return to the community naturally or assisted by human re-introductions already in place before the alien taxon led to its local population extinction. Local extinctions which were considered irreversible (**MV**) because the native taxon was globally extinct, because of a disconnection of the local population, or because of changes in the habitat characteristics due to the alien, should remain classified as **MV** under the revised guidance. Local extinctions which were classified as **MR** because it was judged logistically feasible to re-introduce the native taxon with extra effort (i.e. with measures not already in place before the alien taxon led to the native taxon extinction) or by restoring the habitat modified by the alien, should be considered irreversible and re-classified as **MV** under the revised guidance.

3.4 Impact mechanisms

3.4.1 Broadening of impact mechanisms in order to capture all types of impacts

EICAT considers that impacts caused by alien taxon to a native taxon can occur through 12 EICAT impact mechanisms, which align with those identified in the IUCN Global Invasive Species Database (GISD) (http://www.iucngisd.org/gisd). In the previous EICAT guidance, these mechanisms were: (1) Competition, (2) Predation, (3) Hybridization, (4) Transmission of diseases to native species, (5) Parasitism, (6) Poisoning / toxicity, (7) Biofouling, (8) Grazing / herbivory / browsing, (9, 10, 11) Chemical, physical, or structural impact on ecosystem, (12) Interaction with other alien species (Hawkins *et al.* 2015). Impact mechanisms describe the way a native taxon is affected by an alien taxon: e.g. by feeding on plants, alien herbivores can affect native plants through 'Grazing', and at the same time they can affect native insects or ground-nesting birds through 'Chemical, physical, or structural impact on ecosystem', because of above-ground plant biomass removal.

Indirect impacts to native taxon were not completely captured by these 12 mechanisms. In indirect impacts, the alien taxon does not directly interact with the impacted native taxon: it affects the native taxon by modifying another factor of the environment, which can be biotic (a population of another alien or native taxon), or abiotic (e.g. water or soil composition). In the 12 mechanisms, indirect impacts occurring through changes in abiotic factors are captured by the mechanism 'Chemical, physical, or structural impact on ecosystem'. Indirect impacts through changes to biotic factors can occur **a)** when the alien taxon facilitates the negative effect of an intermediate species on the native taxon of interest. This is the case in the 'Transmission of disease' or in the 'Interaction with another alien species' mechanisms, where the alien facilitates the negative impact respectively of a parasite (by vectoring it) or of another alien species. However, other examples of such indirect impacts exist, and were not described by any mechanisms of the previous guidance: for instance, on San Miguel and Santa Cruz Islands (California Channel Islands), an introduced pig (*Sus scrofa*) population enabled the colonisation by mainland golden eagles (*Aquila chrysaetos*) and caused an increase in their population by providing a supplemental food source, leading the golden eagle population to start feeding on the native fox (*Urocyon littoralis*) population and causing its decline (Roemer *et al.* 2001, 2002). In this example, the alien pig had an indirect impact on the native fox, by facilitating the impact of the golden eagle. Indirect impacts can also occur when **b)** the alien taxon inhibits a positive effect of an intermediate species on the native taxon of interest. This is the case in the 'Competition' mechanism, where the alien taxon decreases the availability of a resource and thereby decreases the benefits brought by this resource to the native taxon. However, other mechanisms for this type of indirect impacts were previously ignored as well. In North American forests, for example, the European plant garlic mustard (*Alliaria petiolata*) has been found to release antifungal phytochemicals which eliminate the activity of native arbuscular mycorrhizal fungi and suppresses the growth of native tree seedlings by disrupting their mutualistic associations (Stinson *et al.* 2006; Callaway *et al.* 2008). Such impacts are not described by any mechanism and cannot be systematically and consistently classified.

With respect to direct mechanisms, impacts occurring through direct physical disturbances, such as vegetation trampling or tree rubbing, were not captured either. Alien populations of ungulates often cause direct physical disturbances: for instance, an alien population of the Asian elephant (*Elephas maximus*) on the Andaman Islands (India) contributed to the declines of several native plant populations by heavily grazing upon them, but also by uprooting and debarking trees (Ali 2004). In such impacts, native individuals are not indirectly affected by a change in some environmental characteristics (impact on ecosystem), but are affected by their direct interaction with alien individuals.

Revised guidance

To capture all indirect impacts occurring through changes to biotic factors, the mechanism ‘Interaction with other alien species’ has been amended to ‘Indirect impacts through interaction with other species’ and the semi-quantitative scenarios updated accordingly (see Table 1).

Unlike the direct mechanisms of ‘Predation’, ‘Grazing / herbivory / browsing’ or ‘Parasitism’, the direct impacts caused by physical disturbances (e.g. vegetation trampling) do not concern trophic interactions. The existing ‘Biofouling’ mechanism is also a direct mechanism not concerning trophic interactions but occurring through a physical disturbance of native individuals: therefore, the mechanism ‘Biofouling’ has been amended to ‘Biofouling or other direct physical disturbance’, to capture all types of impacts occurring through direct physical disturbances.

These extensions of two mechanism definitions allow the classification of impacts that were not captured in a systematic way under the previous guidance: impacts falling into these new definitions, and previously classified into unsuited mechanisms, should be re-classified into one of these two extended mechanisms.

3.4.2 Refinement and clarification of the criteria for the mechanism ‘Transmission of disease’

In the ´transmission of disease´ mechanism, the alien taxon acts as a vector of a (native or alien) disease agent (e.g. virus, bacteria or prion) or parasite which impacts upon native taxa. When we evaluate the impact of the alien taxon through transmission of disease, we evaluate its impact as a vector (i.e. the increase in the spread of the disease agent/parasite (hereafter, parasite) caused by the alien vector impacts the native taxon). However, evidence of the alien taxon being a host is more frequently available than evidence of the alien taxon being a vector. For instance, the chytrid fungus *Batrachochytrium dendrobatidis*, which has contributed to global amphibian declines, has been shown to be transmitted by alien amphibians populations to the native ones (e.g. Fisher & Garner 2007; Miaud *et al.* 2016); yet, most studies only show that alien amphibian populations are reservoirs for the chytrid fungus instead of showing that they transmit the disease to the native populations (Measey *et al.* 2016). The responsibility of the alien taxon for disease spread and observed impact is difficult to evaluate from such evidence.

Revised guidance

Based on the available types of evidence for this mechanism, the information required to classify impacts through transmission of disease has been clarified. For an impact to be classified as **MO**, **MR** or **MV**, the following information is needed: an impact on the native population (e.g. a decline [**MO]** or a local extinction [**MR**/**M]**) has to be observed and the alien taxon has to be shown to be a host of the parasite at the same time and space as the native population (based on Kumschick *et al.* 2017). When only evidence is available that the alien taxon is a host (or a vector) of a disease that affects individuals, the impact should be scored as **MN**: the extent of the impact on the native population is not shown or studied, so we can only suppose that the performance of the infected individuals has been affected. Impacts are classified as **MC** when the disease or parasite carried by the alien taxon was not found in the native taxa, or when the disease or parasite was found in the native taxa but shown to be harmless to the native individuals. The semi-quantitative scenarios of the transmission of disease mechanism have been updated accordingly (see Table 1).

Establishing whether the alien taxon is the only (or main) vector of the parasite in the recipient environment, or whether multiple vectors are present and are aiding the spread of the parasite, helps to evaluate the impact of the alien vector. If the alien taxon is the only vector, the impact of the alien taxon equates to the impact of the parasite. If the alien taxon is not the only vector of the parasite, the impact of the alien taxon equates to the impact caused by the increase in the spread of the parasite due to the alien taxon.

If the parasite vectored by the alien taxon is also an alien in the area of interest, separate EICAT assessments need to be performed for it, under the mechanism ‘parasitism’. In cases where the alien vector is the only vector present in the recipient environment, the same impact magnitude would be recorded for the alien vector and for the alien parasite (because if either of them were absent, the observed impact would not occur). In cases where the alien vector is increasing the spread of an alien parasite, the impacts of the alien parasite and of the alien vector might be of different magnitudes (but the impact of the alien parasite will always be the same or higher than the impact of the alien vector in this specific mechanism).

These updates show how to apply the information usually available regarding the 'Transmission of disease' mechanism: impact reports showing that the alien is a host of a parasite causing damage to the individual performance or population of a native species can now be classified in a consistent way. Such impact reports might have been classified differently under the previous guidance, because of a lack of solid evidence showing that the alien taxon was transmitting the parasite to native species: these reports should be re-classified based on the new criteria.

3.4.3 Revised scenarios to describe the severity of hybridization impacts

For all impact mechanisms, the five semi-quantitative scenarios categorizing severity should follow the same general logic. However, the semi-quantitative scenarios used to describe the severity of hybridization impacts are not in-line with those used to describe the severity of impacts associated with other mechanisms, because they focus on the viability of the hybrid offspring, rather than on the native individuals. The semi-quantitative scenarios are also based on hypothetical (projected) impacts, instead of on observed impacts. Indeed, these scenarios assume that as soon as hybrids can reproduce with the native population, the latter is inevitably lost. In so doing, they ignore the possibilities that hybrid individuals may be removed from the population, that hybrids may only reproduce with other hybrids (assortative mating), that stable hybrid and native populations may coexist, that backcrossing processes may occur, or simply that hybridization may not have been happening for long enough for the native population to go extinct. For example, the ruddy duck (*Oxyura jamaicensis*) hybridizes with the endangered white-headed duck (*Oxyura leucocephala*) in Spain, but even though hybrids are fertile and produce viable offspring, early control programs of the alien population and the hybrids allowed to avoid a decline in the white-headed duck population (Muñoz-Fuentes *et al.* 2007). The Asian sika deer (*Cervus nippon*) is known to hybridize with the native red deer (*Cervus elaphus*) in Scotland and England, but local red deer populations show very different levels of hybridization. The sika deer have led to population declines in some locations where high proportions of hybrids were detected (e.g. in Kintyre Peninsula), but not in others, where a low frequency of hybrids was detected in large sample sizes, revealing past hybridization followed by extensive backcrossing (e.g. in Lake District and North Highlands) (Smith *et al.* 2018).

Revised guidance

Each hybridization event between native and alien or hybrid individuals reduces the reproduction rate of the pure native taxon, which can lead to a decline in population size or to local extinction, depending on the frequency of the hybridization events and on whether hybrids are fertile. The criteria are now based on observed instead of projected impacts: hence, cases where hybrids are fertile but did not lead to local extinctions would no longer be classified as **MR** or **MV** (but maximum as **MO**). With increasing impact severity, the reproduction rate of the pure native taxon reduces, which may lead to declining populations of a native taxon (**MO** impacts) or to reversible and irreversible species extinctions (**MR** and **MV** impacts), depending on the frequency of the hybridization events (see Table 1).

Hybridization impacts classified using the previous guidance can be adapted to the revised guidance as follows:

- Impacts initially classified in the **MC** or **MN** categories can remain classified in the **MC** or **MN** categories, respectively;
- Impacts initially classified in the **MO** category because hybridization is regularly observed in the wild and has led to a decline of the pure native population can remain classified in the **MO** category. In contrast, impacts initially classified in the **MO** category only because hybrids are vigorous but sterile, but with no decline of the pure native population observed, should be re-classified in the **MN** category;
- Because, in the previous guidance, the criteria of the **MR** category did not describe any replacement of the pure native population, impacts initially classified in the **MR** category should be re-classified in the **MO** category;
- Impacts initially classified in the **MV** category because hybridization is common in the wild and /or because hybrids are fully vigorous and fertile should be:
    - re-classified in the **MO** category if hybridization has led to a decline in the pure native taxon but no replacement of the pure native population;
    - re-classified in the **MR** category if hybridization has led to the replacement of the local pure native population, but the native pure bred population can recover (either naturally or assisted by human re-introductions already in place before the alien taxon led to the local population extinction) if the alien and hybrids are no longer present;
    - remain classified in the **MV** category if hybridization has led to the replacement of the local pure native population, and the native pure bred population cannot recover (either naturally or assisted by human re-introductions already in place before the alien taxon led to the local population extinction) even if the alien and hybrids are no longer present.

Table 1. Criteria used to classify alien taxa by EICAT impact category (**MC**, **MN**, **MO**, **MR**, **MV**) for the three modified mechanisms: Indirect impacts through interaction with other species, Transmission of disease to native species and Hybridization. Reproduced from Appendix 1 (IUCN EICAT Categories and Criteria, with permission from IUCN).

	Massive (**MV**)	Major (**MR**)	Moderate (**MO**)	Minor (**MN**)	Minimal Concern (**MC**)
Categories should adhere to the following general meaning	*Causes local extinction of at least one native taxon (i.e., taxa vanish from communities at sites where they occurred before the alien arrived), which is naturally irreversible; even if the alien taxon is no longer present the native taxon cannot recolonise the area*	*Causes local or subpopulation extinction of at least one native taxon (i.e., taxa vanish from communities at sites where they occurred before the alien arrived); which is naturally reversible if the alien taxon is no longer present*	*Causes population decline in at least one native taxon, but no local population extinction*	*Causes reduction in individual performance (e.g., growth, reproduction, defense, immunocompetence), but no decline in local native population sizes*	*Negligible level of impact; no reduction in performance (e.g., growth, reproduction, defense, immunocompetence) of individuals of native taxa*
Mechanisms					
Indirect impacts through interaction with other species	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) causing local extinction of one or several native taxa, leading to naturally irreversible changes that would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) causing local population extinction of at least one native taxon; changes are naturally reversible but would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) causing a decline of population size of at least one native taxon, but no local population extinction; impacts would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) affecting performance of native individuals without decline of their populations; impacts would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) but reduction in performance of native individuals is not detectable

	Massive (**MV**)	Major (**MR**)	Moderate (**MO**)	Minor (**MN**)	Minimal Concern (**MC**)
Transmission of disease to native species	Transmission of disease to native taxa resulting in local extinction of at least one native taxon; changes are naturally irreversible	Transmission of disease to native taxa resulting in local population extinction of at least one native taxon; naturally reversible when the alien taxon is no longer present	Transmission of disease to native taxa resulting in a decline of population size of at least one native taxon, but no local population extinction; disease is severely affecting native taxa, including mortality of individuals, and it has been found in native and alien co-occurring individuals (same time and space)	Transmission of disease to native taxa affects performance of native individuals without leading to a decline of their populations; alien taxon is a host of a disease which has also been detected in native taxa and affects the performance of native taxa	The alien taxon is a host or vector of a disease transmissible to native taxa but disease not detected in native taxa; reduction in performance of native individuals is not detectable
Hybridization	Hybridization between the alien taxon and native taxa leading to the loss of at least one pure native local population (genomic extinction); pure native taxa cannot be recovered even if the alien and hybrids are no longer present	Hybridization between the alien taxon and native taxa leading to the loss of at least one pure native local population (genomic extinction); naturally reversible when the alien taxon and hybrids are no longer present	Hybridization between the alien taxon and native taxa is regularly observed in the wild; local decline of populations of at least one pure native taxon, but pure native taxa persist	Hybridization between the alien taxon and native taxa is observed in the wild, but rare; no decline of pure local native populations	No hybridization between the alien taxon and native taxa observed in the wild (prezygotic barriers), hybridization with a native taxon is possible in captivity

3.5 Overall impact of an alien taxon

3.5.1 Distinction between spatial scale of assessments and geographic scale of assessments

The previous guidelines independently addressed the concepts of spatial scale of assessments and geographic scale of assessments. The term 'spatial scale of assessments' is used in the context of an individual EICAT assessment (based on one impact observation, or study), whereas the term 'geographic scale of assessments' is used in the context of the overall classification of an alien taxon. While these terms are used at different stages of the assessment process, they might be confused, as they both involve spatial aspects of assessments. The distinction between the two terms is made clear in the revised guidance.

Spatial scale of assessments

The term spatial scale of assessments relates to the evidence of impacts being assessed using the EICAT Categories and Criteria. Impacts caused by alien taxa need to be observed or investigated at an appropriate spatial and temporal scale, over which the original native communities can be characterized. Assessments based on evidence generated at spatial or temporal scales that are very different to the scales over which the local native population can be characterized are likely to be subject to greater uncertainty.

Geographic scale of assessments

Where impacts are assessed based on evidence from across an alien taxon's global introduced range, the geographic scale of the Maximum recorded impact would be 'Global'. However, where impacts are assessed based on evidence from a single country to which an alien taxon has been introduced (excluding impacts from areas of its alien range in other countries), the geographic scale of the Maximum Recorded Impact would be 'National' (Fig. 3). IUCN will only review and display global EICAT assessments on their website.

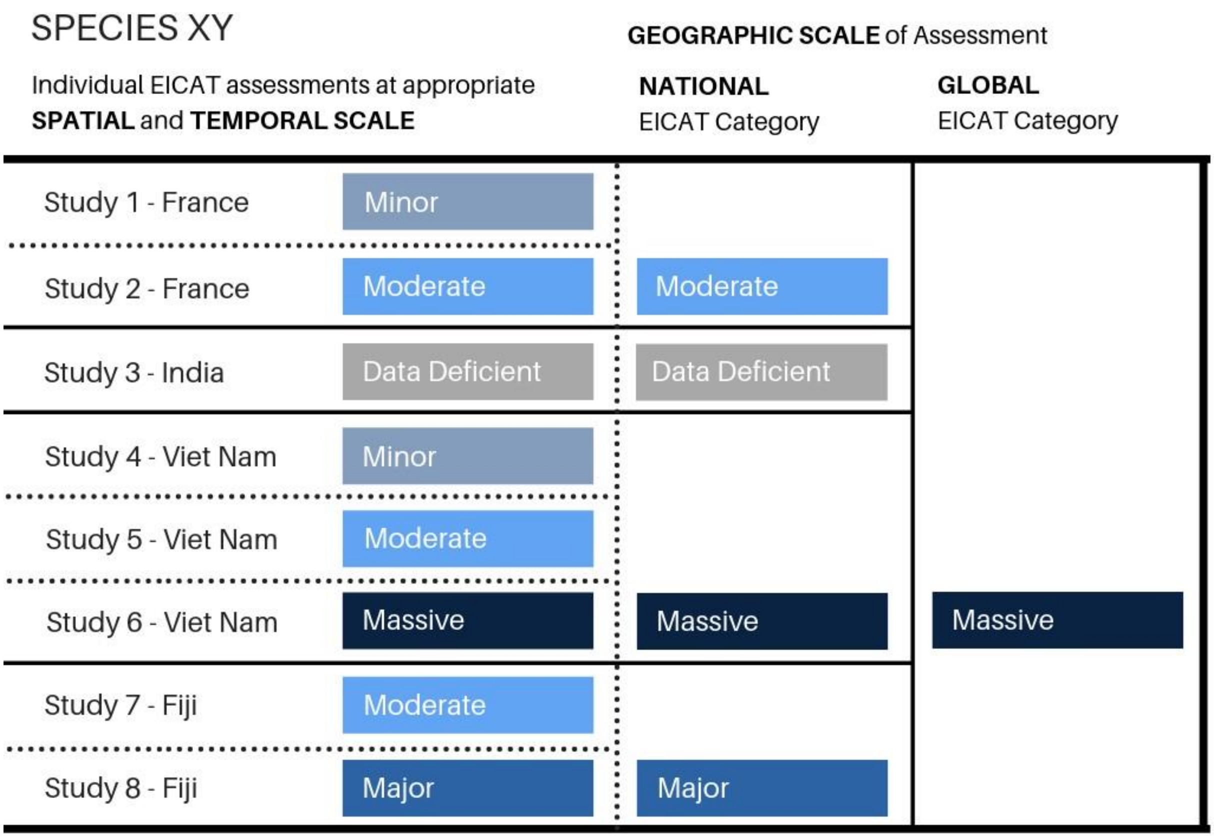


Figure 3. How data from individual EICAT assessments of the impacts of a hypothetical alien taxon (species XY) inform the EICAT Category to which the taxon is assigned at national and global scales. The global assessment categorizes the taxon based on its highest impact anywhere (in this case, a Massive (MV) impact in Vietnam). National scale assessments are based only on impacts reported from those countries (e.g. Major (MR) for Fiji). Data Deficient (DD) in India indicates that the alien taxon was assessed but no impact reports from India were found. Reproduced from Appendix 1 (IUCN EICAT Categories and Criteria, with permission from IUCN).

3.5.2 No longer recording Current (Maximum) Impact

Under the previous guidance, a dual assessment of the alien taxon's impacts was required (Hawkins *et al.* 2015):

- Maximum Recorded Impact (**MC**, **MN**, **MO**, **MR** or **MV**)
- Current (Maximum) Impact: the severity of impacts associated with an alien taxon's current impacts to a native species (at the time of the EICAT assessment) (**MC**, **MN**, **MO**, **MR** or **MV**)

The rationale here was that the two measures of impact severity could be compared to demonstrate whether the impacts of an alien taxon were increasing or decreasing over time. For instance, an impact could be downgraded to a lower magnitude once management practices had been established to control the alien population.

While downgrading or upgrading an impact to lower or higher magnitudes can be informative for the impact caused by a specific alien population, downgrading or upgrading the overall impact of an alien taxon with multiple introduced populations is not straightforward and might lead to the loss of information on impacts, for the following reasons:

- Different introduced populations of the alien taxon are likely to vary over time in different ways: the same reduction or increase in the impact magnitude will probably not be observed in all its introduced populations. It is difficult to define in such cases how to treat the different scenarios with one global Current Impact score.
- Moreover, it is unclear when an impact should be considered as 'current' when considering the overall impact of an alien taxon (i.e. it is difficult to define a reasonable time scale over which impact magnitudes should be re-evaluated).
- Finally, information on the variation of impacts over time will likely not be available for most of the introduced populations of the alien taxon. It is unclear if potential differences in recent impact reports are the result of temporal changes in impact magnitudes.

Revised guidance

The requirement to assess an alien taxon's Current Impact has been removed: an assessment of the alien taxon's Maximum Recorded Impact is still required, which equals the taxon's EICAT Classification (as in Kumschick *et al.* 2020). EICAT is an evidence-based scheme: the classification of an alien taxon is only based on its observed impacts (or impacts inferred based on evidence), but potential, hypothetical or projected impacts are not assessed by the framework (Appendix 1).

3.6 Dealing with uncertainty

The assessor should assign each (relevant) impact report to its most likely impact Category and assign a level of confidence to this assessment (high, medium or low), depending on the likelihood of the assigned impact Category being correct. In the previous guidance, the factors listed as potentially reducing the assessors' confidence in the impact magnitude assigned to an impact observation included: the availability, reliability and type of data used as evidence of impacts, the spatial scale over which data were collected, the ease of interpretation of the available data, and whether or not all available data were in agreement with respect to the magnitude of recorded impacts.

The previous guidance did not address three important sources of uncertainty in EICAT assessments (see also Appendix 3):

- **Confounding effects:** The presence of confounding effects is a frequent source of uncertainty in impact reports when changes are happening at the local population level (**MO**, **MR** or **MV**). Large-scale phenomena such as changes in native population dynamics usually do not allow an 'ideal' experimental set-up with control situations to exclude the possibility that other biotic or abiotic factors have caused or contributed to the observed impact (Kumschick *et al.* 2015b; Christie *et al.* 2019). It is therefore often difficult to distinguish whether an alien taxon is the driver of these changes, or whether confounding effects are at play. For instance, when a decline of a native taxon is observed but multiple stressors - including the alien taxon - act on that species, it is possible that the observed decline would have happened in the absence of the alien taxon. The impact caused by the alien taxon might therefore be lower than the one assigned (e.g. **MO**), if the decline would have happened anyway: the presence of other stressors can reduce the confidence in the assigned impact category. Conversely, when no other stressor is known to act on the impacted native taxon, the alien taxon is more likely to be responsible for the observed change.
- **Study design:** Impact studies are rarely designed to determine which impact magnitude is caused by the alien taxon based on the EICAT criteria (i.e. at which level of organization are the native taxa affected by the alien taxon). Therefore, even in well-designed impact studies, uncertainty can exist regarding the impact magnitude that has been assigned to the impacts they report. For instance, some studies focus only on one particular level of impact (e.g. the individual performance) and are not investigating higher levels of impact (e.g. whether the impact on the individual performance is affecting the size of the population) even when these are likely (Appendix 3). In such cases, the assessor should be aware that the study design creates uncertainty: the 'true' impact magnitude could be higher than the one assigned, if the alien causes a decline in the native population. Hence, these impacts cannot be classified as **MN** impacts with high confidence, as the **MN** category corresponds to impacts at the individual performance level and no impact at the population level (Appendix 2). In contrast, impact reports from study designs that describe an impact at the individual performance level, and which would have allowed detection of an impact at higher levels, can be classified as **MN** with high confidence regarding the 'Study design'.
- **Temporal scale:** Studies performed over time periods that are too short to capture the changes in a native population might lead to an over- or under-estimation of the severity of an impact. As previously explained, a study investigating impacts at the native population level (**MO**, **MR**

or **MV**) should be performed at a temporal scale that allows changes in the dynamics of native populations to be captured, over several generations.

Revised guidance

The revised guidance for the confidence classification distinguishes between five sources of uncertainty in EICAT assessments: confounding effects, study design, data quality and type, spatial and temporal scales, and coherence of evidence (see Appendix 3). The source 'Data quality and type' addresses the uncertainty associated with the use of inferred information in the assessment, but also the uncertainty associated with the way the impact observation is communicated in the report. For instance, if no detail is provided on the way the observation or experiment has been performed in the report, the assessor cannot evaluate the relevance of the spatial/temporal scale or of the study design. The guidance also specifies how each of these sources can affect the assessor's level of confidence in their assessment, and in which circumstances these sources would lead to a high, medium or low score (Table 2).

3.7 Conclusions

Here we have provided clarifications to improve the understanding of the EICAT framework. We highlighted the problematic aspects of the initial EICAT framework and guidelines (Blackburn *et al.* 2014; Hawkins *et al.* 2015), which have been modified, but not explained, in the revised versions (Appendix 1,2). We also provided concrete examples and additional explanations on the impact assessment process.

It is, however, impossible to completely avoid differences in interpretation amongst assessors for some aspects of the framework. Therefore, we stress the importance of following the recommendations given by González-Moreno *et al.* (2019): assessors should be adequately trained, and continuously discuss and exchange their work with other assessors for feedback and review.

Author contributions

Lara Volery, Sven Bacher, Sabrina Kumschick and Thomas Evans conceived the study, Lara Volery prepared the first draft with support of Sven Bacher, all authors provided input and contributed substantially to revisions.

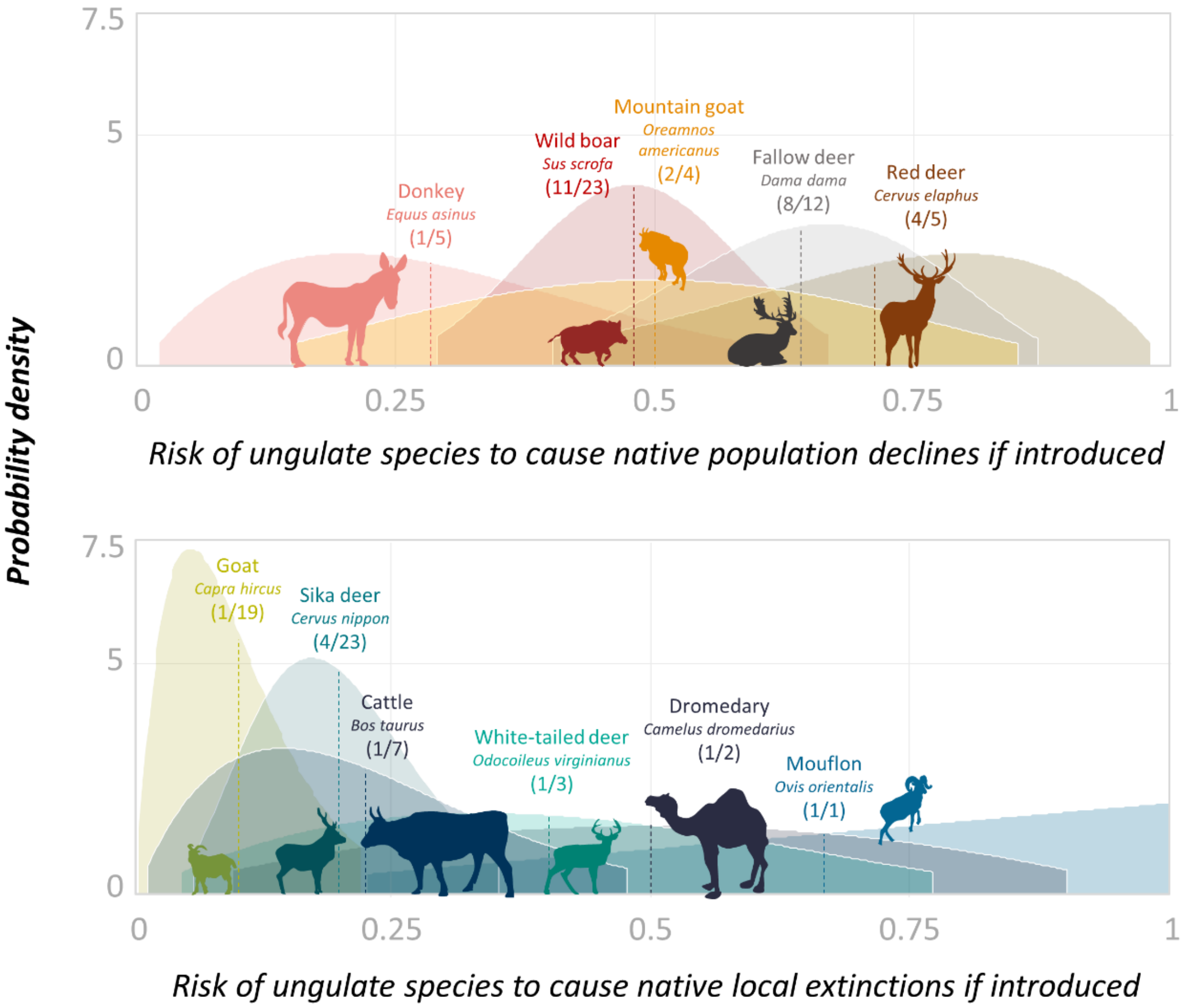
Table 2. Guidance for confidence classification (Reproduced from Appendix 2).

Sources of uncertainty that influence the confidence rating	*Presence of confounding effects*	*Study design*	*Data quality and type*	*Spatial and temporal scale*	*Coherence of evidence*
High confidence: it is likely (approximately 90% chance) that the true Impact Category is equal to the assigned one	The likelihood of including confounding effects is low (i.e. it is unlikely that the level of impact would have been observed if the alien taxon was not introduced)	The study design would have allowed the detection of higher/lower impact magnitudes than the one assigned	There is relevant direct observational evidence to support the assessment; the data are reliable and of good quality	Impacts are recorded at the typical spatial and temporal scales at which the local native population can be characterized	All evidence points in the same direction (no contradictory evidence)
Medium confidence: there is potential for the true Impact Category to be different from the assigned one (approximately 65-75% chance of the assigned impact category being correct)	Confounding effects may be at least partly responsible for the observed impact (i.e. potentially the observed level of impact would still have happened if the alien taxon was not introduced)	The study design would not have allowed the detection of higher/lower impact magnitudes than the one assigned (i.e. it cannot be reasonably excluded)	There is some direct observational evidence to support the assessment, but some of the data are inferred	Impacts are recorded at a spatial or temporal scale which may not be relevant to the scale over which the local native population can be characterized, but extrapolation or downscaling of the data to relevant scales is considered reliable or embraces little uncertainty	Most evidence points in the same direction, but some is contradictory or ambiguous
Low confidence: it is likely that the true Impact Category is different from the assigned one (approximately 35% change of the assigned impact category being correct)	The likelihood of including confounding effects is high (i.e. it is likely that the observed level of impact would have happened if the alien taxon was not introduced)	The study design does not allow any conclusions about higher or lower impact magnitudes and it is likely that the true impact magnitude is higher or lower	There is no direct observational evidence to support the assessment; data are of low quality	Impacts are recorded at a spatial or temporal scale which is unlikely to be relevant to the scale at which the local native population can be characterized, and extrapolation or downscaling of the data to relevant scales is considered unreliable or embraces significant uncertainties	Data are strongly ambiguous, or contradictory

Chapter 4 — Ranking Alien Species based on their Risks of Causing Environmental Impacts: a Global Assessment of Alien Ungulates

Lara Volery[1], Divija Jatavallabhula[1], Laura Scillitani[2], Sandro Bertolino[2], Sven Bacher[1]

[1] Department of Biology, University of Fribourg, Chemin du Musée 10, CH-1700 Fribourg, Switzerland. [2] Department of Life Sciences and Systems Biology, University of Turin, Via Accademia Albertina 13, 10123 Torino, Italy.



Abstract

For an efficient allocation of the limited resources to alien species management, the most damaging species should be prioritised. Comparing alien species based on their impacts is not straightforward, as the same species can cause different types and magnitudes of impacts when introduced to different contexts, making it difficult to summarise its overall impact. The Environmental Impact Classification for Alien Taxa (EICAT) systematically summarises and compares detrimental impacts caused by alien populations to native biota and has been adopted by the International Union for Conservation of Nature. For each alien species, all reported impacts to native populations within the introduced range are classified into five levels of severity, from negligible impact to irreversible local extinction. Currently, EICAT only compares alien species based on their highest impact, thereby ignoring variation in impact magnitudes. Here, we used information on the variation in impact magnitudes of alien species to estimate their risks to cause high impacts if introduced to a novel environment. We demonstrate the usefulness of this approach by classifying the global impacts of alien ungulates. We found impact reports for 27 of the 66 alien ungulate species established worldwide, highlighting substantial knowledge gaps in invasion science. We classified a total of 441 impacts to native fauna and flora caused by these 27 species. Twenty-six of the species were found to cause harmful impacts (native population declines or local extinctions). Mouflon (Ovis orientalis, Gmelin, 1774) and dromedary (Camelus dromedarius, Linnaeus, 1758) had a higher risk of causing local extinctions if introduced to a novel environment than sika deer (Cervus nippon, Temminck, 1838) and goats (Capra hircus, Linnaeus, 1758). Including risk of high impacts allows to discriminate among species with the same EICAT classification and improves alien species prioritisation for management.

4.1 Introduction

Alien species introductions are accumulating around the globe at increasing and concerning rates (Seebens *et al.* 2017). Though the majority of alien species are not perceived as harmful, occasionally they can cause serious impacts to their recipient environments, leading to irreversible changes, such as causing local or global species extinctions (Bellard *et al.* 2016a; Pyšek *et al.* 2017). In order to effectively allocate the limited resources available to alien species management, identifying the most damaging species for prioritization is critical (Roy *et al.* 2014, 2015). This is not straightforward because impacts can occur in different environments and through various mechanisms, and because the same species might cause different types and magnitudes of impacts when introduced to different contexts (Parker *et al.* 1999; Ricciardi *et al.* 2013), making it difficult to summarize the overall impact of an alien species in a meaningful way and thus to compare species.

The first challenge is to compare the various changes alien populations are causing in their recipient environments (Nentwig *et al.* 2010). The Environmental Impact Classification for Alien Taxa (EICAT) allows the classification of impacts in a standardized way, making comparisons among diverse taxa and impact scenarios possible (Blackburn *et al.* 2014; Hawkins *et al.* 2015; Appendix 1,2): impacts are defined as detrimental effects on local native populations and are classified into five magnitudes (from Minimal Concern to Massive), depending on which level of organisation of the native populations is affected (decreased performance of individuals, population decline, or local extinction; Table 1). EICAT can be applied to the impacts caused by any alien taxon, in any type of environment, and through any mechanism. The criteria used in EICAT for classifying impacts are independent of subjective value judgments and only rely on empirical evidence (i.e. direct observations of impact). EICAT was recently adopted by the International Union for Conservation of Nature (IUCN) as its formal classification system of alien species' impacts (Appendix 1). So far, EICAT has been implemented to classify the impacts of alien birds (Evans *et al.* 2016) and amphibians (Kumschick *et al.* 2017), marine fishes invasive to the Mediterranean (Galanidi *et al.* 2018), alien bamboos (Canavan *et al.* 2019b), gastropods alien to South Africa (Kesner & Kumschick 2018), alien terrestrial invertebrates in the pet trade of South Africa (Nelufule *et al.* 2020) and feral mammals in South Africa (Hagen & Kumschick 2018).

Under EICAT, alien species are classified and compared according to their highest recorded impact magnitude (Hawkins *et al.* 2015; Appendix 1). Using only the Maximum impact to classify alien species results in five coarse classifications. This might be uninformative when applied to larger groups of alien species (e.g. for global IUCN assessments of major taxa) because many aliens will receive the same rank. It also means that a large part of the available information about an alien's impact is ignored in the ranking, in particular the variation in impact magnitudes. For example, an alien species that has consistently been causing high impacts to native species in a variety of environmental contexts and another alien species having only occasionally caused high impacts, under very specific environmental conditions, would be classified the same under EICAT. However, it seems plausible that the former alien presents a higher risk of causing high impacts if introduced in a new place than does the latter. Since historical records of impacts can be used as a predictor of an alien's future impacts (Ricciardi 2003; Kulhanek *et al.* 2011), we propose that the frequency at which a species' introduced populations caused its highest impact magnitude could be incorporated in EICAT assessments as an indicator of the alien's risk of causing high impacts when introduced. This would allow more fine-grained comparisons among alien species: aliens with greater risks of causing high impacts could be prioritized for management over aliens with lower risks.

Table 1. The five steps impact magnitude classification of EICAT: the categories **MO**, **MR** and **MV** are considered 'harmful' categories (adapted from Appendix 1).

Impact magnitude	*Meaning/Criteria*
Minimal Concern (**MC**)	The alien causes negligible levels of impacts, but does not affect the individual performance of natives (i.e. their capacity to survive, gather resources, grow, or reproduce).
Minor (**MN**)	The alien causes reductions in the performance of native individuals, but does not cause any decline in any native population.
Moderate (**MO**)	The alien causes a decline in at least one native population, but no local extinction of any population.
Major (**MR**)	The alien causes a local extinction of at least one native population; this local extinction is reversible (i.e. if the alien population was no longer present in the area, the native population would be likely to recolonize the area through natural dispersal processes within three generations or 10 years, whichever is longer).
Massive (**MV**)	The alien causes an irreversible local extinction of at least one native population (i.e. if the alien population was no longer present in the area, the native population would not be likely to recolonize the area, for instance because of little demographic exchange between sub-populations).

Here, we present a procedure to incorporate the risk of alien species to cause their highest impact into global EICAT assessments. We demonstrate the usefulness of our approach by systematically reviewing and classifying the impacts caused by alien ungulates worldwide using EICAT. Ungulates have been extensively introduced over the world in various regions and environments for farming and hunting purposes, making them an ideal group for capturing and investigating impact variation (Long 2003; Spear & Chown 2009). We compare the ranking of alien ungulates by only considering their highest impact (current EICAT procedure) with rankings obtained by additionally considering the risk of the species to cause these highest impacts (new procedure). By estimating the risks of alien species to harm native biota through different mechanisms, this study represents a first step towards more meaningful predictions of their impacts across taxa.

In addition, we used our EICAT assessments to investigate factors associated with high impacts and biases in impact reporting. The EICAT classification allows the synthesis of available knowledge on alien species' impacts: it is therefore subject to the biases existing in invasion science. Geographic and taxonomic information biases have been already been identified in the field (e.g. Pyšek *et al.* 2008; Hulme *et al.* 2013; Evans & Blackburn 2020). Measey *et al.* (2020) recently showed that studies on high impacts (i.e. impacts involving local extinctions of native populations) require more complex designs and are more costly; this might be introducing another bias, where easy-to-demonstrate impacts are more studied because of their lower cost and complexity. On the other hand, negligible impacts are likely to be under-represented compared to higher impact magnitudes, as most studies aim at reporting impacts instead of the absence of impacts. It should also be noted that although the criteria of the five EICAT impact magnitudes are independent of subjective judgment, the assessment process is not: the assessor, by translating impact observations into one of the five EICAT category, might incorporate some biases as well (González-Moreno *et al.* 2019). However, this bias may be minimised by exchange between assessors and assessments' reviews by independent assessors (González-Moreno *et al.* 2019).

4.2 Material & Methods

4.2.1 Ungulate species with alien populations

A list of 66 ungulate species (orders Cetartiodactyla, Perissodactyla and Proboscidea), from 6 families, with established alien populations was compiled based on the Global Register of Introduced and Invasive Species (GRIIS) database (http://www.griis.org; accessed in March 2017). Proboscidea are closely related to ungulates and were included because of their functional similarity. In cases of taxonomic ambiguity (e.g. deciding whether a taxon is a distinct species or a sub-species), we followed the taxonomy of the IUCN Red List of Threatened Species (hereafter 'IUCN Red List'; https://www.iucnredlist.org). Re-introductions, introductions of hybrid populations (e.g. the introduction of *Bison bison* x *Bison bonasus* hybrids in the Caucasus mountains; Zablotskaya *et al.* 2004) and introductions of non-native subspecies were not considered.

4.2.2 Comparing impacts caused by alien species: EICAT assessments

For each of the 66 ungulate species with alien populations, we performed a search for (peer-reviewed and grey) literature reporting observations of negative impacts caused by their established alien populations on native populations (i.e. primary sources). We followed the search protocol described in Evans *et al.* (2016): search terms (e.g. 'introduced' OR 'invasive' OR 'alien' OR 'non-native' OR 'non-indigenous' OR 'feral' OR 'exotic' AND 'sika deer' OR '*Cervus nippon*') were used to find impact reports in online databases (Google Scholar [https://scholar.google.com], Web of Science [https://webofknowledge.com], the CABI's Invasive Species Compendium [ISC; https://www.cabi.org/ISC] and Google [https://www.google.com]), until no new information sources were found. Impact reports containing relevant information for EICAT assessments were selected based on the title, abstract and a screening of the content. We did not assess impact observations described in secondary sources (e.g. reviews) but always search for primary reports (but see Sheet 1 in the online supporting information of this article for inaccessible primary reports [https://doi.org/10.1111/gcb.15467; Supp. 2]). In accordance with the EICAT standards (Appendix 1; Chapter 3), only observed impacts were classified; potential, hypothetical, projected or extrapolated impacts were considered non-relevant (but see Sheet 2 for non-relevant information sources [https://doi.org/10.1111/gcb.15467; Supp. 2]). Species for which no impact observation was found were classified as Data Deficient (Appendix 1).

We classified 441 impact observations on native biota into one of the five EICAT magnitudes (Table 1), based on the EICAT guidelines (Appendix 1,2). Each impact observation was also assigned to one of 12 impact mechanisms (competition, predation, hybridization, transmission of disease, parasitism, poisoning/toxicity, bio-fouling or other direct physical disturbance, grazing/herbivory/browsing, chemical/physical/structural impact on ecosystem, indirect impact through interaction with other species), which can be grouped into direct (i.e. alien taxon directly interacts with the impacted native taxon) and indirect (i.e. alien taxon modifies another factor of the environment, thereby indirectly affecting the native taxon) mechanisms (Chapter 3). Uncertainty was captured by assigning a confidence level (high, medium or low) to each observation indicating how confident the assessor is that the assigned magnitude is the 'true' one (Appendix 2; Chapter 3). A High confidence level indicates that the assessor is confident that the assigned magnitude is the true one, a Medium confidence level indicates that there is potential for the true magnitude to be different from the assigned one, and a Low confidence level indicates that it is likely that the true magnitude is different from the assigned one. More details on the assessment procedure are given in Appendix 6a.

Each impact of a certain magnitude, associated with a confidence level, and occurring through a particular mechanism at a specific location and time (affecting one or more native species) was considered as an impact observation. For each impact observation, the following information was collected: reference of the report, quotation (extracted from the report by the assessor and used as the rationale for the assigned impact magnitude), impact magnitude, impact mechanism(s) (and type: direct vs indirect), confidence score, confidence score rationales, impacted native species (and kingdom), location of impact (precise location, region [i.e. country's sub-unit such as district, state, territory, county, etc. or island/archipelago], country, sub-continent, and continent), assessor ID, date of assessment, and reviewer ID. To minimise assessor biases (González-Moreno *et al.* 2019), all classifications of impact magnitude, mechanism and confidence score were reviewed by at least one independent expert. Discrepancies between the assessor and the reviewer were explained and a consensus score was reached after discussion. This is similar to the IDEA protocol for structured expert elicitation (Hemming *et al.* 2018), but differs in that discussion of scores was not anonymous and that consensus scores were reached (i.e. all assessors agreed on a score). All assessments and reviews were carried out by DJ, LV and LS.

Patterns in impacts and potential biases

All statistical analyses were performed in R version 3.6.2 (R Core Team 2019). We first tested whether indirect or direct mechanisms led to higher impacts, we grouped harmful (**MO**, **MR** and **MV**) against non-harmful (**MC** and **MN**) impacts (Appendix 1; Table 1) and tested for an association using a Generalized Linear Mixed-Effects Model (GLMM), with region of impact as random factor (*glmer* function of the lme4 package; version 1.1-21, Bates *et al.* 2014) to account for spatial autocorrelation. We tested this on all 441 impact observations (excluding observations occurring through both direct *and* indirect mechanisms) and we assumed that the response variable (harmful/lower impacts) followed a binomial distribution. To test whether native flora or fauna was more severely affected by alien ungulates, we again grouped harmful against non-harmful impacts and used a GLMM, with region of impact as a random factor. Mechanism type (direct/indirect) and impacted kingdom (flora/fauna) are correlated, therefore we tested them separately.

To further investigate patterns in impacts and potential information biases, we compiled a list of the countries to which each ungulate species has been successfully introduced (see Tables S1, S2 and S3 in Appendix 6 for summaries, and see Sheet 3 for the complete list [https://doi.org/10.1111/gcb.15467; Supp. 2]), based on Long (2003), the ISC (accessed in November 2020), the IUCN Red List (accessed in November 2020), the Global Biodiversity Information Facility (GBIF, https://www.gbif.org; accessed in November 2020), GRIIS (accessed in 2017), and our own EICAT assessments. We used a Linear Mixed-Effects Model (*lmer* function of the lme4 package) to test if the number of impact observations per country increased with the number of ungulate species introduced to that country, with continent as a random effect. We tested this on all countries with available impact observations, as well as on countries with no impact observations but with at least six introduced ungulate species (see Table S2 in Appendix 6). Both variables were log-transformed and the predictor variable was scaled to 0 mean and 1 standard deviation.

We used a simple linear model (*lm* function) to test if the number of impact observations of a species increased with the number of countries the species has been introduced to. We used data on all 66 ungulate species; species classified as Data Deficient were assigned as having 0 impact observations. Both variables were log-transformed and the predictor variable was scaled to 0 mean and 1 standard deviation. Finally, we used a simple linear model to test whether species causing higher impacts were more studied (log-transformed number of impact observations), and a generalized linear model (*glm* function) to test whether more widely introduced species (log-transformed numbers of countries each species has been introduced to) were causing higher impacts. For both tests, we excluded Data Deficient species and used the highest impact magnitudes for the assessed species. Distributions of residuals for all fitted (Generalized) Linear Mixed-Effects Models were interpreted using the *testDispersion* and *simulateResiduals* functions of the DHARMa package (version 0.3.3.0; Hartig 2020); with default number [n= 250] of simulations).

Comparisons of the frequency distributions of the confidence scores across impact magnitudes (harmful/lower impacts) were conducted using a Pearson's Chi-squared test (*chisq.test* function). To compare the distributions of impact magnitudes (harmful/lower impacts) across assessed vertebrate groups (ungulates, amphibians [Kumschick *et al.* 2017] and birds [Evans *et al.* 2016]), we used an unconditional exact functional test (small expected values) (*fun.chisq.test* function of the *FunChisq* package; version 2.4.9.2, Zhong & Song 2019).

4.2.3 Comparisons between alien species within impact categories: Incorporating risk to comparisons between species

We first classified all species into the impact categories based on their highest impact magnitude following EICAT guidelines (Appendix 2).

Within each EICAT impact category, we aimed to distinguish between alien species that systematically cause their highest impact magnitude when introduced to a novel environment from alien species that only occasionally cause their highest impact magnitude. Only considering the frequency at which the species' populations caused their highest impacts (e.g. 1 out of 10 introduced populations) does not account for differences in 'sampling effort' between species. For example, a species widely introduced and having caused harmful impacts every time it has been introduced would not be differentiated from a species introduced once and having caused harmful impacts. However, we can be more confident of the high risk to cause harmful impacts for the widely introduced species than for the species introduced once. The more often a species has been (successfully) introduced and studied, the more information we have on the variation in its impact magnitude and thus on its risk to cause harmful impacts when introduced. To account for these differences in 'sampling effort' among species, we calculated Bayesian binomial 95% confidence intervals (CIs) and their highest probability density (hpd) means from the frequencies at which the species' populations caused their highest impacts, using the function *binom.bayes* of the R package *binom* (version 1.1-1; Sundar, 2014) with a flat beta prior distribution ($\alpha = \beta = 1$). The hpd means were used as estimations of the species' risk of causing their highest impact magnitude when introduced (hereafter 'impact risk'). We used, for each species, the number of regions (i.e. countries' sub-units; 'region' in our EICAT dataset) with impact observations as a proxy of the number of studied introduced populations. Species with few studied regions (i.e. species introduced to few regions and/or poorly studied species) will have wide CIs, providing limited information about their impact risks, whereas widely introduced and studied species will have narrower CIs. Using the number of studied regions allowed to account for differences in country sizes.

The species' impact risks were used to rank ungulate species from the most to least detrimental within their impact category (i.e. from the one with the highest to the lowest impact risk). To test whether the impact risks of the species classified in the same impact category significantly differed from each other, we performed pairwise comparisons of their impact risks' CIs (generated based 100,000 simulations from the frequencies at which each species caused its highest impact magnitude, by using the function *rbeta* of the *binom* package). Two CIs with an overlap of < 10% were considered significantly different from each other (the R code for this significance test is provided in Appendix 6b).

4.3 Results

4.3.1 Comparing impacts caused by alien species: EICAT assessments

We found 281 reports documenting 441 impact observations for 27 of the 66 ungulate species with populations introduced outside their native range (Table 2; see Sheet 4 for the complete database [https://doi.org/10.1111/gcb.15467; Supp. 2]). The remaining 39 species were classified as Data Deficient (Table S1 in Appendix 6). In addition, we recorded 252 inaccessible primary reports and 436 non-relevant reports (e.g. reports describing potential impacts, reports describing impacts on soil properties, etc.; see Sheets 1 and 2 [https://doi.org/10.1111/gcb.15467; Supp. 2]).

Table 2. Results of the EICAT classification of the 27 assessed ungulate species, and the ranking of species from the most to the least detrimental. Species were first ranked into three categories (Major, Moderate, Minor) based on the highest impact magnitude they have reached. They were further ranked within these three categories, from the species with the higher impact risk to the species with the lower impact risk. 95% Confidence intervals given along the impact risk indicate that we can be 95% confident that the impact risk of a species lies within the upper and lower bounds (in squared brackets), and can therefore be considered as indicators of the uncertainty about each impact risk (the wider the interval, the higher the uncertainty). Impact risks were calculated from the species' frequencies of highest impact, which are the numbers of regions in which the alien species caused their highest impact magnitudes (on their total number of regions with impact observations).

Alien scientific name(s)	*Common name*	*Order*	*Family*	*Highest impact magnitude*	*Frequency of highest impact*	*Impact risk*	*Rank*
Ovis orientalis (syn. *Ovis aries musimon, Ovis ammon musimon*)	Mouflon	Cetartiodactyla	Bovidae	Major (**MR**)	1/1	0.67 [0.22; 1.00]	1
Camelus dromedarius	Dromedary	Cetartiodactyla	Camelidae	Major (**MR**)	1/2	0.50 [0.09; 0.91]	2
Rusa timorensis (syn. *Cervus timorensis*)	Javan deer	Cetartiodactyla	Cervidae	Major (**MR**)	1/3	0.40 [0.04; 0.77]	3-4
Odocoileus virginianus	White-tailed deer	Cetartiodactyla	Cervidae	Major (**MR**)	1/3	0.40 [0.04; 0.77]	3-4
Ovis aries	Sheep	Cetartiodactyla	Bovidae	Major (**MR**)	1/5	0.29 [0.02; 0.59]	5
Bos taurus	Cattle	Cetartiodactyla	Bovidae	Major (**MR**)	1/7	0.22 [0.01; 0.48]	6
Cervus nippon	Sika deer	Cetartiodactyla	Cervidae	Major (**MR**)	4/23	0.20 [0.06; 0.35]	7
Capra hircus	Goat	Cetartiodactyla	Bovidae	Major (**MR**)	1/19	0.10 [0.00; 0.22]	8
Bubalus bubalis	Water buffalo	Cetartiodactyla	Bovidae	Moderate (**MO**)	3/3	0.80 [0.47; 1.00]	9-10
Axis axis	Chital	Cetartiodactyla	Cervidae	Moderate (**MO**)	3/3	0.80 [0.47; 1.00]	9-10
Rangifer tarandus	Reindeer	Cetartiodactyla	Cervidae	Moderate (**MO**)	2/2	0.75 [0.37; 1.00]	11

Cervus elaphus	Red deer	Cetartiodactyla	Cervidae	Moderate (**MO**)	4/5	0.71 [0.41; 0.98]	12
Hemitragus jemlahicus	Himalayan tahr	Cetartiodactyla	Bovidae	Moderate (**MO**)	1/1	0.67 [0.22; 1.00]	13-14-15-16
Elephas maximus	Asian elephant	Proboscidea	Elephantidae	Moderate (**MO**)	1/1	0.67 [0.22; 1.00]	13-14-15-16
Oryx gazella	Gemsbok	Cetartiodactyla	Bovidae	Moderate (**MO**)	1/1	0.67 [0.22; 1.00]	13-14-15-16
Lama guanicoe	Guanaco	Cetartiodactyla	Camelidae	Moderate (**MO**)	1/1	0.67 [0.22; 1.00]	13-14-15-16
Dama dama	Fallow deer	Cetartiodactyla	Cervidae	Moderate (**MO**)	8/12	0.64 [0.40; 0.87]	17
Equus caballus	Horse	Perissodactyla	Equidae	Moderate (**MO**)	8/14	0.56 [0.33; 0.79]	18
Muntiacus reevesi	Reeves' muntjac	Cetartiodactyla	Cervidae	Moderate (**MO**)	4/7	0.56 [0.25; 0.85]	19
Oreamnos americanus	Mountain goat	Cetartiodactyla	Bovidae	Moderate (**MO**)	2/4	0.50 [0.15; 0.85]	20
Odocoileus hemionus	Mule deer	Cetartiodactyla	Cervidae	Moderate (**MO**)	1/2	0.50 [0.09; 0.91]	21-22-23-24
Ammotragus lervia	Aoudad	Cetartiodactyla	Bovidae	Moderate (**MO**)	1/2	0.50 [0.09; 0.91]	21-22-23-24
Cervus canadensis	Wapiti	Cetartiodactyla	Cervidae	Moderate (**MO**)	1/2	0.50 [0.09; 0.91]	21-22-23-24
Rusa unicolor (syn. *Cervus unicolor*)	Sambar deer	Cetartiodactyla	Cervidae	Moderate (**MO**)	1/2	0.50 [0.09; 0.91]	21-22-23-24
Sus scrofa	Wild boar	Cetartiodactyla	Suidae	Moderate (**MO**)	11/23	0.48 [0.29; 0.67]	25
Equus asinus	Donkey	Perissodactyla	Equidae	Moderate (**MO**)	1/5	0.29 [0.02; 0.59]	26
Bison bison	American bison	Cetartiodactyla	Bovidae	Minor (**MN**)	1/1	0.67 [0.22; 1.00]	27

Impact observations of alien ungulates were most often assigned Moderate (native population decline; 46%) or Minor (decrease in performance of native individuals; 44%) magnitudes (Fig. 1; Table S4 in Appendix 6). Eight species, the Javan deer (*Rusa timorensis*, de Blainville, 1822), dromedary, mouflon, cattle (*Bos taurus*, Linnaeus, 1758), sika deer, sheep (*Ovis aries*, Linnaeus, 1758), white-tailed deer (*Odocoileus virginianus*, Zimmermann, 1780) and goat, caused extirpations of at least one local native population (Major impacts). All alien ungulates at least once caused a decline in a native population (Moderate impact) (Table 1), except for the American bison (*Bison bison*, Linnaeus, 1758), which was only documented to cause one Minor impact. 50% impact observations were assigned a Low confidence score, 42% a Medium confidence score and the remaining 8% observations were assigned a High confidence score (Fig. 1; Table S5 in Appendix 6). Confidence scores were equally distributed across impact magnitudes (p = 0.23; Table S6 in Appendix 6).

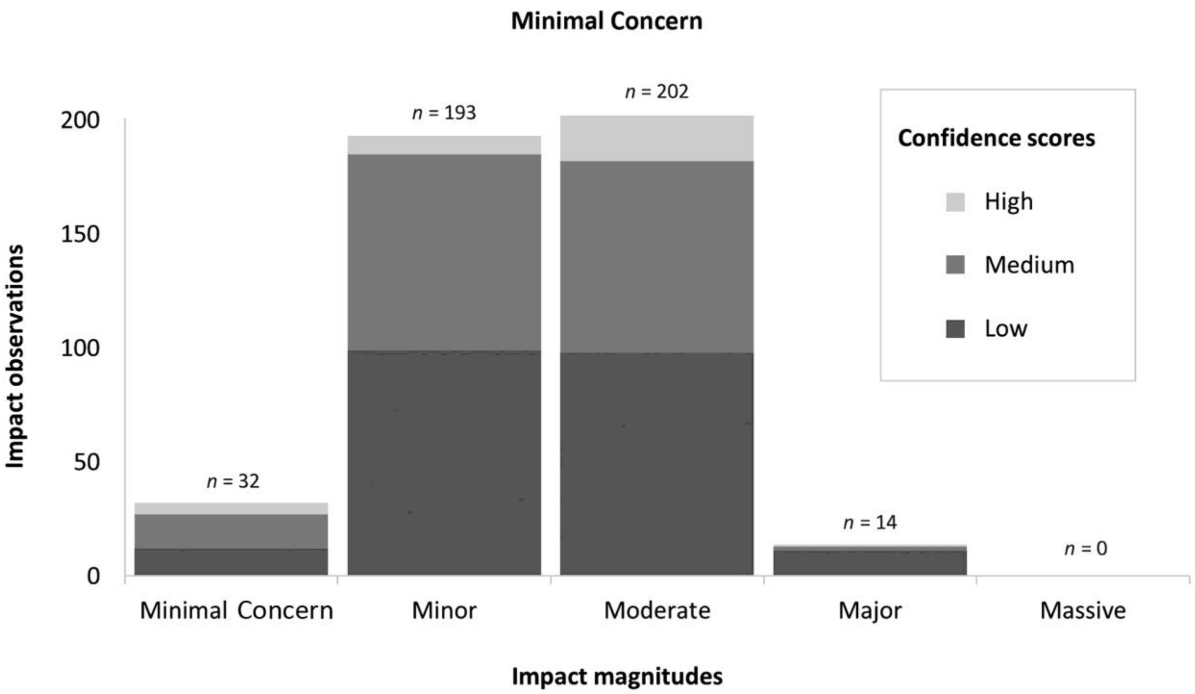


Figure 1. Impact magnitude (and their confidence scores) distribution of all impact observations of alien ungulates classified with EICAT (N = 441). Within each impact magnitude, the lighter shade (top part) represents observations classified with a low confidence score, the intermediate shade (middle part) represents observations classified with a medium confidence score, and the darker shade (bottom part) represents observations classified with a high confidence score.

Impacts of alien ungulates were caused through 8 mechanisms (Fig. 2; Table S7 in Appendix 6): the most frequently recorded mechanisms were grazing/herbivory/browsing (59%), direct physical disturbance (18%), and chemical/physical/structural impact on ecosystems (15%). Sika deer was the only species with reported impacts through hybridization in the wild, and goats and wild boars (*Sus scrofa*, Linnaeus, 1758) were the only species found to cause impacts through predation. Local extirpations of native populations (Major impacts) were only reported through grazing/herbivory/browsing (43%), hybridization (36%) and chemical/physical/structural impacts on ecosystems (21%). Native population declines (Moderate impacts) occurred through all 8 mechanisms but mainly through grazing/herbivory/browsing (55%), chemical/physical/structural impacts on ecosystems (25%) and direct physical disturbance (e.g. trampling; 18%). Indirect mechanisms (competition, transmission of disease, chemical/physical/structural impact on ecosystem, indirect impact through interaction with other species) were recorded less frequently than direct mechanisms (predation, hybridization, direct physical disturbance, grazing/herbivory/browsing) (20% vs. 80%), but led to higher impact magnitudes ($p < 0.001$; Table S8 in Appendix 6). Except for seven impact observations, plants were only affected via direct mechanisms, whereas animals were mostly (64%) indirectly affected. Native plants were affected more than twice as often as native animals (70% vs. 30%; Table S9 in Appendix 6), but animals were affected more severely than plants ($p = 0.004$; Table S10 in Appendix 6). However, we found both native plants and native animals to have suffered local extirpations (Major impacts).

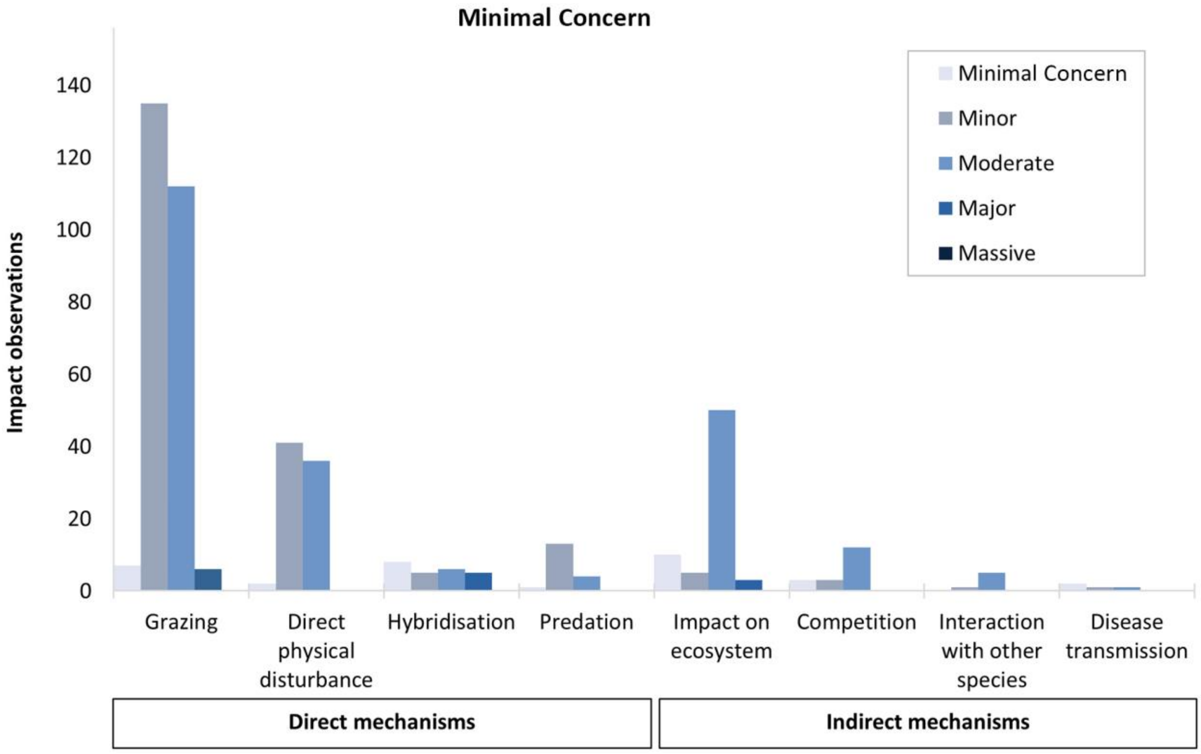


Figure 2. Impact mechanism distribution of all impact observations of alien ungulates classified with EICAT. Impact mechanisms can be grouped into direct and indirect mechanisms. Within each impact mechanism, the different blue shades represent observations classified into the five impact magnitudes. No Massive impacts were recorded for any species, under any of the mechanisms. Impact mechanisms can be classified as direct (i.e. alien taxon directly interacts with the impacted native taxon), or indirect (i.e. alien taxon modifies another factor of the environment, thereby indirectly affecting the native taxon).

For most indirect mechanisms, we found more reports describing the possibility that alien species cause impacts or describing impact mechanisms than reports describing impact magnitudes. For instance, for the mechanism competition, we found 60 sources showing diet or niche overlap (see Sheet 2 [https://doi.org/10.1111/gcb.15467; Supp. 2]), which were not used in the EICAT classification, but only 18 direct observations of competition impacts (classified with EICAT). Likewise, for transmission of disease, 20 articles showed that alien or native individuals were hosts of parasites, but only 4 studies reported how much native individuals or populations were suffering from the infection (see Sheet 2 [https://doi.org/10.1111/gcb.15467; Supp. 2]). Several articles described alien ungulates as dispersal agents of alien plants or fungi (e.g. Loydi & Zalba 2009; Davis *et al.* 2010; O'Connor & Kelly 2012), but the consequences of this for native species were not measured, preventing their classification under EICAT. By contrast, this was not the case for the indirect mechanism 'chemical/physical/structural impact on ecosystems', for which impact magnitudes were often studied (in 68 impact observations).

Impact observations of alien ungulates were recorded in 34 countries on seven continents, but mainly in the United States (27%), New Zealand (14%), the United Kingdom (11%), Australia (11%), Canada (9%) and Argentina (5%) (Fig. 3; Table S2 in Appendix 6). Although we found the number of impact observations for a country to generally increase with the number of introduced ungulate species (Table S11 in Appendix 6), we identified reporting biases. For several countries with high numbers of introduced ungulate species, such as South Africa, France, Germany, the Russian Federation, Cuba, Papua New Guinea and Columbia, we found no, or few, impact reports (Fig. 3). We found a continental reporting bias, where Asia, Africa and Europe had fewer impact reports than other continents relative to their number of introduced ungulate species, while Northern America was the most-studied continent (Fig. S1 in Appendix 6). Local extirpations of native populations (Major impacts) have been reported in Europe (6: Ireland, United Kingdom and Czech Republic), Northern America (5: United States and Canada), Oceania (2: Australia and New Caledonia) and South America (1: Brazil). Of all the species that caused local population extirpations, only sika deer caused them in different regions (in 4 out of the 23 regions with impact observations; Table 2).

The impact of widely introduced species (i.e. species introduced to many countries) was generally more often studied than the impact of species introduced to few countries (p < 001; Table S12 in Appendix 6). By contrast, species having caused local extinctions were not more often studied than other species (p = 0.14, Table S13 in Appendix 6), as more widely introduced species did not cause more local extinctions (p = 0.12, Table S14 in Appendix 6).

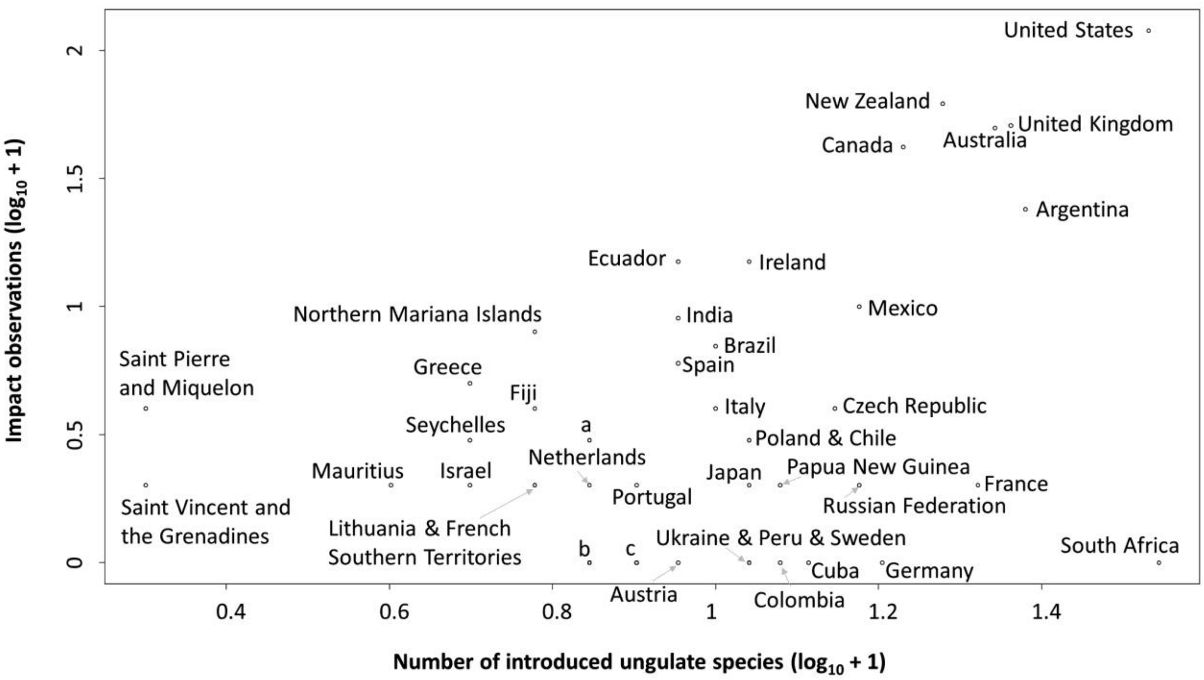


Figure 3. Relationship between the number of impact observations found per country, and the number of introduced ungulate species per country (see Sheet 3 [https://doi.org/10.1111/gcb.15467; Supp. 2]). Countries towards the top right are well-studied countries with many introduced ungulate species; countries towards the bottom right are countries with many introduced ungulate species but comparatively few impact observations. The letter a. stands for New Caledonia and the Falkland Islands, the letter b. stands for Bolivia, Denmark, Finland, Grenada, Haiti, Indonesia, Kazakhstan, Latvia, Madagascar, Saint Kitts and Nevis, Sao Tomé and Principe, Slovenia, Sri Lanka, Switzerland, Vanuatu, Venezuela and Yemen, and the letter c. stands for Antigua and Barbuda, Belgium, China, Kyrgyzstan, Malaysia and Slovakia.

4.3.2 Comparisons between alien species within impact categories: Incorporating risk in comparisons between species

Classifying and comparing ungulates based on their highest impact magnitude, as proposed in the current EICAT procedure, resulted in only three categories (Table 2): only one species (4%) did not cause a higher impact than a decreased performance of native individuals (classified in the Minor category), two thirds of the species (18 species; 66%) caused at least once a native population decline (Moderate category), and about one third (8 species; 30%) caused at least once a (reversible) local extinction (Major category).

When further ranking ungulates within each of these three categories based on their impact risks, i.e. how frequently they would cause their highest impact magnitude, the mouflon was ranked highest among the seven species of the Major category, with the dromedary ranking second (Table 2). Due to the generally low numbers of regions with impact observations for each species, a high uncertainty existed regarding their risks of causing Major impacts. Species with impact observations from less than five regions, such as the mouflon, dromedary, Javan deer and white-tailed deer, had the widest 95% CIs (Fig. 4a), resulting in very little information about their risk of causing Major impacts. The narrower CIs of cattle and sheep (impact observations from 5 to 10 regions; Fig. 4b) indicated a slightly higher confidence about their impact risks, and the relatively narrow CIs of the goat and sika deer (impact observations from > 10 regions) provided the most informative impact risks in the Major category (i.e. impact risks with lowest uncertainty) (Fig. 4c). Species' pairwise comparisons revealed that the mouflon had a significantly higher risk of causing Major impacts than the goat and sika deer, and that the dromedary had a significantly higher risk than the goat (Table S15 in Appendix 6). The impact risks of the other species classified in the Major category did not significantly differ from each other (Table S15 in Appendix 6).

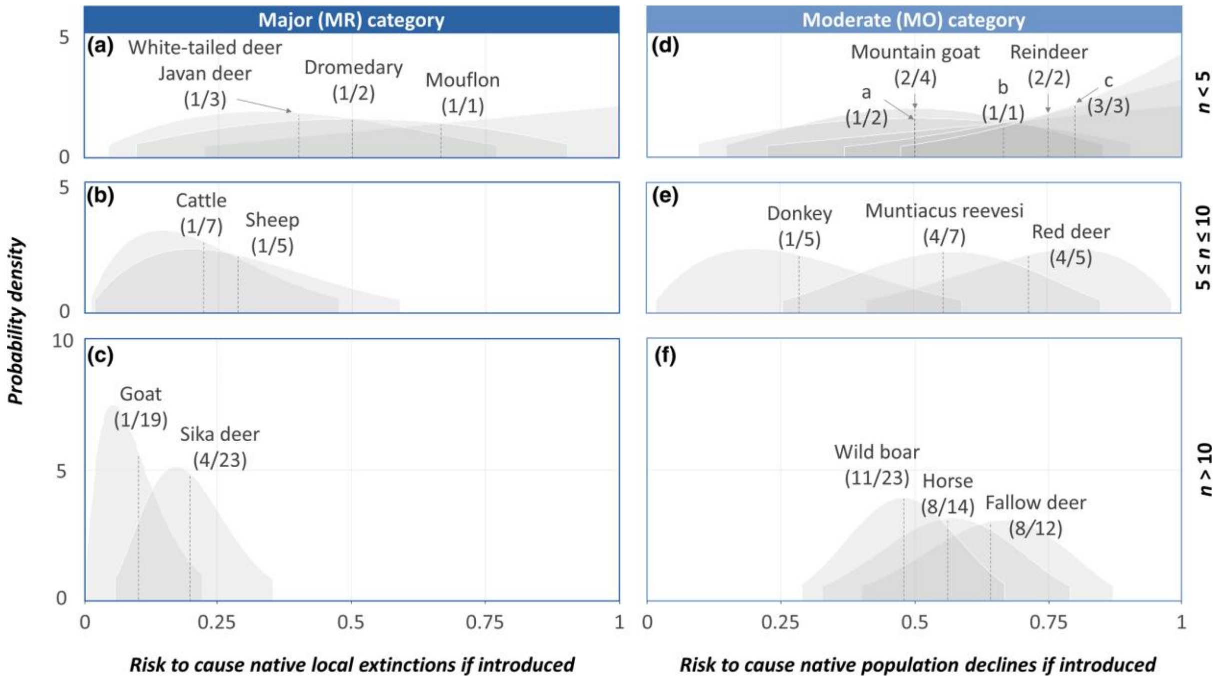


Figure 4. Impact risk of the 26 alien species classified in the Major (left column; i.e. species whose alien populations have led to at least one documented local extinction of a native species) or Moderate (right column; i.e. species whose alien populations have led to at least one decline in a native population) categories. Impact risk is represented by the mean (vertical dashed lines), with beta density probability distributions providing 95% confidence intervals. Frequencies given after the species names indicate the numbers of regions (i.e. countries' sub-units) in which each alien species reached its highest impact magnitude/on the total number of regions with impact observations. For better visualization, the species have been split into three groups: (a) and (d) show species with wider confidence intervals and high uncertainty in their risk of causing their highest impact magnitude (< 5 regions with impact observations [n]); (b) and (e) show species with intermediate confidence interval widths and medium uncertainty in their risk of causing their highest impact magnitude (5 ≤ n ≥ 10); and (c) and (f) show species with narrow confidence intervals and lower uncertainty in their risk of causing their highest impact magnitude (n > 10). In (e), the letter a. stands for the mule deer, aoudad, wapiti and sambar deer, the letter b. stands for the Himalayan tahr, Asian elephant, gemsbok and guanaco, and the letter c. stands for the chital and water buffalo.

Within the Moderate category, most species (12/18) had few regions with impact observations (< 5), providing little information about their risk to cause Moderate impacts (Fig. 4d-f). Therefore, pairwise comparisons between the species classified in the Moderate category revealed that their impact risks were rarely significantly different (Table S16 in Appendix 6). The only significant differences concerned the donkey (*Equus asinus*, Linnaeus, 1758), ranked as the least detrimental species of the Moderate category, which was found to have a lower impact risk than the reindeer (*Rangifer tarandus*, Linnaeus, 1758), water buffalo (*Bubalus bubalis*, Linnaeus, 1758), chital (*Axis axis*, Erxleben, 1777), fallow deer (*Dama dama*, Linnaeus, 1758) and red deer (*Cervus elaphus*, Linnaeus 1758) (Table S16 in Appendix 6). The wild boar had the most numerous impact observations (63 impact observations) and still never reached a higher impact than the Moderate category.

4.4 Discussion

We used the EICAT classification to compare 441 impacts caused by 27 alien ungulates on the native fauna and flora in their recipient environments, by systematically classifying them into five impact magnitudes. Based on these individual impacts, an overall environmental impact should be assigned to each alien species, to enable comparisons between them and the prioritization of the most damaging ones. EICAT only discriminates five impact categories, by comparing species based on their highest impact magnitude (Appendix 1), which limits its practical use for prioritization if many species are compared. When comparing alien ungulates based on their highest impact magnitude, 26 out of 27 species were classified in the harmful EICAT categories (i.e. MO, MR and MV). Comparisons of impacts across taxa (e.g. an animal species *vs* a plant species) are crucial for informing decisions about which species to manage, as resources for management are usually allocated to priority alien species without taxonomic distinction (Kumschick *et al.* 2015a). However, if too many species end up in high-impact categories (which is likely once many species from different taxa will be assessed), EICAT classifications become uninformative for prioritization. When we compare the EICAT impacts of alien ungulate species with the EICAT impacts of species from other taxonomic groups for which global assessments exist, such as alien amphibians (Kumschick *et al.* 2017), birds (Evans *et al.* 2016) and bamboos (Canavan *et al.* 2019), a total of 196 species are classified within the five EICAT categories (Table 3): almost half (44%) of the species are classified in the harmful categories.

Table 3. Contingency table of the EICAT classifications of alien ungulates, amphibians (Kumschick *et al.* 2017), birds (Evans *et al.* 2016) and bamboos (Canavan *et al.* 2019): number of species assigned to different impact magnitudes. Bold values provide the total numbers of species classified in each impact magnitude (**MC**, **MN**, **MO**, **MR** and **MV**), and the total numbers of assessed species for each taxonomic group; italic values provide the total numbers of species having caused harmful (**MO**, **MR** and **MV**) and lower (**MC** and **MN**) impacts in each taxonomic group (and across all taxonomic groups: bold and italic values).

Impact magnitude		*Alien ungulates*	*Alien amphibians*	*Alien birds*	*Alien bamboos*	*Total*
Lower impacts	Minimal Concern (**MC**)	0	4	36	0	***40***
	Minor (**MN**)	1	20	46	2	***69***
		1	*24*	*82*	*2*	***109***
Harmful impacts	Moderate (**MO**)	18	7	28	2	***55***
	Major (**MR**)	8	5	4	6	***23***
	Massive (**MV**)	0	4	5	0	***9***
		26	*16*	*37*	*8*	***87***
	Total	***27***	***40***	***119***	***10***	***196***

4.4.1 Improvement of the EICAT ranking: impact risks

Integrating impact risk allowed the consideration of the variation in species' impacts, which is ignored in final EICAT scores. Based on this risk, we discriminated among species that have caused local extirpations of native species, which are all scored in the same EICAT category. The mouflon was identified as the worst alien ungulate. We showed that the mouflon is more likely than the goat and sika deer to cause native local extirpations, and that the donkey is less likely to cause native population declines than the reindeer, water buffalo, chital, fallow deer and red deer. Similarly, we found that it is unlikely for the wild boar to cause Major impacts; although it is the species with the most impact observations, none of them documented a Major impact. However, as most ungulate species were only studied in few regions (63% had impact observations from less than five regions), we did not find other significant differences between their impact risks, because of the large overlap of their wide CIs.

EICAT identifies knowledge gaps for species with no impact reports as they are classified as Data Deficient; for the IUCN Red List, the classification of species within the Data Deficient category has been shown to efficiently redirect priorities of research efforts towards these species (Jarić *et al.* 2017).

Considering the impact risk allowed to identify knowledge gaps for species with impact reports only available for a small region of their total introduced range. Some species have rarely been introduced (e.g. Asian elephant (*Elephas maximus*, Linnaeus, 1758) or gemsbok (*Oryx gazella*, Linnaeus, 1758); Table S3 in Appendix 6); however, other widely introduced species, such as the mouflon, white-tailed deer or water buffalo (Table S3 in Appendix 6), have been studied in only few of the regions to which they were introduced. This prevents the accurate evaluation of their impact risks, because information on the variation in their impacts is not available. The impact of such species needs to be described in other parts of their introduced range to get more representative data on their impacts and for improved comparisons with other species. The number of data points largely determines the width of the CIs, thus, adding more impact reports from a variety of regions to the database will be the most efficient way to improve impact rankings. Like the EICAT classification (Hawkins *et al.* 2015), our assessment of the impact risks of alien ungulates should be dynamic and updated with new observations, and the ranking should be adapted based on new evidence.

The ranking of the worst ungulates presented in this article is only based on the species' risks of causing impacts. However, other aspects must be considered in management decisions, such as the management feasibility and costs, or the species' risk of being introduced and of establishing and spread. Several frameworks have been developed to combine all these different aspects in the decision process (e.g. Bertolino *et al.* 2020; Kumschick *et al.* 2020).

4.4.2 Comparisons with other rankings

Our ranking of alien ungulates with the highest impacts can be compared with other rankings. Several non-quantitative listings of the most detrimental aliens have been produced based on expert opinion: the IUCN Invasive Species Specialist Group (ISSG) listed the goat, red deer and wild boar on their '100 of the world's worst invasive alien species' list (Lowe *et al.* 2000; Luque *et al.* 2014). At the European scale, Carboneras *et al.* (2018) established a prioritization list for risk assessments, with the sika deer and American bison evaluated as first priority species, and the chital and dromedary as second priority species, because of their high impacts. While these listings are consistent with our ranking regarding some species (e.g. sika deer, dromedary and goats as priority species), the selection of other species might have been subject to expert opinions rather than based on evidence of high impacts (Nentwig *et al.* 2010). For instance, species ubiquity might have biased expert opinions, as the wild boar, red deer and chital are all part of the 12 most widely introduced ungulates (Table S3 in Appendix 6).

Bellard *et al.* (2016b) evaluated the most damaging aliens to vertebrates by analysing their main threats listed in the Global Invasive Species Database (GISD) and IUCN Red List. They evaluated wild boar, goat and cattle as the fifth, sixth and respectively seventh most threatening alien species (i.e. threatening the largest numbers of vertebrate species; after the amphibian chytrid fungus (*Batrachochytrium dendrobatidis*), rats, cats and dogs). In our study, we found the sika deer to have caused several extinctions of red deer populations through hybridization, making it the most damaging alien ungulate for native vertebrates based on our criteria. We found wild boars to affect vertebrates in 23 impact observations, goats in 11 observations and cattle in only one: neither species caused local extinctions; the highest impacts were declines in vertebrate populations. Still, consistent with the findings of Bellard *et al.* (2016b), we also found wild boars and goats to represent important threats to native vertebrates on islands: they both led to population declines of vertebrates on almost half of the archipelagos they have been introduced to (6/15 archipelagos compared to 1/5 mainland regions for goats; 4/12 archipelagos compared to 0/11 mainland regions for wild boars).

Nentwig *et al.* (2018b) ranked 498 invasive alien species introduced to Europe, from the most to the least detrimental, based on their environmental and socio-economic impacts, classified with the Generic Impact Scoring System (GISS; Nentwig *et al.* 2010, 2016). GISS is an additive scoring system which classifies impacts from 0 to 5 via 12 mechanisms: the overall impact of an alien is summarized by summing the highest score of each mechanism. Nentwig *et al.* (2018) ranked species by combining two ranking approaches: based on their GISS overall scores and by the number of the highest impact scores (i.e. maximum impact, analogous to the EICAT procedure). Six ungulates were listed among the 149 worst aliens (excluding domestic species and only considering species alien to—and successfully introduced in—Europe). In order of the most to the least detrimental, these were: sika deer, reeves' muntjac (*Muntiacus reevesi*, Ogilby, 1839), chital, aoudad (*Ammotragus lervia*, Pallas, 1777), white-tailed deer and mouflon. Our ranking of these species is quite different (Table 2). As highlighted by Nentwig *et al.* (2018), the two ranking approaches they used have benefits: GISS overall scores inform on the variation in the species impact, whereas maximum impacts identify species with potential of causing high impacts. However, the drawbacks of additive scoring systems in prioritization are well known (e.g. Game *et al.* 2013). The GISS overall score is indeed biased: widely studied species will rank higher than poorly studied species (as mechanisms without data score 0) and species causing impacts through multiple mechanisms will rank higher than species causing impacts through a single mechanism. Our ranking system captures intraspecific variation without adopting an additive system and captures uncertainty associated with small sampling effort.

4.4.3 Reporting biases

Indirect impacts are reported mainly when they are severe

Native animals were found to be more severely impacted by alien ungulates than native plants, because, in contrast to native plants, they were mainly affected via indirect mechanisms. An explanation for indirect impacts to be associated with more severe impacts might be that indirect negligible or minor impacts are difficult to detect. When interactions between species can be directly observed (e.g. an alien deer grazing on a native plant), impacts are assumed and studied. However, for indirect impacts to be studied they must first be detected, which is easier if impacts are severe. Moreover, as indirect impacts are more difficult to demonstrate, studies usually focus on studying the mechanisms, rather than on quantifying impact magnitudes. Spear and Chown (2009) also observed a lack of robust evidence for impacts occurring through competition on the native fauna in contrast to direct impacts to the native vegetation through herbivory.

Biases in impact magnitudes

A potential bias towards studies requiring simpler designs has already been highlighted by Measey *et al.* (2020), who found that studies showing native local extinctions are more costly because of the complexity of their designs. In our study, we indeed found only few observations of native local extinctions in comparison to other impact magnitudes. This alone does not indicate a bias, as it is likely that local extinctions caused by alien species occur less frequently than lower impacts. However, for 19% of the observations classified with a Moderate impact magnitude, the assessor specified that the impact might have been higher (i.e. that the alien might have led to a local extinction), but that the design of the study did not allow to determine whether this was the case (see EICAT assessments, Sheet 4 [https://doi.org/10.1111/gcb.15467; Supp. 2]). Similarly, for 91% of the Minor impacts, the assessor specified that the impact might have been higher but that the study did not investigate changes at the native population level (or not adequately). Thus, native local extinctions and population declines might have been under-evaluated, probably because most impact reports focus on what is easier and less costly to demonstrate (Measey *et al.* 2020).

On the other hand, it is likely that negligible impacts (Minimal Concern impacts) are not frequently reported as studies will focus on demonstrating impacts rather than the absence of impact, i.e. the so-called file drawer problem (Sterling 1959). In our study, only 7% of impact observations reported negligible impacts, which might be a strong under-representation. This is also seen in the IUCN Red List where research effort is biased towards species expected to be threatened (Bachman *et al.* 2019). To prevent this bias, the IUCN Red List recently reduced the data requirements for assessing non-threatened species (‘Least Concern’ category) (IUCN 2016; Bachman *et al.* 2019), and approaches to rapidly assess these species from open-sources databases have been developed (Rivers 2017; Bachman *et al.* 2020). Such rapid assessment approaches for negligible impacts of alien populations could be developed in EICAT, in order to decrease this bias and improve the quantity of available information about the intraspecific variation in impacts.

Taxonomic and geographic biases

Data availability concerning impacts of aliens has been shown to be unevenly distributed around the world (Pyšek *et al.* 2008; Hulme *et al.* 2013) and in alien birds, mainly determined by their alien range (Evans *et al.* 2018a; Evans & Blackburn 2020). Like for other taxa (Pyšek *et al.* 2008; Evans & Blackburn 2020), we found that impacts were more frequently studied in regions with more introduced ungulate species. We also found that Asia and Africa were understudied compared to other continents: this is often explained by the generally lower economic development and wealth of these continents resulting in a smaller research effort (Pyšek *et al.* 2008; Evans & Blackburn 2020). However, we also found impacts of alien ungulates to be relatively less studied in Europe. This might indicate a language bias, where reports in their regional language might not often be translated into English and thereby poorly represented in the literature. This is supported by the fact that the most-studied countries were all English-speaking (United States, New Zealand, United Kingdom, Australia and Canada; Fig. 3). Increased efforts should be made to identify and include non-English reports in assessments to counter this language bias.

Like for alien birds (Evans *et al.* 2018a), we found the impact of widely-introduced alien species to generally be more studied than the impact of rarely-introduced species. This might be also true when comparing different taxonomic groups: alien ungulates are among the most widely introduced groups and we found them to be equally well, or better, studied than alien birds, amphibians and bamboos: 59% of the ungulate species were classified as Data Deficient, compared to 62% for amphibians (Kumschick *et al.* 2017), 71% for birds (Evans *et al.* 2016) and 85% for bamboos (Canavan *et al.* 2019). This does not necessarily indicate a bias, as more widely introduced species or taxa likely cause more numerous impacts overall, because of their multiple introduced populations. Also, the more widely a species is introduced, the higher is its chance to be introduced to a country where impacts of aliens are well-studied. By contrast, unlike previous findings on birds (Evans *et al.* 2018a) and plants (Pyšek *et al.* 2008), we did not find alien ungulates causing higher impacts to be more studied.

4.4.4 Study limitations

So far, the EICAT system does not propose a method to consider different levels of uncertainty associated with impact assessments in the final species ranking. Hence, all impact reports were given the same weight when summarizing the results, regardless of the confidence assigned to them. Half of the impact observations were assigned a low confidence score, and 5 out of the 8 species of the Major category (Javan deer, mouflon, cattle, sheep, goat) were classified based on impact observations with low confidence scores. However, we did not find differences in the distribution of confidence levels across impact magnitudes, indicating no general bias in our species ranking due to uncertainty associated with the quality of the EICAT assessments. Ultimately, this type of uncertainty would need to be considered in the final ranking, as it might make sense to prioritize species causing high impacts with high certainty over species with uncertain impacts (Annexe 3).

4.4.5 Future research: towards predictions of impacts

Comparing impacts of different taxonomic groups

Impact magnitudes are not randomly distributed among taxa. Comparing our results to other vertebrates that were also assessed using EICAT, alien ungulates caused higher impacts than alien birds and amphibians ($p < 0.001$; Table S17 in Appendix 6). These findings corroborate previous studies at the European level that alien mammals generally cause higher impacts than other animals (Kumschick *et al.* 2015a). Even though great variation among species has been found within all the compared taxonomic groups (see Table 3), comparisons between taxonomic groups (mammals *vs* birds and amphibians) can help improving our general understanding of impacts. For instance, the generally higher impacts of alien ungulates could be explained by their role as ecosystem engineers and their large influences on community compositions and ecosystem processes (e.g. nitrogen cycle or fire regime), through selective foraging, seed dispersal, trampling, etc. (e.g. Rooney 2009; Lecomte *et al.* 2019; Velamazán *et al.* 2020).

Understanding impacts by studying context

In this study, we aimed at approximating the global impact risks of alien ungulates. When setting priorities for regional management, it is important to compare species only based on impacts potentially relevant for the region of interest. To achieve this, we need to understand the conditions associated with high and low impacts. EICAT (and GISS) assessments have already been used in attempts to explain variation in impact magnitude across species, but not within species (EICAT: Evans *et al.* 2016, 2018b; Kumschick *et al.* 2017; Kesner & Kumschick 2018; GISS: Nentwig *et al.* 2010, 2018b; Kumschick *et al.* 2015a). Ignoring intraspecific variation represents a loss of crucial information when context-dependency is investigated. In this study, we provide a dataset capturing inter- and intraspecific variation in impacts. Future research can build on this dataset to identify potential drivers of this variation, across and within alien ungulate species. A recent framework identified three types of factors and their interactions that explain invasions: alien species traits, location characteristics, and event-related factors (Pyšek *et al.* 2020b). This framework can guide the quest for a better understanding of the context-dependency of impact magnitudes.

Global Impact Database

Many EICAT studies provided little information on the assessments and did not publish their raw data; most of them only provided the highest impact magnitude per species (Evans *et al.* 2016; Kumschick *et al.* 2017; Kesner & Kumschick 2018; Nelufule *et al.* 2020; but see Galanidi *et al.* 2018; Hagen & Kumschick 2018; Canavan *et al.* 2019). This prevents others from calculating the impact risk of species for cross-taxonomic comparisons or study context dependence of impacts. Likewise, some studies did not provide uncertainty estimates (Kumschick *et al.* 2017; Hagen & Kumschick 2018; Nelufule *et al.* 2020), preventing quality checks of classifications and leaving room for inconsistencies (González-Moreno *et al.* 2019). Thus, incomplete publication of raw data from EICAT assessments limits the progress in understanding the variation of impacts. We strongly recommend that future studies performing EICAT assessments provide complete assessments, encompassing all impact observations - and not only the highest - to have a full picture of the impacts of an alien species and to allow relevant analyses of these.

We advocate the creation of a public, freely-accessible Global Impact Database in which all impact reports could be deposited (see also Strubbe *et al.* 2019). EICAT could play a pivotal role in that it offers a standardized way of collecting data. A Global Impact Database will render the information directly accessible to policy makers and the public (instead of distributed in scientific publications; (Cadotte *et al.* 2020) and will allow global analyses looking for potential patterns in impacts across alien taxa and/or recipient environments.

Author contributions

Lara Volery and Sven Bacher conceived the study; Lara Volery, Divija Jatavallabhula and Laura Scillitani collected data; Lara Volery and Sven Bacher analysed data; Lara Volery, Sandro Bertolino and Sven Bacher wrote the first draft; all authors commented and approved the final paper.

General Discussion

Key messages and findings

Chapter 1

The quantification of alien species' impacts must consider the temporal dynamics of the system. In Chapter 1, we provided a conceptual impact framework to account for temporal dynamics and provided two metrics for the impacts of alien species, one measuring impact magnitude and one measuring the rate of change in the impact magnitude. The proposed metrics are readily applied to other impacted variables such as biodiversity indicators, human well-being, or economy, and allow for comparisons of alien species' impacts across time, taxa, and regions, as well as with impacts caused by other anthropogenic stressors. The metrics also allow to quantify interactive effects between alien species and other stressors; we discuss how these can vary over time.

Chapter 2

Impacts caused by alien species can occur through a wide range of mechanisms; direct mechanisms are easy to observe and understand, while indirect impacts are more subtle and complex. We show that many of these have been overlooked in reviews on indirect impacts, which have so far focused on the well-known and -studied indirect mechanisms. Chapter 2 aimed at improving our understanding of indirect mechanisms, by providing a comprehensive classification capturing their complexity. We showed that indirect impacts can occur through any combination between direct (and/or indirect) impacts, and through different mediators like other populations, abiotic factors, or other stressors. Our classification will be of particular use for impact management and mitigation, as it can be used to identify alternative management strategies to alien eradication or control, which would rather target the intermediate steps of indirect impacts.

Chapter 3

In Chapter 3, we explained the rationales behind the revisions that were brought to the initial EICAT guidelines. Among other revisions, we broadened existing mechanisms to capture overlooked indirect mechanisms, we removed the dual assessment in which a current impact was evaluated because this approach was inaccurately capturing variation in impacts, and we addressed important but overlooked sources of uncertainty in impact assessments.

Chapter 4

In Chapter 4, we used the EICAT framework to classify the reported impacts caused by alien ungulates worldwide. We found that on the 27 assessed species; all except one caused at least one local population declines when introduced, and 8 caused at least once a local extinction. We developed a method for measuring the risk of each species to cause impacts, based on the proportion of introduced locations where it caused its highest EICAT impact magnitude. This approach summarizes the overall impact of an alien species by considering variation in its impact across contexts. It thereby provides more information for prioritization than just the five EICAT impact magnitudes. The lack of information about the variation of an alien species' impact across its invaded range prevented the accurate evaluation of their risk of causing high impacts, and hence limited our ability to compare species. The impact of alien species should be described across their whole invaded ranges (or larger parts of their invaded ranges), to better inform on impacts' context-dependency.

Measuring impacts' temporal dynamics

In Chapter 1, we provide metrics for quantifying impacts of alien species and briefly described how the uninvaded trajectory could be forecasted for applying our metrics. Different study designs and types of data can be used to forecast the uninvaded trajectory, which I discuss below in more details.

Estimating the uninvaded trajectory

Estimating the uninvaded trajectory may be done by inferring the trajectory from measurements before the alien introduction or removal (Before-After designs: 'BA'), from the trajectories of other populations in a similar context but at sites uninvaded by the alien or where the alien has been removed (Control-Impact designs: 'CI'), or both (Before-After-Control-Impact designs: 'BACI') (Chapter 1).

In invasion science, most studies quantify impacts using CI designs because they are the most logistically feasible (Crystal-Ornelas & Lockwood 2020), although they perform less well than BA and BACI designs, even with large sample sizes (Christie *et al.* 2019). CI designs assume that the observed difference between the uninvaded and invaded trajectories is caused by the presence of the alien, and that no local disturbance or environmental characteristic influences only one of the trajectories. However, the assumption cannot be tested (although statistical matching might help accounting for some biases [Schleicher *et al.* 2020]), which can lead to strong biases in impact quantification (Christie *et al.* 2019).

BA designs assume that the uninvaded trajectory would have continued in the same way as if the alien had not been introduced. When this is true, the prediction of the uninvaded trajectory can be achieved through simple extrapolation of the trajectory measured in the uninvaded situation. However, this approach might lead to inaccurate predictions when other stressors influence the native population's trajectory, because the intensity or frequency of these stressors can evolve over time, which might lead to variability in the general trend (Oliver & Roy 2015; Jackson *et al.* 2021). Moreover, Keith *et al.* (2015) showed that although past population trajectories were good predictors of future trajectories for birds, declines in mammals and fishes were often followed by increases, possibly due to density-dependent processes or conservation actions.

BACI designs are a combination of BA and CI designs and have been shown to perform better than these simpler designs (Christie *et al.* 2019), because they circumvent their respective limitations. BACI designs make the assumption that, without the alien introduction, the invaded trajectory would have had a parallel trend to the uninvaded trajectory (Stewart-Oaten *et al.* 1986). Therefore, like for CI designs, no local factors should influence only one of the trajectories; however, in contrary to CI designs, this assumption can be directly tested. The control and invaded situations can be statistically matched (see e.g. Stuart 2010; Linden 2018; Schleicher *et al.* 2020), so that the uninvaded trajectory can be directly inferred from the control situation. Although they are logistically more demanding, BACI designs are the most accurate at estimating impacts (Christie *et al.* 2019).

Alternatively, if information on other uninvaded situations is not available, the invaded situation can be studied alone. In such cases, the uninvaded situation can be modelled with mechanistic models, if the mechanism of interaction is easily identifiable (e.g. competition and disease transmission between the alien grey squirrel and the native red squirrel [Tompkins *et al.* 2003]). When the mechanism of interaction is unclear, simple correlative models or phenomenological models can be used to test how changes in alien abundance over time influence native abundance. When other stressors influence the native trajectory, or conservation measures are being undertaken, these drivers would also need to be included in the model, to consider the effect of their temporal dynamic on the native trajectory (Oliver & Roy 2015; Jackson *et al.* 2021). To calibrate and validate models, sufficient data must be collected on the variation in the native and alien populations, and in the potential other driver(s). Obviously, the more interacting stressors, the more parameters need to be estimated and the more data need to be collected. However, a good compromise between the excessive complexity of considering all possible drivers and the simplistic approach of considering only one driver is to identify only the minimum number of key stressors (empirically or based on expert opinion) (Oliver & Roy 2015). Moreover, the evolution of drivers can be directly measured, in contrast to anticipatory predictions, where their evolution must be estimated.

Data availability

Long-term studies are logistically more demanding than short-term studies; additionally, they are slow to deliver answers when these would often be urgently needed. We showed that long-term data are not necessary for accurately quantifying alien species' impacts, as long as uncertainty is accounted for. When the variable of interest exhibits high variability, the resulting uncertainty in an impact measure can be substantial (Chapter 1).

Replicating sampling efforts across invaded areas would increase the accuracy of impact measurements in such cases (Chapter 1). Alternatively, large-scale and long-term datasets of biodiversity monitoring resulting from citizen science projects or remote sensing methods (e.g. BioTIME [Dornelas *et al.* 2018] or the Pan-European Common Bird Monitoring Scheme [PECBMS, https://pecbms.info]) are becoming more and more available and would provide relevant data for quantifications of alien species' impacts (Appendix 5). Invasion scientists are ever more calling for such routine tracking of alien species and of their impacts (Latombe *et al.* 2017; Pergl *et al.* 2020). Yet, replicated sampling over time is not the only available data source for making temporal inferences. Chronosequences (i.e. the use of sites differing in their time since invasion) can highlight how impacts evolve over long periods (e.g. Dostál *et al.* 2013; Iacarella *et al.* 2015; Grove *et al.* 2017) and should be part of the planning of long-term ecosystem research programmes (Musche *et al.* 2019). Finally, for assessing historical impacts, information from dated tree rings, bivalve shells and coral, or sedimentation records of pollen and micro-organisms can help reconstructing past population dynamics over extensive periods of time (Strayer *et al.* 2006; Büntgen *et al.* 2020). Such alternative data sources can be used to improve model quality or to replace replicated sampling over time.

Comparing impacts of alien species

The EICAT framework allows impacts on native species to be categorized in standardized terms, thereby providing a method for performing all sorts of comparisons across impacts, alien species and impacted environments. For instance, in Chapter 4, we used EICAT to compare alien species based on their risk of causing high impacts when introduced to a location. EICAT also provides a standardized way of collecting data on impacts of alien species. The IUCN will soon host a public database on the impacts of alien species, similar to the Red List for Threatened Species, based on EICAT assessments. This will likely facilitate information exchange between invasion scientists and policy makers or the public (Cadotte *et al.* 2020). Furthermore, it will facilitate global analyses investigating patterns in impacts, as it centralizes knowledge on impacts. This thesis nevertheless gives insights on aspects of the EICAT framework which could be re-evaluated to improve comparisons between impacts and alien species and increase its relevance to policy makers and scientists.

EICAT and impacts' temporal dynamics

To date, the majority of impact reports available for EICAT assessments are measuring impacts at a point in time (or over short periods of time) and are based on punctual comparisons (Crystal-Ornelas & Lockwood 2020). Therefore, EICAT was designed in a way that does not record the temporal variation of impacts, although such information is crucial for prioritization and management. In addition, such impact reports might contain unknown biases due to inaccurate impact quantification (Chapter 1), potentially leading to biased information in EICAT. The importance of considering temporal dynamics in impact quantification is increasingly stressed in invasion science (e.g. Strayer *et al.* 2006; Strayer 2012; Latombe *et al.* 2017; Pergl *et al.* 2020; Ricciardi *et al.* 2020) and other field of ecological research (De Palma *et al.* 2018; Büntgen *et al.* 2020; Wauchope *et al.* 2021). It can thus be expected that future impact quantifications in invasion science will progressively consider the temporal dynamics of their study systems. I hence suggest revising the EICAT framework to incorporate temporal dynamics of impacts. This could be done, for instance, by integrating the metrics proposed in Chapter 1, which are—when they focus on native population abundances—extensions of the EICAT metric accounting for temporal dynamics of the system and which therefore also allows comparisons across taxa. Incorporating our metrics in EICAT would probably be straightforward, as our first impact metric, $R(t)$, can be used to describe the different EICAT categories:

- $R(t) = 0$ means that no decline in the native population size is detected, what would correspond to the Minimal Concern (**MC**) and Minor (**MN**) EICAT categories (describing negligible impact and impact on individuals' performance, respectively);
- $R(t) < 0$ means that the alien causes a decline in the native population size, what would correspond to the Moderate (**MO**) EICAT category;
- $R(t) = -\infty$ means that the alien causes a (reversible or irreversible) local extinction, corresponding to the Major (**MR**) and Massive (**MV**) EICAT categories.

Adapting EICAT to enable tracking changes in *R(t)* over time for each impact observation would allow us to obtain a measurement of the rate of change in impacts ($\rho(t_1, t_2)$), to discriminate between increasing, decreasing and stable impacts. Another advantage of expanding the Moderate category ($R(t)$ < 0) to our impact metrics is that small (e.g. <10%) population declines could be distinguished from important (e.g. >80%) ones. This information has so far been disregarded in EICAT but would enable more meaningful comparisons of species causing population declines. Indeed, distinguishing species causing declines less than 10% from species causing declines larger than 80% might be more relevant for conservation than distinguishing species causing no declines (**MN** or **MC** impacts) from species not causing declines larger than 10%. Finally, measures of *R(t)* and $\rho(t_1, t_2)$ could also provide relevant information to the IUCN Red List, as they inform on local (and potentially global) trajectories of native species (Mace *et al.* 2008). However, it is likely that only limited information could be shared between the two databases, because the IUCN Red List has specific criteria for their assessments (e.g. declines must be assessed over 10 years or three generations, whichever is the longer; IUCN 2019).

Global impact of alien species

To compare alien species based on their impacts, the current EICAT procedure compares the highest impact documented for each species (Appendix 1). In chapter 4, we argued that such comparisons ignore intraspecific variation in the impacts of alien species. To better summarize the overall impacts of alien species, we proposed a method evaluating the risk of each species to cause high impacts, which improved comparisons between alien species (Chapter 4). As impact risks were measured based on the proportion of locations in which alien species caused their highest impacts, this approach is well suited when impacts are given at a point in time. If impacts are measured as trends instead of punctual impacts, for instance by using our metrics, the joint impact of an alien species can be measured from its multiple introduced populations and impacted native species (Chapter 1). Depending on the research question, the multiple impacts of an alien species can be aggregated in different ways: for instance, the alien's joint impact can be measured for different impacted native taxa (e.g. mammals *vs* birds) or for different types of recipient environments (e.g. island *vs* mainland). Differences in resident time (i.e. time since introduction) across the introduced populations of an alien species and differences in time scales between impact measurements would, however, need to be accounted for when measuring joint impacts. We discuss in Appendix 4 the importance of accounting for positive impacts of alien species in impact frameworks, although it is not yet clear if, and how, this information should be incorporated along negative impacts and potentially outweigh them. Because our metrics also apply to positive impacts of alien species, they could, if necessary and relevant, be incorporated in the joint impact of assessed alien species.

The impact risk approach presented in Chapter 4 is useful in that it provides straightforward and simple summaries of the impacts assessed in the EICAT database, which might be more accessible to the general public. For instance, based on this approach, summaries about the proportion of locations in which an alien species has caused local extinctions, in which the impact of the alien is heading towards local extinctions, or in which the alien is causing population declines of > 50%, could be provided on the IUCN EICAT public database.

Uncertainty

The incorporation of the new metrics would also improve the way uncertainty is captured in EICAT. While EICAT proposes a way for evaluating uncertainty in impact assessments, the current suggestion (i.e. high/medium/low confidence score based on whether the assigned magnitude is likely to be correct) is prone to subjectivity and hence to inconsistencies across assessors (Chapter 3; Appendix 3; Clarke *et al.* 2021). Although we aimed at reducing this subjectivity between assessors by identifying the main sources of uncertainty in EICAT assessments and their possible consequences on the confidence scores (Chapter 3; Appendix 2,3), it is impossible to completely avoid differences in interpretation amongst assessors. Furthermore, under the current procedure, uncertainty is not considered in the overall impact of a species (Appendix 3; Chapter 4).

In Chapter 1, we discussed how uncertainty associated with our impact metrics can be accounted for. This objective approach to account for uncertainty would be an appropriate alternative to the current EICAT confidence scores. Even in cases where uncertainty in impact assessments will be substantial, impacts or alien species may be ranked based on their probabilities of having larger $R(t)$ values than the others (Chapter 1). In addition, uncertainty in impact categories other than the Moderate (**MO)** category could also be estimated, because $R(t)$ can be used to express the five EICAT impact categories. Species of the Minimal Concern (**MC)** or Minor (**MN**) impact categories could be compared based on their probabilities to cause no population declines ($R(t) = 0$), and species of the Major (**MR**) or Massive (**MV**) categories could be compared based on their probabilities to cause local extinctions ($R(t) = -\infty$). Even for impact estimates associated with very high uncertainty, it may still be possible to confidently exclude some EICAT impact categories (e.g. to say that there is a negative impact, $R(t) < 0$).

EICAT and indirect mechanisms of impacts

Classifications and frameworks have proven useful in improving our understanding of biological invasions (Wilson *et al.* 2020). For instance, they have been developed to synthetize knowledge on the pathways of introduction (Hulme *et al.* 2008), the invasion process (Blackburn *et al.* 2011), and the impacts of alien species (e.g. Nentwig *et al.* 2010; Blackburn *et al.* 2014). The mechanisms through which impacts occur have also been classified by existing frameworks (e.g. see the IUCN Global Invasive Species Database [http://www.iucngisd.org/gisd/]; Blackburn *et al.* 2014; Hawkins *et al.* 2015; Appendix 1), but several indirect mechanisms were overlooked (Chapter 3; McGeoch *et al.* 2015). We revised the EICAT framework, which now better integrates indirect impact mechanisms (Chapter 3; Appendix 1), which comprise transmission of disease, physical/chemical/structural impacts on ecosystems, competition, and indirect impact through interaction with other species. I argue that a better integration of the complexity and variety of indirect mechanisms in EICAT would provide a more efficient tool to improve our understanding of the impacts of alien species. For instance, it would be useful to assess and differentiate whether an alien species negatively affects a native species by facilitating the negative impact of a predatory population (apparent competition) or by suppressing a pollinator population. Based on the classification proposed in Chapter 2, the existing mechanisms of EICAT could be divided into sub-categories, which would more precisely described indirect mechanisms. Information on impact mechanisms also brings valuable information for management (Chapter 2); a better inclusion of indirect mechanisms would thus render EICAT more useful to policy makers.

Future perspectives: Towards predictions of impacts

Predicting future impacts of alien species and their future interactions with other anthropogenic stressors is essential to set priorities for conservation purposes. Due to a general lack of predictive quantitative models for impacts in invasion science (Lenzner *et al.* 2019; but see e.g. Cuthbert *et al.* 2019), predictions have mainly relied on expert knowledge (e.g. Roy *et al.* 2019; Essl *et al.* 2020; Hughes *et al.* 2020). Although expert-based assessments are the best alternative in absence of quantitative methods (Essl *et al.* 2020), they might be biased by several factors. For instance, we found in Chapter 4 that the ubiquity of widely introduced ungulates might have biased experts, leading to an overestimation of their impacts. It is hence crucial to move towards quantitative methods for predicting the future impacts of alien species.

To be able to predict impacts, we must understand under which contexts and why impacts follow which trajectory. For instance, while capturing the dynamic of the alien species is not required for quantifying impacts (Chapter 1), understanding the relationship between alien abundance and impacts will contribute to develop predictions (Sofaer *et al.* 2018; Bradley *et al.* 2019; Strayer 2020). Bradley *et al.* (2019) showed that the abundance-impact relationship takes different shapes depending on the trophic level of the alien, with species at higher trophic levels causing strong non-linear declines in native populations and species at the same levels rather causing linear declines. The relationship between life-history traits and impacts has also been frequently investigated. High fecundity and ecological flexibility were for example found to be good predictors of high impacts for mammals (using GISS; Nentwig *et al.* 2010), and body size, ecological flexibility, alien range size, and residence time for birds (using EICAT; Evans *et al.* 2018b). Impacts of alien species do not only vary with alien abundance and traits, but have been shown to be also influenced by the abiotic and socio-economic characteristics of the recipient environment and its biotic community (Thomsen *et al.* 2011; Kumschick *et al.* 2015; Pyšek *et al.* 2020b). Extending EICAT with our metrics would provide more precise quantification of native population declines, information on temporal dynamics of impacts, and precise quantification of interactive effects with other anthropogenic stressors—which are increasingly influencing the impacts of alien species (Mazor *et al.* 2018; Essl *et al.* 2020; Ricciardi *et al.* 2020). Such information would increase the accuracy of future investigations of patterns in impacts and thus facilitate the development of predictive models. In Chapter 4, we found that the impacts of alien ungulates were studied in only limited parts of their introduced ranges, with strong geographic biases in data availability; geographic biases would need to be reduced for better studying context-dependency and developing more accurate predictive models.

Finally, our metrics can also be used to compare the relative impacts of alien species with that of other stressors (Chapter 1), which is needed to set priorities between stressors for conservation actions and research effort (Mazor *et al.* 2018), and to study the dynamic of their impacts. Most studies comparing the impacts of alien species with that of other anthropogenic stressors have used the IUCN Red List or similar databases to evaluate the frequency at which alien species and other stressors were listed as drivers of local extinctions or ongoing declines (McGeoch *et al.* 2010; Szabo *et al.* 2012; Bellard *et al.* 2016a, b; Carboneras *et al.* 2018). The relative contributions of the different stressors in the species declines or extinctions is not disentangled in such approaches (each stressor is listed as driver of the decline or extinction, or not), what limits the resulting comparisons between stressors. Using our metrics, the relative contributions of each anthropogenic stressor in species declines or extinction could be measured and compared.

Concluding remarks

The number of established alien species worldwide is expected to massively increase in the next decades (Sardain *et al.* 2019; Seebens *et al.* 2021), and although numerous biosecurity policies have been implemented, they do not seem efficient enough to halt or slow biological invasions (Seebens *et al.* 2017; Turbelin *et al.* 2017). New challenges are arising, with many new source pools introducing new alien species with unknown impacts (Diez *et al.* 2012; Seebens *et al.* 2018; Pyšek *et al.* 2020a) and new interactions between anthropogenic stressors resulting in unknown effects (Mazor *et al.* 2018; Essl *et al.* 2020; Ricciardi *et al.* 2020). Predictions on the future impacts of alien species and of their interactive effects with other anthropogenic stressors are thus urgently needed for conservation planning but have been hampered by a lack of quantitative models (Lenzner *et al.* 2019). The first step towards quantitative predictive models is to accurately quantify impacts and their temporal variation, across alien taxa and contexts. The IUCN EICAT framework has paved the way towards this goal, by developing a generic tool which successfully compares the environmental impacts of alien species using semi-quantitative scenarios.

A major limitation of the IUCN EICAT framework is that it does not consider the temporal dynamics of impacts. This thesis sheds light on important conceptual aspects of the quantification of impacts of alien species under temporal dynamics and of their interactions with other anthropogenic stressors, and thereby addresses several ongoing issues in invasion science (Ricciardi *et al.* 2020). It provides tools to accurately quantify impacts and their temporal trends, and suggests ways for integrating these trends in EICAT. These suggestions are likely to improve the EICAT usefulness for conservation purposes; it would also make the framework more informative for future investigation of context-dependency in impacts and would thereby facilitate the development of predictive models. Although mainly conceptual, this work also has practical implications, regarding impact measurements, prioritization of alien species for management, and the development of new management strategies.

Acknowledgements

I am extremely thankful to the following people for their assistance during my PhD:

Sven Bacher, for always pushing me out of my comfort zone and for all the trust you placed in me; for your availability, encouragements, support, patience, enthusiasm, and caring; for all the things you taught me and your great advices during this PhD; for all the apéros and rubber boat trips you organized, for bringing us with you to so many great trips over the world, and for the nice atmosphere you created in your group. You have been a wonderful supervisor!

Daniel Wegmann, for the hours you spent explaining me modeling and stochasticity, and making it look easy; for your enthusiasm, interest, and availability, and all the your incredibly helpful feedbacks (I really learned a lot!). Sabrina Kumschick, for all the great and insightful discussions and exchanges of ideas, here in Switzerland, but also in Cyprus, Dublin, or South Africa; thank you for welcoming us and showing us your country of adoption. Helen Roy, for coming all your way to Switzerland to discuss my thesis, and for your great support, interest, feedbacks, positivity, and kindness. All my experts, for taking the time to read and evaluate this work.

Divija Jatavallabhula, for suffering with me on the impacts of alien ungulates, it was nice to have someone that understands the pain; for your support, and all the fun at conferences, in the botanical garden, festivals, and so on. Shyama Pagad and Lucilla Carnevali for providing us ungulate data, Alix Badel and Maddie Smith for their help with literature search and EICAT assessments. Rudolf Rohr for his availability and statistical support. Laura Scillitani and Sandro Bertolino, for the great collaboration, and for visiting us in Fribourg and welcoming us in Torino.

Rachel Korn, our honorary group member and office mate, for all our running sessions and outdoor activities, and your great support and philosophy; and for dealing with my stress towards the end of this thesis. Magdalena Steiner, for showing us the way; for all your funny and incredible stories, and for being a perfect flat mate. All my great colleagues and friends, Andrew Francis Brown, Giovanni Vimercati, Vasco Lepori, Anne-Marth, for all the burgers, pumpking carving, yoga sessions, apéros, lunch, and so on.

Special thanks to Anna Frances Probert, my secret-swimming partner, for the time you spent helping me with basically *everything* with this thesis, I was so lucky to have you; and to Anne-Laure Fragnière, my home office and spa buddy, for all the pancakes, orange juice, coffee, and great company. Thank you both for your daily support and precious friendship.

Thomas Gruet, Catherine Cuennet, Adeline Guélat, Sophie Gross, Evelyne Boll, for informatic and administrative support.

My friends Laurence and Michelle (and Liam and Olivia) for your constant support and interest, and for always being there for me.

My family, Luc, Cathy, Anouk and Jonathan, Céline, Elise and Ariane, Emma and Bénédicte, for your unconditional and constant support in every aspect of my life during this PhD; for always being there for me; for your interest and endless encouragements. Special thanks to my parents, for raising my environmental awareness and giving me the motivation to study biology: this thesis is for you. Special thanks also to my sister, for always being there, listening to me, cheering me up, and for her company. I am the luckiest person in the world.

Last but not least, François Gallot, for your priceless daily support, enthusiasm, encouragement, and interest, and for being the best anti-stress ever. Thank you for everything.

References

Alexander, J.M. & Levine, J.M. (2019). Earlier phenology of a nonnative plant increases impacts on native competitors. *PNAS*, 116, 6199–6204.

Ali, R. (2004). The effect of introduced herbivores on vegetation in the Andaman Islands. *CURRENT SCIENCE*, 86, 10.

Anton, A., Geraldi, N.R., Ricciardi, A. & Dick, J.T.A. (2020). Global determinants of prey naiveté to exotic predators. *Proc. R. Soc. B.*, 287, 20192978.

Bacher, S., Blackburn, T.M., Essl, F., Genovesi, P., Heikkilä, J., Jeschke, J.M., *et al.* (2018). Socio-economic impact classification of alien taxa (SEICAT). *Methods in Ecology and Evolution*, 9, 159–168.

Bachman, S., Walker, B.E., Barrios, S., Copeland, A. & Moat, J. (2020). Rapid Least Concern: towards automating Red List assessments. *Biodivers Data J*, 8.

Bachman, S.P., Field, R., Reader, T., Raimondo, D., Donaldson, J., Schatz, G.E., *et al.* (2019). Progress, challenges and opportunities for Red Listing. *Biological Conservation*, 234, 45–55.

Baker, R.H.A., Black, R., Copp, G.H., Haysom, K.A., Thomas, M.B., Brown, A., *et al.* (2008). The UK risk assessment scheme for all non-native species, 12.

Ballari, S.A., Kuebbing, S.E. & Nuñez, M.A. (2016). Potential problems of removing one invasive species at a time: a meta-analysis of the interactions between invasive vertebrates and unexpected effects of removal programs. *PeerJ*, 4, e2029.

Bates, D., Mächler, M., Bolker, B. & Walker, S. (2014). Fitting Linear Mixed-Effects Models using lme4. *arXiv:1406.5823 [stat]*.

Bellard, C., Cassey, P. & Blackburn, T.M. (2016a). Alien species as a driver of recent extinctions. *Biol. Lett.*, 12, 20150623.

Bellard, C., Genovesi, P. & Jeschke, J.M. (2016b). Global patterns in threats to vertebrates by biological invasions. *Proc. R. Soc. B.*, 283, 20152454.

Bellard, C., Jeschke, J.M., Leroy, B. & Mace, G.M. (2018). Insights from modeling studies on how climate change affects invasive alien species geography. *Ecology and Evolution*, 8, 5688–5700.

Bergstrom, D.M., Lucieer, A., Kiefer, K., Wasley, J., Belbin, L., Pedersen, T.K., *et al.* (2009). Indirect effects of invasive species removal devastate World Heritage Island. *Journal of Applied Ecology*, 46, 73–81.

Bertolino, S., Ancillotto, L., Bartolommei, P., Benassi, G., Capizzi, D., Gasperini, S., *et al.* (2020). A framework for prioritising present and potentially invasive mammal species for a national list. *NB*, 62, 31–54.

Birk, S., Chapman, D., Carvalho, L., Spears, B.M., Andersen, H.E., Argillier, C., *et al.* (2020). Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. *Nat Ecol Evol*, 4, 1060–1068.

Blackburn, T.M. (2004). Avian Extinction and Mammalian Introductions on Oceanic Islands. *Science*, 305, 1955–1958.

Blackburn, T.M., Essl, F., Evans, T., Hulme, P.E., Jeschke, J.M., Kühn, I., *et al.* (2014). A Unified Classification of Alien Species Based on the Magnitude of their Environmental Impacts. *PLoS Biol*, 12, e1001850.

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., *et al.* (2011). A proposed unified framework for biological invasions. *Trends in Ecology & Evolution*, 26, 333–339.

Boscutti, F., Pellegrini, E., Casolo, V., Nobili, M. de, Buccheri, M. & Alberti, G. (2020). Cascading effects from plant to soil elucidate how the invasive Amorpha fruticosa L. impacts dry grasslands. *Journal of Vegetation Science*, 31, 667–677.

Bradley, B.A., Laginhas, B.B., Whitlock, R., Allen, J.M., Bates, A.E., Bernatchez, G., *et al.* (2019). Disentangling the abundance–impact relationship for invasive species. *Proc Natl Acad Sci USA*, 116, 9919–9924.

Braga, R.R., Ribeiro, V.M., Padial, A.A., Thomaz, S.M., Affonso, I. de P., Wojciechowski, J., *et al.* (2020). Invasional meltdown: an experimental test and a framework to distinguish synergistic, additive, and antagonistic effects. *Hydrobiologia*, 847, 1603–1618.

Bruder, A., Frainer, A., Rota, T. & Primicerio, R. (2019). The Importance of Ecological Networks in Multiple-Stressor Research and Management. *Front. Environ. Sci.*, 7.

Brunel, S., Branquart, E., Fried, G., Valkenburg, J.V., Brundu, G., Starfinger, U., *et al.* (2010). The EPPO prioritization process for invasive alien plants. *EPPO Bulletin*, 40, 407–422.

Büntgen, U., González-Rouco, J.F., Luterbacher, J., Stenseth, N.C. & Johnson, D.M. (2020). Extending the climatological concept of ‘Detection and Attribution’ to global change ecology in the Anthropocene. *Functional Ecology*, 34, 2270–2282.

Burgess, B.J., Purves, D., Mace, G. & Murrell, D.J. (2021). Classifying ecosystem stressor interactions: Theory highlights the data limitations of the additive null model and the difficulty in revealing ecological surprises. *Global Change Biology*, n/a.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., *et al.* (2010). Global Biodiversity: Indicators of Recent Declines. *Science*, 328, 1164–1168.

Cadotte, M.W., Jones, H.P. & Newton, E.L. (2020). Making the applied research that practitioners need and want accessible. *Ecological Solutions and Evidence*, 1, e12000.

Callaway, R.M., Cipollini, D., Barto, K., Thelen, G.C., Hallett, S.G., Prati, D., *et al.* (2008). Novel Weapons: Invasive Plant Suppresses Fungal Mutualists in America but Not in Its Native Europe. *Ecology*, 89, 1043–1055.

Canavan, S., Kumschick, S., Le Roux, J.J., Richardson, D.M. & Wilson, J.R.U. (2019). Does origin determine environmental impacts? Not for bamboos. *Plants People Planet*, 1, 119–128.

Carboneras, C., Genovesi, P., Vilà, M., Blackburn, T.M., Carrete, M., Clavero, M., *et al.* (2018). A prioritised list of invasive alien species to assist the effective implementation of EU legislation. *Journal of Applied Ecology*, 55, 539–547.

Carter, E.T., Eads, B.C., Ravesi, M.J. & Kingsbury, B.A. (2015). Exotic invasive plants alter thermal regimes: implications for management using a case study of a native ectotherm. *Functional Ecology*, 29, 683–693.

Carthey, A.J.R. & Banks, P.B. (2016). Naiveté is not forever: responses of a vulnerable native rodent to its long term alien predators. *Oikos*, 125, 918–926.

Caudera, E., Viale, S., Bertolino, S., Cerri, J. & Venturino, E. (2021). A Mathematical Model Supporting a Hyperpredation Effect in the Apparent Competition Between Invasive Eastern Cottontail and Native European Hare. *Bull Math Biol*, 83, 51.

Caut, S., Angulo, E. & Courchamp, F. (2009). Avoiding surprise effects on Surprise Island: alien species control in a multitrophic level perspective. *Biol Invasions*, 11, 1689–1703.

Caut, S., Casanovas, J.G., Virgos, E., Lozano, J., Witmer, G.W. & Courchamp, F. (2007). Rats dying for mice: Modelling the competitor release effect. *Austral Ecology*, 32, 858–868.

Chadés, I., Nicol, S., Leeuwen, S. van, Walters, B., Firn, J., Reeson, A., *et al.* (2015). Benefits of integrating complementarity into priority threat management. *Conservation Biology*, 29, 525–536.

Chevalier, M., Russell, J.C. & Knape, J. (2019). New measures for evaluation of environmental perturbations using Before-After-Control-Impact analyses. *Ecol Appl*, 29.

Chiadmi, I., Traoré, S.A.A. & Salles, J.-M. (2020). Asian tiger mosquito far from home: Assessing the impact of invasive mosquitoes on the French Mediterranean littoral. *Ecological Economics*, 178, 106813.

Chiba, S. (2010). Invasive Non-Native Species' Provision of Refugia for Endangered Native Species. *Conservation Biology*, 24, 1141–1147.

Christie, A.P., Amano, T., Martin, P.A., Shackelford, G.E., Simmons, B.I. & Sutherland, W.J. (2019). Simple study designs in ecology produce inaccurate estimates of biodiversity responses, 13.

Clarke, D.A., Palmer, D.J., McGrannachan, C., Burgess, T.I., Chown, S.L., Clarke, R.H., *et al.* (2021). Options for reducing uncertainty in impact classification for alien species. *Ecosphere*, 12.

Clinchy, M., Sheriff, M.J. & Zanette, L.Y. (2013). Predator-induced stress and the ecology of fear. *Functional Ecology*, 27, 56–65.

Connors, B.M., Cooper, A.B., Peterman, R.M. & Dulvy, N.K. (2014). The false classification of extinction risk in noisy environments. *Proc. R. Soc. B.*, 281, 20132935.

Côté, I.M., Darling, E.S. & Brown, C.J. (2016). Interactions among ecosystem stressors and their importance in conservation. *Proc. R. Soc. B.*, 283, 20152592.

Courchamp, F., Chapuis, J.-L. & Pascal, M. (2003). Mammal invaders on islands: impact, control and control impact. *Biological Reviews*, 78, 347–383.

Cowan, P. & Warburton, B. (2011). Animal welfare and ethical issues in island pest eradication. *Island invasives: eradication and management*, 418–421.

Crees, J.J. & Turvey, S.T. (2015). What constitutes a 'native' species? Insights from the Quaternary faunal record. *Biological Conservation*, 186, 143–148.

Crooks, J.A. (2002). Characterizing ecosystem-level consequences of biological invasions: the role of ecosystem engineers. *Oikos*, 97, 153–166.

Crooks, J.A., Chang, A.L. & Ruiz, G.M. (2011). Aquatic pollution increases the relative success of invasive species. *Biol Invasions*, 13, 165–176.

Crooks, K.R. & Soulé, M.E. (1999). Mesopredator release and avifaunal extinctions in a fragmented system. *Nature*, 400, 563–566.

Crystal-Ornelas, R. & Lockwood, J.L. (2020). The 'known unknowns' of invasive species impact measurement. *Biol Invasions*, 22, 1513–1525.

Cuthbert, R.N., Dickey, J.W.E., Coughlan, N.E., Joyce, P.W.S. & Dick, J.T.A. (2019). The Functional Response Ratio (FRR): advancing comparative metrics for predicting the ecological impacts of invasive alien species. *Biol Invasions*, 21, 2543–2547.

D'Antonio, C.M., Yelenik, S.G. & Mack, M.C. (2017). Ecosystem vs. community recovery 25 years after grass invasions and fire in a subtropical woodland. *Journal of Ecology*, 105, 1462–1474.

Davis, N.E., Forsyth, D.M. & Coulson, G. (2010). Facilitative interactions between an exotic mammal and native and exotic plants: hog deer (Axis porcinus) as seed dispersers in south-eastern Australia. *Biol Invasions*, 12, 1079–1092.

De Palma, A., Sanchez-Ortiz, K., Martin, P.A., Chadwick, A., Gilbert, G., Bates, A.E., *et al.* (2018). Challenges With Inferring How Land-Use Affects Terrestrial Biodiversity: Study Design, Time, Space and Synthesis. *Advances in ecological research*, 58, 163–199.

D'hondt, B., Vanderhoeven, S., Roelandt, S., Mayer, F., Versteirt, V., Adriaens, T., *et al.* (2015). Harmonia+ and Pandora+: risk screening tools for potentially invasive plants, animals and their pathogens. *Biol Invasions*, 17, 1869–1883.

Diagne, C., Leroy, B., Vaissière, A.-C., Gozlan, R.E., Roiz, D., Jarić, I., *et al.* (2021). High and rising economic costs of biological invasions worldwide. *Nature*.

Dick, J.T.A., Alexander, M.E., Jeschke, J.M., Ricciardi, A., MacIsaac, H.J., Robinson, T.B., *et al.* (2014). Advancing impact prediction and hypothesis testing in invasion ecology using a comparative functional response approach. *Biol Invasions*, 16, 735–753.

Didham, R.K., Basset, Y., Collins, C.M., Leather, S.R., Littlewood, N.A., Menz, M.H.M., *et al.* (2020). Interpreting insect declines: seven challenges and a way forward. *Insect Conservation and Diversity*, 13, 103–114.

Didham, R.K., Tylianakis, J.M., Gemmell, N.J., Rand, T.A. & Ewers, R.M. (2007). Interactive effects of habitat modification and species invasion on native species decline. *Trends in Ecology & Evolution*, 22, 489–496.

Diez, J.M., D'Antonio, C.M., Dukes, J.S., Grosholz, E.D., Olden, J.D., Sorte, C.J., *et al.* (2012). Will extreme climatic events facilitate biological invasions? *Frontiers in Ecology and the Environment*, 10, 249–257.

Doherty, T.S., Glen, A.S., Nimmo, D.G., Ritchie, E.G. & Dickman, C.R. (2016). Invasive predators and global biodiversity loss. *Proc Natl Acad Sci USA*, 113, 11261–11265.

Dornelas, M., Antão, L.H., Moyes, F., Bates, A.E., Magurran, A.E., Adam, D., *et al.* (2018). BioTIME: A database of biodiversity time series for the Anthropocene. *Global Ecology and Biogeography*, 27, 760–786.

Dostál, P., Müllerová, J., Pyšek, P., Pergl, J. & Klinerová, T. (2013). The impact of an invasive plant changes over time. *Ecology Letters*, 16, 1277–1284.

Dunham, J.B., Arismendi, I., Murphy, C., Koeberle, A., Olivos, J.A., Pearson, J., *et al.* (2020). What to do when invaders are out of control? *WIREs Water*, 7, e1476.

Early, R., Bradley, B.A., Dukes, J.S., Lawler, J.J., Olden, J.D., Blumenthal, D.M., *et al.* (2016). Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature Communications*, 7, 12485.

Ebrahim, S.A.M., Talross, G.J.S. & Carlson, J.R. (2021). Sight of parasitoid wasps accelerates sexual behavior and upregulates a micropeptide gene in Drosophila. *Nat Commun*, 12, 2453.

Emery-Butcher, H.E., Beatty, S.J. & Robson, B.J. (2020). The impacts of invasive ecosystem engineers in freshwaters: A review. *Freshw Biol*, 65, 999–1015.

d'Eon-Eggertson, F., Dulvy, N.K. & Peterman, R.M. (2015). Reliable Identification of Declining Populations in an Uncertain World. *Conservation Letters*, 8, 86–96.

Essl, F., Bacher, S., Genovesi, P., Hulme, P.E., Jeschke, J.M., Katsanevakis, S., *et al.* (2018). Which Taxa Are Alien? Criteria, Applications, and Uncertainties. *BioScience*, 68, 496–509.

Essl, F., Dullinger, S., Genovesi, P., Hulme, P.E., Jeschke, J.M., Katsanevakis, S., *et al.* (2019). A Conceptual Framework for Range-Expanding Species that Track Human-Induced Environmental Change. *BioScience*, 69, 908–919.

Essl, F., Lenzner, B., Bacher, S., Bailey, S., Capinha, C., Daehler, C., *et al.* (2020). Drivers of future alien species impacts: An expert-based assessment. *Glob Change Biol*, 26, 4880–4893.

Essl, F., Nehring, S., Klingenstein, F., Milasowszky, N., Nowack, C. & Rabitsch, W. (2011). Review of risk assessment systems of IAS in Europe and introducing the German–Austrian Black List Information System (GABLIS). *Journal for Nature Conservation*, 19, 339–350.

Evans, T. & Blackburn, T.M. (2020). Global variation in the availability of data on the environmental impacts of alien birds. *Biol Invasions*, 22, 1027–1036.

Evans, T., Kumschick, S. & Blackburn, T.M. (2016). Application of the Environmental Impact Classification for Alien Taxa (EICAT) to a global assessment of alien bird impacts. *Diversity Distrib.*, 22, 919–931.

Evans, T., Pigot, A., Kumschick, S., Şekercioğlu, Ç.H. & Blackburn, T.M. (2018a). Determinants of data deficiency in the impacts of alien bird species. *Ecography*, 41, 1401–1410.

Evans, T., Kumschick, S., Şekercioğlu, Ç.H. & Blackburn, T.M. (2018b). Identifying the factors that determine the severity and type of alien bird impacts. *Divers Distrib*, 24, 800–810.

Ewel, J.J. & Putz, F.E. (2004). A place for alien species in ecosystem restoration. *Frontiers in Ecology and the Environment*, 2, 354–360.

Falaschi, M., Melotto, A., Manenti, R. & Ficetola, G.F. (2020). Invasive Species and Amphibian Conservation. *Herpetologica*, 76, 216–227.

Fisher, M.C. & Garner, T.W.J. (2007). The relationship between the emergence of Batrachochytrium dendrobatidis, the international trade in amphibians and introduced amphibian species. *Fungal Biology Reviews*, 21, 2–9.

Flory, S.L., Bauer, J., Phillips, R.P. & Clay, K. (2017). Effects of a non-native grass invasion decline over time. *Journal of Ecology*, 105, 1475–1484.

Foster, C.N., Sato, C.F., Lindenmayer, D.B. & Barton, P.S. (2016). Integrating theory into disturbance interaction experiments to better inform ecosystem management. *Global Change Biology*, 22, 1325–1335.

Fox, R., Harrower, C.A., Bell, J.R., Shortall, C.R., Middlebrook, I. & Wilson, R.J. (2019). Insect population trends and the IUCN Red List process. *J Insect Conserv*, 23, 269–278.

Frost, C.M., Allen, W.J., Courchamp, F., Jeschke, J.M., Saul, W.-C. & Wardle, D.A. (2019). Using Network Theory to Understand and Predict Biological Invasions. *Trends in Ecology & Evolution*, 34, 831–843.

Gaertner, M., Biggs, R., Beest, M.T., Hui, C., Molofsky, J. & Richardson, D.M. (2014). Invasive plants as drivers of regime shifts: identifying high-priority invaders that alter feedback relationships. *Diversity and Distributions*, 20, 733–744.

Galanidi, M., Zenetos, A. & Bacher, S. (2018). Assessing the socio-economic impacts of priority marine invasive fishes in the Mediterranean with the newly proposed SEICAT methodology. *Medit. Mar. Sci.*, 19, 107.

Gallardo, B., Clavero, M., Sánchez, M.I. & Vilà, M. (2016). Global ecological impacts of invasive species in aquatic ecosystems. *Global Change Biology*, 22, 151–163.

Game, E.T., Kareiva, P. & Possingham, H.P. (2013). Six Common Mistakes in Conservation Priority Setting. *Conservation Biology*, 27, 480–485.

Garcia, L.C. & Eubanks, M.D. (2019). Overcompensation for insect herbivory: a review and meta-analysis of the evidence. *Ecology*, 100, e02585.

García-Díaz, P., Cassey, P., Norbury, G., Lambin, X., Montti, L., Pizarro, J.C., *et al.* (2021). Management Policies for Invasive Alien Species: Addressing the Impacts Rather than the Species. *BioScience*, 71, 174–185.

García-Llorente, M., Martín-López, B., González, J.A., Alcorlo, P. & Montes, C. (2008). Social perceptions of the impacts and benefits of invasive alien species: Implications for management. *Biological Conservation*, 141, 2969–2983.

Garnier, A., Pennekamp, F., Lemoine, M. & Petchey, O.L. (2017). Temporal scale dependent interactions between multiple environmental disturbances in microcosm ecosystems. *Global Change Biology*, 23, 5237–5248.

Geary, W.L., Nimmo, D.G., Doherty, T.S., Ritchie, E.G. & Tulloch, A.I.T. (2019). Threat webs: Reframing the co-occurrence and interactions of threats to biodiversity. *Journal of Applied Ecology*, 56, 1992–1997.

Giejsztowt, J., Classen, A.T. & Deslippe, J.R. (2020). Climate change and invasion may synergistically affect native plant reproduction. *Ecology*, 101, e02913.

González-Moreno, P., Lazzaro, L., Vilà, M., Preda, C., Adriaens, T., Bacher, S., *et al.* (2019). Consistency of impact assessment protocols for non-native species. *NB*, 44, 1–25.

Grove, S., Parker, I.M. & Haubensak, K.A. (2017). Do impacts of an invasive nitrogen-fixing shrub on Douglas-fir and its ectomycorrhizal mutualism change over time following invasion? *Journal of Ecology*, 105, 1687–1697.

Gurevitch, J. & Padilla, D.K. (2004a). Are invasive species a major cause of extinctions? *Trends in Ecology & Evolution*, 19, 470–474.

Gurevitch, J. & Padilla, D.K. (2004b). Response to Ricciardi. Assessing species invasions as a cause of extinction. *Trends in Ecology & Evolution*, 19, 620.

Hagen, B.L. & Kumschick, S. (2018). The relevance of using various scoring schemes revealed by an impact assessment of feral mammals. *NB*, 38, 35–75.

Hanski, I. (1994). A Practical Model of Metapopulation Dynamics. *Journal of Animal Ecology*, 63, 151–162.

Hanski, I., Schulz, T., Wong, S.C., Ahola, V., Ruokolainen, A. & Ojanen, S.P. (2017). Ecological and genetic basis of metapopulation persistence of the Glanville fritillary butterfly in fragmented landscapes. *Nat Commun*, 8, 14504.

Hartig, F. (2020). *DHARMa: Residual diagnostics for hierarchical (multilevel/ mixed) regression models.* R package.

Hawkins, C.L., Bacher, S., Essl, F., Hulme, P.E., Jeschke, J.M., Kühn, I., *et al.* (2015). Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). *Diversity Distrib.*, 21, 1360–1363.

Hemming, V., Burgman, M.A., Hanea, A.M., McBride, M.F. & Wintle, B.C. (2018). A practical guide to structured expert elicitation using the IDEA protocol. *Methods in Ecology and Evolution*, 9, 169–180.

Hernández-Brito, D., Carrete, M., Ibáñez, C., Juste, J. & Tella, J.L. (2018). Nest-site competition and killing by invasive parakeets cause the decline of a threatened bat population. *R. Soc. open sci.*, 5, 172477.

Hoyle, R.H. (1995). The structural equation modeling approach: Basic concepts and fundamental issues. In: *Structural equation modeling: Concepts, issues, and applications*. Sage Publications, Inc, Thousand Oaks, CA, US, pp. 1–15.

Hughes, K.A., Pescott, O.L., Peyton, J., Adriaens, T., Cottier-Cook, E.J., Key, G., *et al.* (2020). Invasive non-native species likely to threaten biodiversity and ecosystems in the Antarctic Peninsula region. *Global Change Biology*, 26, 2702–2716.

Hulme, P.E. (2020). Plant invasions in New Zealand: global lessons in prevention, eradication and control. *Biol Invasions*, 22, 1539–1562.

Hulme, P.E., Bacher, S., Kenis, M., Klotz, S., Kühn, I., Minchin, D., *et al.* (2008). Grasping at the routes of biological invasions: a framework for integrating pathways into policy. *Journal of Applied Ecology*, 45, 403–414.

Hulme, P.E., Pyšek, P., Jarošík, V., Pergl, J., Schaffner, U. & Vilà, M. (2013). Bias and error in understanding plant invasion impacts. *Trends in Ecology & Evolution*, 28, 212–218.

Hunt, J. & Hodgson, D. (2010). What is fitness, and how do we measure it. *Evolutionary behavioral ecology*, 46–70.

Iacarella, J.C., Mankiewicz, P.S. & Ricciardi, A. (2015). Negative competitive effects of invasive plants change with time since invasion. *Ecosphere*, 6, art123.

IPBES. (2019). *The global assessment report on biodiversity and ecosystem services: Summary for policy makers*. Available at: https://ri.conicet.gov.ar/handle/11336/116171. Last accessed 23 February 2021.

IUCN. (2012). IUCN Red List Categories and Criteria : Version3.1. *Gland, Switzerland and Cambridge, UK: IUCN*, 32.

IUCN. (2016). Rules of procedure for IUCN Red List assessments 2017– 2020.Version 3.0. Approved by the IUCN SSC Steering Committee in September 2016.

IUCN. (2019). Guidelines for Using the IUCN Red List Categories and Criteria. Version 14. Prepared by the Standards and Petitions Committee.

IUCN. (2020a). Guidelines for using the IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria): First edition.

IUCN. (2020b). *IUCN EICAT Categories and Criteria. The Environmental Impact Classification for Alien Taxa*. First edition. Gland, Switzerland and Cambridge, UK: IUCN.

Jackson, M.C., Pawar, S. & Woodward, G. (2021). The Temporal Dynamics of Multiple Stressor Effects: From Individuals to Ecosystems. *Trends in Ecology & Evolution*.

Jarić, I., Roberts, D.L., Gessner, J., Solow, A.R. & Courchamp, F. (2017). Science responses to IUCN Red Listing. *PeerJ*, 5, e4025.

Jeschke, J.M. (2008). Across islands and continents, mammals are more successful invaders than birds. *Diversity and Distributions*, 14, 913–916.

Jeschke, J.M., Bacher, S., Blackburn, T.M., Dick, J.T.A., Essl, F., Evans, T., *et al.* (2014). Defining the Impact of Non-Native Species. *Conservation Biology*, 28, 1188–1194.

Jones, C.O., Lawton, J.H. & Shachak, M. (1994). Organisms as Ecosystem Engineers. *Ecosystem management*, 130–147.

Keith, D., Akçakaya, H.R., Butchart, S.H.M., Collen, B., Dulvy, N.K., Holmes, E.E., *et al.* (2015). Temporal correlations in population trends: Conservation implications from time-series analysis of diverse animal taxa. *Biological Conservation*, 192, 247–257.

Keitt, B., Campbell, K., Saunders, A., Clout, M., Wang, Y., Heinz, R., *et al.* (2011). The Global Islands Invasive Vertebrate Eradication Database: A tool to improve and facilitate restoration of island ecosystems. *Island invasives: eradication and management. IUCN, Gland, Switzerland*, 74–77.

Kesner, D. & Kumschick, S. (2018). Gastropods alien to South Africa cause severe environmental harm in their global alien ranges across habitats. *Ecology and Evolution*, 8, 8273–8285.

Kleunen, M. van, Essl, F., Pergl, J., Brundu, G., Carboni, M., Dullinger, S., *et al.* (2018). The changing role of ornamental horticulture in alien plant invasions. *Biological Reviews*, 93, 1421–1437.

Klinger, R. & Brooks, M. (2017). Alternative pathways to landscape transformation: invasive grasses, burn severity and fire frequency in arid ecosystems. *Journal of Ecology*, 105, 1521–1533.

Kopf, R.K., Nimmo, D.G., Humphries, P., Baumgartner, L.J., Bode, M., Bond, N.R., *et al.* (2017). Confronting the risks of large-scale invasive species control. *Nat Ecol Evol*, 1, 0172.

Krimbas, C.B. (2004). On fitness. *Biology & Philosophy*, 19, 185–203.

Kulhanek, S.A., Ricciardi, A. & Leung, B. (2011). Is invasion history a useful tool for predicting the impacts of the world's worst aquatic invasive species? *Ecological Applications*, 21, 189–202.

Kumschick, S., Bacher, S., Bertolino, S., Blackburn, T.M., Evans, T., Roy, H.E., *et al.* (2020). Appropriate uses of EICAT protocol, data and classifications. *NB*, 62, 193–212.

Kumschick, S., Bacher, S., Dawson, W., Heikkilä, J., Sendek, A., Pluess, T., *et al.* (2012). A conceptual framework for prioritization of invasive alien species for management according to their impact. *NB*, 15, 69–100.

Kumschick, S., Bacher, S., Evans, T., Marková, Z., Pergl, J., Pyšek, P., *et al.* (2015a). Comparing impacts of alien plants and animals in Europe using a standard scoring system. *Journal of Applied Ecology*, 52, 552–561.

Kumschick, S., Gaertner, M., Vilà, M., Essl, F., Jeschke, J.M., Pyšek, P., *et al.* (2015b). Ecological Impacts of Alien Species: Quantification, Scope, Caveats, and Recommendations. *BioScience*, 65, 55–63.

Kumschick, S., Vimercati, G., de Villiers, F.A., Mokhatla, M.M., Davies, S.J., Thorp, C.J., *et al.* (2017). Impact assessment with different scoring tools: How well do alien amphibian assessments match? *NB*, 33, 53–66.

Laender, F.D. (2018). Community- and ecosystem-level effects of multiple environmental change drivers: Beyond null model testing. *Global Change Biology*, 24, 5021–5030.

Langkilde, T.L., Thawley, C.J. & Robbins, T.R. (2017). Behavioral Adaptations to Invasive Species: Benefits, Costs, and Mechanisms of Change. *Advances in the Study of Behavior*, 49, 199–235.

Lapointe, N.W.R., Pendleton, R.M. & Angermeier, P.L. (2012). A Comparison of Approaches for Estimating Relative Impacts of Nonnative Fishes. *Environmental Management*, 49, 82–95.

Latombe, G., Pyšek, P., Jeschke, J.M., Blackburn, T.M., Bacher, S., Capinha, C., *et al.* (2017). A vision for global monitoring of biological invasions. *Biological Conservation*, SI:Measures of biodiversity, 213, 295–308.

Laverty, C., Brenner, D., McIlwaine, C., Lennon, J.J., Dick, J.T.A., Lucy, F.E., *et al.* (2017). Temperature rise and parasitic infection interact to increase the impact of an invasive species. *International Journal for Parasitology*, 47, 291–296.

Lecomte, X., Caldeira, M.C., Catry, F.X., Fernandes, P.M., Jackson, R.B. & Bugalho, M.N. (2019). Ungulates mediate trade-offs between carbon storage and wildfire hazard in Mediterranean oak woodlands. *Journal of Applied Ecology*, 56, 699–710.

Leger, E.A. & Goergen, E.M. (2017). Invasive Bromus tectorum alters natural selection in arid systems. *Journal of Ecology*, 105, 1509–1520.

Lenzner, B., Leclère, D., Franklin, O., Seebens, H., Roura-Pascual, N., Obersteiner, M., *et al.* (2019). A Framework for Global Twenty-First Century Scenarios and Models of Biological Invasions. *BioScience*, 69, 697–710.

Leung, B., Roura-Pascual, N., Bacher, S., Heikkilä, J., Brotons, L., Burgman, M.A., *et al.* (2012). TEASIng apart alien species risk assessments: a framework for best practices. *Ecology Letters*, 15, 1475–1493.

Leuven, R., Collas, F., Koopman, K.R., Matthews, J. & van der Velde, G. (2014). Mass mortality of invasive zebra and quagga mussels by desiccation during severe winter conditions. *AI*, 9, 243–252.

Levine, J.M., Vila, M., D’Antonio, C.M., Dukes, J.S., Grigulis, K. & Lavorel, S. (2003). Mechanisms underlying the impacts of exotic plant invasions, 7.

Linden, A. (2018). A matching framework to improve causal inference in interrupted time-series analysis. *Journal of Evaluation in Clinical Practice*, 24, 408–415.

Linders, T.E.W., Schaffner, U., Eschen, R., Abebe, A., Choge, S.K., Nigatu, L., *et al.* (2019). Direct and indirect effects of invasive species: Biodiversity loss is a major mechanism by which an invasive tree affects ecosystem functioning. *Journal of Ecology*, 107, 2660–2672.

Long, J.L. (2003). *Introduced mammals of the world: their history distribution and influence*. CSIRO PUBLISHING and CABI Publishing.

Long, J.L. (1981). *Introduced birds of the world: their worldwide history, distribution and influence of birds introduced to new environments*.

Lowe, S., Browne, M., Boudjelas, S. & De Poorter, M. (2000). 100 of the world’s worst invasive alien species: a selection from the global invasive species database. Published by The Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), 12pp. First published as special lift-out In Aliens

12, December 2000. Updated and reprinted version: November 2004. *Journal of Experimental Marine Biology and Ecology 258*, 3954.

Loydi, A. & Zalba, S.M. (2009). Feral horses dung piles as potential invasion windows for alien plant species in natural grasslands. *Plant Ecol*, 201, 471–480.

Luque, G.M., Bellard, C., Bertelsmeier, C., Bonnaud, E., Genovesi, P., Simberloff, D., *et al.* (2014). The 100th of the world's worst invasive alien species. *Biol Invasions*, 16, 981–985.

Mace, G.M., Collar, N.J., Gaston, K.J., Hilton-Taylor, C., Akçakaya, H.R., Leader-Williams, N., *et al.* (2008). Quantification of Extinction Risk: IUCN's System for Classifying Threatened Species. *Conservation Biology*, 22, 1424–1442.

Mačić, V., Albano, P.G., Almpanidou, V., Claudet, J., Corrales, X., Essl, F., *et al.* (2018). Biological Invasions in Conservation Planning: A Global Systematic Review. *Front. Mar. Sci.*, 5.

Manfrin, C., Souty-Grosset, C., Anastácio, P.M., Reynolds, J. & Giulianini, P.G. (2019). Detection and Control of Invasive Freshwater Crayfish: From Traditional to Innovative Methods. *Diversity*, 11, 5.

Mazor, T., Doropoulos, C., Schwarzmueller, F., Gladish, D.W., Kumaran, N., Merkel, K., *et al.* (2018). Global mismatch of policy and research on drivers of biodiversity loss. *Nature Ecology & Evolution*, 2, 1071–1074.

Mazza, G. & Tricarico, E. (2018). *Invasive Species and Human Health*. CABI.

McCain, C., Szewczyk, T. & Knight, K.B. (2016). Population variability complicates the accurate detection of climate change responses. *Global Change Biology*, 22, 2081–2093.

McGeoch, M.A., Butchart, S.H.M., Spear, D., Marais, E., Kleynhans, E.J., Symes, A., *et al.* (2010). Global indicators of biological invasion: species numbers, biodiversity impact and policy responses. *Diversity and Distributions*, 16, 95–108.

McGeoch, M.A., Lythe, M.J., Henriksen, M.V. & McGrannachan, C.M. (2015). Environmental impact classification for alien insects: a review of mechanisms and their biodiversity outcomes. *Current Opinion in Insect Science*, Neuroscience * Special Section: Insect conservation, 12, 46–53.

MEA (Ed.). (2005). *Millennium ecosystem assessment: Ecosystems and human well-being.* World Resources Institute. Washington, DC.

Measey, G.J., Vimercati, G., Villiers, F.A. de, Mokhatla, M., Davies, S.J., Thorp, C.J., *et al.* (2016). A global assessment of alien amphibian impacts in a formal framework. *Diversity and Distributions*, 22, 970–981.

Measey, J., Wagener, C., Mohanty, N.P., Baxter-Gilbert, J. & Pienaar, E.F. (2020). The cost and complexity of assessing impact. *NB*, 62, 279–299.

Medina, F.M., Bonnaud, E., Vidal, E., Tershy, B.R., Zavaleta, E.S., Donlan, C.J., *et al.* (2011). A global review of the impacts of invasive cats on island endangered vertebrates. *Global Change Biology*, 17, 3503–3510.

Miaud, C., Dejean, T., Savard, K., Millery-Vigues, A., Valentini, A., Curt Grand Gaudin, N., *et al.* (2016). Invasive North American bullfrogs transmit lethal fungus Batrachochytrium dendrobatidis infections to native amphibian host species. *Biol Invasions*, 18, 2299–2308.

Mooney, H.A. & Cleland, E.E. (2001). The evolutionary impact of invasive species. *Proceedings of the National Academy of Sciences*, 98, 5446–5451.

Muñoz-Fuentes, V., Vilà, C., Green, A.J., Negro, J.J. & Sorenson, M.D. (2007). Hybridization between white-headed ducks and introduced ruddy ducks in Spain. *Molecular Ecology*, 16, 629–638.

Musche, M., Adamescu, M., Angelstam, P., Bacher, S., Bäck, J., Buss, H.L., *et al.* (2019). Research questions to facilitate the future development of European long-term ecosystem research infrastructures: A horizon scanning exercise. *Journal of Environmental Management*, 250, 109479.

Nelson, D.W.M., Crossland, M.R. & Shine, R. (2010). Indirect ecological impacts of an invasive toad on predator–prey interactions among native species. *Biol Invasions*, 12, 3363–3369.

Nelufule, T., Robertson, M.P., Wilson, J.R.U., Faulkner, K.T., Sole, C. & Kumschick, S. (2020). The threats posed by the pet trade in alien terrestrial invertebrates in South Africa. *Journal for Nature Conservation*, 55, 125831.

Nentwig, W., Bacher, S., Kumschick, S., Pyšek, P. & Vilà, M. (2018). More than "100 worst" alien species in Europe. *Biol Invasions*, 20, 1611–1621.

Nentwig, W., Bacher, S., Pyšek, P., Vilà, M. & Kumschick, S. (2016). The generic impact scoring system (GISS): a standardized tool to quantify the impacts of alien species. *Environ Monit Assess*, 188, 315.

Nentwig, W., Kühnel, E. & Bacher, S. (2010). A Generic Impact-Scoring System Applied to Alien Mammals in Europe. *Conservation Biology*, 24, 302–311.

O'Connor, S.-J. & Kelly, D. (2012). Seed dispersal of matai (Prumnopitys taxifolia) by feral pigs (Sus scrofa). *New Zealand Journal of Ecology*, 36, 228–231.

Oliver, T.H. & Roy, D.B. (2015). The pitfalls of ecological forecasting. *Biol J Linn Soc Lond*, 115, 767–778.

Parker, I.M., Simberloff, D., Lonsdale, W.M., Goodell, K., Wonham, M., Kareiva, P.M., *et al.* (1999). Impact: Toward a Framework for Understanding the Ecological Effects of Invaders. *Biological Invasions*, 1, 3–19.

Pergl, J., Pyšek, P., Essl, F., Jeschke, J.M., Courchamp, F., Geist, J., *et al.* (2020). Need for routine tracking of biological invasions. *Conservation Biology*, 34, 1311–1314.

Piggott, J.J., Townsend, C.R. & Matthaei, C.D. (2015). Reconceptualizing synergism and antagonism among multiple stressors. *Ecology and Evolution*, 5, 1538–1547.

Pimentel, D., Zuniga, R. & Morrison, D. (2005). Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics*, Integrating Ecology and Economics in Control Bioinvasions, 52, 273–288.

Probert, A.F., Volery, L., Kumschick, S., Vimercati, G. & Bacher, S. (In press.). Understanding uncertainty in S/EICAT impact assessments. *NeoBiota*.

Pyšek, P., Bacher, S., Kühn, I., Novoa, A., Catford, J.A., Hulme, P.E., *et al.* (2020b). MAcroecological Framework for Invasive Aliens (MAFIA): disentangling large-scale context dependence in biological invasions. *NB*, 62, 407–461.

Pyšek, P., Blackburn, T.M., García-Berthou, E., Perglová, I. & Rabitsch, W. (2017). Displacement and Local Extinction of Native and Endemic Species. In: *Impact of Biological Invasions on Ecosystem Services* (eds. Vilà, M. & Hulme, P.E.). Springer International Publishing, Cham, pp. 157–175.

Pyšek, P., Hulme, P.E., Simberloff, D., Bacher, S., Blackburn, T.M., Carlton, J.T., *et al.* (2020a). Scientists' warning on invasive alien species. *Biological Reviews*, 95, 1511–1534.

Pyšek, P., Richardson, D.M., Pergl, J., Jarošík, V., Sixtová, Z. & Weber, E. (2008). Geographical and taxonomic biases in invasion ecology. *Trends in Ecology & Evolution*, 23, 237–244.

R Core Team. (2019). *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria.

Rayner, M.J., Hauber, M.E., Imber, M.J., Stamp, R.K. & Clout, M.N. (2007). Spatial heterogeneity of mesopredator release within an oceanic island system. *PNAS*, 104, 20862–20865.

Ricciardi, A. (2003). Predicting the impacts of an introduced species from its invasion history: an empirical approach applied to zebra mussel invasions. *Freshwater Biology*, 48, 972–981.

Ricciardi, A. (2004). Assessing species invasions as a cause of extinction. *Trends in Ecology & Evolution*, 19, 619.

Ricciardi, A., Blackburn, T.M., Carlton, J.T., Dick, J.T.A., Hulme, P.E., Iacarella, J.C., *et al.* (2017). Invasion Science: A Horizon Scan of Emerging Challenges and Opportunities. *Trends in Ecology & Evolution*, 32, 464–474.

Ricciardi, A., Hoopes, M.F., Marchetti, M.P. & Lockwood, J.L. (2013). Progress toward understanding the ecological impacts of nonnative species. *Ecological Monographs*, 83, 263–282.

Ricciardi, A., Iacarella, J.C., Aldridge, D.C., Blackburn, T.M., Carlton, J.T., Catford, J.A., *et al.* (2020). Four priority areas to advance invasion science in the face of rapid environmental change. *Environ. Rev.*, er-2020-0088.

Rivers, M. (2017). THE GLOBAL TREE ASSESSMENT – RED LISTING THE WORLD’S TREES. *BGjournal*, 14, 16–19.

Robertson, P.A., Mill, A., Novoa, A., Jeschke, J.M., Essl, F., Gallardo, B., *et al.* (2020). A proposed unified framework to describe the management of biological invasions. *Biol Invasions*, 22, 2633–2645.

Rodriguez, L.F. (2006). Can Invasive Species Facilitate Native Species? Evidence of How, When, and Why These Impacts Occur. *Biol Invasions*, 8, 927–939.

Roemer, G.W., Coonan, T.J., Garcelon, D.K., Bascompte, J. & Laughrin, L. (2001). Feral pigs facilitate hyperpredation by golden eagles and indirectly cause the decline of the island fox. *Animal Conservation*, 4, 307–318.

Roemer, G.W., Donlan, C.J. & Courchamp, F. (2002). Golden eagles, feral pigs, and insular carnivores: How exotic species turn native predators into prey. *PNAS*, 99, 791–796.

Romero, F., Acuña, V., Font, C., Freixa, A. & Sabater, S. (2019). Effects of multiple stressors on river biofilms depend on the time scale. *Scientific Reports*, 9, 15810.

Rooney, T.P. (2009). High white-tailed deer densities benefit graminoids and contribute to biotic homogenization of forest ground-layer vegetation. *Plant Ecol*, 202, 103–111.

Roy, H.E., Bacher, S., Essl, F., Adriaens, T., Aldridge, D.C., Bishop, J.D.D., *et al.* (2019). Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union. *Global Change Biology*, 25, 1032–1048.

Roy, H.E., European Commission, Directorate-General for the Environment, & CEH (Centre of Ecology & Hydrology). (2015). *Invasive alien species: prioritising prevention efforts through horizon scanning : final report.* Publications Office, Luxembourg.

Roy, H.E., Peyton, J., Aldridge, D.C., Bantock, T., Blackburn, T.M., Britton, R., *et al.* (2014). Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. *Global Change Biology*, 20, 3859–3871.

Roy, H.E., Rabitsch, W., Scalera, R., Stewart, A., Gallardo, B., Genovesi, P., *et al.* (2018). Developing a framework of minimum standards for the risk assessment of alien species. *J Appl Ecol*, 55, 526–538.

Russell, J.C., Meyer, J.-Y., Holmes, N.D. & Pagad, S. (2017). Invasive alien species on islands: impacts, distribution, interactions and management. *Environmental Conservation*, 44, 359–370.

Ryo, M., Aguilar-Trigueros, C.A., Pinek, L., Muller, L.A.H. & Rillig, M.C. (2019). Basic Principles of Temporal Dynamics. *Trends in Ecology & Evolution*, 34, 723–733.

Rytwinski, T., Taylor, J.J., Donaldson, L.A., Britton, J.R., Gresswell, R.E., Lintermans, M., *et al.* (2019). The effectiveness of non-native fish removal techniques in freshwater ecosystems: a systematic review. *Environmental Reviews*, 27.

Sala, O.E. (2000). Global Biodiversity Scenarios for the Year 2100 *Science*, 287, 1770–1774.

Sardain, A., Sardain, E. & Leung, B. (2019). Global forecasts of shipping traffic and biological invasions to 2050. *Nat Sustain*, 2, 274–282.

Saul, W.-C. & Jeschke, J.M. (2015). Eco-evolutionary experience in novel species interactions. *Ecology Letters*, 18, 236–245.

Saul, W.-C., Roy, H.E., Booy, O., Carnevali, L., Chen, H.-J., Genovesi, P., *et al.* (2017). Assessing patterns in introduction pathways of alien species by linking major invasion data bases. *J Appl Ecol*, 54, 657–669.

Schäfer, R.B. & Piggott, J.J. (2018). Advancing understanding and prediction in multiple stressor research through a mechanistic basis for null models. *Global Change Biology*, 24, 1817–1826.

Schindler, S., Staska, B., Adam, M., Rabitsch, W. & Essl, F. (2015). Alien species and public health impacts in Europe: a literature review. *NB*, 27, 1–23.

Schleicher, J., Eklund, J., Barnes, M.D., Geldmann, J., Oldekop, J.A. & Jones, J.P.G. (2020). Statistical matching for conservation science. *Conservation Biology*, 34, 538–549.

Schooley, R.L. & Branch, L.C. (2009). Enhancing the area–isolation paradigm: habitat heterogeneity and metapopulation dynamics of a rare wetland mammal. *Ecological Applications*, 19, 1708–1722.

Seebens, H., Bacher, S., Blackburn, T.M., Capinha, C., Dawson, W., Dullinger, S., *et al.* (2021). Projecting the continental accumulation of alien species through to 2050. *Glob. Change Biol.*, 27, 970–982.

Seebens, H., Blackburn, T.M., Dyer, E.E., Genovesi, P., Hulme, P.E., Jeschke, J.M., *et al.* (2017). No saturation in the accumulation of alien species worldwide. *Nat Commun*, 8, 14435.

Seebens, H., Blackburn, T.M., Dyer, E.E., Genovesi, P., Hulme, P.E., Jeschke, J.M., *et al.* (2018). Global rise in emerging alien species results from increased accessibility of new source pools. *Proc Natl Acad Sci USA*, 115, E2264–E2273.

Shackleton, R.T., Biggs, R., Richardson, D.M. & Larson, B.M.H. (2018). Social-ecological drivers and impacts of invasion-related regime shifts: consequences for ecosystem services and human wellbeing. *Environmental Science & Policy*, 89, 300–314.

Shackleton, R.T., Richardson, D.M., Shackleton, C.M., Bennett, B., Crowley, S.L., Dehnen-Schmutz, K., *et al.* (2019). Explaining people's perceptions of invasive alien species: A conceptual framework. *Journal of Environmental Management*, The human and social dimensions of invasion science and management, 229, 10–26.

Simberloff, D. & Gibbons, L. (2004). *Now you See them, Now you don't! – Population Crashes of Established Introduced Species | SpringerLink*. Available at: https://link.springer.com/article/10.1023/B:BINV.0000022133.49752.46. Last accessed 23 February 2021.

Simberloff, D., Martin, J.-L., Genovesi, P., Maris, V., Wardle, D.A., Aronson, J., *et al.* (2013). Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution*, 28, 58–66.

Smith, K.E., Aronson, R.B., Steffel, B.V., Amsler, M.O., Thatje, S., Singh, H., *et al.* (2017). Climate change and the threat of novel marine predators in Antarctica. *Ecosphere*, 8, e02017.

Smith, S.L., Carden, R.F., Coad, B., Birkitt, T. & Pemberton, J.M. (2014). A survey of the hybridisation status of Cervus deer species on the island of Ireland. *Conserv Genet*, 15, 823–835.

Smith, S.L., Senn, H.V., Pérez-Espona, S., Wyman, M.T., Heap, E. & Pemberton, J.M. (2018). Introgression of exotic Cervus (nippon and canadensis) into red deer (Cervus elaphus) populations in Scotland and the English Lake District. *Ecology and Evolution*, 8, 2122–2134.

Sofaer, H.R., Jarnevich, C.S. & Pearse, I.S. (2018). The relationship between invader abundance and impact. *Ecosphere*, 9, e02415.

Spear, D. & Chown, S.L. (2009). Non-indigenous ungulates as a threat to biodiversity. *Journal of Zoology*, 279, 1–17.

Sterling, T.D. (1959). Publication Decisions and their Possible Effects on Inferences Drawn from Tests of Significance—or Vice Versa. *Journal of the American Statistical Association*, 54, 30–34.

Stewart-Oaten, A., Murdoch, W.W. & Parker, K.R. (1986). Environmental Impact Assessment: "Pseudoreplication" in Time? *Ecology*, 67, 929–940.

Stinson, K.A., Campbell, S.A., Powell, J.R., Wolfe, B.E., Callaway, R.M., Thelen, G.C., *et al.* (2006). Invasive Plant Suppresses the Growth of Native Tree Seedlings by Disrupting Belowground Mutualisms. *PLOS Biology*, 4, e140.

Stokes, V.L., Pech, R.P., Banks, P.B. & Arthur, A.D. (2004). Foraging behaviour and habitat use by Antechinus flavipes and Sminthopsis murina (Marsupialia: Dasyuridae) in response to predation risk in eucalypt woodland. *Biological Conservation*, 117, 331–342.

Stout, J.C. & Morales, C.L. (2009). Ecological impacts of invasive alien species on bees. *Apidologie*, 40, 388–409.

Strauss, S.Y. (1991). Indirect effects in community ecology: Their definition, study and importance. *Trends in Ecology & Evolution*, 6, 206–210.

Strayer, D.L. (2012). Eight questions about invasions and ecosystem functioning. *Ecology Letters*, 15, 1199–1210.

Strayer, D.L. (2020). Non-native species have multiple abundance–impact curves. *Ecology and Evolution*, 10, 6833–6843.

Strayer, D.L., D'Antonio, C.M., Essl, F., Fowler, M.S., Geist, J., Hilt, S., *et al.* (2017). Boom-bust dynamics in biological invasions: towards an improved application of the concept. *Ecology Letters*, 20, 1337–1350.

Strayer, D.L., Eviner, V.T., Jeschke, J.M. & Pace, M.L. (2006). Understanding the long-term effects of species invasions. *Trends in Ecology & Evolution*, 21, 645–651.

Strayer, D.L., Solomon, C.T., Findlay, S.E.G. & Rosi, E.J. (2019). Long-term research reveals multiple relationships between the abundance and impacts of a non-native species. *Limnology and Oceanography*, 64, S105–S117.

Strubbe, D., White, R., Edelaar, P., Rahbek, C. & Shwartz, A. (2019). Advancing impact assessments of non-native species: strategies for strengthening the evidence-base. *NB*, 51, 41–64.

Stuart, E.A. (2010). Matching methods for causal inference: A review and a look forward. *Stat Sci*, 25, 1–21.

Sundar, D. (2014). binom: Binomial Confidence Intervals For Several ParameterizationsR package version 1.1-1.

Szabo, J.K., Khwaja, N., Garnett, S.T. & Butchart, S.H.M. (2012). Global Patterns and Drivers of Avian Extinctions at the Species and Subspecies Level. *PLoS ONE*, 7, e47080.

Thomsen, M.S., Olden, J.D., Wernberg, T., Griffin, J.N. & Silliman, B.R. (2011). A broad framework to organize and compare ecological invasion impacts. *Environmental Research*, Invasive Species, 111, 899–908.

Tomasevic, J.A. & Marzluff, J.M. (2017). Cavity nesting birds along an urban-wildland gradient: is human facilitation structuring the bird community? *Urban Ecosyst*, 20, 435–448.

Tompkins, D.M., White, A.R. & Boots, M. (2003). Ecological replacement of native red squirrels by invasive greys driven by disease. *Ecology Letters*, 6, 189–196.

Turbelin, A.J., Malamud, B.D. & Francis, R.A. (2017). Mapping the global state of invasive alien species: patterns of invasion and policy responses. *Global Ecology and Biogeography*, 26, 78–92.

Velamazán, M., Perea, R. & Bugalho, M.N. (2020). Ungulates and ecosystem services in Mediterranean woody systems: A semi-quantitative review. *Journal for Nature Conservation*, 55, 125837.

Vilà, M., Espinar, J.L., Hejda, M., Hulme, P.E., Jarošík, V., Maron, J.L., *et al.* (2011). Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. *Ecology Letters*, 14, 702–708.

Vilà, M. & Hulme, P.E. (Eds.). (2017). *Impact of Biological Invasions on Ecosystem Services*. Springer International Publishing, Cham.

Vilà, M. & Ibáñez, I. (2011). Plant invasions in the landscape. *Landscape Ecol*, 26, 461–472.

Vimercati, G., Kumschick, S., Probert, A.F., Volery, L. & Bacher, S. (2020). The importance of assessing positive and beneficial impacts of alien species. *NB*, 62, 525–545.

Vitousek, P.M. (1990). Biological Invasions and Ecosystem Processes: Towards an Integration of Population Biology and Ecosystem Studies. *Oikos*, 57, 7.

Wauchope, H.S., Amano, T., Geldmann, J., Johnston, A., Simmons, B.I., Sutherland, W.J., *et al.* (2021). Evaluating Impact Using Time-Series Data. *Trends in Ecology & Evolution*, 36, 196–205.

Wells, J.V. & Richmond, M.E. (1995). Populations, Metapopulations, and Species Populations: What Are They and Who Should Care? *Wildlife Society Bulletin (1973-2006)*, 23, 458–462.

White, E.M., Wilson, J.C. & Clarke, A.R. (2006). Biotic indirect effects: a neglected concept in invasion biology. *Diversity and Distributions*, 12, 443–455.

White, E.R. (2019). Minimum Time Required to Detect Population Trends: The Need for Long-Term Monitoring Programs. *BioScience*, 69, 40–46.

Wiles, G.J., Bart, J., Beck, R.E. & Aguon, C.F. (2003). Impacts of the Brown Tree Snake: Patterns of Decline and Species Persistence in Guam's Avifauna. *Conservation Biology*, 17, 1350–1360.

Williamson, M. & Fitter, A. (1996). The Varying Success of Invaders. *Ecology*, 77, 1661–1666.

Wilson, J.R.U., Bacher, S., Daehler, C.C., Groom, Q.J., Kumschick, S., Lockwood, J.L., *et al.* (2020). Frameworks used in invasion science: progress and prospects. *NB*, 62, 1–30.

Wolkovich, E.M., Cook, B.I., McLauchlan, K.K. & Davies, T.J. (2014). Temporal ecology in the Anthropocene. *Ecology Letters*, 17, 1365–1379.

Woodhams, D.C., Bosch, J., Briggs, C.J., Cashins, S., Davis, L.R., Lauer, A., *et al.* (2011). Mitigating amphibian disease: strategies to maintain wild populations and control chytridiomycosis. *Front Zool*, 8, 8.

Wootton, J.T. (1993). Indirect Effects and Habitat Use in an Intertidal Community: Interaction Chains and Interaction Modifications. *The American Naturalist*, 141, 71–89.

Wootton, J.T. (2002). Indirect effects in complex ecosystems: recent progress and future challenges. *Journal of Sea Research*, 48, 157–172.

Yokomizo, H., Possingham, H.P., Thomas, M.B. & Buckley, Y.M. (2009). Managing the impact of invasive species: the value of knowing the density–impact curve. *Ecological Applications*, 19, 376–386.

Zablotskaya, L.V., Zablotsky, M.A. & Zablotskaya, M.M. (2004). Origin of the Hybrids of North American and European Bison in the Caucasus Mountains. In: *European Bison. Status Survey and Conservation Action Plan.* IUCN, Gland, Switzerland and Cambridge, UK, pp. 49–52.

Zavaleta, E.S., Hobbs, R.J. & Mooney, H.A. (2001). Viewing invasive species removal in a whole-ecosystem context. *Trends in Ecology & Evolution*, 16, 454–459.

Zhong, H. & Song, M. (2019). A Fast Exact Functional Test for Directional Association and Cancer Biology Applications. *IEEE/ACM Transactions on Computational Biology and Bioinformatics*, 16, 818–826.

IUCN EICAT Categories and Criteria

The Environmental Impact Classification for Alien Taxa (EICAT)

First edition

INTERNATIONAL UNION FOR CONSERVATION OF NATURE

SSC Species Survival Commission

ISSG Invasive Species Specialist Group

About IUCN (International Union for Conservation of Nature)

IUCN is a membership Union uniquely composed of both government and civil society organisations. It provides public, private and non-governmental organisations with the knowledge and tools that enable human progress, economic development and nature conservation to take place together.

Created in 1948, IUCN is now the world's largest and most diverse environmental network, harnessing the knowledge, resources and reach of more than 1,300 Member organisations and some 15,000 experts. It is a leading provider of conservation data, assessments and analysis. Its broad membership enables IUCN to fill the role of incubator and trusted repository of best practices, tools and international standards.

IUCN provides a neutral space in which diverse stakeholders including governments, NGOs, scientists, businesses, local communities, indigenous peoples organisations and others can work together to forge and implement solutions to environmental challenges and achieve sustainable development.

Working with many partners and supporters, IUCN implements a large and diverse portfolio of conservation projects worldwide. Combining the latest science with the traditional knowledge of local communities, these projects work to reverse habitat loss, restore ecosystems and improve people's well-being.

www.iucn.org
https://twitter.com/IUCN/

About IUCN Species Survival Commission (SSC)

IUCN Species Survival Commission (SSC) IUCN SSC is a science-based network composed of around 9,000 species experts including scientists, field researchers, government officials and conservation leaders, volunteer experts from almost every country of the world, all working together towards achieving the vision of "A just world that values and conserves nature through positive action to reduce the loss of diversity of life on earth". SSC advises IUCN and its members on the wide range of technical and scientific aspects of species conservation, and is dedicated to securing a future for biodiversity. SSC has significant input into the international agreements dealing with biodiversity conservation.

www.iucn.org/species

About IUCN SSC ISSG

The Invasive Species Specialist Group (ISSG) is a global network of scientific and policy experts on invasive species, organized under the auspices of the Species Survival Commission (SSC) of the International Union for Conservation of Nature (IUCN). The ISSG promotes and facilitates the exchange of invasive species information and knowledge across the globe and ensures the linkage between knowledge, practice and policy so that decision making is informed. The two core activity areas of the ISSG are policy and technical advice, and, information exchange through our online resources and tools and through networking.

www.issg.org

IUCN EICAT Categories and Criteria

IUCN EICAT Categories and Criteria

The Environmental Impact Classification for Alien Taxa

First edition

Prepared by the IUCN Species Survival Commission (SSC)
As approved by the
98th meeting of the IUCN Council
Gland, Switzerland
10-11/02/2020

Published by: IUCN, Gland, Switzerland and Cambridge, UK

Citation: IUCN (2020). *IUCN EICAT Categories and Criteria. The Environmental Impact Classification for Alien Taxa* First edition. Gland, Switzerland and Cambridge, UK: IUCN. X + Xpp.

Layout by: www.naturebureau.co.uk

ISBN: 978-2-8317-2040-1 (PDF)
ISBN: 978-2-8317-2041-8 (print)
DOI: https://doi.org/10.2305/IUCN.CH.2020.05.en

Printed by: www.langhampress.co.uk
The text of this book is printed on 115gsm FSC Silk

Cover Photo: Grey Squirrel, *Sciurus carolinensis* © Tim Blackburn

Available from: IUCN (International Union for Conservation of Nature)
IUCN SSC Invasive Species Specialist Group (ISSG)
Rue Mauverney 28
1196 Gland
Switzerland
Tel +41 22 999 0000
Fax +41 22 999 0002
www.iucn.org/resources/publications
http://www.issg.org/

Contents

About this publication

This document has been adapted from:
Hawkins *et al*. 2015. 'Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT)'. *Diversity and Distributions,* 21(11): 1360-1363 https://doi.org/10.1111/ddi.12379

Charlotte L. Hawkins[1], Sven Bacher[2], Franz Essl[3], Philip E. Hulme[4], Jonathan M. Jeschke[5,6], Ingolf Kühn[7,8], Sabrina Kumschick[9, 10], Wolfgang Nentwig[11], Jan Pergl[12], Petr Pyšek[12,13], Wolfgang Rabitsch[14], David M. Richardson[9], Montserrat Vilà[15,16], John R.U. Wilson[9,10], Piero Genovesi[17] and Tim M. Blackburn[1,18,19]

This document has been prepared by:
Sven Bacher[2], Tim M. Blackburn[1,18], Sandro Bertolino[19], Thomas Evans[5,6], Piero Genovesi[17], Sabrina Kumschick[9, 10], Helen E. Roy[20], Kevin G. Smith[21] and Lara Volery[2].

Affiliations:
[1]Department of Genetics, Evolution & Environment, Centre for Biodiversity & Environment Research, Darwin Building, UCL, Gower Street, London WC1E 6BT, UK
[2]Department of Biology, Unit Ecology & Evolution, University of Fribourg, Chemin du Musée 10, 1700 Fribourg, Switzerland
[3]Division of Conservation Biology, Vegetation and Landscape Ecology, University of Vienna, Rennweg 14, 1030 Vienna, Austria
[4]The Bio-Protection Research Centre, PO Box 84, Lincoln University, Christchurch, New Zealand
[5]Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587 Berlin, Germany
[6]Freie Universität Berlin, Department of Biology, Chemistry, Pharmacy, Institute of Biology, Königin-Luise-Str. 1-3, 14195 Berlin, Germany
[7]UFZ, Helmholtz Centre for Environmental Research, Department of Community Ecology, Theodor-Lieser-Str. 4, 06120 Halle, Germany
[8]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany
[9]Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[10]South African National Biodiversity Institute, Kirstenbosch National Botanical Gardens, Claremont 7735, South Africa
[11]Institute of Ecology and Evolution, University of Bern, Baltzerstrasse 6, CH-3012 Bern, Switzerland
[12]Institute of Botany, Department of Invasion Ecology, The Czech Academy of Sciences, CZ-252 43 Průhonice, Czech Republic

[13]Department of Ecology, Faculty of Science, Charles University in Prague, Viničná 7, CZ-128 44 Praha 2, Czech Republic
[14]Environment Agency Austria, Department of Biodiversity and Nature Conservation, Spittelauer Lände 5, 1090 Vienna, Austria
[15]Estación Biológica de Doñana (EBD-CSIC), Avda. Américo Vespucio, s/n, Isla de la Cartuja, 41092 Sevilla, Spain
[16]Department of Plant Biology and Ecology, University of Seville, Seville, Spain
[17]ISPRA, Institute for Environmental Protection and Research, and Chair IUCN SSC Invasive Species Specialist Group, Via Vitaliano Brancati 48, 00144 Rome, Italy
[18]Institute of Zoology, Zoological Society of London, Regent's Park, London NW1 4RY, UK
[19]Department of Life Sciences and Systems Biology, University of Turin, Italy
[20]UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, UK
[21]Global Species Programme, IUCN, Cambridge, UK.

Preface

The IUCN Species Survival Commission (SSC) Invasive Species Specialist Group (ISSG) were invited by Parties to the Convention on Biological Diversity (CBD) to develop a '*system for classifying invasive alien species based on the nature and magnitude of their impacts'* (CBD, 2014). In 2015, the ISSG published a *framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT)* (Hawkins et al., 2015) developed from the original framework proposed by Blackburn et al. (2014).

Following the publication of Hawkins et al. (2015), Resolution WCC-2016-Res-018-EN *Toward an IUCN standard classification of the impact of invasive alien species* was adopted at the 2016 IUCN World Conservation Congress. This Resolution requested the SSC to develop EICAT, and to consult with all relevant stakeholders within the Union to inform this process. It also requested that the SSC integrate the outcomes into the IUCN Global Invasive Species Database and the IUCN Red List of Threatened Species, thus providing an essential background for the achievement of Aichi Target 9 (and subsequent related targets) and SDG Target 15.8. Additionally the Resolution requested IUCN Council to adopt the framework for the IUCN Environmental Impact Classification for Alien Taxa, once the consultation process referred to above had been completed, as the Union's standard for classifying alien species in terms of their environmental impact.

In 2017, IUCN undertook a Union-wide consultation on the science underpinning EICAT (Version 1), its processes and governance. The results showed that the Union overwhelmingly supported EICAT becoming an IUCN Standard for classifying alien taxa against the magnitude of their environmental impacts. However, based on feedback received through this consultation process and lessons learnt through its application, significant edits were made to the proposed standard. In 2019, a second Union-wide consultation was undertaken on the *EICAT Categories and Criteria* (Version 2.3), *Guidelines for the application of EICAT* (Version 2.3), and the *EICAT data reporting template* (Version 2.7): the comments received during this consultation resulted in minor edits being made to the documentation. Following this, the IUCN Council (98th Meeting, February 2020), adopted Version 3.3. of the EICAT Categories and Criteria as the Union's Standard for classifying alien species in terms of their environmental impact.

This document presents the IUCN Standard for classifying alien species in terms of their environmental impact; the *IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria: First edition* (the same as Version 3.3 adopted by IUCN Council).

To ensure full understanding of the application of EICAT, it is very important to refer to all of the following documents:
(1) *IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria: First edition* (IUCN, 2020) – this document.
(2) The latest version of the 'Guidelines for using the IUCN EICAT Categories and Criteria' (check the IUCN ISSG website http://issg.org/ for regular updates of this document)
All of the above documents are freely available to download from the IUCN ISSG (http://www.issg.org).

The intention is to keep the EICAT Categories and Criteria (the IUCN Standard) consistent to enable genuine changes in the magnitude of environmental impacts of alien species to be detected. As a greater clarity emerges on tricky and unresolved issues, these will be addressed through updates to the comprehensive set of user guidelines.

Blackburn et al. (2014). 'A unified classification of alien species based on the magnitude of their environmental impacts'. *PLoS Biology*, 12, e1001850. https://doi.org/10.1371/journal.pbio.1001850

CBD (2014). Decision adopted by the Conference of the Parties to the Convention on Biological Diversity XII/17. Invasive alien species: review of work and considerations for future work. https://www.cbd.int/decision/cop/default.shtml?id=13380

Hawkins et al. (2015). 'Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT)'. *Diversity and Distributions,* 21(11) https://doi.org/10.1111/ddi.12379

Acknowledgements

IUCN gratefully acknowledges the dedication and efforts of the IUCN SSC and IUCN Secretariat Members, and other experts involved in the EICAT criteria review in attending numerous workshops to discuss and debate the merits and demerits of the EICAT Categories and Criteria. In addition, IUCN would like to thank all those who took part in both rounds of the IUCN-wide EICAT consultation, in which we received invaluable feedback and insightful suggestions.

Particular thanks must go to Kevin Smith who chaired the review and steered an extremely complex process through to a successful conclusion. This review culminated in the adoption of the EICAT Categories and Criteria by the IUCN Council.

Abbreviations

CBD – Convention on Biological Diversity
COP – Conference of Parties
EICAT – Environmental Impact Classification for Alien Taxa
GISD – Global Invasive Species Database
ISSG – Invasive Species Specialist Group
IUCN – International Union for Conservation of Nature
SSC – Species Survival Commission

EICAT Categories and labels:
CG – Cryptogenic
DD – Data Deficient
MC – Minimal Concern
MN – Minor
MO – Moderate
MR – Major
MV – Massive
NA – No Alien Population
NE – Not Evaluated

1. Introduction

Human activities are transforming natural environments by moving taxa beyond the limits of their native geographic ranges into areas where they do not naturally occur. Many of these alien taxa have had substantial adverse impacts on the recipient ecosystems. For example, they have been shown to cause significant changes in native species extinction probabilities, genetic composition of native populations, behaviour patterns, taxonomic, functional and phylogenetic diversity, trophic networks, ecosystem productivity, nutrient cycling, hydrology, habitat structure, and various components of disturbance regimes [1-8]. For these reasons, most governments, scientists and conservation organisations consider many alien taxa to be undesirable additions to ecosystems, and frequently devote considerable resources towards preventing or mitigating their impacts. The magnitude and type of impacts generated by alien taxa vary greatly among recipient ecosystems, and many of these impacts only become obvious or influential long after the onset of invasion. Moreover, many impacts remain or are difficult to redress even if the alien taxa of concern are removed or controlled. As such, there is a critical need for scientifically robust tools to evaluate, compare, and predict the magnitudes of the impacts of different alien taxa, in order to determine and prioritise appropriate actions where necessary [9].

A unified classification of alien taxa based on the magnitude of their environmental impacts [10] (hereafter referred to as the Environmental Impact Classification for Alien Taxa, abbreviated to EICAT) has been developed in response to these issues. EICAT is a simple, objective and transparent method for classifying alien taxa in terms of the magnitude of their detrimental environmental impacts in recipient areas. Based on evidence on the impacts they have been causing on native taxa in their introduced range, alien taxa are classified into one of five impact categories. Each of these five impact categories represents a different impact magnitude, depending on the level of biological organisation of the native biota impacted (individual, population or community) and the reversibility of this impact. Alien taxa are also classified according to the mechanisms by which these impacts occur: the mechanisms are aligned with those identified in the IUCN Global Invasive Species Database (GISD) http://www.iucngisd.org/gisd/.

EICAT has the following five objectives: (i) identify alien taxa by levels of environmental impact, (ii) compare the level of impact by alien taxa among regions and taxonomic groups, (iii) facilitate predictions of potential future impacts of taxa in the target region and elsewhere, (iv) aid the prioritisation of management actions, and (v) facilitate the evaluation of management methods. It is envisaged that EICAT will be used by scientists, environmental managers and conservation practitioners as a tool to gain a better understanding of the magnitude of impacts caused by different alien taxa, to alert relevant stakeholders to the possible consequences of the arrival of certain alien taxa, and to inform the prioritisation, implementation and evaluation of management policies and actions.

It must be emphasised at the outset that EICAT is not a risk assessment, and its **output alone should not be used to prioritise management actions for alien taxa**. Risk assessments and priority setting require information on many issues related to the biology and ecology of the alien taxa and the pathways of introduction, which are not incorporated in EICAT. The output of EICAT is also not a statutory list of invasive alien taxa. Thus, while it is intended to inform the prioritization of management activities against alien taxa causing environmental impacts within a country or a region, EICAT should not be used alone to identify which alien taxa should be regulated. Furthermore, any decision that could have effects on the regulation of trade of species must comply with existing international agreements, including, amongst others, the CBD and its guidance on invasive alien species, the World Trade Organisation (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement), and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). EICAT has the potential to inform statutes adhering to the relevant international agreements, to assist the implementation of appropriate measures, and to inform risk assessments, but it does not replace them.

EICAT must be applied in a consistent and comparable manner when assessing the impacts of different alien taxa. Therefore, **we present the IUCN EICAT Categories and Criteria: First edition** which should be used to inform the assessment process. The EICAT Categories and Criteria are analogous to, and draw heavily upon, the framework adopted for the globally recognised IUCN Red List of Threatened Species™ [11]. There is also a separate accompanying Guidelines document that provides additional guidance to support the application of the EICAT Categories and Criteria, including on how to deal with uncertainty, the required documentation standards, and EICAT assessment process. The EICAT Guidelines document will be periodically updated, and will be made available on the IUCN SSC ISSG website (www.issg.org).

The EICAT Categories and Criteria: First edition and the accompanying EICAT Guidelines document are adapted from – and replace – the EICAT guidelines proposed by Hawkins et al. (2015). The following EICAT Categories and Criteria: First edition and accompanying EICAT Guidelines document are therefore the documents to use when undertaking EICAT assessments.

2. Definitions

This section defines key terms used in the application of the EICAT Categories and Criteria. It is necessary to refer to these terms when interpreting them as some are commonly used terms that are defined in a particular sense here.

Taxon

This term is used for convenience to represent species or lower taxonomic levels (subspecies, varieties, cultivars, or breeds), including those that are not yet formally described.

Alien taxon

A species, subspecies or variety or cultivar or breed, moved intentionally or unintentionally by human activities beyond the limits of its native geographic range, or resulting from breeding or hybridisation and being released into an area in which it does not naturally occur. The movement allows the taxon to overcome fundamental biogeographic barriers to its natural dispersal. The definition includes any part, gametes, seeds, eggs, or propagules of such taxa that might survive and subsequently reproduce. Natural dispersal of a taxon either within postglacial habitat expansion or due to climate shift does not qualify to label a taxon as alien. Common synonyms include non-native, non-indigenous, foreign, and exotic. The definition follows the CBD (COP 6 Decision VI/23 https://www.cbd.int/decisions/cop/?m=cop-06) and [12]. See also taxon; invasive alien taxon.

Invasive alien taxon

An alien taxon whose introduction and/or spread threatens biological diversity. This definition follows the CBD (COP 6 Decision VI/23). The requirement that an invasive alien taxon causes threat or harm is common in policy usage (see also Executive Order 13112 – Invasive Species, of the United States Government), but less so in scientific usage where “invasive” usually simply implies that the taxon has spread widely and rapidly from the point of establishment [12].

Environmental impact

A measurable change to the properties of an ecosystem caused by an alien taxon [2]. This definition applies to all ecosystems, whether largely natural or largely managed by humans, but explicitly considers only changes that have impacts on the native biota. Changes in abiotic properties of the environment caused by an alien taxon are only considered if they affect the native biota. The same alien taxon may also have impacts on human societies and economies [14], but these are not considered here.

Deleterious environmental impact

An impact that changes the environment in such a way as to modify native biodiversity or alter ecosystem properties to the detriment of native taxa [15]. This definition intentionally excludes societal judgments regarding the desirability or value of alien taxa, and it is assumed here that the classification will be used as a mechanism to prevent impacts that are judged to be "negative" by those concerned.

Global population

The total number of individuals of a taxon. See also population size.

Sub-population and local population

A sub-population is a geographically or otherwise distinct group in the global population for which there is little demographic or genetic exchange. A local population is a group of individuals within a sub-population. It may encompass all of the individuals within the sub-population (e.g., local population 1 in Figure 1), or only some of those individuals (e.g., local populations 2 – 4 in Figure 1). In the latter case, a local population is spatially disjunct from other groups of individuals, but shares individuals with other local populations through natural immigration, in which case it may form part of a meta-population [16]. An EICAT assessment considers impacts happening at least at the level of the local population. See also population size.

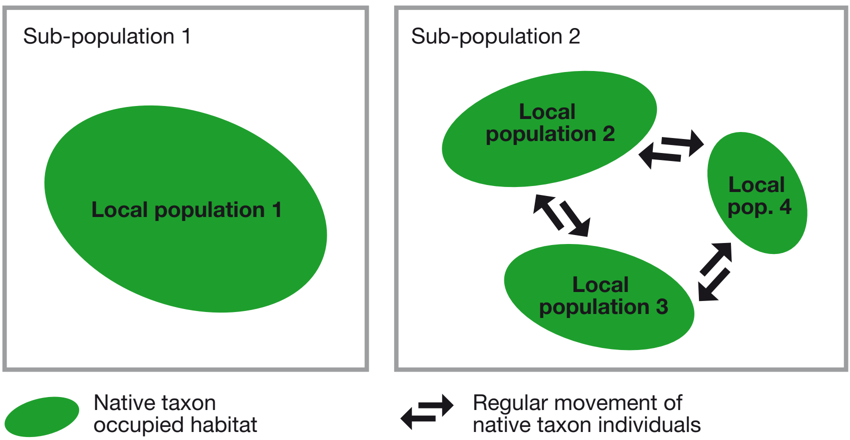


Figure 1. The relationship between global population, sub-population and local population for the purposes of EICAT assessments. The global population includes all individuals of the taxon, a sub-population is a geographically or otherwise distinct group in the population, and a local population is a group of individuals within a sub-population. In this example, local population 1 includes all individuals within sub-population 1. Local populations 2, 3 and 4 are connected by frequent natural immigration, whereas sub-populations 1 and 2 are largely isolated from each other.

Population size

For functional reasons, primarily owing to differences between life forms, population size (whether global, sub or local) is measured as numbers of mature individuals only. In the case of taxa dependent on other taxa for all or part of their life cycles, biologically appropriate values for the host taxon should be used.

Mature individuals

Mature individuals are the number of individuals known, estimated or inferred to be capable of reproduction. When estimating this quantity, the following points should be considered:

- Mature individuals that will never produce new recruits should not be counted (e.g., densities are too low for fertilisation).
- In the case of populations with biased adult or breeding sex ratios, it is appropriate to use lower estimates for the number of mature individuals, which take this into account.
- Where the population size fluctuates, use a lower estimate. In most cases this will be much less than the mean.
- Reproducing units within a clone should be counted as individuals, except where such units are unable to survive alone.
- In the case of taxa that naturally lose all or a subset of mature breeding individuals at some point in their life cycle, the estimate should be made at the appropriate time, when mature individuals are available for breeding.

Native community

The assemblage of populations of naturally occurring taxa present in the area occupied by the alien taxon.

Changes to a community

Changes to a community refer to the loss of at least one native species in a community (local population extinction of one or more native species) due to impacts caused by the alien taxon.

Performance

Performance is a measurable fitness trait that affects the capacity of an individual organism to survive, gather resources, grow, or reproduce [see 17, 18]. Examples include biomass, plant height, number of offspring or seeds, and immunocompetence.

Decline in population size

A decline in global, sub- or local population size is a reduction in the number of mature individuals of a native species resulting from the introduction of the alien taxon. The downward phase in a normally fluctuating population will not count as a reduction. In cases where an alien taxon impacts the recruitment of native species, this impact will not count as a reduction in population size, unless there is also an impact on the number of mature individuals.

Local population extinction

The elimination of one or more native taxa due to impacts caused by the alien taxon, in part or all of the area invaded by the alien taxon (also known as extirpation). A native taxon is presumed locally extinct when there is evidence from known and/or expected habitat within the local area invaded by the alien taxon that no individuals of the native taxon remain. Local population extinction differs from global (species) extinction, which refers to the complete elimination of a native taxon from all parts of its range. In situations where a species is only known from one locality, local population extinction may also result in the species' global extinction. This may occur on islands for example, if the introduction of an alien taxon leads to the local extinction of an island endemic species.

Naturally reversible changes

Following on from a local population extinction, naturally reversible means there is evidence that if the alien taxon is no longer present, the native taxon would be likely to return to the community within 10 years or 3 generations, whichever is longer. The native taxon can return to the community naturally (e.g., individuals migrating from a metapopulation), or assisted by human re-introductions, either intentionally or unintentionally, but only where the re-introductions were occurring at a similar rate before the alien taxon led to the native species local population extinction, and the re-introductions are not for conservation purposes. Therefore, re-introductions assisted by humans that were not already in place at the time the alien taxon led to the local population extinction, and that would require extra effort (e.g., re-introductions from captivity or from other areas), are not considered as naturally reversible changes.

Naturally irreversible changes

Naturally irreversible means there is evidence that if the alien taxon is no longer present, the native species would not return to the community within 10 years or 3 generations, whichever is longer, without additional human assistance that was not already in place at the time the alien taxon led to the local population extinction (see naturally reversible changes). Local extinctions are naturally irreversible when there is no propagule influx of the native taxon (e.g., global extinction, isolation of the local population), or when the alien population changes the environment making it unsuitable for the native taxon to re-establish.

3. Description of the EICAT Categories and Criteria

3.1. Categories

The impacts of an alien taxon are classified based on the level of biological organisation it affects (individuals → populations → communities), and the magnitude and reversibility of these impacts. The impact category assigned to an alien taxon should reflect its most severe impact to native taxa under any of the criteria listed in section 4.2.

There are eight clearly defined categories into which taxa can be classified (Figure 2). Complete definitions of the categories are given in Box 1. The first five categories, termed ***'impact'*** categories, follow a sequential series of impact scenarios describing increasing levels of impact by alien taxa. These scenarios have been designed such that each step change in category reflects an increase in the order of magnitude of the particular impact so that a new level of biological organisation is involved. Thus: **Minimal Concern (MC)** – negligible impacts, and no reduction in performance of a native taxon's individuals; **Minor (MN)** – performance of individuals reduced, but no decrease in population size; **Moderate (MO)** – native taxon population decline; **Major (MR)** – native taxon local extinction (i.e. change in community structure), which is naturally reversible; and **Massive (MV)** – naturally irreversible local, or global extinction of a native taxon (i.e. change in community structure). Alien taxa should be classified based on the highest criterion level met across any of the impact mechanisms (section 4.2, Table 1). Impacts that fall within the categories **Moderate**, **Major** or **Massive** are termed ***'harmful'***.

The remaining three categories do not reflect the impact status of a taxon. The **Data Deficient (DD)** category highlights taxa for which evidence suggests that alien populations exist, but for which current information is insufficient to assess their level of impact. The category **No Alien Population (NA)** should be applied when there is no evidence to suggest the taxon has or had individuals existing in the wild (i.e. outside of captivity), beyond the boundary of its native geographic range. The category **Not Evaluated (NE)** applies to taxa that have not yet been evaluated against the EICAT impact categories.

Finally, the label **Cryptogenic (CG)** should be applied to taxa for which it is unclear, following evaluation, whether individuals present at a location are native or alien [13]. **CG** is not a category in itself; cryptogenic taxa should be evaluated as if they are aliens, on the basis of the precautionary principle, but their impact classification modified by the **CG** label (e.g., for a cryptogenic species with Major impact: *Genus species* **MR** [**CG**]).

Box 1. Category definitions
The abbreviation of each category (in parenthesis) follows the denomination.

Minimal Concern (MC)
A taxon is considered to have impacts of **Minimal Concern** when it causes negligible levels of impacts, but no reduction in performance of individuals in the native biota. Note that all alien taxa have impacts on the recipient environment at some level, for example by altering species diversity or community similarity (e.g., biotic homogenisation), and for this reason there is no category equating to "no impact". Only taxa for which changes in the individual performance of natives have been studied but not detected are assigned an **MC** category. Taxa that have been evaluated under the EICAT process but for which impacts have not been assessed in any study should not be classified in this category, but rather should be classified as **Data Deficient**.

Minor (MN)
A taxon is considered to have **Minor** impacts when it causes reductions in the performance of individuals in the native biota, but no declines in native population sizes, and has no impacts that would cause it to be classified in a higher impact category.

Moderate (MO)
A taxon is considered to have **Moderate** impacts when it causes declines in the population size of at least one native taxon, but has not been observed to lead to the local extinction of a native taxon.

Major (MR)
A taxon is considered to have **Major** impacts when it causes community changes through the local or sub-population extinction (or presumed extinction) of at least one native taxon, that would be naturally reversible if the alien taxon was no longer present. Its impacts do not lead to naturally irreversible local population, sub-population or global taxon extinctions.

Massive (MV)
A taxon is considered to have **Massive** impacts when it causes naturally irreversible community changes through local, sub-population or global extinction (or presumed extinction) of at least one native taxon.

Data Deficient (DD)
A taxon is categorised as **Data Deficient** when the best available evidence indicates that it has (or had) individuals existing in a wild state in a region beyond the boundary of its native geographic range, but either there is inadequate information to classify the taxon with respect to its impact, or insufficient time has elapsed since introduction for impacts to have become apparent. It is expected that all introduced taxa will have an impact at some level, because by definition an alien taxon in a new environment has a nonzero impact. However, listing a taxon as **Data Deficient** recognises that current information is insufficient to assess that level of impact.

No Alien Populations (NA)
A taxon is categorised as having **No Alien Populations** when there is no reliable evidence that it has (or had) individuals existing in a wild state in a region beyond the boundary of its native geographic range. In this case, absence of evidence is assumed to be evidence of absence, as it is impossible to prove that a taxon has no alien individuals anywhere in the world. Taxa with individuals kept in captivity or cultivation in an area to which it is not native would be classified here. A taxon could currently have no individuals existing in a wild state in a region beyond the boundary of its native geographic range because it has died out in, or has been eradicated from, such an area. In these cases, there should be evidence relating to impact that causes it to be classified in one of the impact categories (**MC**, **MN**, **MO**, **MR**, **MV**), or alternatively no evidence of impact, which would cause it to be classified as **DD**.

Not Evaluated (NE)
A taxon is categorised as **Not Evaluated** when it has not yet been evaluated against the EICAT impact categories.

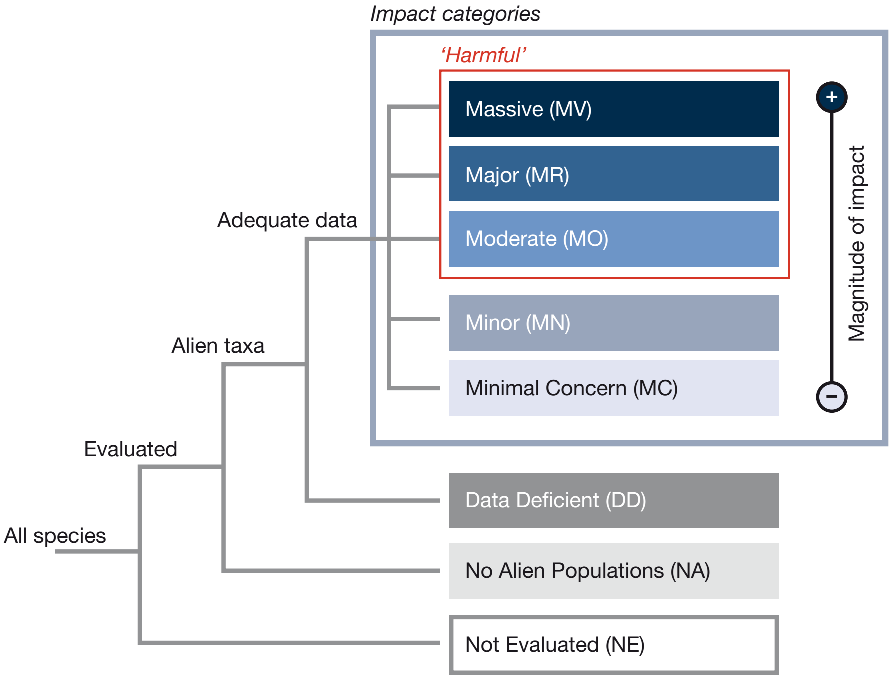


Figure 2. The different EICAT categories and the relationship between them. Descriptions of the categories are provided in Box 1. The cryptogenic (CG) label is not represented here as CG taxa may be found in any category.

Cyrptogenic species are a particular problem in the marine realm, for cosmopolitan plants, for species that spread easily, for taxa possibly introduced into a location many centuries ago, and for species from taxonomic groups who's biogeography is poorly understood, including many stored product arthropod pests, for which the native geographic ranges are unknown. Cryptogenic taxa may have deleterious impacts where they occur.

In many cases, it is difficult to distinguish whether an alien taxon is the driver of environmental changes, or simply a passenger responding to the same driver as the natives [19]. Moreover, synergistic interactions between alien taxa and other stressors are also possible (and perhaps increasingly common) but difficult to anticipate [20]. The EICAT scheme takes a precautionary approach: when the main driver of change is unclear, it should be assumed to be the alien taxon for the purposes of the EICAT assessment. However, the classification is intended to be dynamic, allowing for updates as new or more reliable data become available, and as the documented impact history of a taxon unfolds across space and time.

3.2. Criteria

Twelve **impact mechanisms** have been identified by which alien taxa may cause deleterious impacts in areas to which they have been introduced (Table 1). For each mechanism, there are five criteria against which taxa should be evaluated, to determine the level of deleterious impact caused under that mechanism. Taxa should be evaluated against every relevant mechanism and criterion, and the highest level of criterion met under any mechanism then determines the EICAT category to which the taxon is assigned. These mechanisms are based on those proposed by Nentwig *et al.* 2010 [21], Kumschick *et al.* 2012 [22] and Blackburn *et al.* 2014 [10]. They are aligned with those identified in the IUCN Global Invasive Species Database (GISD) http://www.iucngisd.org/gisd/.

The impact mechanisms are:

1. **Competition** – the alien taxon competes with native taxa for resources (e.g., food, water, space), leading to deleterious impact on native taxa.
2. **Predation** – the alien taxon predates on native taxa, leading to deleterious impact on native taxa.
3. **Hybridisation** – the alien taxon hybridises with native taxa, leading to deleterious impact on native taxa.
4. **Transmission of disease** – the alien taxon transmits diseases to native taxa, leading to deleterious impact on native taxa.
5. **Parasitism** – the alien taxon parasitises native taxa, leading to deleterious impact on native taxa.
6. **Poisoning/toxicity** – the alien taxon is toxic, or allergenic by ingestion, inhalation or contact, or allelopathic to plants, leading to deleterious impact on native taxa.
7. **Bio-fouling or other direct physical disturbance** – the accumulation of individuals of the alien taxon on the surface of a native taxon (i.e., bio-fouling), or other direct physical disturbances not involved in a trophic interaction (e.g., trampling, rubbing, etc.) leads to deleterious impact on native taxa.
8. **Grazing/herbivory/browsing** – grazing, herbivory or browsing by the alien taxon leads to deleterious impact on native taxa.
9. **Chemical impact on ecosystem** – the alien taxon causes changes to the chemical characteristics of the native environment (e.g., pH; nutrient and/or water cycling), leading to deleterious impact on native taxa.
10. **Physical impact on ecosystem** – the alien taxon causes changes to the physical characteristics of the native environment (e.g., disturbance or light regimes), leading to deleterious impact on native taxa.
11. **Structural impact on ecosystem** – the alien taxon causes changes to the habitat structure (e.g., changes in architecture or complexity), leading to deleterious impact on native taxa.
12. **Indirect impacts through interactions with other species** – the alien taxon interacts with other native or alien taxa (e.g., through any mechanism, including pollination, seed dispersal, apparent competition, mesopredator release), facilitating indirect deleterious impact on native taxa.

Alien taxa should be assessed for their impact under all the mechanisms for which data are available, and classified on the basis of evidence of their most severe impacts under any of the impact mechanisms. For a taxon to qualify in any of the EICAT impact categories (**MC**, **MN**, **MO**, **MR**, **MV**), evidence of impact is needed for one (or more) of the twelve mechanisms that caused the highest impact. The criteria used for classifying impacts associated with each impact mechanism are described in Table 1. Impacts which do not fit any of the mechanisms can still be classified, based on the general rules given in the top row of Table 1.

These categories are for taxa that have been evaluated, have alien populations (i.e., are known to have been introduced outside their native range), and for which there is adequate data to allow classification (see Figure 2). Classification follows the general principle outlined in the first row. However, the different mechanisms through which an alien taxon can cause impacts are outlined, in order to guide the assessment process.

Table 1. Criteria used to classify alien taxa by EICAT impact category (MC, MN, MO, MR, MV).

	Massive (MV)	Major (MR)	Moderate (MO)	Minor (MN)	Minimal Concern (MC)
Categories should adhere to the following general meaning	*Causes local extinction of at least one native taxon (i.e., taxa vanish from communities at sites where they occurred before the alien arrived), which is naturally irreversible; even if the alien taxon is no longer present the native taxon cannot recolonise the area*	*Causes local or sub-population extinction of at least one native taxon (i.e., taxa vanish from communities at sites where they occurred before the alien arrived); which is naturally reversible if the alien taxon is no longer present*	*Causes population decline in at least one native taxon, but no local population extinction*	*Causes reduction in individual performance (e.g., growth, reproduction, defence, immunocompetence), but no decline in local native population sizes*	Negligible level of impact; no reduction in performance (e.g., growth, reproduction, defence, immunocompetence) of individuals of native taxa
Mechanisms					
(1) Competition	Competition resulting in replacement or local extinction of one or several native taxa; changes are naturally irreversible	Competition resulting in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Competition resulting in a decline of population size of at least one native taxon, but no local population extinction	Competition affects performance of native individuals without decline of their populations	Negligible level of competition with native taxa; reduction of performance of native individuals is not detectable
(2) Predation	Predation results in local extinction of one or several native taxa; changes are naturally irreversible	Predation results in local population extinction of at least one native taxon; naturally reversible when the alien taxon is no longer present	Predation results in a decline of population size of at least one native taxon, but no local population extinction	The alien taxon preys on native taxa, without leading to a decline in their populations	Not applicable; predation on native taxa is classified at least as MN
(3) Hybridisation	Hybridisation between the alien taxon and native taxa leading to the loss of at least one pure native local population (genomic extinction); pure native taxa cannot be recovered even if the alien and hybrids are no longer present	Hybridisation between the alien taxon and native taxa leading to the loss of at least one pure native local population (genomic extinction); naturally reversible when the alien taxon and hybrids are no longer present	Hybridisation between the alien taxon and native taxa is regularly observed in the wild; local decline of populations of at least one pure native taxon, but pure native taxa persist	Hybridisation between the alien taxon and native taxa is observed in the wild, but rare; no decline of pure local native populations	No hybridisation between the alien taxon and native taxa observed in the wild (prezygotic barriers), hybridisation with a native taxon is possible in captivity

	Massive (MV)	Major (MR)	Moderate (MO)	Minor (MN)	Minimal Concern (MC)
(4) Transmission of disease to native species	Transmission of disease to native taxa resulting in local extinction of at least one native taxon; changes are naturally irreversible	Transmission of disease to native taxa resulting in local population extinction of at least one native taxon; naturally reversible when the alien taxon is no longer present	Transmission of disease to native taxa resulting in a decline of population size of at least one native taxon, but no local population extinction; disease is severely affecting native taxa, including mortality of individuals, and it has been found in native and alien co-occurring individuals (same time and space)	Transmission of disease to native taxa affects performance of native individuals without leading to a decline of their populations; alien taxon is a host of a disease which has also been detected in native taxa and affects the performance of native taxa	The alien taxon is a host or vector of a disease transmissible to native taxa but disease not detected in native taxa; reduction in performance of native individuals is not detectable
(5) Parasitism	Parasites or pathogens directly result in local extinction of one or several native taxa; changes are naturally irreversible	Parasites or pathogens directly result in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Parasites or pathogens directly result in a decline of population size of at least one native taxon, but no local population extinction	Parasites or pathogens directly affect performance of native individuals without decline of their populations	Negligible level of parasitism or disease incidence (pathogens) on native taxa, reduction in performance of native individuals is not detectable
(6) Poisoning/ toxicity	The alien taxon is toxic/ allergenic by ingestion, inhalation, or contact to wildlife or allelopathic to plants, resulting in local extinction of at least one native taxon; changes are naturally irreversible	The alien taxon is toxic/ allergenic by ingestion, inhalation, or contact to wildlife or allelopathic to plants, resulting in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is removed	The alien taxon is toxic/ allergenic by ingestion, inhalation, or contact to wildlife or allelopathic to plants, resulting in a decline of population size of at least one native taxon, but no local population extinction	The alien taxon is toxic/allergenic by ingestion, inhalation, or contact to wildlife or allelopathic to plants, affecting performance of native individuals without decline of their populations	The alien taxon is toxic/ allergenic/ allelopathic, but the level is very low, reduction of performance of native individuals is not detectable

	Massive (MV)	Major (MR)	Moderate (MO)	Minor (MN)	Minimal Concern (MC)
(7) Bio-fouling or other direct physical disturbance	Bio-fouling or other direct physical disturbance resulting in local extinction of one or several native taxa; changes are naturally irreversible	Bio-fouling or other direct physical disturbance resulting in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Bio-fouling or other direct physical disturbance resulting in a decline of population size of at least one native taxon, but no local population extinctions	Bio-fouling or other direct physical disturbance affects performance of native individuals without decline of their populations	Negligible level of bio-fouling or direct physical disturbance on native taxa; reduction in performance of native individuals is not detectable
(8) Grazing/ herbivory/ browsing	Herbivory/grazing/ browsing resulting in local extinction of one or several native taxa; changes are naturally irreversible	Herbivory/grazing/ browsing resulting in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Herbivory/grazing/ browsing resulting in a decline of population size of at least one native taxon, but no local population extinction	Herbivory/grazing/ browsing affects performance of individuals of native taxa without decline of their populations	Negligible level of herbivory/grazing/ browsing on native taxa, reduction in performance of native taxa is not detectable
(9) Chemical impact on ecosystems	Changes in chemical ecosystem characteristics (e.g., changes in nutrient cycling, pH) resulting in local extinction of at least one native taxon; changes are naturally irreversible	Changes in chemical ecosystem characteristics (e.g., changes in nutrient cycling, pH) resulting in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Changes in chemical ecosystem characteristics (e.g., changes in nutrient cycling, pH) resulting in a decline of population size of at least one native taxon, but no local population extinction	Changes in chemical ecosystem characteristics (e.g., changes in nutrient cycling, pH) affecting performance of native individuals without decline of their populations	Changes in chemical ecosystem characteristics detectable (e.g., changes in nutrient cycling, pH), but no reduction in performance of native individuals detectable

	Massive (MV)	Major (MR)	Moderate (MO)	Minor (MN)	Minimal Concern (MC)
(10) Physical impact on ecosystems	Changes in physical ecosystem characteristics (e.g., changes in temperature, fire or light regime) resulting in local extinction of native taxa; changes are naturally irreversible	Changes in physical ecosystem characteristics (e.g., changes in temperature, fire or light regime) resulting in local population extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Changes in physical ecosystem characteristics (e.g., changes in temperature, fire or light regime) resulting in a decline of population size of at least one native taxon, but no local population extinction	Changes in physical ecosystem characteristics (e.g., changes in temperature, fire or light regime) affecting performance of native individuals without decline of their populations	Changes in physical ecosystem characteristics detectable (e.g., changes in temperature, fire or light regime), but no reduction in performance of native individuals detectable
(11) Structural impact on ecosystems	Changes in structural ecosystem characteristics (e.g., changes in architecture or complexity) resulting in local extinction of native taxa; changes are naturally irreversible	Changes in structural ecosystem characteristics (e.g., changes in architecture or complexity) resulting in local extinction of at least one native taxon, but changes are naturally reversible when the alien taxon is no longer present	Changes in structural ecosystem characteristics (e.g., changes in architecture or complexity) resulting in a decline of population size of at least one native taxon, but no local population extinction	Changes in structural ecosystem characteristics (e.g., changes in architecture or complexity) affecting performance of native individuals without decline of their populations	Changes in structural ecosystem characteristics detectable (e.g., changes in architecture or complexity), but no reduction in performance of native individuals detectable
(12) Indirect impacts through interaction with other species	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) causing local extinction of one or several native taxa, leading to naturally irreversible changes that would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) causing local population extinction of at least one native taxon; changes are naturally reversible but would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) causing a decline of population size of at least one native taxon, but no local population extinction; impacts would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) affecting performance of native individuals without decline of their populations; impacts would not have occurred in the absence of the alien taxon	Interaction of an alien taxon with other taxa leading to indirect impacts (e.g., pollination, seed dispersal, apparent competition) but reduction in performance of native individuals is not detectable

4. Applying EICAT

4.1. Evidence-based scheme

EICAT assessments are based on available data, published or unpublished, on the environmental impacts of alien taxa. While EICAT provides important insights into the threat posed to new regions, it is based only on impacts that have actually been observed, or inferred based on evidence, in the introduced range. Potential impact is an estimate of the magnitude of impact that would result if an invasion occurred, which might incorporate information from the native range, trait analyses and mechanistic models. Potential impact is an essential part of risk assessment, but is not part of EICAT. The classification should not be used alone as a proxy for potential impact. Furthermore, EICAT is solely concerned with impacts in the alien range of a taxon and data and observations from the native range should not be used in assessing impacts under EICAT. Where there is uncertainty as to whether a study is in the native range or not, this should be recorded in the essential documentation.

4.2. Taxonomic scope

The EICAT process may be applied to species, subspecies or (for plants) varieties or cultivars, or (for animals) breeds introduced outside their natural past or present distribution (CBD COP 6 Decision VI/23) or to newly occurring taxa arising from breeding or hybridisation. For any EICAT assessment, the taxonomic unit used (species, subspecies, lower taxon) should be specified in the supporting documentation.

Note that invasion, and by extension impact, is a characteristic of a population, rather than a species: not all populations of a given taxon cause the same impacts. It follows that the EICAT classification of a taxon will generally reflect impacts recorded from one or a small number of populations, and that population level impacts translate into taxon-level assessments. This reflects the precautionary principle, as impact caused by one population suggests the potential for other alien populations of the same taxon to cause similar impacts elsewhere.

4.3 Lack of evidence of impact

EICAT is applicable to alien populations occurring in any biome; terrestrial, freshwater, or marine. However, the impacts of alien populations within some habitats will initially be less studied than within others, and therefore it is important that a lack of evidence of impacts is not interpreted as lack of impact. Within EICAT, lack of evidence of impact (categorised as **DD**) is treated differently to evidence of lack of impact (categorised as **MC**).

4.4. Spatial and temporal scale of impact

Assessments using EICAT are undertaken on impact data currently available for alien taxa at appropriate spatial and temporal scales. This needs to take into account the typical spatial and temporal scales over which the original native communities can be characterised. Assessments based on evidence generated at spatial or temporal scales that are very different to the scales over which the local native population can be characterised are likely to be subject to greater uncertainty.

4.5. Classification

Assessments using EICAT Categories and Criteria are undertaken on evidence of impacts at the appropriate spatial and temporal scales. An alien taxon may have been subject to many different assessments of impact, each with a different EICAT classification (Figure 3). The final EICAT category assigned to the alien taxon is the maximum recorded impact across all of the different impact assessments (Figure 3).

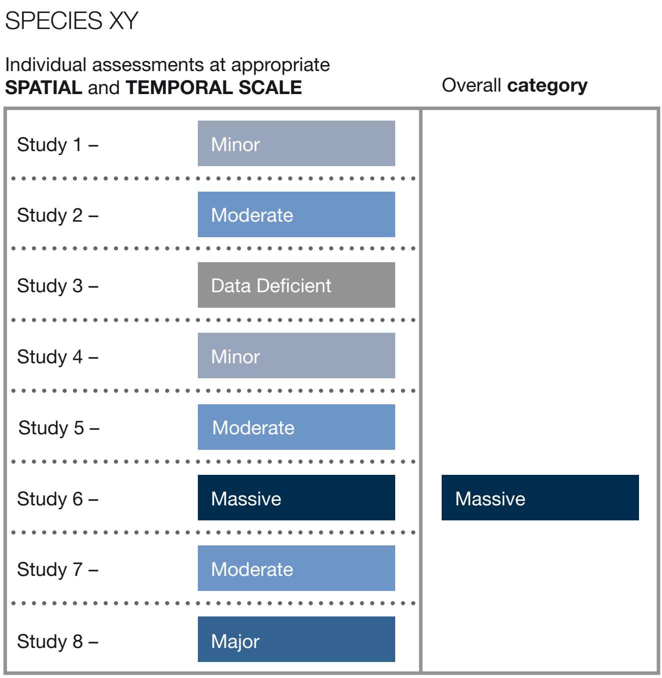


Figure 3. How data from individual EICAT assessments of the impacts of a hypothetical alien taxon (species XY) inform the overall EICAT Category to which the taxon is assigned. The overall assessment categorises the taxon based on its highest impact anywhere (in this case, Massive (MV)).

It is likely that some alien taxa will be subject to management plans to control or eradicate their populations in invaded areas. A possible result is that the current highest level of impact caused by the taxon is below the highest level of impact ever recorded for the taxon (i.e. before the management took place). However, due to the known potential of the taxon to cause the highest level of impact, the maximum recorded impact remains the IUCN EICAT category assigned to the taxon.

4.6. Geographic scale of the classification

IUCN currently only reviews and displays global assessments. Global assessments are based on evidence of impact from the taxon's entire alien range, and the highest level of impact recorded anywhere in the alien range of the taxon being assessed. In practice, as most alien taxa with recorded impacts are yet to have their impacts studied in most areas where they occur, the vast majority of EICAT assessments will use data from only part of the alien range to generate a global level taxon assessment. While the EICAT Categories and Criteria are focused only on assessments undertaken at the global scale, the EICAT process can be applied to impacts at different geographic scales, including regional, national or local (Figure 4). However, impact listings are likely to be context dependent: an impact that is observed in one area of the introduced range may not occur elsewhere, or may not be as severe elsewhere. Therefore, national or regional level assessments, which only take into account impacts which have occurred within a particular country or region, may differ markedly from global level assessments which are based on the highest level of impact recorded anywhere in the alien range of the taxon being assessed (Figure 4). Regardless of the geographic scale of the assessment, evidence of the impacts of alien taxa used for the assessment should be measured at an appropriate spatial scale, taking into account the typical spatial and temporal scale at which the invaded native communities can be characterised.

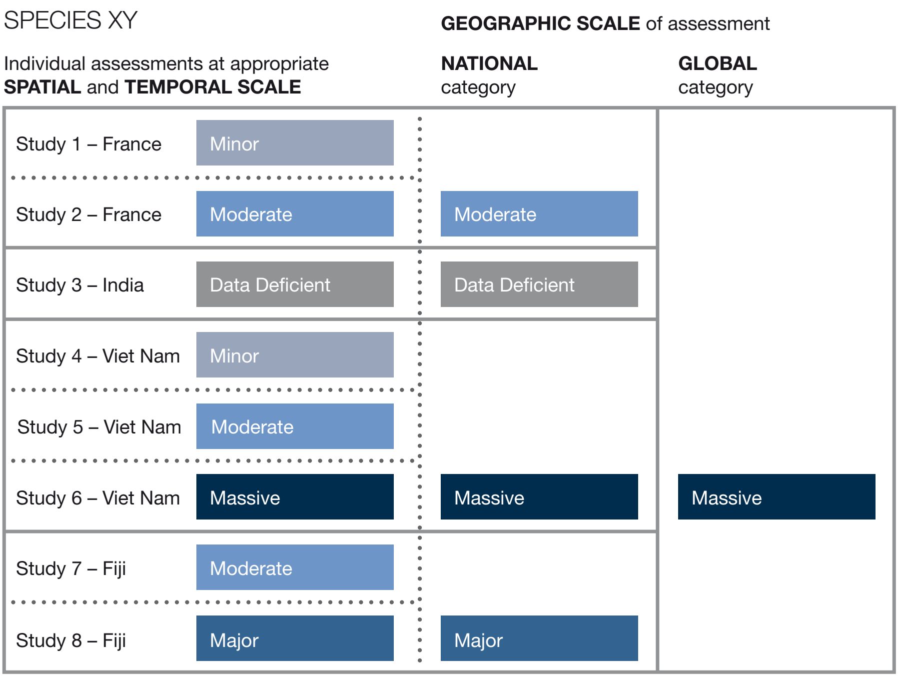


Figure 4. How data from individual EICAT assessments of the impacts of a hypothetical alien taxon (species XY) inform the EICAT category to which the taxon is assigned at national and global scales. The global assessment categorises the taxon based on its highest impact anywhere (in this case, a Massive (MV) impact in Viet Nam). National scale assessments are based only on impacts reported from those countries (e.g. Major (MR) for Fiji). Data Deficient (DD) in India indicates that the alien taxon was assessed but no impact reports from India were found.

References

1. Pyšek, P., Jarošík, V., Hulme, P., Pergl, J. Hejda, M., Schaffner, U. and Vilà, M. (2012). 'A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species' traits and environment'. *Global Change Biology*, 18(5): 1725-1737. https://doi.org/10.1111/j.1365-2486.2011.02636.x
2. Ricciardi, A., Hoopes, M., Marchetti, M. and Lockwood, J. (2013). 'Progress toward understanding the ecological impacts of non-native species'. *Ecological Monographs*, 83(3): 263-282. https://doi.org/10.1890/13-0183.1
3. Brooks, M., D'Antonio, C., Richardson, D., Grace, J., Keeley, J., DiTomaso, J., Hobbs, R., Pellant, M. and Pyke, D. (2004). 'Effects of invasive alien plants on fire regimes'. *BioScience*, 54(7): 677-688. https://doi.org/10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2
4. Hendrix, P., Callaham, M., Drake, J., Huang, C-Y., James, S., Snyder, B. and Zhang, W. (2008). 'Pandora's Box Contained Bait: The Global Problem of Introduced Earthworms'*. *Annual Review of Ecology, Evolution, and Systematics*, 39: 593-613. https://doi.org/10.1146/annurev.ecolsys.39.110707.173426
5. Suarez, A. and Tsutsui, N. (2008). 'The evolutionary consequences of biological invasions'. *Molecular Ecology*, 17(1): 351-360. https://doi.org/10.1111/j.1365-294X.2007.03456.x
6. Kenis, M., Auger-Rozenberg, M-A., Roques, A., Timms, L., Pere, C., Cock, M., Settele, J., Augustin, S. and Lopez-Vaamonde, C. (2009). 'Ecological effects of invasive alien insects'. In: D. Langor and J. Sweeney (eds.), *Ecological Impacts of Non-Native Invertebrates and Fungi on Terrestrial Ecosystems*, pp. 21-45. Springer. https://doi.org/10.1007/978-1-4020-9680-8_3
7. Vilà, M., Espinar, J., Hejda, M., Hulme, P., Jarošík, V., Maron, J., Pergl, J., Schaffner, U., Sun, Y. and Pyšek, P. (2011). 'Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems'. *Ecology Letters*, 14(7): 702-708. https://doi.org/10.1111/j.1461-0248.2011.01628.x
8. Winter, M., Schweiger, O., Klotz, S., Nentwig, W., Andriopoulos, P., Arianoutsou, M., Basnou, C., Delipetrou, P., Didžiulis, V., Hejda, M., Hulme, P., Lambdon, P., Pergl, J., Pyšek, P., Roy, D. and Kühn, I. (2009). 'Plant extinctions and introductions lead to phylogenetic and taxonomic homogenization of the European flora'. *Proceedings of the National Academy of Sciences*, 106(51): 21721-21725. https://doi.org/10.1073/pnas.0907088106
9. Vilà, M., Gallardo, B., Preda, C., García-Berthou, E., Essl, F., Kenis, M., Roy, H.E. and González-Moreno, P. (2019). 'A review of impact assessment protocols of non-native plants'. *Biological Invasions* (21): 709-723. https://doi.org/10.1007/s10530-018-1872-3
10. Blackburn, T.M, Essl, F., Evans, T., Hulme, P.E., Jeschke, J.M., Kühn, I., Kumschick, S., Marková, Z., Mrugała, A., Nentwig, W., Pergl, J., Pyšek, P., Rabitsch, W., Ricciardi, A., Richardson, D.M., Sendek, A., Vilà, M., Wilson, J.R.U., Winter, M., Genovesi, P. and Bacher, S. (2014). 'A unified classification of alien species based on the magnitude of their environmental impacts'. *PLoS Biology*, 12(5): https://doi.org/10.1371/journal.pbio.1001850
11. IUCN (2012). I*UCN Red List Categories and Criteria: Version 3.1.* Second edition. Gland, Switzerland and Cambridge, UK: IUCN. https://portals.iucn.org/library/node/10315
12. Richardson, D.M., P. Pyšek, and Carlton, J.T. (2011). 'A compendium of essential concepts

and terminology in invasion ecology'. In: D. Richardson (ed.), *Fifty years of invasion ecology: The legacy of Charles Elton*, pp. 409-420. Oxford: Wiley-Blackwell. https://doi.org/10.1002/9781444329988.ch30

13. Carlton, J.T. (1996). 'Biological invasions and cryptogenic species'. *Ecology*, 77(6): 1653-1655. https://doi.org/10.2307/2265767
14. Kumschick, S. and Nentwig, W. (2010). 'Some alien birds have as severe an impact as the most effectual alien mammals in Europe'. *Biological Conservation*, 143(11): 2757-2762. https://doi.org/10.1016/j.biocon.2010.07.023
15. Jeschke, J., Bacher, S., Blackburn, T., Dick, J., Essl, F., Evans, T., Gaertner, M., Hulme, P., Kühn, I., Mrugala, A., Pergl, J., Pyšek, P., Rabitsch, W., Ricciardi, A., Richardson, D., Sendek, A., Vilà, M., Winter, M. and Kumschick, S. (2014). 'Defining the impact of non-native species'. *Conservation Biology* 28(5): 1188-1194. https://doi.org/10.1111/cobi.12299
16. Hanski, I. and Simberloff, D. (1997). 'The metapopulation approach, its history, conceptual domain, and application to conservation'. In: I. Hanski and M. Gilpin (eds.), *Metapopulation biology. Ecology, genetics, and evolution*, pp. 5-26. San Diego: Academic Press. https://doi.org/10.1016/B978-012323445-2/50003-1
17. McGill,B.J., Enquist, B.J., Weiher, E. and Westoby, M. (2006). 'Rebuilding community ecology from functional traits'. *TRENDS in Ecology and Evolution*. 21(4): 178-185. https://doi.org/10.1016/j.tree.2006.02.002
18. Violle, C., Navas, M-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I. and Garnier, E. (2007). 'Let the concept of trait be functional!' *Oikos*, 116(5):882-892. https://doi.org/10.1111/j.0030-1299.2007.15559.x
19. MacDougall, A. and Turkington, R. (2005). 'Are invasive species the drivers or passengers of change in degraded ecosystems?' *Ecology*, 86(1): 42-55. https://doi.org/10.1890/04-0669
20. Didham, R., Tylianakis, J., Gemmell, N., Rand, T. and Ewers, R. (2007). 'Interactive effects of habitat modification and species invasion on native species decline'. *Trends in Ecology & Evolution*, 22(9): 489-496. https://doi.org/10.1016/j.tree.2007.07.001
21. Nentwig, W., Kuehnel, E. and Bacher, S. (2010). 'A Generic Impact Scoring System Applied to Alien Mammals in Europe'. *Conservation Biology*, 24(1): 302-311. https://doi.org/10.1111/j.1523-1739.2009.01289.x
22. Kumschick, S., Bacher, S., Dawson, W., Heikkilä, J., Sendek, A., Pluess T., Robinson T. and Kühn, I. (2012). 'A conceptual framework for prioritization of invasive alien species for management according to their impact'. *NeoBiota*, 15: 69-100. https://doi.org/10.3897/neobiota.15.3323

IUCN

INTERNATIONAL UNION
FOR CONSERVATION OF NATURE
WORLD HEADQUARTERS
Rue Mauverney 28
1196 Gland, Switzerland
mail@iucn.org
Tel +41 22 999 0000
Fax +41 22 999 0002
www.iucn.org

Guidelines for using the IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria

Version 1.1 (September 2020)

Citation: IUCN. 2020. Guidelines for using the IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria. Version 1.1. IUCN, Gland Switzerland, Cambridge, UK.

This document has been adapted from:

Hawkins *et al*. 2015. Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). *Diversity and Distributions.*

Charlotte L. Hawkins[1], Sven Bacher[2], Franz Essl[3], Philip E. Hulme[4], Jonathan M. Jeschke[5,6], Ingolf Kühn[7,8], Sabrina Kumschick[9, 10], Wolfgang Nentwig[11], Jan Pergl[12], Petr Pyšek[12,13], Wolfgang Rabitsch[14], David M. Richardson[9], Montserrat Vilà[15], John R.U. Wilson[9,10], Piero Genovesi[16] and Tim M. Blackburn[1,17,18]

This document has been prepared by:

Sven Bacher[2], Tim M. Blackburn[1,17] Sandro Bertolino[18], Thomas Evans[5,6], Piero Genovesi[16], Sabrina Kumschick[9, 10], Helen Roy[19], Kevin Smith[20] and Lara Volery[2].

Affiliations:

[1]Department of Genetics, Evolution & Environment, Centre for Biodiversity & Environment Research, Darwin Building, UCL, Gower Street, London WC1E 6BT, UK

[2]Department of Biology, Unit Ecology & Evolution, University of Fribourg, Chemin du Musée 10, 1700 Fribourg, Switzerland

[3]Division of Conservation Biology, Vegetation and Landscape Ecology, University of Vienna, Rennweg 14, 1030 Vienna, Austria

[4]The Bio-Protection Research Centre, PO Box 84, Lincoln University, Christchurch, New Zealand

[5]Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 310, 12587 Berlin, Germany

[6]Freie Universität Berlin, Department of Biology, Chemistry, Pharmacy, Institute of Biology, Königin-Luise-Str. 1-3, 14195 Berlin, Germany

[7]UFZ, Helmholtz Centre for Environmental Research, Department of Community Ecology, Theodor-Lieser-Str. 4, 06120 Halle, Germany

[8]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Deutscher Platz 5e, 04103 Leipzig, Germany

[9]Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

[10]South African National Biodiversity Institute, Kirstenbosch National Botanical Gardens, Claremont 7735, South Africa

[11]Institute of Ecology and Evolution, University of Bern, Baltzerstrasse 6, CH-3012 Bern, Switzerland

[12]Institute of Botany, Department of Invasion Ecology, The Czech Academy of Sciences, CZ-252 43 Průhonice, Czech Republic

[13]Department of Ecology, Faculty of Science, Charles University in Prague, Viničná 7, CZ-128 44 Praha 2, Czech Republic

[14]Environment Agency Austria, Department of Biodiversity and Nature Conservation, Spittelauer Lände 5, 1090 Vienna, Austria

[15]Estación Biológica de Doñana (EBD-CSIC), Avda. Américo Vespucio, s/n, Isla de la Cartuja, 41092 Sevilla, Spain

[16]ISPRA, Institute for Environmental Protection and Research and Chair IUCN SSC Invasive Species Specialist Group, Via Vitaliano Brancati 48, 00144 Rome, Italy

[17]Institute of Zoology, Zoological Society of London, Regent's Park, London NW1 4RY, UK

[18]Department of Life Sciences and Systems Biology, University of Turin, Italy

[19]Centre for Ecology and Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, UK

[20]Global Species Programme, IUCN, Cambridge, UK.

Contents

1. Introduction

This document provides guidelines for the application of the IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria First Edition. It explains the EICAT assessment process, and provides detailed explanations of the definitions of many of the terms used in the EICAT Criteria. The guidelines should be used in conjunction with the IUCN EICAT Categories and Criteria First Edition. We expect to review and update these guidelines periodically, and input from all users of the IUCN EICAT Categories and Criteria are welcome. We expect that the changes to these guidelines will be mostly additions of detail and not changes in substance. In addition, we do not expect the IUCN EICAT Categories and Criteria to be revised in the near future, because a stable system is necessary to allow comparisons over time.

1.1. Abbreviations

CITES – Convention on International Trade in Endangered Species of Wild Fauna and Flora
COP – Conference of Parties
EICAT – Environmental Impact Classification for Alien Taxa
GISD – Global Invasive Species Database
ISSG – Invasive Species Specialist Group
IUCN – International Union for Conservation of Nature
SPS Agreement – WTO Agreement on the Application of Sanitary and Phytosanitary Measures
WTO – World Trade Organisation

EICAT Categories and Labels:
CG – Cryptogenic
DD – Data Deficient
MC – Minimal Concern
MN – Minor
MO – Moderate
MR – Major
MV – Massive
NA – No Alien Population
NE – Not Evaluated

2. IUCN EICAT process

2.1. Overview of the EICAT process

The EICAT process is managed by the IUCN Species Survival Commission (SSC) Invasive Species Specialist Group (ISSG), alongside the IUCN Global Species Programme. In order to maintain the credibility of EICAT, the process by which taxa can be assessed and included on the IUCN Global Invasive Species Database (GISD) has been formalised. In particular, this process includes the designation of an EICAT Authority under the auspices of the SSC, the responsibilities of which (and whom) are outlined in this document (Section 2.3). These procedures, while clearly essential for implementation of the EICAT process, do not comprise part of the EICAT Categories and Criteria. IUCN will only review and display global EICAT assessments (i.e. assessments of an alien taxon's impacts across its entire alien range, not part thereof), which should be submitted to IUCN following the procedure described in this document.

The basic process for preparing and submitting EICAT assessments to IUCN for publication is summarised below (see also Figure 1).

2.1.1. Pre-assessment

Prior to the assessment phase, raw data from the alien ranges of the taxon being assessed are gathered using an established search protocol (see Section 2.4). Data must be recorded in a format compatible with the EICAT Categories and Criteria and with appropriate supporting documentation (see Section 2.5). Individuals who provide data through the pre-assessment phase, but are not involved in the application of the EICAT Categories and Criteria are termed *Contributors*.

2.1.2. Assessment

All assessments are based on data currently available for alien taxa, compiled in the Pre-assessment step. For each alien taxon, the assessment is performed at two levels:

- assessments of single impact reports
- overall assessment of the alien taxon of interest (i.e. assigning the taxon's global EICAT Category)

More details on these two assessment levels are provided in Section 2.4.

Assessments can be carried out by EICAT Authority members working alone, in small groups, or in large groups for example in a workshop or email/internet forum. Alternatively, other experts can prepare assessments to be submitted to the EICAT Authority, through its Chair, for review. A template has been developed for Assessors to complete to aid the assessment and review processes (see Appendix 2). All Assessors are required to submit EICAT assessments to the EICAT Authority using this template – until an online database with an end-user interface is developed.

Draft assessments may be made available to the wider community of invasive species experts for additional comment within a defined time period via the ISSG list server. Once a consensus is reached on the taxon's classification by the Assessors, or a majority decision in the case of no consensus being reached, they will be sent for review.

2.1.3. Review

All assessments must go through a review process before they can be accepted for publication on the IUCN GISD. The Chair of the EICAT Authority, or a delegated member of the EICAT Authority, will arrange a review by at least one appropriate expert Reviewer that has not been involved in the assessment as an Assessor. The Reviewer(s) thus appointed will check that the data used have been interpreted correctly and consistently, the EICAT Categories and Criteria have been applied correctly, and that uncertainty has been handled appropriately. The assessments should also be checked to ensure that all essential supporting documentation and any available recommended documentation, is attached and formatted correctly. If an assessment is rejected by the Reviewer, it will be returned to the Assessor(s) detailing the areas that need to be addressed.

2.1.4. Submission

After a satisfactory review, assessments are submitted to the EICAT Unit (via the Chair of the EICAT Authority), which conducts consistency checks to ensure that the EICAT Categories and Criteria have been applied consistently and correctly across all taxa, and that all essential supporting documentation and any available recommended documentation, is attached and formatted correctly.

2.1.5. Publication

Finally, for each alien taxon, its overall classification under the scheme (its global EICAT Category and Criteria), supporting information (including the rationale for the classification and supporting documentation), and the names of the assessors and reviewers will be published on the IUCN GISD.

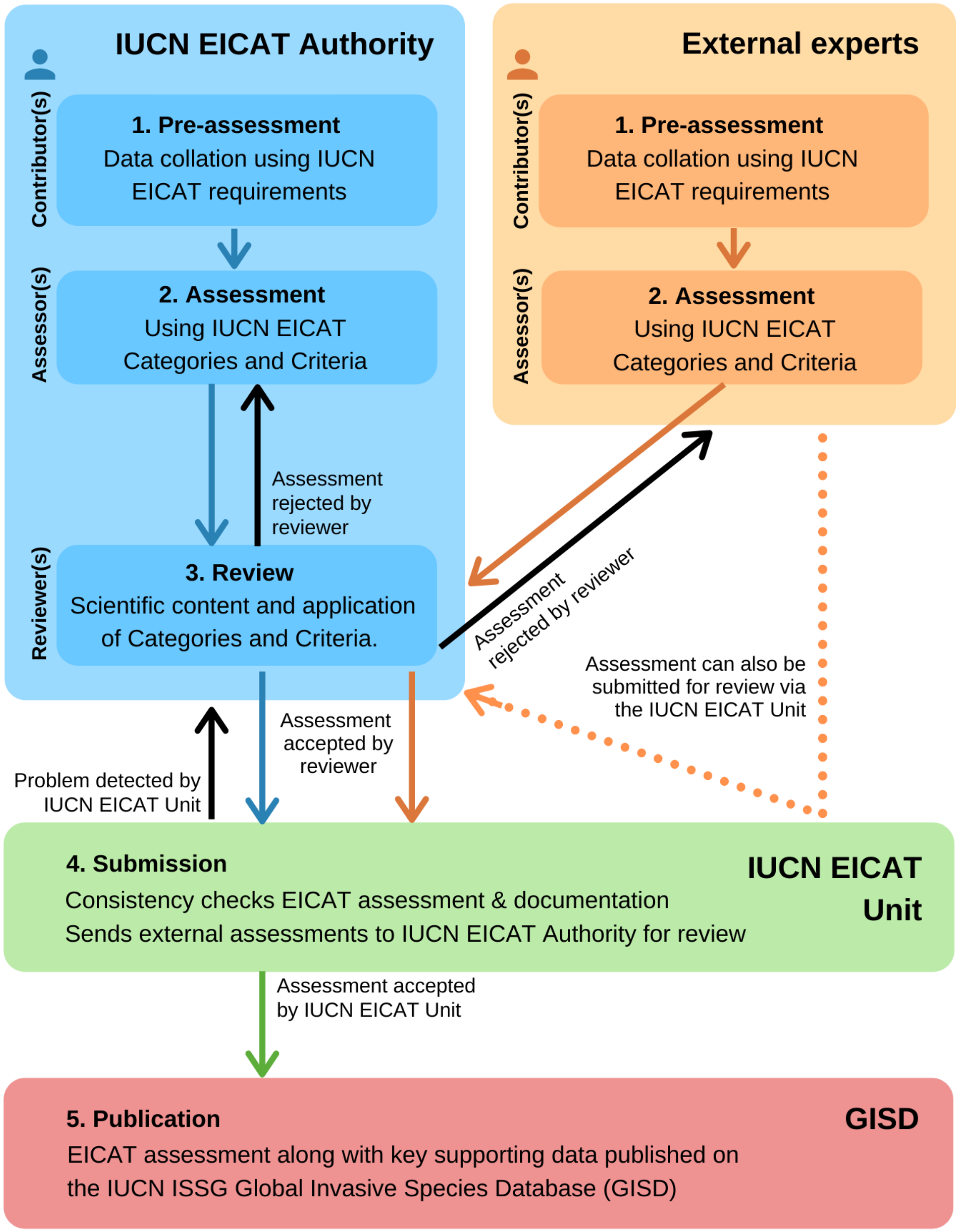


Figure 1. A schematic showing the EICAT process.

2.2. Assessors, Reviewers, and Contributors

Assessors are usually experts on the alien taxon of concern who also have good knowledge of the EICAT Categories and Criteria. Assessors are likely to be members of the EICAT Authority, but they may also be external experts. The Assessor's role in the assessment process is: to use all appropriate data currently available for a taxon with regard to its environmental impacts as an alien; to assess the taxon appropriately; and to determine a confidence rating for the assessment. Assessors ensure that the assessment has the appropriate supporting information as outlined in this document. It is strongly recommended that Assessors are named people (note: there can be more than one Assessor per assessment), but sometimes organisations may be responsible for producing assessments based on data contributed to them (see Contributors below).

Reviewers are people with good knowledge of the EICAT Categories and Criteria. Ideally, Reviewers should also have good knowledge of the taxon being assessed, but sometimes (e.g. through lack of available species experts) this is not possible. Reviewers are people within the EICAT Authority who have not been involved in the assessment process (as an Assessor) for the particular taxon, or may be delegated by the EICAT Authority to external experts. The Reviewer's role in the assessment process is: to read the information presented in the assessment and confirm whether the information has been interpreted appropriately; to check that the EICAT Categories and Criteria have been applied correctly; and to check that confidence levels have been applied appropriately.

Contributors are usually taxon experts or owners of databases containing taxon data. They provide information specifically for use in the taxon account, but they are not directly involved in the actual assessment itself. Reviewers may also have contributed information for the assessment without being directly involved in the assessment. Therefore, a Reviewer may also be named as a Contributor. The purpose of this category is to acknowledge the input of those individuals providing data to an EICAT assessment but not involved in the assessment otherwise. It also enables the acknowledgement of Assessors from a previous EICAT assessment who are not involved in a reassessment.

Box 1. Relationship between Assessors, Contributors, and Reviewers

Yes = The same person can perform both roles for the same assessment

No = The same person cannot perform both roles for the same assessment

	Contributors	***Assessors***	***Reviewers***
Contributors		No	Yes
Assessors	No		No
Reviewers	Yes	No	

2.3. EICAT Authority and EICAT Unit

In summary, the EICAT Unit (once established), will be the administrative body with capacity to processes assessments (see Figure 1). The EICAT Authority is the governing body formed of members of the SSC ISSG and will co-ordinate the overall assessment process.

The Chair of the IUCN SSC ISSG is responsible for establishing or appointing the **EICAT Authority**. The EICAT Authority comprises of individuals who may have remits relating to specific taxonomic groups or geographic regions. The majority of the members of the EICAT Authority will be members of the IUCN Invasive Species Specialist Group, but they may also be members of other SSC specialist groups, independent networks or other organisations. The EICAT Authority is responsible for coordinating the EICAT assessment process, carrying out the majority of assessments, and ensuring that at least one named independent Reviewer (who was not directly involved with the assessment as an Assessor) agrees with the status of each taxon, and that all the documentation to support the assessment is in place.

The EICAT Unit [*will be fully established when funding has been attained*] is formed from selected members of the IUCN Invasive Species Specialist Group and IUCN Global Species Programme. The EICAT Unit checks each assessment to ensure consistency. It will serve as a focal point to receive EICAT assessments undertaken outside of the EICAT Authority, and distribute them for review to appropriate members of the EICAT Authority. It will develop the work-plan, co-ordinate the reporting of status and trends in impacts as documented by the EICAT process, and oversee any proposals for changes or revisions to the EICAT Categories and Criteria, and these guidelines. The EICAT Unit, in consultation with the EICAT Authority, will also develop required policies, for example in relation to the use and application of EICAT, and will manage the petitions process (see below).

The Chair of the EICAT Authority is the overseer and co-ordinator for official IUCN EICAT activities. The Chair acts as the point of contact for the submission of EICAT assessments, and for interactions between the EICAT Authority, EICAT Unit and other IUCN structures, including the IUCN Red List Committee (that oversees the analogous Red List of Threatened Species process), other SSC Specialist Groups, and the office of the Chair of the Species Survival Committee. The Chair is responsible for initiating the consistency checking process, including delegating the process to another member of the EICAT Authority, for EICAT assessments submitted by other members of the EICAT Authority, and for initiating the review process for EICAT assessments submitted from outside the EICAT Authority. The Chair is also responsible for final acceptance of EICAT assessments following the formal review process.

Rules and regulations for membership of the EICAT Authority and EICAT Unit, and for nomination and election of the Chair, will be developed through the IUCN once the mechanisms for the appointment and governance of the EICAT Authorities and EICAT Unit have been developed.

2.4. The Assessment process in more detail

To derive maximum benefit from the EICAT scheme, it must be applied in a consistent and comparable manner across different assessments. The EICAT Categories and Criteria describes the system and provides a framework for the assessment process. Here, further guidelines are provided to:

- *i) Clarify elements of the assessment process.*
- *ii) Identify the documentation required to support assessments.*
- *iii) Demonstrate how to deal with uncertainty in the assessment process.*

2.4.1. Pre-assessment information search protocol

Searches for information to quantify the impacts of alien taxa should preferably be undertaken following an established search protocol. In general, this protocol should follow the process described in Section 4.1 of the Guidelines for Systematic Review and Evidence Synthesis in Environmental Management [1] (here after the Guidelines for Systematic Review). As part of the EICAT assessment, the search protocol should be documented in sufficient detail to enable those reviewing the assessment to replicate the protocol. The search for information should consider both published and unpublished sources (grey literature), and extend to the following:

- Searches of online literature databases and catalogues (as a minimum these databases should include the Web of Science (http://login.webofknowledge.com), Google Scholar (https://scholar.google.co.uk) and Scopus (https://www.scopus.com).
- Searches of the world-wide web (e.g. Google).
- Searches of organisations (as a minimum, including the IUCN Red List of Threatened Species (http://www.iucnredlist.org), Delivering Alien Invasive Species Inventories for Europe (DAISIE) (http://www.europe-aliens.org), the CABI Invasive Species Compendium (http://www.cabi.org/isc/) and the Global Invasive Species Database (GISD) of the Invasive Species Specialist Group (ISSG) (http://www.issg.org/database/welcome/).
- Key texts (for example, for alien birds these may include Lever, C. (2005). Naturalized birds of the world. A&C Black Publishers Ltd. London; and Long, J.L. (1981). Introduced birds of the world. The worldwide history, distribution and influence of birds introduced to new environments. David & Charles. London.)

The literature search should be exhaustive. A review of the bibliographies / references listed in the articles / data sources found through the initial search should be undertaken to identify any additional sources of information. This process should be repeated to a point where no new sources of data are identified.

A search string should be used for effective database searching. The string should include the alien species' scientific and common name, along with relevant terms to identify the impacts of alien species. The following example is a search string to identify impacts associated with the Eurasian blackbird (*Turdus merula*): ("introduced species" OR "invasive species" OR "invasive alien species" OR "IAS" OR "alien" OR "non-native" OR "non-indigenous" OR "invasive bird" OR "pest" OR "feral" OR "exotic") AND ("Eurasian blackbird" OR "blackbird" OR "Turdus merula").

Screening of articles for relevance (and hence inclusion in the EICAT assessment) should be undertaken in accordance with Section 4.2 of the Guidelines for Systematic Review. An initial review of article titles should be undertaken, and for those articles considered relevant based on their title, a review of the abstract should then be undertaken. This process should be recorded for transparency of the decision-making process, as described in Section 4.2.1 of the Guidelines for Systematic Review.

2.4.2. Assessment of individual impact reports

Each relevant impact report gathered during the Pre-Assessment step needs to be assessed using the EICAT Categories and Criteria, and assigned an EICAT Category (Figure 2).

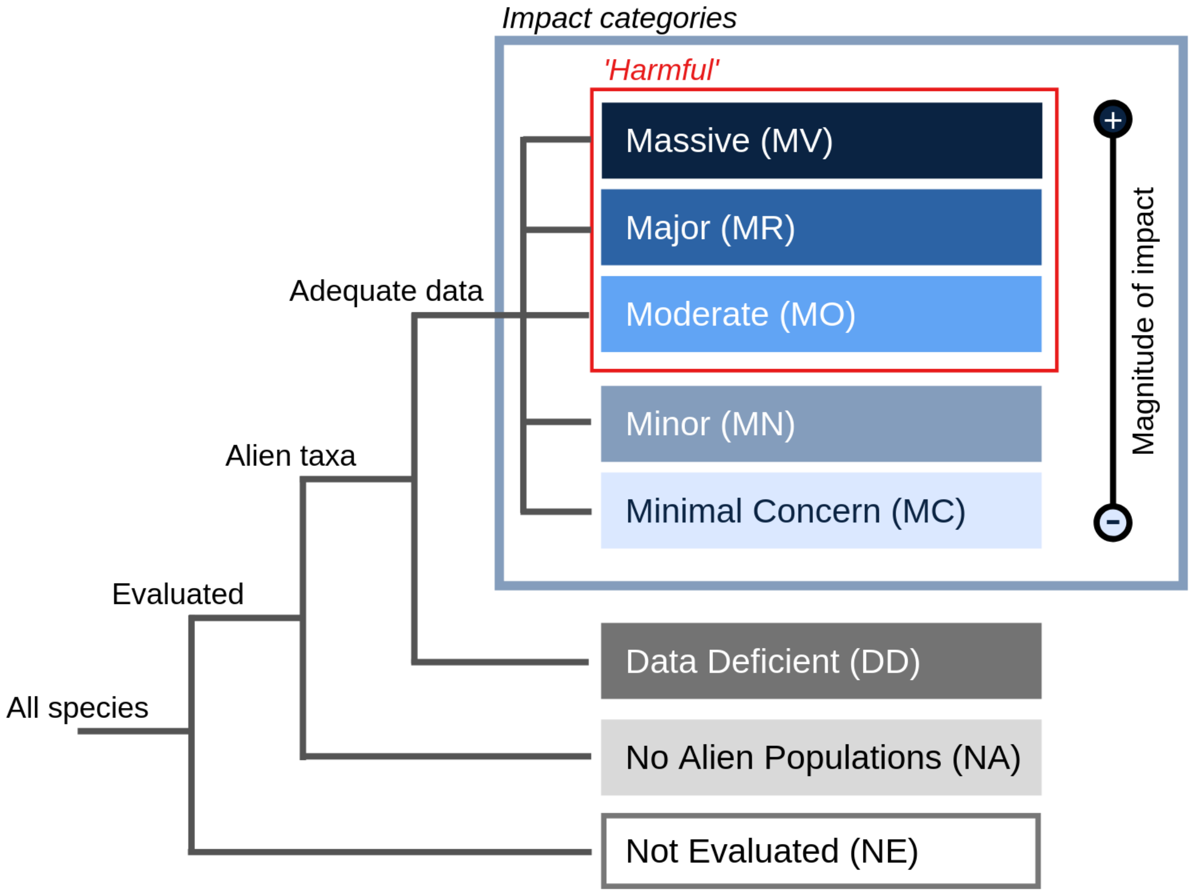


Figure 2. The different EICAT Categories and the relationship between them.

2.4.2.1. Which data sources are relevant for EICAT assessments?

A number of different sources of data may be used as evidence of the impacts of alien taxa on the native biota in EICAT assessments. These data may be held in:

i) *published documents including papers, articles, books and reports.*

ii) *unpublished documents including reports, press articles, grey literature, datasets, databases, GIS data, satellite imagery.*

Data are broadly classified as either observed or inferred:

Observed: Information that is directly based on documented observations of the impacts of an alien population upon native taxa. In this context, the term "observed data" incorporates empirical observations, designed observational studies (natural experiments) and manipulative experiments. Examples include comparison of sites before and after invasions [e.g. 2]; comparison of reference plots in invaded and uninvaded areas [e.g. 3] or fenced and unfenced plots within the invaded range; and field removal experiments [e.g. 4].

Inferred: Information that is not based on documented observations of the impacts of an alien population that may include assumptions about relationships between an observed variable to the variable of interest. Variables of interest for EICAT assessments are include the performance of individuals (for an impact magnitude **MN**), the number of mature individuals in a population (for **MO**) or its extinction status (for **MR**/**MV**). Sometimes, these variables are not directly observed, but other variables are, from which the variable of interest can be inferred. For example, changes in the number of mature individuals of a native taxon (criterion for **MO**) can be inferred from changes in the number of all individuals (index of abundance); changes in catch statistics; mathematical models; or a decrease in range or an ecosystem function or service provided by the native taxon of interest. Any assumptions should be stated and justified in the documentation. In all these examples, even though they do not directly observe the variables of interest, the observed variables are assumed to be related to the variables of interest for the EICAT assessment (individual performance, number of mature individuals, extinction). Variables not directly related to the variables of interest should not be used to infer impacts. For example, changes in abiotic ecosystem properties (e.g. pH, water availability, etc.) should not be used to assign an impact magnitude unless they have been explicitly shown how they are affecting a native taxon (performance of individuals, the number of mature individuals in a population, or its extinction status).

To be classified in EICAT, changes in the native populations have to be observed or measured in the context in which they are reported: extrapolations or projections in time or space are not considered.
Examples:

- An observed population decline should not be extrapolated to result in a local extinction in the future.
- An impact observed in one location should not be extrapolated to another location where no observations have been done.

Studies that do not allow the detection of any of the five impact magnitudes described in EICAT should not be classified.
Examples:

- Diet/niche overlap between the alien and native populations alone does not show that the performance of native individuals is reduced, or that their populations decline.
- The measure of water quality degradation alone cannot be used to infer an impact on the native fish populations.

- An observed impact on a native plant population cannot be used alone to infer an impact on a native pollinator.

2.4.2.2. Spatial and temporal scales

The spatial and temporal scales over which impact data are recorded can affect interpretation of the severity of impacts caused by an alien taxon, and will affect confidence in the assessment. Studies at restricted spatial scales (e.g. patches of 10s of square metres) might overestimate impacts if extrapolated to larger scales, while studies at extensive spatial scales (i.e. regional or national) might underestimate them. Similarly, studies over time periods that are too short to capture the changes in a native population might over- or underestimate the severity of an impact. In other words, there may be a mismatch between the scale of study and the scale of the impact. For example, an alien taxon might be shown in a field experiment to exclude a native taxon from areas the size of experimental plots, and perhaps even to extirpate the native taxon from entire habitat patches, but at larger spatial scales a part of the local population of the native taxon might still persist (e.g. because of the influence of spatial dynamics, refugia, or rescue effects). In this case, the local population of the native taxon would have declined in the habitats in which the alien taxon occurs, without resulting in a local population extinction. However, impacts demonstrated even at small spatial scales can highlight cause for greater concern in the future, and thus small-scale studies may provide useful evidence of impacts for informing EICAT assessments.

Impacts should ideally be measured at appropriate spatial and temporal scales, taking into account the typical spatial and temporal scale at which the local native population can be characterised. Assessments based on evidence generated at spatial or temporal scales that are very different to the scales over which the local native population can be characterised are likely to be subject to greater uncertainty, due to the challenges involved in extrapolating or down-scaling data to scales relevant to local populations. However, in practise it is difficult to generate a universally applicable definition to describe “the typical spatial scale at which local native populations can be characterised”, as this will depend on the particular native taxon and the location. For example, a local native fish population in a lake may have a clearly defined spatial scale, determined by the size of the lake, whereas it may be much harder to delineate the spatial scale of a particular local native population within a rainforest ecosystem.

2.4.2.3. Additional guidance for key terms

Decline in Population Size

In cases where an alien taxon impacts on recruitment in native taxa, this impact would not count as a reduction in population size (unless there is also an impact on the number of mature individuals); the impact of the alien taxon would be classified as **MN** because it causes a reduction in the performance of native individuals. If and when this decrease in performance leads to a decrease in the resultant number of mature individuals within the native population, the alien taxon would be reclassified as **MO**.

Presumed Extinction

A taxon is presumed to be locally extinct when the impact study tried to find individuals of the local native taxon but no individual was observed, and the study design would have allowed detection of the presence of the native taxon. Local population extinction should be evaluated at the correct spatial scale according to the dynamics of the target native taxon (e.g. a group of individuals spatially disjunct in a metapopulation).

Transmission of disease to native taxa

Due to the nature of the phenomenon of disease transmission, it is often difficult (if not impossible) to observe it happening, nor retrospectively to study where the disease came from. Furthermore, this impact mechanism includes the interaction between two organisms, the alien taxon under assessment, and the disease agent. Where no direct evidence for transmission of the disease from alien taxa to native taxa is available, we suggest that the following evidence is needed in order to classify taxa as **MO** or higher for impact from disease transmission (based on Kumschick et al. 2017 [5]): (1) The disease agent has been shown to be highly devastating to native taxa (see also disease agents in Parasitism, below); (2) the alien taxon is a host of the disease agent in the same time and space as the native population occurs. If these conditions are met at a certain location, no direct evidence for disease transmission is needed. Ideally, we would be interested to know whether the disease agent arrived with the alien, or whether it had an effect on the native community before the alien arrived. However, these aspects cannot be retrospectively assessed and are therefore virtually impossible to study when the invasion has already occurred. Often evidence for the alien taxon being a host of a (more or less devastating) disease is available, and in some cases, spread of the disease with the alien host is studied. In these cases, impacts through transmission of diseases under EICAT should be scored as **MN**. It should in most cases not be scored **MC**, unless the disease or parasite carried by the alien was not found in the native taxa. Furthermore, the impact of the disease itself needs to distinguished from the impact of the host. Separate EICAT assessments need to be performed for the disease agent (identifying if it is alien, and if so, its level of impact) and linked to the assessment of disease transmission of the host – most of these would be captured under the mechanism (5) Parasitism. This can also be important for management, as removing a host from an area might not solve the disease problem itself if the disease agent is already widespread in the native community, or if it is not reliant on the alien host.

Parasitism

Under this mechanism, direct impacts of parasites or pathogens and other disease agents on native taxa need to be noted. This includes the impacts of disease agents transmitted by another alien taxon (see also "Transmission of diseases to native species").

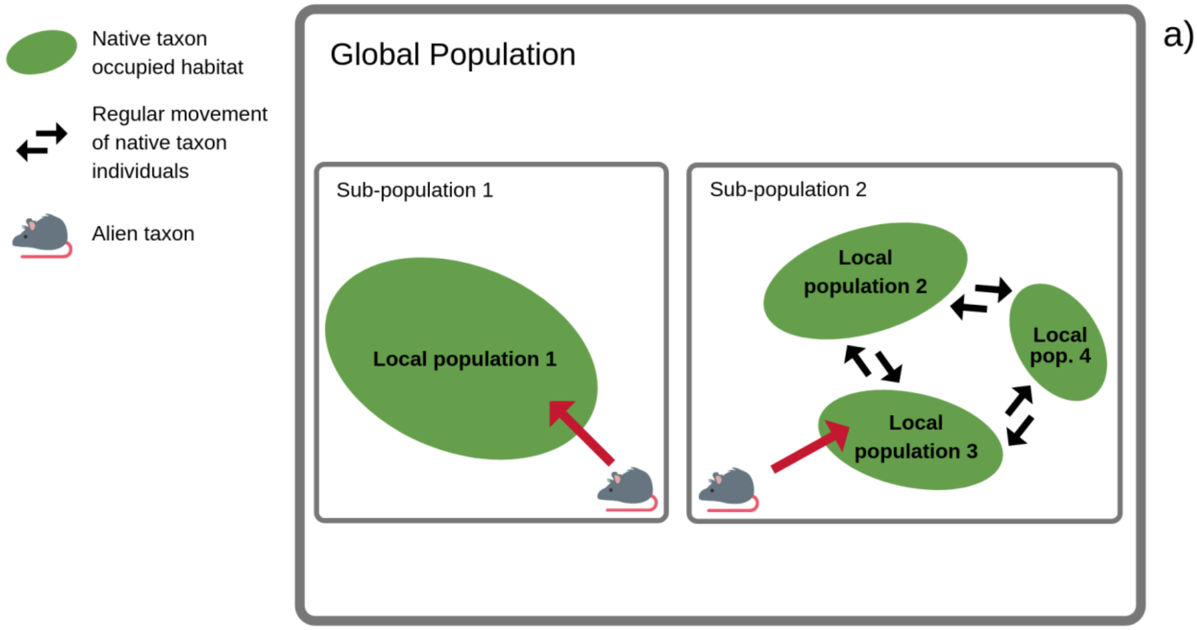
Changes in native community composition

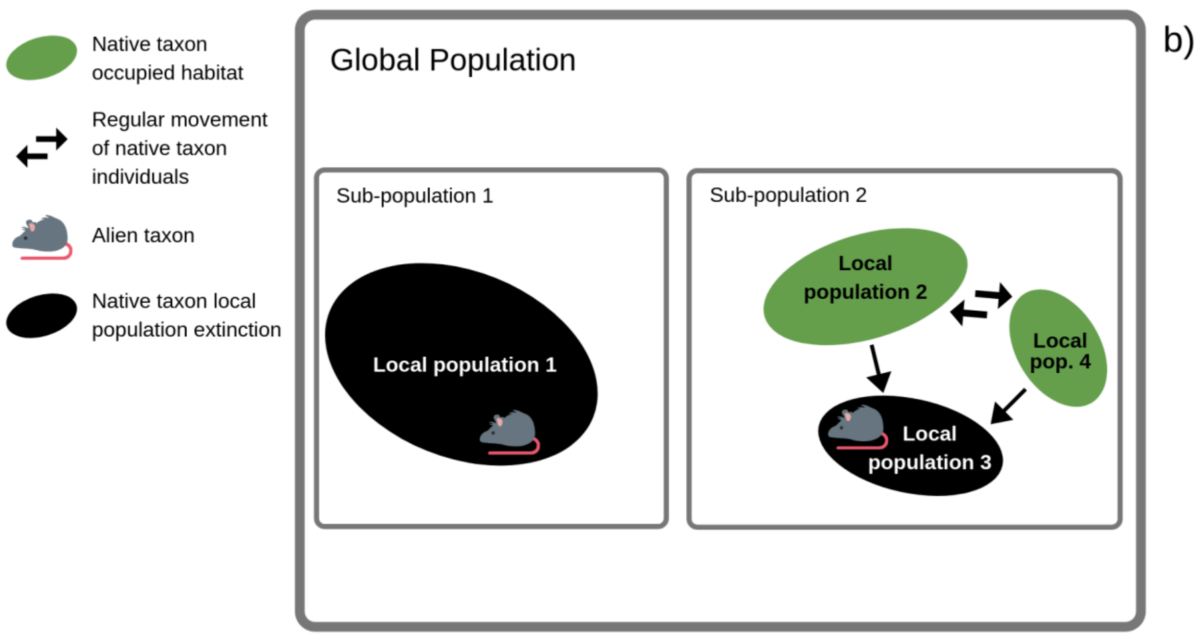
Changes to communities refer to the loss of at least one native taxon in a community (local population extinction of one or more native taxa) due to impacts caused by the alien taxon. Impacts that do not lead to the loss of local populations are not included under this definition, as these are covered by the criterion relating to changes in population size (**MO** impacts), including changes to the species-abundance distribution or other elements of the structure of the community.

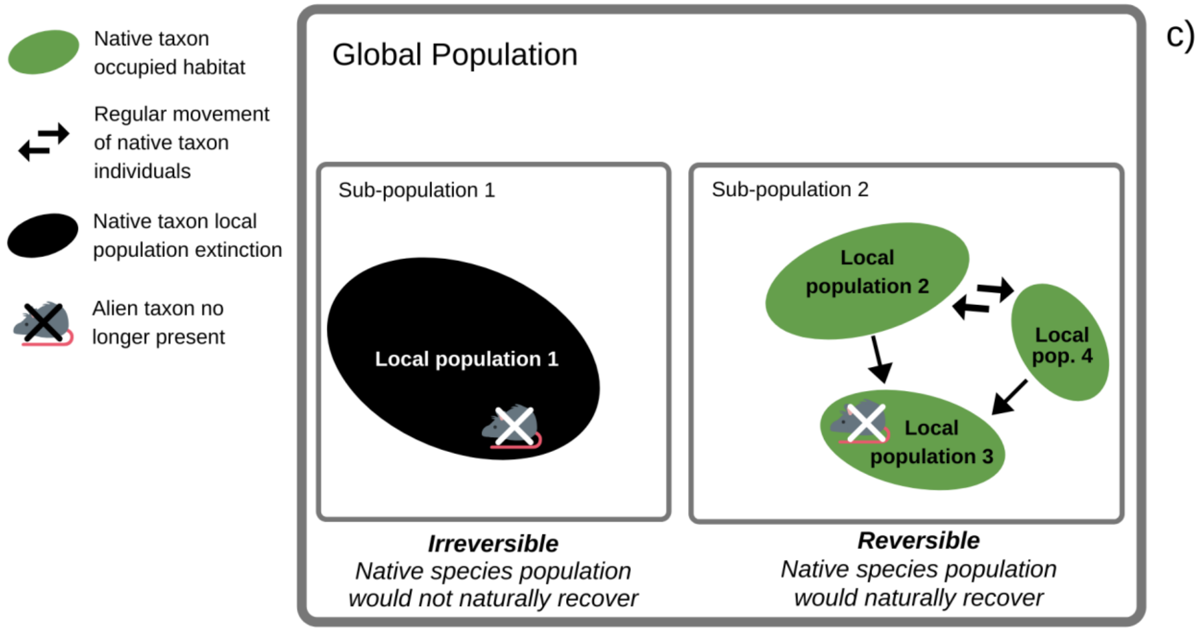
Studies describing impacts do not always focus on particular native taxa: they sometimes report a change in the community composition, a decrease in community biomass or a decrease in species richness due to the alien taxon. This information is difficult to translate directly into an EICAT assessment, but the information necessary for an EICAT assessment (which native taxa are impacted and how) can often be extracted from these reports. For example, a decrease in native alpha diversity (local species richness) may indicate a local population extinction, but care must be taken in assessing the sampling effort of the study (e.g. spatial scale, number of replicates), while a change in beta diversity (e.g. species turnover between sites) does not necessarily imply local extinctions or population declines.

Naturally reversible and irreversible changes

The (ir-)reversibility of local extinctions is not only determined by the action of the alien taxon but depends on the context. The feasibility of human assisted measures (eradication of the alien population, re-introduction of the native taxon, or habitat restoration after the degradation due to the alien taxon) is not evaluated when assessing the (ir-)reversibility of a local extinction. Figure 3 provides more guidance on the interpretation of naturally reversible and irreversible changes, and the resulting EICAT Category.


Native taxon occupied habitat
Regular movement of native taxon individuals
Alien taxon
Global Population
Sub-population 1
Sub-population 2
Local population 1
Local population 2
Local pop. 4
Local population 3
a)


Native taxon occupied habitat
Regular movement of native taxon individuals
Alien taxon
Native taxon local population extinction
Global Population
Sub-population 1
Sub-population 2
Local population 1
Local population 2
Local pop. 4
Local population 3
b)



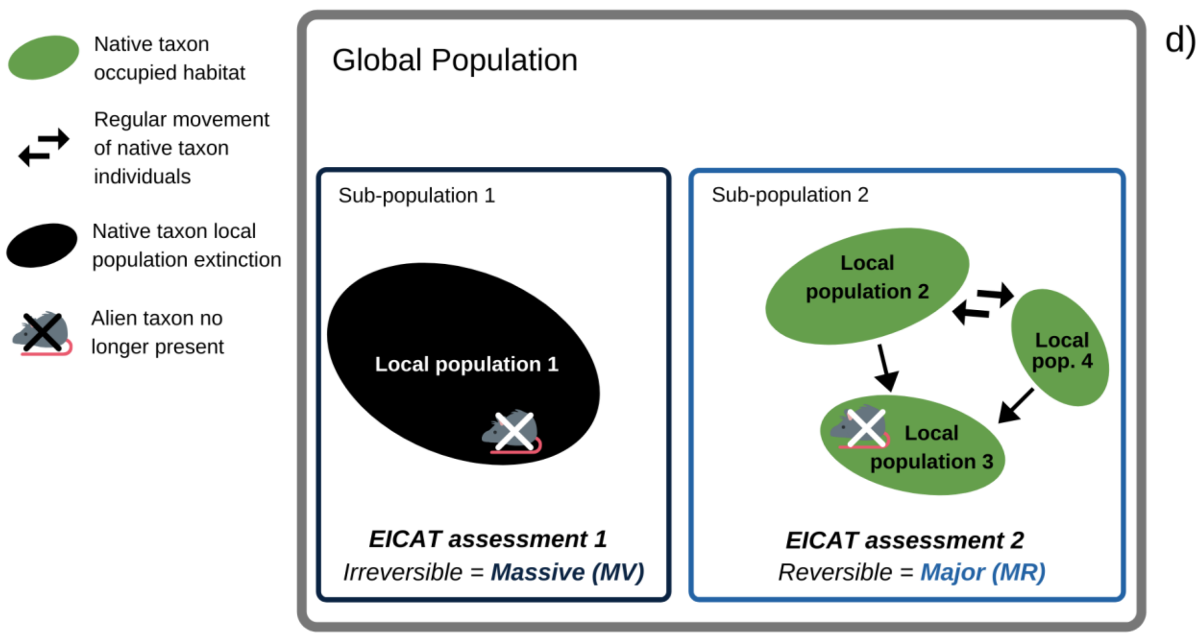


Figure 3. Examples of naturally reversible and naturally irreversible extinctions in the context of EICAT assessments.

The occupied habitat of two local populations of a native taxon (Local Populations 1 and 3) are colonised by an alien taxon (a), and subsequently go locally extinct (local population extinction) (b). If the alien taxon was then no longer present in these areas (for example because of successful eradication of the alien taxon population, or boom-and-bust dynamics in the alien taxon population), the native taxon would be likely to return to the area previously occupied by Local Population 3 through natural dispersal processes (from Local Population 2 and 4), within three generations or ten years, whichever is longer (c). However, this return would not happen for Local Population 1: the loss of this local population has also resulted in the extinction of Sub-population 1, and given that by definition there is little demographic or genetic exchange between Sub-populations (typically one successful migrant individual or gamete per year or less), the native taxon would not return to this area. Therefore, an EICAT assessment on the impacts of the alien taxon on Local Population 1 would result in categorisation as **MV**, and an assessment of the impacts on Local Population 2 would result in categorisation as **MR** (d).

2.4.2.4. Dealing with uncertainty

There are many cases where uncertainty exists about the correct classification of an impact. Consequently, an estimate of the degree of uncertainty should be attached to all classifications, so that the degree of confidence in every classification is made explicit. Only epistemic or reducible uncertainty (i.e., uncertainty due to data quality) is of importance. Uncertainty related to variation in impacts in space or time (stochasticity or irreducible uncertainty) is not relevant here because only the highest impact reported is considered for assessment purposes.

A number of factors affect the confidence in an assessment, including the reliability and type of data used as evidence of impacts; the spatial and temporal scales over which data were collected; the ease of interpretation of the available data; the chances of including confounding effects in the observation; and whether or not evidence within a single source of information is contradictory.

Data quality and type: In some cases, information about impacts is inferred from observations of variables that are (seemingly) related to the variables of interest in EICAT (individual performance, number of mature individuals, extinction). Inferred data are likely to provide a much lower level of confidence in the assessment. Some studies focus only on one particular level of impact (e.g. the individual performance) not investigating higher levels of impact (e.g. whether the impact on the individual performance is affecting the size of the population). Uncertainty in the assigned Impact Category can exist in such cases since the impact might be higher than the observed and reported one, but the study design and reporting of results does not allow detection of such impacts.

Spatial and temporal scale: Assessors must judge the suitability of the spatial and temporal scales over which evidence of impacts is recorded, for each EICAT assessment. This is used to help determine the confidence rating for the assessment. A full justification for this evaluation should be provided in the rationale for the confidence rating (see below) in the supporting documentation, along with details of the spatial scale at which impacts have been measured, and how this relates to the spatial scale over which the local native population can be characterised or to the probability of detecting the taxon.

Confounding effects: In most impact reports, it cannot be excluded that other biotic or abiotic factors might have caused or contributed to the observed impact. Therefore, it is difficult to distinguish whether an alien taxon is the driver of environmental changes, or whether confounding effects are at play. The likelihood that the impact level would have been observed if the alien taxon was not introduced must be evaluated by the assessor, based on the context in which the impact is happening (e.g. presence of other stressors which are likely to have led to the observed impact even in the absence of the alien taxon). Confounding effects can lead to an over- or underestimation of the impact caused by an alien taxon.

2.4.2.5. Assigning a confidence score

For each impact report that is relevant for an EICAT assessment, the assessor should place it in the most likely of the five Impact Categories (**MC**, **MN**, **MO**, **MR**, **MV**) and assign a level of confidence to this placement, depending on the likelihood of the assigned Impact Category being correct, based on the reliability of evidence, the type of data used to make the assessment, the spatial scale over which data were recorded, the chances of including confounding effects in the observation, and whether or not the evidence is contradictory (Table 1). Confidence is categorised into three levels: **high**, **medium** and **low,** and can be translated into arbitrary (but indicative) probabilities that the assigned category is correct (Appendix 1).

Table 1: Guidance for confidence classification.

Sources of uncertainty that influence the confidence rating	*Presence of confounding effects*	*Study design*	*Data quality and type*	*Spatial and temporal scale*	*Coherence of evidence*
High confidence: it is likely (approximately 90% chance) that the true Impact Category is equal to the assigned one	The likelihood of including confounding effects is low (i.e. it is unlikely that the level of impact would have been observed if the alien taxon was not introduced)	The study design would have allowed the detection of higher/lower impact magnitudes than the one assigned	There is relevant direct observational evidence to support the assessment; the data are reliable and of good quality	Impacts are recorded at the typical spatial and temporal scales at which the local native population can be characterised	All evidence points in the same direction (no contradictory evidence)
Medium confidence: there is potential for the true Impact Category to be different from the assigned one (approximately 65-75% chance of the assigned impact category being correct)	Confounding effects may be at least partly responsible for the observed impact (i.e. potentially the observed level of impact would still have happened if the alien taxon was not introduced)	The study design would not have allowed the detection of higher/lower impact magnitudes than the one assigned (i.e. it cannot be reasonably excluded)	There is some direct observational evidence to support the assessment, but some of the data are inferred	Impacts are recorded at a spatial or temporal scale which may not be relevant to the scale over which the local native population can be characterised, but extrapolation or downscaling of the data to relevant scales is considered reliable or embraces little uncertainty	Most evidence points in the same direction, but some is contradictory or ambiguous
Low confidence: it is likely that the true Impact Category is different from the assigned one (approximately 35% change of the assigned impact category being correct)	The likelihood of including confounding effects is high (i.e. it is likely that the observed level of impact would have happened if the alien taxon was not introduced)	The study design does not allow any conclusions about higher or lower impact magnitudes and it is likely that the true impact magnitude is higher or lower	There is no direct observational evidence to support the assessment; data are of low quality	Impacts are recorded at a spatial or temporal scale which is unlikely to be relevant to the scale at which the local native population can be characterised, and extrapolation or downscaling of the data to relevant scales is considered unreliable or embraces significant uncertainties	Data are strongly ambiguous, or contradictory

2.4.3 The overall EICAT Category of an alien taxon (Global EICAT assessment)

2.4.3.1. Assigning an EICAT Category to an alien taxon

Each alien taxon is assigned an EICAT Category based on its highest observed impact across all recorded impacts (as described in Section 2.4.2., and see Figure 4). Note that to assign a species to an Impact Category (i.e. from **MC** to **MV**), one impact study is enough as long as it provides the required information (at appropriate temporal and spatial scale etc.).

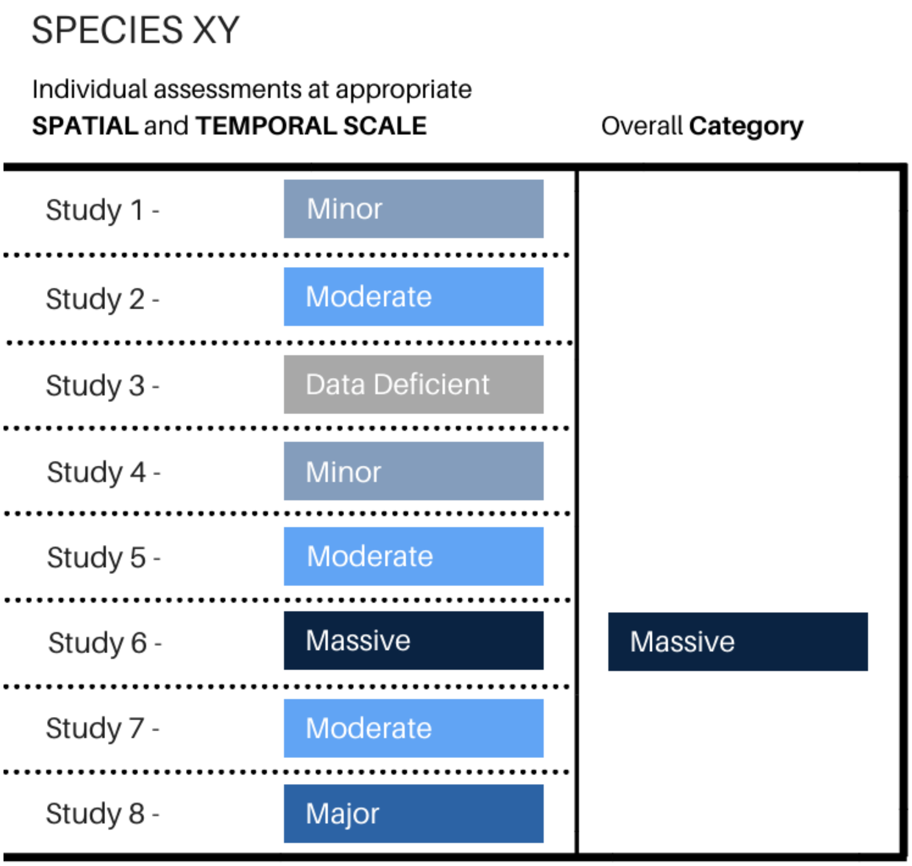


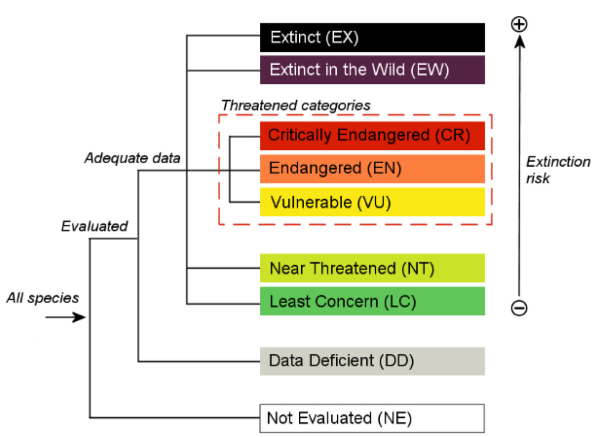
Figure 4. How data from individual EICAT assessments of the impacts of a hypothetical alien taxon (species XY) inform the overall EICAT Category to which the alien taxon is assigned. The overall assessment categorises the taxon based on its highest impact anywhere (in this case, a **Massive** (**MV**) impact).

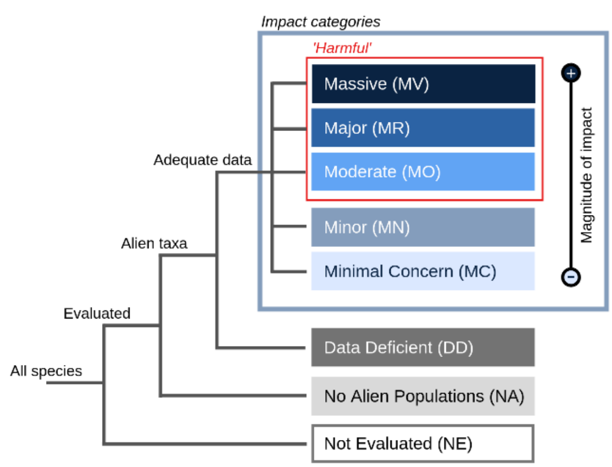
2.4.3.2. Harmful categories

Alien taxa that are assessed as **Moderate** (**MO**), **Major** (**MR**) or **Massive** (**MV**) are termed 'harmful' (see Figure 2). These are those alien taxa that are currently known to be having the most deleterious impacts upon native biodiversity, leading to population declines (**MO**) and local population extinctions (**MR**, and

MV). However, it is important to note that those categorized as **Minor** (**MN**), and possibly those as **Minimal Concern** (**MC**), are still having deleterious impacts, but not at the level of biological organization of population or communities, and may move to a higher impact category in future assessments if more information becomes available.

The purpose of the 'harmful' tag, is to support in the application of the results of EICAT, for example to aid in communication, or in the prioritisation of alien taxa. The term 'harmful' is used in a similar way to the term 'threatened' is used by the IUCN Red List of Threatened Species™. The term 'threatened' is applied to those species with the greatest risk of extinction (i.e. those assessed as Critically Endangered, Endangered, or Vulnerable) (see Figure 5). This term is used to support application of the results of the IUCN Red List, for example in communication (e.g. 40% of primate species in West and Central Africa are now *threatened* with extinction[1]), or to aid in the prioritisation of species for conservation actions (e.g. the Save our Species fund which funds conservation actions for *threatened* species[2]). The EICAT Category **Minor** (**MN**), is similar in scope to the IUCN Red List Category of Near Threatened which is used for species that are close to qualifying for a 'threatened' category, and IUCN Red List Category of Least Concern, used for widespread and abundant species (though these can have declining populations but not at a rate to qualify for a threatened category or Near Threatened), is similar to the EICAT Category of **Minimal Concern** (**MC**).





[1] IUCN Press Release for the 2019.2 update to the IUCN Red List https://www.iucn.org/news/species/201907/unsustainable-fishing-and-hunting-bushmeat-driving-iconic-species-extinction-iucn-red-list

[2] Save Our Species https://www.saveourspecies.org/

Figure 5 – The IUCN Red List Categories and EICAT Category charts.

2.4.3.3. Confidence at the alien taxon level

The confidence associated with the observation of the highest impact is reported as the overall confidence for the alien taxon. If multiple observations are assigned the same highest Impact Category, the highest confidence of any of them is taken as the overall confidence.

The possibility that higher impacts might have occurred, but were not reported, is not taken into account when evaluating the confidence of the EICAT classification of an alien taxon.

As the spatial extent and timeline of invasions varies widely among taxa, so too will the availability and quality of data on the impacts of aliens. For taxa with well-established and widespread alien populations, there is likely to have been sufficient opportunity to gather data relating to their impacts on native biota. However, for taxa with short alien population residence times, or invasions restricted to small areas, data evidencing impacts on native biota may be limited, or restricted to impacts in one particular area. Irrespective of the invasion history and spatial extent of the invasion, data from the entire area of impact is used to generate a global-level species assessment.

All alien taxa, especially the ones with limited data available on impact, should be re-assessed as and when more direct observational data become available to confirm the classification and improve the confidence rating of the assessment. If there is inadequate or no information to classify an alien taxon with respect to its impact, the taxon should be assessed as **Data Deficient** (**DD**).

2.4.3.4. Lack of evidence of impact

EICAT is applicable to alien populations occurring in any biome, terrestrial, freshwater, and marine. While initially, the impacts within some habitats might be less studied than in others (e.g. see [6] in relation to the marine realm), EICAT criteria are generic and can be applied to any habitat [7] including the marine environment [8]. It is important to stress that a lack of evidence of impacts does not mean there are no impacts. Within EICAT, lack of evidence of impact (categorised as Data Deficient) is treated differently to evidence of lack of impact (categorised as Minimal Concern).

2.5. Supporting documentation

EICAT assessments of any taxon need to be supported by documentation which serves to justify the assessment and to provide relevant information about the taxon and its impacts, which can be used, for example, by regulatory bodies and management practitioners to inform the development of risk assessments and prioritise management actions. There is a minimum level of supporting information that is essential for any assessment, and further recommended documentation that would be useful if the information is available. The **Essential** and **Recommended** documentation for EICAT assessments is outlined below.

2.5.1. Essential documentation

The supporting information detailed below must accompany all EICAT assessments before they can be accepted for publication. The reporting template provided should assist reviewers in this process (see Appendix 2).

2.5.1.1. Documentation relating to the overall EICAT classification of each alien taxon (Global EICAT assessment)

a. Assessor, Contributor, and Reviewer details

- *The names and email addresses (ideally valid for the foreseeable future) of the people or organisations responsible for making the assessment and compiling the supporting information (Assessor(s)).*
- *The names of any other individuals that have provided data, information, comments or helped in some way with the assessment, but who are not responsible for the EICAT assessment itself and/or were not involved in the overall compilation of the assessment (Contributor(s)).*
- *Submission date of the assessment – the final date when all Assessors involved in the assessment agreed on the appropriate EICAT Category for the taxon.*
- *The names and email addresses of the people who have peer reviewed the assessment (and the supporting documentation (Reviewer(s)).*

b. Taxonomy

- *Higher taxonomy details for Kingdom, Phylum, Class, Order and Family.*
- *Scientific name (genus name and species epithet) including authority details. Infra-specific details (e.g., sub-species, variety) must also be provided if relevant.*
- *Common names should be provided, in English, French and Spanish if available.*
- *Common synonyms should be provided.*

- *Taxonomic notes should be included when there are particular problems or issues. Examples include taxa that have undergone recent taxonomic revision or where there are any taxonomic doubts or debates about the validity or identity of the taxon. Taxonomic notes should include synonyms for taxa with commonly used alternative names.*

c. EICAT assessment

- *The country and region of the most severe impact recorded.*
- *The EICAT Category assigned and the Criteria (impact mechanism) met.*
- *A justification (rationale) for the classification, including a detailed explanation to provide evidence for the EICAT Category selected. Further, reasons for any change in classification since previous assessment should be noted, and any numerical data and parameter estimates that underpin the assessment summarised.*
- *If the taxon has been previously assessed, and the Category has changed, select the correct reason for change (see Section 3.).*
- *The confidence rating for the EICAT Category assigned should be stated, including a justification for the level. Uncertainty as to whether a study is in the native range should be recorded, as well as a rationale for the confidence ratings relating to the type, quality, spatial scale and interpretation of data.*

d. Detailed description of impacts

- *A succinct description of all recorded impact Categories and Criteria, including ones of lower magnitude*
- *Native taxa impacted by the alien taxon (provide scientific names as listed on the IUCN Red List of Threatened Species, if they have been assessed).*
- *Pathways of introduction, if known.*
- *Management actions performed on the taxon which (potentially) influenced the impact category.*
- *A description of further research required to clarify or improve data on impact of this taxon.*
- *List of all references with evidence for the EICAT Category assigned.*

2.5.1.2. Documentation pertaining to the assessment of single impact reports

a. All recorded impacts

- *A detailed description of all the impacts recorded for the alien taxon, including the EICAT Categories and Criteria met for each record. This should include a description of where (country and region) and when each impact has been recorded/documented, and the native biota that* *are impacted. Uncertainty as to whether a study is in the native range should be noted. It should also be noted whether these impacts were recorded in the presence or absence of any management actions.*

- *A confidence rating for each impact record should be provided, with a justification for the level chosen.*
- *Supporting evidence for each impact listed, including the exact text from the reference supporting the classification (copy and pasted), and the respective reference details.*
- *Observations or data required to improve confidence in the current assessment (e.g. the likelihood of spatial variation in impacts, such that classification may be improved by data from other specified regions).*
- *Information on the likelihood of a classification changing in the near future, with consequences for the urgency of management responses or future assessments, if known.*

b. Management actions

- *A list of management actions in place to manage the spread of the alien taxon, or to remove the taxon from an introduced area (see Appendix 3 for further information).*
- *Further detail about management actions, including the area that is being managed, and the length of time since management action began, if known.*

2.5.2. Recommended documentation

Recommended supporting information is not essential for publication of an EICAT assessment, but its submission is encouraged (see *Appendix 3* for more information on the classification schemes discussed below).

a. Alien range

- *A detailed description of the alien range of the taxon, including dates of introductions where this information is known.*
- *A list of countries of occurrence and sub-country units for large countries and islands far from mainland countries, where the taxon has been introduced outside of its native range.*
- *A list of occurrence in marine regions outside of the native range.*
- *Pathways and vectors of introduction and spread where this information is known.*
- *A GIS map of the alien distribution, preferably shown as polygons (but point occurrences may also be displayed).*

b. Habitat and ecology

- *A summary of the habitat and ecology of the alien taxon.*

- *The major biomes in which the alien taxon occurs (i.e. marine, freshwater, terrestrial).*
- *A list of habitat preferences of the alien taxon.*

c. Native geographic range

- *Detailed description of the native distribution of the taxon.*
- *A GIS map of the distribution of the taxon, preferably shown as polygons (but point occurrences may also be displayed).*
- *A list of countries of occurrence and sub-country units for large countries and islands far from mainland countries.*
- *A list of marine regions in which the taxon occurs.*

d. Alien populations

- *A detailed description of alien populations including information on location, size, trends and spread.*
- *Where relevant, cultivated distribution should be identified separately from naturalised/established or invasive distribution.*

e. Other impacts of the alien taxon

- *Information on the socio-economic impacts of the alien taxon, including beneficial (e.g. human use) as well as deleterious impacts, if known. Note that this information should not contribute to the classification of the alien taxon under EICAT.*

f. Links to images and other sources of information

- *Links to other web sites and databases that may contain further information and images of the alien taxon concerned.*

2.5.3. Sensitive information

Typically, all data supplied in support of an EICAT assessment will be published alongside the assessment on the GISD website. However, in some cases data supplied with an assessment may be sensitive, for example relating to an alien taxon that impacts upon individuals of a threatened species, or upon sites occupied by a threatened species, where publishing those data may have the potential to negatively impact that threatened species. Examples may include the impact of an alien taxon upon economically valuable species or species specifically threatened by trade. In such cases, Assessors may make a case that IUCN withholds the data considered to be sensitive. The EICAT Unit will be responsible for assessing the evidence provided by the Assessors, and assuming that the case can be considered proven, the EICAT Unit will comply with any such request.

3. Reassessment and change in EICAT Category

EICAT assessments for a taxon should be repeated on a regular basis, so that changes in the severity of recorded impacts, or changes in the alien status of taxa that were previously **NA**, can be identified. It is recommended that reassessments should take place at least every five years. Reassessment may result in up-listing to a higher impact category (e.g. from **MO** to **MV** or from **DD** to an impact category), which can take place without delay. Taxa can also be down-listed if the evidence from a previous assessment has erroneously placed a taxon in a higher category, or the information has improved and clarified the impact level. As the overall EICAT Category assigned to a taxon records the maximum observed impact, a taxon cannot be moved into the **NA** category from an impact category, if there are no longer alien populations that exist (e.g. if all alien populations have been eradicated).

Any reassessment of an alien taxon that already has a published IUCN EICAT classification should begin with reference to a copy of the previously published assessment. This can be used as the basis to identify and collate any new published or unpublished information available (either relevant to the taxon in question or relevant contextual information). Data and text fields in the previously published assessment can then be edited and updated on the basis of the new information. The new assessment can then be treated in the same way as any other assessment, with reference to information provided in this document. The citation and authorship for assessments and re-assessments are detailed in Section 4.

3.1. Transfer between Categories

Classification is based on the best available current evidence. Hence, in successive assessments, taxa can move up, and in some cases down Impact Categories as the quality of evidence improves, as environmental or societal conditions change, or as an invasion proceeds. At the most trivial level, we would expect taxa to move, in successive assessments, from **Not Evaluated** (**NE**) into one of the evaluated categories (Figure 2.), or from **No Alien Population** (**NA**) to an alien category (**Data Deficient** (**DD**), or **Minimal Concern** (**MC**), **Minor** (**MN**), **Moderate** (**MO**), **Major** (**MR**), or **Massive** (**MV**)) if introduced into areas beyond natural range limits.

3.2. Maximum recorded impact

An evaluated alien taxon is assigned the EICAT Category according to the maximum recorded impact across all the individual impact assessments made at the appropriate spatial and temporal scale. This Category should remain the same throughout successive assessments unless new evidence suggests that the maximum recorded impact for a particular taxon is higher or lower than previously assessed. For example, if new evidence suggests that the alien taxon is a passenger rather than a driver of change, the EICAT Category assigned to the taxon may be reduced to a lower EICAT Category. Similarly, if new evidence suggests that the taxon has greater impacts than previously known, which cross the threshold for the next impact Category, the EICAT Category assigned to the taxon may be increased to a higher Category. A full justification for any change to the EICAT Category assigned to the taxon should be provided in the assessment documentation.

The following rules govern changes to the EICAT Category assigned to an alien taxon:

A. If the original classification is found to have been erroneous, the taxon may be transferred to the appropriate EICAT Category without delay. In this case, the taxon should be re-evaluated against all the EICAT Criteria to clarify its status.

B. Changes from the **Not Evaluated** (**NE**), **No Alien Population** (**NA**), or **Data Deficient** (**DD**) categories, should be made without delay, if the change is a result of the taxon being evaluated for the first time, becoming introduced for the first time, or due to sufficient information becoming available to categorise the taxon into one of the EICAT Impact Categories for the first time.

C. The reason for a transfer between Categories must be documented as one of the following:

i. **Genuine**. *The change in Category is the result of a genuine status change that has taken place since the previous assessment, due to the taxon being recorded as alien for the first time, or because of a real increase in impact of the taxon where it is alien. Only changes from **NA** into one of the alien Categories (**DD**, **MC**, **MN**, **MO**, **MR**, **MV**), or from a lower to a higher impact Category, can be coded as Genuine.*

ii. **Criteria revision.** *The change in Category is the result of the revision of the EICAT Categories and/or Criteria.*

iii. **New information.** *The change in Category is the result of better knowledge about the taxon, e.g. owing to new or newly synthesised information about the status of the taxon or its impacts, but without a genuine change in the impact level itself. That is, the information suggests that the* *previous categorisation was incorrect, so a new Category is assigned based on this new information.*

iv. **Taxonomy**. *The new Category is different from the previous Category owing to a taxonomic change adopted during the period since the previous assessment. Such changes include: newly split (the taxon is newly elevated to the species level), newly described (the taxon is newly described as a species), newly lumped (the taxon is recognised following lumping of two or more previously recognised taxa) and no longer valid/recognised (either the taxon is no longer valid e.g. because it is now considered to be a hybrid or variant, form or subspecies of another species, or the previously recognised taxon differs from a currently recognised one as a result of a split or lump).*

v. **Mistake**. *The previous Category was applied in error because the assessor(s) misunderstood the EICAT Categories and/or Criteria.*

vi. **Incorrect data.** *The previous Category was applied in error because incorrect data were used (e.g. the data referred to a different taxon).*

vii. **Other**. *The change in Category is the result of other reasons not easily covered by the above, and/or requires further explanation.*

Determining the appropriate reason for change will require careful consideration. Category changes may result from a combination of improved knowledge and some element of genuine change in status. In such cases, “Genuine” should only be assigned if the amount of genuine change (e.g., new alien population; impact affecting a new level of organisation) is sufficient on its own to cross the relevant EICAT Category threshold. Genuine and non-genuine reasons for change should never be coded at the same time. All Genuine (recent) or Genuine (since first assessment) Category changes should be supported with appropriate notes to justify why the change is coded as genuine.

4. EICAT Assessment authorship and citation

The *Assessor(s)* are the named authors of an EICAT assessment. The citation for an EICAT assessment is as follows:

> Assessor(s). Year assessment published. *Taxon name.* IUCN Environmental Impact Classification of Alien Taxa (EICAT). http://www.iucngisd.org/gisd/...[URL to species page on the IUCN Global Invasive Species Database].

Reassessment

When a taxon is reassessed the *Assessor(s)* should make every reasonable effort to contact the assessors of the previous assessment to ask if they would like to engage in the reassessment process. If they engage in the assessment process, both the previous and new *Assessors* are named as joint *Assessors* in the reassessment. If the original assessors are unable to engage, cannot be contacted, or only provide additional data and do not want to take part in the reassessment of taxa's EICAT Impact Category, they are automatically named as a *Contributor* and not as a joint *Assessor*.

5. Petitions process

Accepted and published IUCN EICAT assessments are open to challenge, in the case that a party has good reason to disagree with the Category or Criteria assigned to a taxon. Petitions may only be made on scientific or technical grounds on the basis of the EICAT Categories and Criteria, or in reference to any supporting documentation accompanying the assessment. Challenges based on political, emotional, economic, or other reasons not based on the EICAT Categories and Criteria or supporting documentation will not be considered. Any party may contact the EICAT Unit at any time to express disagreement. If this disagreement is based on scientific or technical grounds, the EICAT Unit will put this party in contact with the relevant Assessor(s) with intention of resolving the disagreement. In the event of a disagreement concerning the classification of a taxon that is in the process of being reassessed, the EICAT Unit will seek to involve the party expressing disagreement in the reassessment process, with the objective of reaching consensus on the new classification.

If these processes are not successful in resolving the disagreement, a formal petition may be submitted by the challenger. A formal petition should provide a brief summary of the points of disagreement, with explicit reference to the EICAT Categories and Criteria under which the taxon is listed (2 pages maximum). During the petitions process, all parties should acknowledge receipt of all correspondence as soon as possible, so that any failure in delivery is detected as early as possible. All correspondence should be treated as confidential. The steps for filling petitions are as follows:

1. Petitions can be submitted to the EICAT Unit at any time. The EICAT Unit will acknowledge receipt of the petition, and will inform the petitioner of the date on which the petition was received.
2. The EICAT Unit will consult with members of the EICAT Authority to determine whether or not the petition has been filed on the basis of the EICAT Categories and Criteria. If the petition has not been made on this basis, it will be returned to the petitioner by the EICAT Unit with an explanation as to why the petition cannot be considered.
3. If the petition is made on the basis of the EICAT Categories and Criteria, it will be referred by the EICAT Unit to the particular Assessor/s responsible for the taxon assessment in question. The EICAT Unit will request the Assessor and the petitioner to discuss the petition with the objective of reaching an agreement between them. In seeking to reach agreement, the Assessor and the petitioner should: (i) determine whether or not they are using the same underlying data; and (ii) clarify whether or not the disagreements are due to factual discrepancies, as opposed to differences of either interpretation or application of the EICAT Categories and Criteria.

4. If the Assessor and the petitioner come to agreement, then any changes to the listing will be accepted, and the published EICAT assessment will be amended accordingly.
5. If the Assessor and the petitioner are unable to agree within 4 months of first contact, then the EICAT Unit will notify both the petitioner and the Assessor that each should submit justifications for their case to the EICAT Unit, within the next two months. Justifications should be no more than 4 sides of A4 (12 point font, 1.5 spaced), and should include a synopsis of the failed negotiations, a brief statement of the reasons for the dispute, and a clarification of any factual discrepancies (e.g. different sources of data or information used). All data used in these justifications must either be referenced to publications that are available in the public domain, or else be made available to the EICAT Unit. The data provided should be clearly linked to the use of the EICAT Categories and Criteria. If the petitioner fails to submit a justification within the set time period and in the required format, the petition will be dropped. If the Assessor fails to submit a justification within the set time period, the petition will go forward.
6. The EICAT Unit will send the justifications of each party to the other within one week of the time period set above, or within one week of both justifications having been received. Both parties have three weeks in which to provide a 1-page addendum to their justifications, should they choose to do so. Any addendums received after the three- week period will not be considered. The parties may not make any changes to the original justifications.
7. At the end of this three-week period, whether or not an addendum is received, three members of the EICAT Authority (typically members of the ISSG) will be selected to review the case, on the basis of their relevant expertise. These EICAT Authority members may choose to circulate the justifications to other independent expert reviewers for confidential comments. If needed, the EICAT Unit may seek clarification of particular issues from the Assessor and the petitioner. In instances in which the Assessor failed to submit a justification, the EICAT Unit will make every effort to obtain a balanced set of confidential comments from reviewers.
8. The selected EICAT Authority members will make a ruling on each petition within three months from the time that the petitions were circulated to the three members by the EICAT Unit. The EICAT Unit will issue a notification that will include a full rationale and explanation of each ruling, but will not include a record of the deliberations that the EICAT Authority members made to reach the decision, and the names of any reviewers will be kept confidential. The EICAT Unit will send this notification to the petitioner and to the Assessor. Any changes to the category will be made to the published EICAT assessment. The notification of the ruling on any petition, and any resulting change in category, will be placed on the GISD website.

9. If there is an assertion that the above procedure has been violated, then a formal and documented complaint may be submitted to the Chair of the SSC ISSG.

6. Future documents

IUCN SSC ISSG are planning to produce a number of additional documents to support the application of EICAT and its appropriate use, this includes:

6.1. Appropriate uses for EICAT assessments.

This will address issues on how the results of EICAT should be used, and identify potential misuse of the outputs of EICAT assessments. A similar has been provided for the IUCN Red List. However, it is important to stress that EICAT assessment results should not be used on their own to prioritise invasive alien species (or habitats) for management measures, as additional information is needed (e.g. see [9, 10, 11]).

6.2. Case studies.

Case studies/examples of EICAT assessments will be made available to support the application of the EICAT, as more taxonomic groups are assessed.

6.3. Data management plan.

A detailed data management plan will be developed as a separate document to detail how EICAT assessment information will be handled by IUCN.

7. References

1. Collaboration for Environmental Evidence. 2013. Guidelines for Systematic Review and Evidence Synthesis in Environmental Management. Version 4.2. Compiled on behalf of CEE by Centre for Evidence-Based Conservation, Bangor University, UK. downloadable from http://www.environmentalevidence.org/information-for-authors
2. Roy, H.E., Adriaens, T., Isaac, N.J.B., Kenis, M., Onkelinx, T., San Martin, G., Brown, P.M.J., Hautier, L., Poland, R., Roy, D.B., Comont, R., Eschen, R., Frost, R., Zindel, R., Van Vlaenderen, J., Nedvěd, O., Ravn, H.P., Gregoire, J-C., de Biseau, J-C. and Maes, D. 2012. Invasive alien predator causes rapid declines of native European ladybirds. *Diversity and Distributions*, 18(7): 717-725.
3. Hejda, M., Pyšek, P. and Jarošík, V. 2009. Impact of invasive plants on the species richness, diversity and composition of invaded communities. *Journal of Ecology*,97(3): 393-403.
4. Monks, J., Monks, A. and Towns, D.. 2014. Correlated recovery of five lizard populations following eradication of invasive mammals*. Biological invasions,* 16(1): 167-175.
5. Kumschick, S., Measey, G., Vimercati, G., De Villiers, A., Mokhatla, M., Davies, S., Thorp, C., Rebelo, A., Blackburn, T. and Kraus, F. 2017. How repeatable is the Environmental Impact Classification of Alien Taxa (EICAT)? Comparing independent global impact assessments of amphibians. *Ecology and Evolution*, 7: 10.1002/ece3.2877.
6. Ojaveer, H., Galil, B.S., Campbell, M.L., Carlton, J.T., Canning-Clode, J., Cook, E.J., Davidson, A.D., Hewitt, C.L., Jelmert, A., Marchini, A., McKenzie, C.H., Minchin, D., Occhipinti-Ambrogi, A., Olenin, S. and Ruiz, G. 2015. Classification of non-indigenous species based on their impacts: considerations for application in marine management. *PLoS Biology,* 13(4): e1002130.
7. Blackburn,T.M., Bacher, S., Genovesi, P., Jeschke, J.M., Kumschick, S., Richardson, D.M., Essl, F., Hulme, P.E., Kühn, I., Nentwig, W., Pergl, J., Rabitsch, W., Vilà, M., Wilson, J.R.U. and Pyšek, P. 2015. Classification of Non-Indigenous Species Based on Their Impacts: Considerations for Application in Marine Management. *PLoS Biology*, https://doi.org/10.1371/journal.pbio.1002130
8. Galandi, M., Zenetos, A. and Bacher. S. 2018. Assessing the socio-economic impacts of priority marine invasive fishes in the Mediterranean with the newly proposed SEICAT methodology. *Mediterranean Marine Science*, 19(1):107-123 DOI:10.12681/mms.15940.
9. Booy, O., Mill, A.C., Roy, H.E., Hiley, A., Moore, N., Robertson, P., Baker, S., Brazier, M., Bue, M., Bullock, R., Campbell, S., Eyre, D., Foster, J., Hatton-Ellis, M., Long, J., Macadam, C., Morrison-Bell, C.,Mumford, J., Newman, J., Parrott, D., Payne, R., Renals, T., Rodgers, E., Spencer, M., Stebbing, P., Sutton-Croft, M., Walker, K.J., Ward, A. and Wyn, G., 2017. Risk management to prioritise the eradication of new and emerging invasive non-native species. *Biological Invasions*, 19:2401–2417 https://doi.org/10.1007/s10530-017-1451-z.

10. Roy, H.E., Peyton, J, Aldridge, D.C., Bantock, T., Blackburn, T.M., Britton, R., Clark, P., Cook, E., Dehnen-Schmutz, K., Dines, T., Dobson, M., Edwards, F., Harrower, C., Harvey, M.C., Minchin, D., Noble, D.G., Parrott, D., Pocock, M.J.O., Preston, C.D., Roy, S., Salisbury, A., Schonrogge, K., Sewell, J., Shaw, R.H., Stebbing, P., Stewart, A.J.A. and Walker, K.J. 2014. Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. *Global Change Biology*, 20:3859–3871
11. Roy, H.E., Bacher, S., Essl, F., Adriaens, T., Aldridge, D.C., Bishop, J.D.D., Blackburn, T.M., Branquart, E., Brodie, J., Carboneras, C., Cottier-Cook, E.J., Copp, G.H., Dean, H.J., Eilenberg, J., Gallardo, B., Garcia, M., Garcıa-Berthou, E., Genovesi, P., Hulme, P.E., Kenis, M., Kerckhof, F., Kettunen, M., Minchin, D., Nentwig, W., Nieto, A., Pergl, J., Pescott, O.L., Peyton, J.M., Preda, C., Roques, A., Rorke, S.L., Scalera, R., Schindler, S., Schonrogge, K., Sewell, J., Solarz, W., Stewart, A.J.A., Tricarico, E., Vanderhoeven, S., van der Velde, G., Vila, M., Wood, C.A., Zenetos, A. and Rabitsch, W. 2019. Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union. *Global Change Biology*, 25:1032–1048
12. Holt, J., Leach, A., Knight, J., Griessinger, D., MacLeod, A., van der Gaag, D., Schrader, G. and Mumford, J. 2012. Tools for visualizing and integrating pest risk assessment ratings and uncertainties. *EPPO Bulletin*, 42(1): 35-41.
13. ISO. 1997. ISO-3166-1. Codes for the representation of names of countries and their subdivisions - Part 1: Country Codes. Fifth edition. ISO 3166 Maintenance Agency at DIN, Berlin. 1997.
14. Brummitt, R. 2001. World Geographic Scheme for Recording Plant Distributions. Plant Taxonomic Database Standards No. 2 edition 2. International Working Group on Taxonomic Databases for Plant Sciences (TDWG). Hunt Institute for Botanical Documentation: Pittsburgh.
15. IUCN. 2019. IUCN Red List of Threatened Species, Version 2019-1. IUCN https://www.iucnredlist.org/resources/classification-schemes

Appendix 1: Estimating the distribution of uncertainty

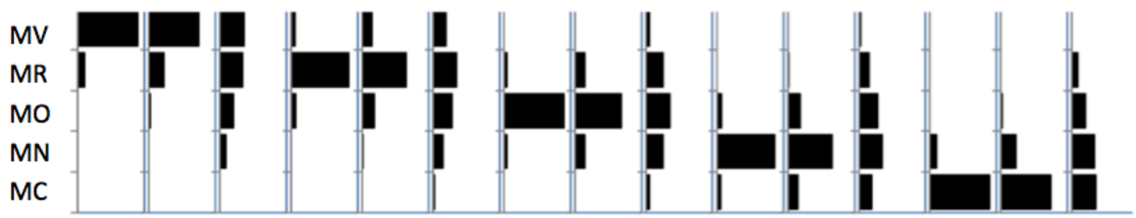
Uncertainty in assessment classifications means that there is some probability that an alien taxon should in reality be assigned to another category (most likely to a neighbouring category; Figure 2.). This probability will be lowest for taxa categorised with High confidence, and highest for taxa categorised with Low confidence. It is possible to estimate the distribution of this probability in each case, by assigning it on the basis of a range of theoretical probability distributions.

Table S1 presents an example of this approach. Confidence levels are translated into probabilities that the assigned category is the correct one. In this example, High confidence means that the assessor feels they have approximately a 90% chance of the given score being correct; Medium confidence, a 65-75% chance of being correct; Low confidence, a 35% chance of being correct. The remaining probability has been assigned to the other categories according to a beta probability density function [12]. The Beta distribution is a continuous distribution on the range [0, 1]. It is defined by two positive parameters, α, β, that control the shape of the distribution. The range [0, 1] was discretised by dividing it into 5 equally-sized intervals, representing the 5 impact categories. We calculated the values of the beta probability density function at the mid-point of each interval, with parameters chosen such that the assigned category had the highest probability and the variance in confidence increased from High to Medium to Low, taking approximate values of 0.007, 0.011, and 0.038, respectively. Values of the beta distribution were standardised such that the 5 values sum up to 1. The table shows that a classification of **MV** with High confidence still has some probability of being incorrect, and that the most likely alternative classification is **MR**; likewise, a classification of **MO** with Low confidence has a relatively high probability of being incorrect, and the correct classification may be any of the other categories (albeit that neighbouring categories in Figure 2 are still the most likely alternatives). These distributions of likelihoods, together with the descriptions of uncertainties in Table S1, may serve as guidance for assessors to assign confidence levels to their assessments. A choice of predefined distributions offers a consistent way to infer a rating distribution from a single confidence rating, but we suggest that assessors examine these distributions carefully to make sure they accord with their own perception of confidence.

Table S1. Suggested distribution of likelihoods (in percent) of the impact of alien taxa being in a certain category depending on the confidence of the assessment.

Probability distributions follow a beta probability density function with parameters α and β, as implemented in Excel. The histogram below the table provides a pictorial representation of the same probabilities.

Category	MV			MR			MO			MN			MC		
Confidence	High	Med	Low	High	Med	Low	High	Med	Low	High	Med	Low	High	Med	Low
Distribution of Likelihoods (%)															
MV	90	75	36	6	15	19	0	0	6	0	0	2	0	0	0
MR	10	23	34	87	66	35	5	15	26	0	1	15	0	0	9
MO	0	2	21	7	18	29	90	70	36	7	18	29	0	2	21
MN	0	0	9	0	1	15	5	15	26	87	66	35	10	23	34
MC	0	0	0	0	0	2	0	0	6	6	15	19	90	75	36
α/β	3/18	2/10	1.4/3	7.3/18	4.4/10	1.8/3	18/18	10/10	3/3	18/7.3	10/4.4	3/1.8	18/3	10/2	3/1.4



Appendix 2: Data reporting template

Please see separate excel spreadsheet "EICAT Data reporting template v 3.3".

Appendix 3: Additional classification schemes

i. Distribution information

The EICAT scheme has adopted the same distribution recording system as used in the IUCN Red List of Threatened Species. Distribution is recorded in terms of country names following the 5th edition (and subsequent web updates) of the ISO-3166-1 standard [13]. For large countries (e.g. Australia, Brazil, China, India, South Africa, the Russian Federation and the United States of America) or countries spanning diverse biogeographic regions (e.g. Colombia, Ethiopia, Pakistan), distributions within the country should also be listed, using the standard set of Basic Recording Units (BRU) provided by the International Working Group World Geographical Scheme for Recording Plant Distributions (TDWG). These Basic Recording Units (BRU) are sub-country units based on provinces or states. Unless geographically very remote from each other, islands and other territories are included with the parent country. In the case of taxa that inhabit islands significantly distant from the mainland, the island name is given in parentheses (e.g. Spain (Canary Islands)). The naming of such islands follows Brummitt (2001) [14], prepared for the TDWG.

For marine taxa, country records should be provided wherever possible. This information can be derived from a number of sources (e.g. FishBase and the many FAO publications). For some marine taxa, particularly those with ranges outside of territorial waters, distributions should also be shown as generalised ranges in terms of the FAO Fishing Areas.

ii. Habitats classification scheme

The EICAT scheme has adopted the same habitat nomenclature as used in the IUCN Red List of Threatened Species [15]. The habitat types listed below are standard terms used to describe the major habitat(s) in which taxa occur.

The three levels of the hierarchy are self-explanatory, as they use familiar habitat terms that take into account biogeography, latitudinal zonation, and depth in marine systems. The inland aquatic habitats are based primarily on the classification system of wetland types used by the Ramsar Convention (see Ramsar Wetland Type Classification System). Further details about applying the habitats classification scheme, including a brief description of each habitat, can be found here.

1 Forest

- 1.1 Boreal Forest
- 1.2 Subarctic Forest

1.3 Subantarctic Forest

1.4 Temperate Forest

1.5 Subtropical/Tropical Dry Forest

1.6 Subtropical/Tropical Moist Lowland Forest

1.7 Subtropical/Tropical Mangrove Forest Vegetation Above High Tide Level

1.8 Subtropical/Tropical Swamp Forest

1.9 Subtropical/Tropical Moist Montane Forest

2 Savanna

2.1 Dry Savanna

2.2 Moist Savanna

3 Shrubland

3.1 Subarctic Shrubland

3.2 Subantarctic Shrubland

3.3 Boreal Shrubland

3.4 Temperate Shrubland

3.5 Subtropical/Tropical Dry Shrubland

3.6 Subtropical/Tropical Moist Shrubland

3.7 Subtropical/Tropical High Altitude Shrubland

3.8 Mediterranean-type Shrubby Vegetation

4 Grassland

4.1 Tundra

4.2 Subarctic Grassland

4.3 Subantarctic Grassland

4.4 Temperate Grassland

4.5 Subtropical/Tropical Dry Lowland Grassland

4.6 Subtropical/Tropical Seasonally Wet/Flooded Lowland Grassland

4.7 Subtropical/Tropical High Altitude Grassland

5 Wetlands (inland)

5.1 Permanent Rivers, Streams, Creeks [includes waterfalls]

5.2 Seasonal/Intermittent/Irregular Rivers, Streams, Creeks

5.3 Shrub Dominated Wetlands

5.4 Bogs, Marshes, Swamps, Fens, Peatlands [generally over 8 ha]

5.5 Permanent Freshwater Lakes [over 8 ha]

5.6 Seasonal/Intermittent Freshwater Lakes [over 8 ha]

5.7 Permanent Freshwater Marshes/Pools [under 8 ha]

5.8 Seasonal/Intermittent Freshwater Marshes/Pools [under 8 ha]

5.9 Freshwater Springs and Oases

5.10 Tundra Wetlands [includes pools and temporary waters from snowmelt]

5.11 Alpine Wetlands [includes temporary waters from snowmelt]

5.12 Geothermal Wetlands

5.13 Permanent Inland Deltas

5.14 Permanent Saline, Brackish or Alkaline Lakes

5.15 Seasonal/Intermittent Saline, Brackish or Alkaline Lakes and Flats

5.16 Permanent Saline, Brackish or Alkaline Marshes/Pools

5.17 Seasonal/Intermittent Saline, Brackish or Alkaline Marshes/Pools

5.18 Karst and Other Subterranean Inland Aquatic Systems

6 Rocky Areas [e.g. inland cliffs, mountain peaks]

7 Caves and Subterranean Habitats (non-aquatic)

7.1 Caves

7.2 Other Subterranean Habitat

8 Desert

8.1 Hot

8.2 Temperate

8.3 Cold

9 Marine Neritic (Submergent Nearshore Continental Shelf or Oceanic Island)

9.1 Pelagic

9.2 Subtidal Rock and Rocky Reefs

9.3 Subtidal Loose Rock/Pebble/Gravel

9.4 Subtidal Sandy

9.5 Subtidal Sandy-Mud

9.6 Subtidal Muddy

9.7 Macroalgal/Kelp

9.8 Coral Reef

9.8.1 Outer Reef Channel

9.8.2 Back Slope

9.8.3 Foreslope (Outer Reef Slope)

9.8.4 Lagoon

9.8.5 Inter-Reef Soft Substrate

9.8.6 Inter-Reef Rubble Substrate

9.9 Seagrass (Submerged)

9.10 Estuaries

10 Marine Oceanic

10.1 Epipelagic (0–200 m)

10.2 Mesopelagic (200–1,000 m)

10.3 Bathypelagic (1,000–4,000 m)

10.4 Abyssopelagic (4,000–6,000 m)

11 Marine Deep Ocean Floor (Benthic and Demersal)

11.1 Continental Slope/Bathyl Zone (200–4,000 m)

11.1.1 Hard Substrate

11.1.2 Soft Substrate

11.2 Abyssal Plain (4,000–6,000 m)

11.3 Abyssal Mountain/Hills (4,000–6,000 m)

11.4 Hadal/Deep Sea Trench (>6,000 m)

11.5 Seamount

11.6 Deep Sea Vents (Rifts/Seeps)

12 Marine Intertidal

12.1 Rocky Shoreline

12.2 Sandy Shoreline and/or Beaches, Sand Bars, Spits, etc.

12.3 Shingle and/or Pebble Shoreline and/or Beaches

12.4 Mud Shoreline and Intertidal Mud Flats

12.5 Salt Marshes (Emergent Grasses)

12.6 Tidepools

12.7 Mangrove Submerged Roots

13 Marine Coastal/Supratidal

13.1 Sea Cliffs and Rocky Offshore Islands

13.2 Coastal Caves/Karst

13.3 Coastal Sand Dunes

13.4 Coastal Brackish/Saline Lagoons/Marine Lakes

13.5 Coastal Freshwater Lakes

14 Artificial - Terrestrial

14.1 Arable Land

14.2 Pastureland

14.3 Plantations

14.4 Rural Gardens

14.5 Urban Areas

14.6 Subtropical/Tropical Heavily Degraded Former Forest

15 Artificial - Aquatic

15.1 Water Storage Areas [over 8 ha]

15.2 Ponds [below 8 ha]

15.3 Aquaculture Ponds

15.4 Salt Exploitation Sites

15.5 Excavations (open)

15.6 Wastewater Treatment Areas

15.7 Irrigated Land [includes irrigation channels]

15.8 Seasonally Flooded Agricultural Land

15.9 Canals and Drainage Channels, Ditches

15.10 Karst and Other Subterranean Hydrological Systems [human-made]

15.11 Marine Anthropogenic Structures

15.12 Mariculture Cages

15.13 Mari/Brackish-culture Ponds

16 Introduced Vegetation

17 Other

18 Unknown

iii. Management action classification

Any management actions in place to eradicate or control an alien taxon, or mitigate its impacts on native taxa, should be classified based on the scheme below, developed for the Global Invasive Species Database (GISD). Actions are broadly classified according to their ultimate aim (monitoring, prevention, control or eradication; Table 3) and then based on the methods used (Tables 4 – 6). A number of different methods are often used together, and where this is the case, all active management actions should be listed. The area covered by the management actions should also be indicated so that impacts can be understood in the context of these actions.

Table S2. Codes, names and definitions of different management actions for alien taxa.

Management CATEGORY CODE	Management CATEGORY NAME	Definition
6	Monitoring	Measures taken to evaluate the distribution, expansion and/or density of the alien taxon.
1	Prevention	Measures taken to stop the taxon from entering an area.
2	Eradication	Actions taken to eliminate all occurrences of a taxon. Long term, on-going eradication projects are included in this category.
3	Control	Measures taken to reduce a taxon or biomass (control), to keep a taxon in a defined area (containment), and/or to reduce harmful effects of a taxon (mitigation).
4	None	
5	Unknown	

Table S3. Codes and names of management actions aiming to prevent alien taxa from entering an area.

Prevention Method CODE	Prevention Method NAME
1	Risk assessment
2	Legal Status (restrictions)
3	Best practises
4	Cultural methods

Table S4. Codes and names of management actions designed to control populations of alien taxa established in an area.

Control Method CODE	Control Method NAME
1	Physical-Mechanical (manual)
2	Chemical
3	Biological
4	Integrated methods
99	Unknown

Table S5. Codes and names of management actions aiming to eradicate populations of alien taxa from an area in which they are established.

Eradication Method CODE	Eradication Method NAME
1	Shooting
2	Trapping
3	Hand removal
4	Pesticides or herbicides
5	Poisoning or toxicants
6	Others (disease, fumigants, draining...)
99	Unknown

NeoBiota 62: 387–405 (2020)
doi: 10.3897/neobiota.62.52010
http://neobiota.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Understanding uncertainty in the Impact Classification for Alien Taxa (ICAT) assessments

Anna F. Probert[1], Lara Volery[1], Sabrina Kumschick[2,3], Giovanni Vimercati[1], Sven Bacher[1]

1 *Department of Biology, Unit Ecology & Evolution, University of Fribourg, Chemin du Musée 10, 1700 Fribourg, Switzerland* **2** *Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Matieland 7602, South Africa* **3** *South African National Biodiversity Institute, Kirstenbosch Botanical Gardens, Claremont, South Africa*

Corresponding author: Anna F. Probert (afprobert@outlook.com)

Academic editor: Q. J. Groom | Received 12 March 2020 | Accepted 3 June 2020 | Published 15 October 2020

Citation: Probert AF, Volery L, Kumschick S, Vimercati G, Bacher S (2020) Understanding uncertainty in the Impact Classification for Alien Taxa (ICAT) assessments. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 387–405. https://doi.org/10.3897/neobiota.62.52010

Abstract

The Environmental Impact Classification for Alien Taxa (EICAT) and the Socio-Economic Impact Classification of Alien Taxa (SEICAT) have been proposed to provide unified methods for classifying alien species according to their magnitude of impacts. EICAT and SEICAT (herein "ICAT" when refered together) were designed to facilitate the comparison between taxa and invasion contexts by using a standardised, semi-quantitative scoring scheme. The ICAT scores are assigned after conducting a literature review to evaluate all impact observations against the protocols' criteria. EICAT classifies impacts on the native biota of the recipient environments, whereas SEICAT classifies impacts on human activities. A key component of the process is to assign a level of confidence (high, medium or low) to account for uncertainty. Assessors assign confidence scores to each impact record depending on how confident they are that the assigned impact magnitude reflects the true situation. All possible sources of epistemic uncertainty are expected to be captured by one overall confidence score, neglecting linguistic uncertainties that assessors should be aware of. The current way of handling uncertainty is prone to subjectivity and therefore might lead to inconsistencies amongst assessors. This paper identifies the major sources of uncertainty for impacts classified under the ICAT frameworks, where they emerge in the assessment process and how they are likely to be contributing to biases and inconsistency in assessments. In addition, as the current procedures only capture uncertainty at the individual impact report, interspecific comparisons may be limited by various factors, including data availability. Therefore, ranking species, based on impact magnitude under the present systems, does not account for such uncertainty. We identify three types of biases occurring beyond the individual impact report level (and not captured by the confidence score): biases in the existing data,

data collection and data assessment. These biases should be recognised when comparing alien species based on their impacts. Clarifying uncertainty concepts relevant to the ICAT frameworks will lead to more consistent impact assessments and more robust intra- and inter-specific comparisons of impact magnitudes.

Keywords
Alien species, confidence score, EICAT, invasive species, risk, SEICAT

Introduction

Understanding the impacts of alien species in their recipient environments is a key research theme in invasion science (Strayer et al. 2006; Pejchar and Mooney 2009; Vilà et al. 2011; Kumschick et al. 2015). However, making comparisons between taxa is difficult as invasions are context-dependent and measurements of impact are not collected using a consistent method (Courchamp et al. 2017). As such, different frameworks have been developed to guide invasion biologists towards more standardised approaches which facilitate comparisons amongst invasion scenarios (Nentwig et al. 2010, 2016; Blackburn et al. 2014). In 2014, Blackburn and colleagues proposed a systematic method for classifying impacts across alien taxa, based on the effects of alien species on native biota. The resulting Environmental Impact Classification System for Alien Taxa (EICAT) (Blackburn et al. 2014; Hawkins et al. 2015) is conceptually based on the International Union for the Conservation of Nature's (IUCN) Red List of Threatened Species, which uses a ranked classification scheme to determine the global conservation status for individual species (IUCN 2012). Since its publication, the EICAT protocol has been formalised (IUCN 2020a, b; Hawkins et al. 2015) and applied to various groups including birds (Evans et al. 2016, 2018a), amphibians (Kumschick et al. 2017), gastropods (Kesner and Kumschick 2018), some mammals (Hagen and Kumschick 2018), marine fishes (Galanidi et al. 2018) and bamboos (Canavan et al. 2019). More recently, Bacher et al. (2018) proposed an adapted version of the EICAT framework to address socio-economic impacts (SEICAT) caused by alien species. The currency used to measure impact for this scheme is observed changes to human activities and/or well-being and, to date, SEICAT has been applied to amphibians, birds, marine fishes, some mammals and gastropods, in conjunction with the EICAT assessments (Bacher et al. 2018; Evans et al. 2020; Galanidi et al. 2018; Hagen and Kumschick 2018; Kesner and Kumschick 2018).

In the ICAT classification schemes, assessors first conduct a comprehensive literature search to collate all impact records for a given alien species. They then classify each of these impact records into one of the five ICAT semi-quantitative scenarios, according to the magnitude of the impact. For instance, under EICAT, impact magnitudes are hierarchically structured, based on the level of organisation of the native population(s) (i.e. individuals or populations) in which they cause an effect: MC (Minimal Concern; negligible level of impact, but no impact on the performance of native individuals is detected), MN (Minor; the performance (e.g. growth, reproduction) of native individuals is decreased by the alien, but no impact at the native population level is detected), MO (Moderate; the alien causes a decline in at least one native population), MR (Major; the alien causes a local extinction of at least one native population, but this local extinction is reversible, which means that the native species could recolonise the area if the alien population were removed), MV (Massive; the alien causes an irreversible local extinction of at least one native population). If there is no relevant information to derive an impact score, then a species is classified as Data Deficient.

A key aspect of each assessment involves assigning a confidence score for each recorded impact to provide an estimate of uncertainty. Both frameworks adopt a similar approach as the Intergovernmental Panel on Climate Change (IPCC) and the European and Mediterranean Plant Protection Organization (EPPO) to deal with uncertainty (Mastrandrea et al. 2010; Holt et al. 2012; Kenis et al. 2012). The assessor must assign a confidence score of either high, medium or low, based on guiding probabilities (Table 1), to each impact report, depending on how confident they are that the assigned impact magnitude is true i.e. could the actual impact be lower or higher than what is classified. Although several key sources of uncertainty are identified in the guidelines (IUCN 2020a; Hawkins et al. 2015; Bacher et al. 2018), whether the current consideration of uncertainty is sufficient has not been critically evaluated.

Inadequately accounting for uncertainty when assigning impact magnitudes could lead to incorrect judgement calls and potentially to non-relevant prioritisation and mismanagement of species. Todd and Burgman (1998) demonstrated how incorporating uncertainty into the conservation status of species can cause differences in the assessment outcome, potentially altering conservation priorities. McGeoch et al. (2012) described the uncertainties associated with alien species listing and demonstrated how they produce inconsistencies at the taxonomic and geographic scale. Insufficient handling of uncertainty may not only be detrimental for the native taxa (EICAT) and human societies (SEICAT) that are affected by alien species; it can lead to public distrust in invasion science and reduce the success of future management and restoration programmes (Liu et al. 2011). Failure to effectively capture and communicate uncertainty may lead to ill-informed decisions, causing people to potentially undermine management objectives (Ascher 2004), which is of particular concern to invasive species management where public support is critical for achieving management outcomes (Bremner and Park 2007; Kraus and Duffy 2010; Novoa et al. 2017; Russell and Stanley 2018).

To address potential sources of uncertainty relevant to the ICAT assessments, we evaluate the current consideration when assigning confidence scores, identifying where uncertainties may arise during the assessment process. In the first part of this manuscript, we explain the key concepts and definitions of uncertainty relevant to the ICAT frameworks and map these along the assessment process. We then proceed to identify new sources of uncertainty currently not considered under the framework guidelines and discuss how these may play a role in both the evaluation of information and the final ICAT scores. In doing so,

Table 1. The three current confidence levels (high, medium, low) assigned to individual impact reports using the ICAT frameworks. Guiding probabilities are given in the guidelines to aid the assessor in interpreting their level of confidence into one of the three qualitative categories.

Confidence level	Approximate probability of the impact being correct
High	~90%
Medium	~65–75%
Low	~35%

we develop a more comprehensive understanding of uncertainty relevant to ICAT assessments, which may be of conceptual relevance to other aspects of risk assessment, particularly when extracting and evaluating impact information from various sources.

General types of uncertainty and how they can be expressed

Uncertainties arise because our knowledge of systems is incomplete and we often deal with imperfect information; thus, uncertainty is inherent to all scientific research (van der Bles et al. 2019). In some cases, uncertainty can be minimised through the collection of additional information, yet it is impossible to eliminate uncertainty altogether (Regan et al. 2002). In cases where uncertainty cannot be reduced, best practice involves quantification of–and when this is not possible, sufficient acknowledgement of–where uncertainties remain and how they may alter the interpretation of evidence (Fischhoff and Davis 2014). Common expressions of uncertainty in science are usually communicated through quantitative terms such as confidence intervals, standard deviations and probability distributions, but generally, they capture only parts of the overall uncertainty (e.g. measurement error).

A taxonomy of uncertainty applicable to ecological research was described by Regan et al. (2002), who distinguish between two key types of uncertainty: epistemic and linguistic (Table 2). Given their broad applicability to ecological concepts, these expressions of uncertainty are relevant to ICAT assessments and have recently been considered in developing a framework for uncertainty in invasion science (Latombe et al. 2019). Epistemic uncertainties arise because of our limited knowledge of the system of interest. They can generally be reduced with increasing information; however, obtaining a complete understanding of such systems is almost always impractical, hence the necessity to use simplified models to characterise the true state (Regan et al. 2002). Different types of epistemic uncertainty are relevant to the understanding of alien species impacts in general. These include natural variation, measurement error, systematic error, model uncertainty and subjective judgement (Table 2; Regan et al. 2002). Linguistic uncertainties arise because language is imprecise and changes over time cause terminology to be both used inconsistently and open to interpretation (Regan et al. 2002). The different types of linguistic uncertainty include vagueness, context-dependency, ambiguity, indeterminacy of theoretical terms and underspecificity (Table 2). It is clear that linguistic uncertainty has pervaded invasion science, given the numerous attempts to standardise concepts and definitions to improve consistency across the discipline (Wilson et al. 2020; Colautti and MacIsaac 2004; Richardson et al. 2010; Blackburn et al. 2011).

Considering uncertainty for ICAT assessments

Uncertainty directly relevant to the ICAT assessments can be considered at two levels: 1) the impact report level and, 2) the species level. The impact report level is the individual record of impact (of an alien species at a specific location and point in time) that is documented in some form–such as a journal article of grey literature—and assigned

Table 2. Different types of epistemic and linguistic uncertainties and their definitions which are relevant to the ICAT assessment process (Regan et al. 2002).

Epistemic	Linguistic
Natural variation Variations in the variables measured in the study system (e.g. temporally, spatially).	*Vagueness* Arises since language allows borderline cases. Particularly relevant to ordinal categories (e.g. high, medium, low) where arbitrary and/or poorly defined cut-offs exist.
Measurement error Imperfections in the measurement equipment or observational techniques which generates random deviation in the measurement data from the true value. Includes operator error and instrument error.	*Ambiguity* When words have more than one meaning and it is unclear which meaning is intended.
Systematic error Bias in the measuring equipment or sampling procedure that generates non-random deviations from the true value (e.g. via poorly-calibrated equipment). This also includes error resulting from the deliberate judgement of a person to exclude (or include) data.	*Context dependence* Lack of specificity related to the context in which something is to be understood. For example, understanding the meaning of something being "small" requires knowledge as to whether the description refers to an insect or a plant.
Model uncertainty Arises due to the necessary simplifications (models) used to represent physical and biological systems.	*Underspecificity* Occurs when there is unwanted generality i.e. there is a lack of specificity to ensure complete understanding.
Subjective judgement Occurs as a result of the interpretation of data, often when data are scarce and/or error prone. Particularly relevant to expert judgement.	*Indeterminacy of theoretical terms* Arises as the meaning of terms can change over time. For instance, this source of uncertainty is particularly relevant to taxonomic terms, which may be subject to revision, leading to changes in the names of species or higher-level groups.

an impact score. In contrast, the species level summarises all the individual records of impact for a particular alien taxon (IUCN 2020a).

Uncertainties relevant at the impact report level

The different types of epistemic and linguistic uncertainty emerge across various stages relevant to an ICAT assessment; first, uncertainties will arise when the impact observation is initially observed and/or measured; second, when the impact is communicated in some form of report and third, when the ICAT assessment is conducted (Figure 1). Any uncertainty that arises at any one stage will continue to be present at all subsequent stages, with uncertainty propagating throughout the process, from the initial impact observation to the final ICAT assessment. Thus, all uncertainties that arise prior to the impact assessment are encapsulated in the subsequent stages (Figure 1). All uncertainties relevant here are included in the *impact report* box of Figure 1.

Uncertainty initially emerges in the form of natural variation, which corresponds to spatial and temporal changes occurring within the study system. An appropriate study design will identify a suitable temporal and spatial scale under which impacts of the alien species can be characterised (Christie et al. 2019).

The next step at which uncertainties emerge is when the impact is observed and measured. Here, four new sources of epistemic uncertainties are identified: measurement error, systematic error, model uncertainty and subjective judgement (Figure 1). Each of these uncertainties may not necessarily be relevant for every impact report as the

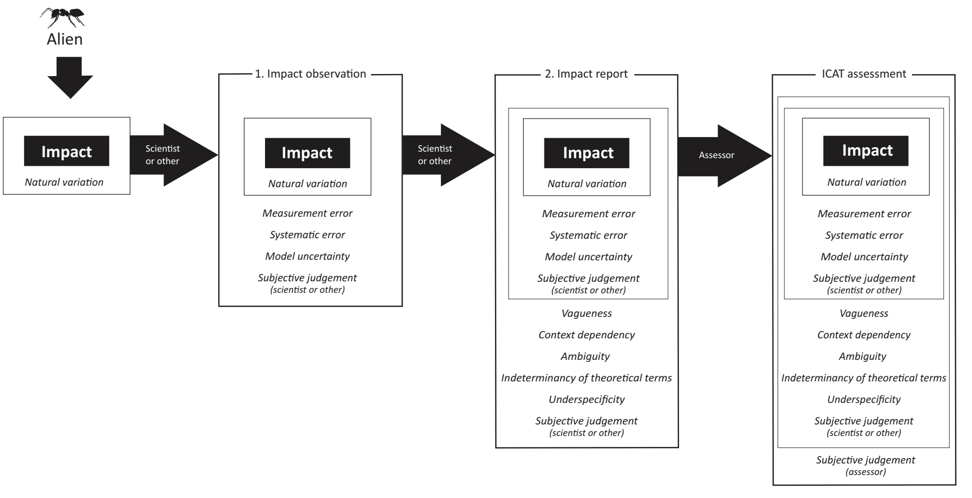


Figure 1. Uncertainties propagate across the process of an impact assessment. The first source of uncertainty emerges due to natural variation associated with the occurrence of an alien species' impact on native biota. Uncertainties arise at three key stages when information on the impact of an alien species is captured 1) the impact observation stage; i.e. when the impact is measured 2) the impact report stage; i.e. when the impact is communicated in some form of report and finally, 3) at the ICAT assessment stage; i.e. when the assessment is conducted. Any uncertainty that arises will be carried through to the subsequent stages, as illustrated through the encapsulation of uncertainties across the process.

ICAT assessments allow the use of different information sources (see Table 3 for the key differences in impact records between EICAT and SEICAT that should be considered). For instance, media reports of a change in local human activities-in response to an alien species-deriving from interviews with residents will not be subject to model uncertainty.

Although currently not directly addressed in the framework guidelines (IUCN 2020a; Hawkins et al. 2015; Bacher et al. 2018), linguistic uncertainties are important for assessors to consider when informing the confidence score. Linguistic uncertainties are of direct relevance for ICAT assessments: they occur when the impact observations, or measurements, are described in a report with imprecise and inconsistent language. Often linguistic uncertainty will be difficult to reduce retrospectively. In some cases, linguistic uncertainty (such as a vaguely described methodology of the impact study) may mask the ability to identify epistemic uncertainties.

The assessment process

Under the published guidelines, assessors are instructed to capture the key sources of epistemic uncertainty for each impact report and ascribe these to one overall level of confidence (IUCN 2020a; Hawkins et al. 2015; Bacher et al. 2018). Following the succession of guidelines, the consideration of uncertainty has been somewhat revised. The most recently-revised EICAT guidelines (IUCN 2020a) identify five major sources of uncertainty that the assessor must consider when assigning a confidence score: i) data quality and type ii) spatial and temporal scale and iii) confounding effects iv) study design and v) overall coherence of evidence. These sources of uncertainty are also relevant for SEICAT; however, given that the currency used to measure impact differs between the two frameworks (native species' populations vs. human activities), interpretation and importance of different uncertainties may vary to fit the criteria and concepts for each framework (Table 3).

When evaluating the magnitude of an impact, the assessor interprets the information contained in the impact report and, when possible, translates this information into one of the five ICAT magnitudes. As impact reports were not aimed at testing the assessment criteria (e.g. which level of organisation of the native population is affected by the alien), the assessor has to interpret the information at hand, a process which inevitably introduces a new source of uncertainty. It may be difficult for ICAT assessors to identify limitations generated by the way the impact was measured and reported. Ideally, authors of an impact study will address limitations with their research; however, ICAT assessors must critically assess all available information (e.g. study design, statistical analyses) to identify potential weakness in the inference of the data. It is at this stage–where the impact measurement is reported—that linguistic uncertainties become relevant and should ideally be recognised by assessors, who should be aware of how language may influence their interpretation of the information.

Assessments will be further compounded by systematic error (i.e. when the assessor systematically decides to include or exclude information that they should otherwise exclude or include) and subjective judgement (Regan et al. 2002). These sources of uncertainty initially become relevant when the assessor conducts a literature review to extract the records of impact for an alien taxon, then decides which fit the framework criteria. For instance, there may be some confusion as to what sources of impact should be included in assessments. Under the EICAT guidelines, impacts are defined as changes to the environment that reduce native biodiversity or alter ecosystem functioning to the detriment of a native species (Hawkins et al. 2015). Therefore, the inclusion of laboratory and mesocosm experiments presents a grey area when considering impact reports. In many cases, such experiments can be informative towards identifying the mechanism(s) through which an alien species impacts on native biodiversity and if native individuals are (potentially) suffering in their performance. However, laboratory and mesocosm studies will always be limited to revealing impacts of MC or MN, given that EICAT measures impacts based on native communities. Therefore, a decline of a natural population or its local extinction cannot be inferred from artificial settings, but such experiments may be useful to provide information about the mechanisms of impact. If assessors include laboratory- or mesocosm-derived sources of information in EICAT assessments, they should be clearly specified as such. Subjective judgement arises due to the interpretation of information; it emerges at the initial impact observation and continues to appear throughout the assessment procedure as each person involved in the process introduces their own form of subjective judgement (Figure 1). An ICAT assessor's subjective judgement is the primary form of uncertainty that we can minimise by clarifying concepts appropriate to assigning confidence scores and improving the consistency amongst assessors when using the two assessment schemes. Subjective judgement is also

Table 3. Major sources of uncertainty are identified in the IUCN (2020a) EICAT guidelines. Each source of uncertainty is relevant to both the EICAT and the SEICAT schemes; assessors must consider each source when assigning confidence scores. The two frameworks differ in their currencies used to measure impact (native populations [EICAT] versus human activities [SEICAT]). Therefore, contextual understanding of how these uncertainties may influence confidence scores is required. We highlight some aspects of how considering uncertainty may differ between EICAT and SEICAT below.

Source of uncertainty	For EICAT	For SEICAT
Presence of confounding effects		
Assessors must consider whether invasive species are drivers or passengers of the recorded impact (MacDougall and Turkington 2005; Bellard et al. 2016; Doherty et al. 2016; Blackburn et al. 2019). Further, they must consider whether there is any evidence for additional driver(s) of change causing the observed effects.	A major challenge in understanding the impacts of alien species is to disentangle the driving causes of biodiversity declines. Studies/reports range from being simple negative correlations between alien and native populations to before-after-control-impact studies, which may influence the data quality and interpretation (Kumschick et al. 2015; Christie et al. 2019). Often, observed correlations between alien species and native biodiversity loss are reported, but the cause of change is not the alien. For instance, the driving cause of change may be habitat modification that facilitates the alien, which works simultaneously to cause a negative impact on native species. An example would be an alien species that establishes and thrives in an urban area may not be the driver of native bird declines; rather, it could be that loss of resources due to urbanisation are causing the native birds to decline.	Alien species altering human activities should be considered in the same way as for EICAT, i.e. the assessor must ask the question "is the alien driving the recorded changes?" However, with SEICAT, given that people can directly communicate the reason for reducing or discontinuing an activity, it may be possible to get a better understanding of the causality behind the recorded impact magnitude with much higher confidence.
Study design		
The ICAT frameworks evaluate the different levels of impact, whereby each step change in a category reflects an increase in the order of magnitude of the particular impact so that a new level of organisation is involved (individuals, population, community). A study/report may describe an impact affecting one organisation level (e.g. performance of the individual), but gives no information of relevance to a higher level (e.g. if the impact reduces the population size). This aspect of uncertainty can be captured by considering the directionality of uncertainty for each impact report.	A study that is designed to assess the impacts of an alien on the individual performance, but does not capture any information about impacts to the population cannot be assigned higher than an MN. This does not mean that the true impact is not higher and thus, the impact report cannot be assigned a high confidence. High confidence scores can be assigned when the criterion of the magnitude higher than the one assigned has been investigated and found to be not true.	Reports relevant for SEICAT may not capture the true level at which the alien is causing an impact. Often, individual people are interviewed to obtain information on the alien's impacts and their experience may not represent the true state of the entire community.

Source of uncertainty	For EICAT	For SEICAT
Data quality and type		
Based on the ICAT guidelines (IUCN 2020a; Hawkins et al. 2015; Bacher et al. 2018), impacts can be classified as either *inferred* or *observed*. Assessors might misinterpret the purpose of this distinction, by considering observational studies as the only studies reporting *observed* impacts (i.e. this presents a form of linguistic uncertainty present in the guidelines). Rather, we assert that assessors should focus only on the quality of the report, given the invasion scenario.	Data used to derive EICAT scores are most frequently sourced from primary (i.e. not secondary referencing) and grey literature.	A decrease in the size of human activity may not be quantified but *inferred* from the evidence. For example, studies of diseases and parasites transmitted by aliens affecting humans will rarely report quantitatively on how they affect activities, although the authors may infer such effects. Data used to derive SEICAT scores are more likely to be anecdotal forms of evidence; personal communications and media reports often contain information of relevance to SEICAT. Although anecdotal evidence may be thought of as lower quality information (Bacher et al. 2018), given people can directly communicate behavioural changes in response to alien species, evidence deriving from such information may reveal the true state of impact. However, as SEICAT uses the change in activity size as the measure of impact, information on how many people participate in the activity and on the local population size, is required for high confidence reports.
Spatial scale		
Understanding if the impact has been recorded at a relevant spatial scale to capture the assigned impact magnitude accurately.	Assessors should ask if the study was conducted on a scale over which native species in the region of interest can be characterised. This requires a basic understanding of what constitutes a local population for a given species. A population can be difficult to delimit given suitable habitat for a species is usually fragmented across a landscape and further, populations are often managed within geopolitical jurisdictions. It may be particularly difficult to discern if an alien taxon causes a decline in population from available data with high confidence. Surveys may make it appear as if the population has declined, when in reality, species that are mobile may avoid areas when an alien species occurs.	The 'focal region' for SEICAT can be highly variable given densities of human communities. Impacts may be assessed on scales ranging from small villages to large metropolitan areas. Therefore, data about the number of people affected (i.e. those that reduce their activity) and the population size across the geographic scale should be included in the assessment when the information is available.

Source of uncertainty	For EICAT	For SEICAT
Temporal scale		
In earlier guidelines, the temporal scale at which the impact was previously recorded was not considered important since the ICAT frameworks assign magnitude, based on the highest impact (Hawkins et al. 2015; Bacher et al. 2018). However, it is important to assess how the "true" impact varies with the temporal scale. Uncertainty at the temporal scale is important in two aspects, whereby the study may not capture a relevant time period to detect maximum impact or the study provides an inaccurate snapshot that is not reflective of impact; for instance, the study focused on one season or was just too short to be able to capture any change.	Changes in native population size may be limited to only a short period (e.g. seasonally), which generally has little effect on reducing the overall population size. Assessors should consider that the impact report may provide only a snapshot in time and determine how relevant the impact is at a suitable temporal scale.	The same issues relating to temporal scale for EICAT are relevant for SEICAT.
Coherence of evidence		
At the individual impact report level, assessors must determine whether all the evidence points towards the same direction or whether evidence may be contradictory or ambiguous.	A study relevant for EICAT may present conflicting evidence based on different variables measured to determine impact. For instance, a study measuring more than one physiological variable of a native species in response to an alien may indicate both negative and positive effects (e.g. a reduction in height of plant growth but increase in leaf area size).	There may be conflicting reports from individuals as to whether an alien species is causing reductions in activity size.

relevant to uncertainties when summarising impacts at the species level (see below). Additionally, it must be considered how the written synthesis of ICAT assessments and the justifications of classifications may propagate linguistic uncertainty further.

Directionality of uncertainty

Uncertainty in impact assessments means that the true impact can be higher or lower than the one assigned. However, assessors may be confident that an impact magnitude is not lower than the one assigned, but could be higher (or vice versa). Thus, uncertainty can be asymmetrically distributed around the assessment value; it may be larger in one direction than in the other. This directionality aspect of uncertainty is currently not captured using the confidence scores, yet may provide important insight to impacts. Using EICAT as an example, it may be that the assessor assigns a minor impact score (MN) to an impact record that robustly demonstrates that an alien taxon affects the performance of individuals of a native species and, thus, is not negligible (i.e. not MC). However, given the study did not address (i.e. measure) whether the impact is causing a decline in the local population, it is not possible to know whether the 'true' impact caused by the alien taxon is higher (MO, MR or MV). For instance, studies that assess physiological responses of native species to invasive species do not necessarily relate such effects beyond the individual (i.e. effects on fitness resulting in declining populations) (Graham et al. 2012). Such cases are quite distinct to impact records that sought to quantify population responses to an alien species, yet found no evidence in support of population decline. Since documenting directionality in uncertainty related to each impact record may improve our overall understanding of potential impacts, this information may be particularly useful once several records of impact are obtained for a single species. Directionality in uncertainty, therefore, presents an important facet of uncertainty to recognise when using the ICAT schemes.

Uncertainties relevant at the species level

Presently, there is no consideration of uncertainty beyond the confidence score assigned to each impact report (IUCN 2020a; Hawkins et al. 2015; Bacher et al. 2018). The ICAT assessment schemes adopt the precautionary principle, whereby the overall classification of an alien taxon is based on the highest magnitude the taxon has reached. Therefore, there is no distinction between species with the same highest impact magnitude, regardless of whether there are few or many accounts of impact. It is also important to acknowledge additional sources of uncertainty which influence the ability to conduct assessments for alien taxa. As these uncertainties occur beyond the individual impact report level, they are not captured by the confidence score as currently described. Uncertainties due to the biases in the collected and the existing (or produced) impact reports contribute to the quality of final assessments, making them of direct relevance when comparing taxa based on ICAT scores. If alien taxa are compared, based on the highest magnitude they have been observed to cause (Hawkins et al. 2015; Bacher et al. 2018), it is pertinent that their highest impact magnitude caused in nature is documented and that these data have been adequately collected and assessed using the ICAT frameworks. It is likely that the more impact reports for an alien species that are produced, collected and assessed, the higher the chance that the maximum impact of the alien taxon will be detected and correctly classified. We recognise three important aspects to evaluate when looking at species-level comparisons: biases in existing data, data collection and data assessment.

Biases in the existing data

The availability of impact records will vary widely within (Evans et al. 2018b) and between taxa (Vilà et al. 2010) and will not necessarily be reflective of impact severity (Evans and Blackburn 2019). Indeed, of the larger taxonomic groups that have been assessed (amphibians, bamboos, birds), the majority of species are classified as data deficient (Evans et al. 2016; Kumschick et al. 2017; Canavan et al. 2019). As biases in biological records (Isaac and Pocock 2015) and within invasion biology are evident (Pyšek et al. 2008), some taxa will be disproportionately represented when conducting literature searches necessary for ICAT assessments. Gaps may be driven by funding availability with regions associated with higher economic status investing more in invasive species research (Pyšek et al. 2008; Bellard and Jeschke 2016). Further, it is usual for a lag time between an alien species becoming established and research effort on the species in the new environment to be observed (Essl et al. 2015; Lyons et al. 2019). Due to this and other reasons, such as the nature and duration of the peer-review process, the dissemination of impacts reports is often delayed (Vilà et al. 2019). Even well-studied species may not have impacts measured that can be easily transferred to ICAT scores, potentially rendering it data deficient or with few reports from which to derive an impact magnitude. For instance, alien species may be well documented to impact via various mechanisms (e.g. predation, competition) under laboratory settings, but poorly represented under natural conditions. Often, biological aspects, related to mechanisms of impact, are well-researched (e.g. dietary overlap, aggressive behaviour) for alien species, but the effects on native biodiversity are not measured, rendering such studies irrelevant to EICAT assessments. Our main suggestion regarding the bias in–or lack of–existing and relevant impact data, is to adapt future impact reports to EICAT criteria: studies should focus more on the changes in the impacted native populations (in natural conditions) and less on the alien populations.

Biases in the data collection

Inconsistencies amongst assessors may be driven from the initial stage of data collection (the literature review), with variation attributed to different search strategies employed by individual assessors (Kumschick et al. 2017). Reproducibility in science is a major topic of discussion (Baker 2016; Fanelli 2018) and how systematic literature searches are conducted is often poorly detailed leading to non-reproducible results (Cooper et al. 2018; Faggion and Diaz 2019). Assessors should be specific on how they conduct their literature searches to promote transparency, which in turn, will facilitate more robust inter-specific comparisons if data requires additional reviewing. Furthermore, documentation of the sources used to score species and the final data for assessments should be published with studies using the assessment schemes (see also Kumschick et al. 2020). Another major difficulty in data accessibility may arise from language barriers that affect the assessor's ability to collate impact reports. This is likely to be particularly applicable for SEICAT assessments, where it is expected that relevant reports of impacts on human well-being will, more often, be published in local languages. Discussions with people in local languages to identify socio-economic issues arising from the presence of alien species may facilitate assessments of species that are otherwise data deficient and help better understand additional human dimensions of biological invasions. Much regional evidence on the impacts of alien species will be confined to sources of information, such as local government reports and student theses.

Biases in the data assessment

Additional inconsistencies amongst assessors may occur because the criteria of the ICAT frameworks are interpreted and applied differently; individual assessors will inevitably introduce their own level of bias to the process of both assigning impact categories and confidence scores. A recent study by González-Moreno et al. (2019) found variation in scoring species' impacts amongst assessors for different assessment schemes, including EICAT. Although a level of subjectivity is inevitable, some of this uncertainty may be reduced through improvement in the protocol, such as the refinement of guidelines, which is already reflected in the succession of EICAT guidelines (Blackburn et al. 2014; Hawkins et al. 2015; IUCN 2020a). However, clarification about the changes and ensuring these are effectively communicated will be important to maximise consistency (see Volery et al. 2020, as the application of different versions of the guidelines may further lead to inconsistencies across different assessments. Conducting workshops, training sessions and developing online tools that help guide assessors through the process–giving examples where uncertainty is most likely to arise–might help reduce these uncertainties. Refinements can be made as feedback from assessors identifies more issues that require additional explanation or adaptation.

It is worth noting that, given the variation observed amongst assessors when applying scoring schemes (Matthews et al. 2017; González-Moreno et al. 2019), confidence scores are likely to be subject to a similar level of inconsistency. The accompanying probabilities (Table 1) to each of the three qualitative confidence scores are intended to reduce variation in the interpretation of terms. Indeed, differences in the interpretation of the descriptions of uncertainty are known to occur amongst individuals (Budescu and Wallsten 1985). Presenting linguistic descriptions and corresponding likelihoods can, therefore, reduce the misinterpretation of confidence scoring (Budescu et al. 2014). The degree of consistency amongst assessors when assigning confidence scores should be examined to determine whether refining the expressions of confidence is necessary to reduce potential misinterpretation.

Conclusions

To produce robust impact assessments and facilitate the comparison of impacts between taxa, procedures must adequately account for uncertainties (McGeoch et al. 2012). We have highlighted key sources of uncertainty to consider when conducting the ICAT assessments and emphasised the importance of acknowledging all forms of uncertainty even when not directly relevant to informing confidence scores. As uncertainties propagate throughout the various stages of any ICAT assessment (deriving from both the impact measurer/reporter and the ICAT assessor), it is important that they are clearly defined and acknowledged to improve the overall impact assessment procedure. However, it should be noted that it will be impossible to address all types of uncertainty in any framework due to unforeseeable changes in the system under investigation or other unknown unknowns.

As the ICAT frameworks become more readily applied across different taxonomic groups, uncertainties must be appropriately considered to improve the overall ability to correctly classify impacts. By improving the consideration of uncertainty under the ICAT guidelines, we may increase the functionality of the tool for researchers and practitioners. All other things being equal (i.e. control effort, cultural values, positive impacts etc.), species that will be the best candidates for prioritisation will be those that have the highest impact with high corresponding confidence.

Acknowledgements

This paper emerged from a workshop on ‘Frameworks used in Invasion Science’ hosted by the DSI-NRF Centre of Excellence for Invasion Biology in Stellenbosch, South Africa, 11–13 November 2019, that was supported by the National Research Foundation of South Africa and Stellenbosch University. We thank Khensani Nkuna, Susan Canavan, Bianca Hagen and David Kesner for useful discussions on uncertainty. SK acknowledges the support of the DSI-NRF Centre of Excellence for Invasion Biology (CIB) and Stellenbosch University and the South African Department of Forestry, Fisheries and the Environment (DFFtE) nothing that this publication does not necessarily represent the views or opinions of DFFtE or its employees. AFP, LV, GV and SB acknowledge funding from the Swiss National Science Foundation (grant numbers 31003A_179491 and 31BD30_184114) and the Belmont Forum – BiodivERsA International joint call project InvasiBES (PCI2018-092939). We are thankful to Jodie Peyton and Sandro Bertolino for their helpful comments in improving the manuscript.

References

Ascher WL (2004) Scientific information and uncertainty: Challenges for the use of science in policymaking. Science and Engineering Ethics 10: 437–455. https://doi.org/10.1007/s11948-004-0002-z

Bacher S, Blackburn TM, Essl F, Genovesi P, Heikkilä J, Jeschke JM, Jones G, Keller R, Kenis M, Kueffer C, Martinou AF, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Roy HE, Saul W-C, Scalera R, Vilà M, Wilson JRU, Kumschick S (2018) Socio-economic impact classification of alien taxa (SEICAT). Methods in Ecology and Evolution 9: 159–168. https://doi.org/10.1111/2041-210X.12844

Baker M (2016) 1,500 scientists lift the lid on reproducibility. Nature 533: 452–454. https://doi.org/10.1038/533452a

Bellard C, Jeschke JM (2016) A spatial mismatch between invader impacts and research publications. Conservation Biology 30: 230–232. https://doi.org/10.1111/cobi.12611

Bellard C, Cassey P, Blackburn TM (2016) Alien species as a driver of recent extinctions. Biology Letters 12. https://doi.org/10.1098/rsbl.2015.0623

Blackburn TM, Bellard C, Ricciardi A (2019) Alien versus native species as drivers of recent extinctions. Frontiers in Ecology and the Environment 17: 203–207. https://doi.org/10.1002/fee.2020

Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JRU, Richardson DM (2011) A proposed unified framework for biological invasions. Trends in Ecology & Evolution 26: 333–339. https://doi.org/10.1016/j.tree.2011.03.023

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Mrugala A, Nentwig W, Pergl J, Pysek P, Rabitsch W, Ricciardi A, Richardson D, Sendek A, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLoS Biology 12: e1001850. https://doi.org/10.1371/journal.pbio.1001850

van der Bles AM, Freeman ALJ, Mitchell J, Galvao AB, Zaval L, Spiegelhalter DJ (2019) Communicating uncertainty about facts, numbers and science. Royal Society Open Science 6: 181870. https://doi.org/10.1098/rsos.181870

Bremner A, Park K (2007) Public attitudes to the management of invasive non-native species in Scotland. Biological Conservation 139: 306–314. https://doi.org/10.1016/j.biocon.2007.07.005

Budescu DV, Wallsten TS (1985) Consistency in interpretation of probabilistic phrases. Organizational Behavior and Human Decision Processes 36: 391–405. https://doi.org/10.1016/0749-5978(85)90007-X

Budescu DV, Por H-H, Broomell SB, Smithson M (2014) The interpretation of IPCC probabilistic statements around the world. Nature Climate Change 4: 508–512. https://doi.org/10.1038/nclimate2194

Canavan S, Kumschick S, Roux JJL, Richardson DM, Wilson JRU (2019) Does origin determine environmental impacts? Not for bamboos. Plants, people, planet 1: 119–128. https://doi.org/10.1002/ppp3.5

Christie AP, Amano T, Martin PA, Shackelford GE, Simmons BI, Sutherland WJ (2019) Simple study designs in ecology produce inaccurate estimates of biodiversity responses. Journal of Applied Ecology 56: 2742–2754. https://doi.org/10.1111/1365-2664.13499

Colautti RI, MacIsaac HJ (2004) A neutral terminology to define "invasive" species. Diversity and Distributions 10: 135–141. https://doi.org/10.1111/j.1366-9516.2004.00061.x

Cooper C, Booth A, Varley-Campbell J, Britten N, Garside R (2018) Defining the process to literature searching in systematic reviews: a literature review of guidance and supporting studies. BMC Medical Research Methodology 18: 1–85. https://doi.org/10.1186/s12874-018-0545-3

Courchamp F, Fournier A, Bellard C, Bertelsmeier C, Bonnaud E, Jeschke JM, Russell JC (2017) Invasion Biology: Specific Problems and Possible Solutions. Trends in Ecology & Evolution 32: 13–22. https://doi.org/10.1016/j.tree.2016.11.001

Doherty TS, Glen AS, Nimmo DG, Ritchie EG, Dickman CR (2016) Invasive predators and global biodiversity loss. Proceedings of the National Academy of Sciences 113: 11261–11265. https://doi.org/10.1073/pnas.1602480113

Essl F, Dullinger S, Rabitsch W, Hulme PE, Pyšek P, Wilson JRU, Richardson DM (2015) Historical legacies accumulate to shape future biodiversity in an era of rapid global change. Diversity and Distributions 21: 534–547. https://doi.org/10.1111/ddi.12312

Evans T, Blackburn TM (2019) Global variation in the availability of data on the environmental impacts of alien birds. Biological Invasions 22: 1027–1036. https://doi.org/10.1007/s10530-019-02153-z

Evans T, Blackburn TM, Jeschke JM, Probert AF, Bacher S (2020) Application of the Socio-Economic Impact Classification for Alien Taxa (SEICAT) to a global assessment of alien bird impacts. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 123–142. https://doi.org/10.3897/neobiota.62.51150

Evans T, Kumschick S, Blackburn TM (2016) Application of the Environmental Impact Classification for Alien Taxa (EICAT) to a global assessment of alien bird impacts. Diversity and Distributions 22: 919–931. https://doi.org/10.1111/ddi.12464

Evans T, Kumschick S, Şekercioğlu ÇH, Blackburn TM (2018a) Identifying the factors that determine the severity and type of alien bird impacts. Diversity and Distributions 24: 800–810. https://doi.org/10.1111/ddi.12721

Evans T, Pigot A, Kumschick S, Şekercioğlu ÇH, Blackburn TM (2018b) Determinants of data deficiency in the impacts of alien bird species. Ecography 41: 1401–1410. https://doi.org/10.1111/ecog.03232

Faggion CM, Diaz KT (2019) Overview authors rarely defined systematic reviews that are included in their overviews. Journal of Clinical Epidemiology 109: 70–79. https://doi.org/10.1016/j.jclinepi.2019.01.004

Fanelli D (2018) Opinion: Is science really facing a reproducibility crisis, and do we need it to? Proceedings of the National Academy of Sciences 115: 2628–2631. https://doi.org/10.1073/pnas.1708272114

Fischhoff B, Davis AL (2014) Communicating scientific uncertainty. Proceedings of the National Academy of Sciences 111: 13664–13671. https://doi.org/10.1073/pnas.1317504111

Galanidi M, Zenetos A, Bacher S (2018) Assessing the socio-economic impacts of priority marine invasive fishes in the Mediterranean with the newly proposed SEICAT methodology. Mediterranean Marine Science 19: 107–123. https://doi.org/10.12681/mms.15940

González-Moreno P, Lazzaro L, Vilà M, Preda C, Adriaens T, Bacher S, Brundu G, Copp GH, Essl F, García-Berthou E, Katsanevakis S, Moen TL, Lucy FE, Nentwig W, Roy HE, Srėbalienė G, Talgø V, Vanderhoeven S, Andjelković A, Arbačiauskas K, Auger-Rozenberg M-A, Bae M-J, Bariche M, Boets P, Boieiro M, Borges PA, Canning-Clode J, Cardigos F, Chartosia N, Cottier-Cook EJ, Crocetta F, D'hondt B, Foggi B, Follak S, Gallardo B, Gammelmo Ø, Giakoumi S, Giuliani C, Guillaume F, Jelaska LŠ, Jeschke JM, Jover M, Juárez-Escario A, Kalogirou S, Kočić A, Kytinou E, Laverty C, Lozano V, Maceda-Veiga A, Marchante E, Marchante H, Martinou AF, Meyer S, Minchin D, Montero-Castaño A, Morais MC, Morales-Rodriguez C, Muhthassim N, Nagy ZÁ, Ogris N, Onen H, Pergl J, Puntila R, Rabitsch W, Ramburn TT, Rego C, Reichenbach F, Romeralo C, Saul W-C, Schrader G, Sheehan R, Simonović P, Skolka M, Soares AO, Sundheim L, Tarkan AS, Tomov R, Tricarico E, Tsiamis K, Uludağ A, van Valkenburg J, Verreycken H, Vettraino AM, Vilar L, Wiig Ø, Witzell J, Zanetta A, Kenis M (2019) Consistency of impact assessment protocols for non-native species. NeoBiota 44: 1–25. https://doi.org/10.3897/neobiota.44.31650

Graham SP, Freidenfelds NA, McCormick GL, Langkilde T (2012) The impacts of invaders: Basal and acute stress glucocorticoid profiles and immune function in native lizards threatened by invasive ants. General and Comparative Endocrinology 176: 400–408. https://doi.org/10.1016/j.ygcen.2011.12.027

Hagen BL, Kumschick S (2018) The relevance of using various scoring schemes revealed by an impact assessment of feral mammals. NeoBiota 38: 37–75. https://doi.org/10.3897/neobiota.38.23509

Hawkins CL, Bacher S, Essl F, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Vilà M, Wilson JRU, Genovesi P, Blackburn TM (2015) Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). Diversity and Distributions 21: 1360–1363. https://doi.org/10.1111/ddi.12379

Holt J, Leach AW, Knight JD, Griessinger D, MacLeod A, Gaag DJ van der, Schrader G, Mumford JD (2012) Tools for visualizing and integrating pest risk assessment ratings and uncertainties. EPPO Bulletin 42: 35–41. https://doi.org/10.1111/j.1365-2338.2012.02548.x

Isaac NJB, Pocock MJO (2015) Bias and information in biological records. Biological Journal of the Linnean Society 115: 522–531. https://doi.org/10.1111/bij.12532

IUCN (2020a) Guidelines for using the IUCN Environmental Impact Classification for Alien Taxa (EICAT) Categories and Criteria. Version 1.1, Gland, Switzerland: IUCN.

IUCN (2020b) IUCN EICAT Categories and Criteria. The Environmental Impact Classification for Alien Taxa, First edition. Gland, Switzerland and Cambridge, UK. https://doi.org/10.2305/IUCN.CH.2020.05.en

IUCN (2012) IUCN Red list Catergories and Criteria: version 3.1. Second edition. Gland: IUCN. www.iucnredlist.org/technical-documents/categories-and-criteria

Kenis M, Bacher S, Baker RHA, Branquart E, Brunel S, Holt J, Hulme PE, MacLeod A, Pergl J, Petter F, Pyšek P, Schrader G, Sissons A, Starfinger U, Schaffner U (2012) New protocols to assess the environmental impact of pests in the EPPO decision-support scheme for pest risk analysis*. EPPO Bulletin 42: 21–27. https://doi.org/10.1111/j.1365-2338.2012.02527.x

Kesner D, Kumschick S (2018) Gastropods alien to South Africa cause severe environmental harm in their global alien ranges across habitats. Ecology and Evolution 8: 8273–8285. https://doi.org/10.1002/ece3.4385

Kraus F, Duffy DC (2010) A successful model from Hawaii for rapid response to invasive species. Journal for Nature Conservation 18: 135–141. https://doi.org/10.1016/j.jnc.2009.07.001

Kumschick S, Bacher S, Bertolino S, Blackburn TM, Evans T, Roy HE, Smith K (2020) Appropriate uses of EICAT protocol, data and classifications. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 193–212. https://doi.org/10.3897/neobiota.62.51574

Kumschick S, Measey GJ, Vimercati G, Villiers FA de, Mokhatla MM, Davies SJ, Thorp CJ, Rebelo AD, Blackburn TM, Kraus F (2017) How repeatable is the Environmental Impact Classification of Alien Taxa (EICAT)? Comparing independent global impact assessments of amphibians. Ecology and Evolution 7: 2661–2670. https://doi.org/10.1002/ece3.2877

Kumschick S, Gaertner M, Vila M, Essl F, Jeschke JM, Pyšek P, Ricciardi A, Bacher S, Blackburn TM, Dick JTA, Evans T, Hulme PE, Kuhn I, Mrugała A, Pergl J, Rabitsch W, Richardson DM, Sendek A, Winter M (2015) Ecological impacts of alien species: quantification, scope, caveats, and recommendations. BioScience 65: 55–63. https://doi.org/10.1093/biosci/biu193

Latombe G, Canavan S, Hirsch H, Hui C, Kumschick S, Nsikani MM, Potgieter LJ, Robinson TB, Saul W-C, Turner SC, Wilson JRU, Yannelli FA, Richardson DM (2019) A four-component classification of uncertainties in biological invasions: implications for management. Ecosphere 10: e02669. https://doi.org/10.1002/ecs2.2669

Liu S, Sheppard A, Kriticos D, Cook D (2011) Incorporating uncertainty and social values in managing invasive alien species: a deliberative multi-criteria evaluation approach. Biological Invasions 13: 2323–2337. https://doi.org/10.1007/s10530-011-0045-4

Lyons TJ, Tuckett QM, Hill JE (2019) Data quality and quantity for invasive species: A case study of the lionfishes. Fish and Fisheries 20: 748–759. https://doi.org/10.1111/faf.12374

MacDougall AS, Turkington R (2005) Are invasive species the drivers or passengers of change in degraded ecosystems? Ecology 86: 42–55. https://doi.org/10.1890/04-0669

Mastrandrea MD, Field CB, Stocker TF, Edenhofer O, Ebi KL, Frame DJ, Held H, Kriegler E, Mach KJ, Matschoss PR, Plattner G-K, Yohe GW, Zwiers FW (2010) Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change, 7 pp.

Matthews J, Velde G van der, Collas FPL, Hoop L de, Koopman KR, Hendriks AJ, Leuven RSEW (2017) Inconsistencies in the risk classification of alien species and implications for risk assessment in the European Union. Ecosphere 8: e01832. https://doi.org/10.1002/ecs2.1832

McGeoch MA, Spear D, Kleynhans EJ, Marais E (2012) Uncertainty in invasive alien species listing. Ecological Applications 22: 959–971. https://doi.org/10.1890/11-1252.1

Nentwig W, Kühnel E, Bacher S (2010) A generic impact-scoring system applied to alien mammals in Europe. Conservation Biology 24: 302–311. https://doi.org/10.1111/j.1523-1739.2009.01289.x

Nentwig W, Bacher S, Pyšek P, Vilà M, Kumschick S (2016) The generic impact scoring system (GISS): a standardized tool to quantify the impacts of alien species. Environmental Monitoring and Assessment 188: 1–315. https://doi.org/10.1007/s10661-016-5321-4

Novoa A, Dehnen-Schmutz K, Fried J, Vimercati G (2017) Does public awareness increase support for invasive species management? Promising evidence across taxa and landscape types. Biological Invasions 19: 3691–3705. https://doi.org/10.1007/s10530-017-1592-0

Pejchar L, Mooney HA (2009) Invasive species, ecosystem services and human well-being. Trends in Ecology & Evolution 24: 497–504. https://doi.org/10.1016/j.tree.2009.03.016

Pyšek P, Richardson DM, Pergl J, Jarošík V, Sixtová Z, Weber E (2008) Geographical and taxonomic biases in invasion ecology. Trends in Ecology & Evolution 23: 237–244. https://doi.org/10.1016/j.tree.2008.02.002

Regan HM, Colyvan M, Burgman MA (2002) A taxonomy and treatment of uncertainty for ecology and conservation biology. Ecological Applications 12: 618–628. https://doi.org/10.2307/3060967

Richardson DM, Pyšek P, Carlton JT (2010) A compendium of essential concepts and terminology in invasion ecology. Fifty Years of Invasion Ecology. Wiley-Blackwell, 409–420. https://doi.org/10.1002/9781444329988.ch30

Russell JC, Stanley MC (2018) An overview of introduced predator management in inhabited landscapes. Pacific Conservation Biology 24: 371–378. https://doi.org/10.1071/PC18013

Strayer DL, Eviner VT, Jeschke JM, Pace ML (2006) Understanding the long-term effects of species invasions. Trends in Ecology & Evolution 21: 645–651. https://doi.org/10.1016/j.tree.2006.07.007

Todd CR, Burgman MA (1998) Assessment of threat and conservation priorities under realistic levels of uncertainty and reliability. Conservation Biology 12: 966–974. https://doi.org/10.1046/j.1523-1739.1998.96470.x

Vilà M, Gallardo B, Preda C, García-Berthou E, Essl F, Kenis M, Roy HE, González-Moreno P (2019) A review of impact assessment protocols of non-native plants. Biological Invasions 21: 709–723. https://doi.org/10.1007/s10530-018-1872-3

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. Ecology Letters 14: 702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

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

Volery L, Blackburn TM, Bertolino S, Evans T, Genovesi P, Kumschick S, Roy HE, Smith KG, Bacher S (2020) Improving the Environmental Impact Classification for Alien Taxa (EICAT): a summary of revisions to the framework and guidelines. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 547–567. https://doi.org/10.3897/neobiota.62.52723

Wilson JRU, Datta A, Hirsch H, Keet J-H, Mbobo T, Nkuna KV, Nsikani MM, Pyšek P, Richardson DM, Zengeya TA, Kumschick S (2020) Is invasion science moving towards agreed standards? The influence of selected frameworks. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 569–589. https://doi.org/10.3897/neobiota.62.53243

NeoBiota 62: 525–545 (2020)
doi: 10.3897/neobiota.62.52793
http://neobiota.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

The importance of assessing positive and beneficial impacts of alien species

Giovanni Vimercati[1], Sabrina Kumschick[2,3], Anna F. Probert[1], Lara Volery[1], Sven Bacher[1]

1 *Department of Biology, Unit Ecology & Evolution, University of Fribourg, Chemin du Musée 10, 1700 Fribourg, Switzerland* **2** *Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Matieland 7602, South Africa* **3** *South African National Biodiversity Institute, Kirstenbosch Research Centre, Cape Town, South Africa*

Corresponding author: Giovanni Vimercati (gvimercati@outlook.com)

Academic editor: Q. J. Groom | Received 1 April 2020 | Accepted 2 September 2020 | Published 15 October 2020

Citation: Vimercati G, Kumschick S, Probert AF, Volery L, Bacher S (2020) The importance of assessing positive and beneficial impacts of alien species. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 525–545. https://doi.org/10.3897/neobiota.62.52793

Abstract

Extensive literature is available on the diversity and magnitude of impacts that alien species cause on recipient systems. Alien species may decrease or increase attributes of ecosystems (e.g. total biomass or species diversity), thus causing negative and positive environmental impacts. Alien species may also negatively or positively impact attributes linked to local human communities (e.g. the number of people involved in a given activity). Ethical and societal values contribute to define these environmental and socio-economic impacts as deleterious or beneficial. Whilst most of the literature focuses on the deleterious effects of alien taxa, some recognise their beneficial impacts on ecosystems and human activities. Impact assessment frameworks show a similar tendency to evaluate mainly deleterious impacts: only relatively few, and not widely applied, frameworks incorporate the beneficial impacts of alien species. Here, we provide a summary of the frameworks assessing beneficial impacts and briefly discuss why they might have been less frequently cited and applied than frameworks assessing exclusively deleterious impacts. Then, we review arguments that invoke a greater consideration of positive and beneficial impacts caused by alien species across the invasion science literature. We collate and describe arguments from a set of 47 papers, grouping them in two categories (value-free and value-laden), which span from a theoretical, basic science perspective to an applied science perspective. We also provide example cases associated with each argument. We advocate that the development of transparent and evidence-based frameworks assessing positive and beneficial impacts might advance our scientific understanding of impact dynamics and better inform management and prioritisation decisions. We also advise that this development should be achieved by recognising the underlying ethical and societal values of the frameworks and their intrinsic limitations. The evaluation of positive and beneficial impacts through impact assessment frameworks should not be seen as an attempt to outweigh or to discount deleterious impacts of alien taxa but rather as an opportunity to provide additional information for scientists, managers and policymakers.

Keywords
Biological invasions, environmental impacts, human well-being, impact assessment frameworks, nature conservation, prioritisation, socio-economic impacts

Introduction

The number of species which are introduced beyond their native ranges (i.e. alien species) continues to rise among geographic regions and taxonomic groups (Essl et al. 2011; Seebens et al. 2017). A vast literature is now available on the variety and magnitude of impacts (here defined as measurable changes as in Ricciardi et al. 2013) that alien species cause in native biodiversity and human well-being (Pimentel et al. 2001; Mazza et al. 2014; Shackleton et al. 2019a). Alien species may decrease and/or increase attributes of their recipient ecosystem (e.g. total biomass or species diversity), thus causing negative and positive environmental impacts. Alien species may also negatively and/or positively impact attributes linked to humans (e.g. the number or income of people involved in a given activity). Ethical and societal values, for instance, associated with nature conservation and human well-being, define whether these environmental and socio-economic impacts are perceived as deleterious or beneficial (Kumschick et al. 2012; Shackleton et al. 2019b). The majority of studies in the field of invasion science have focused on deleterious impacts only (Goodenough 2010; Guerin et al. 2018). The general focus on the deleterious effects of alien species has been motivated by the necessity and urgency to study the serious consequences that some have on native communities and human activities (Richardson et al. 2000; Pyšek et al. 2008; Guerin et al. 2018). The research focus on deleterious impacts has resulted in detailed descriptions of the mechanisms through which alien animals, plants and pathogens may damage recipient ecological and socio-economic systems (Vilà et al. 2010; Ricciardi et al. 2013; Blackburn et al. 2014; Vaz et al. 2017; Bacher et al. 2018). Such knowledge has been used to prioritise the most deleterious alien species and adopt management countermeasures (Oreska and Aldridge 2011; McGeoch et al. 2016; Roy et al. 2017). However, sustained attention on deleterious impacts could have led to an unwarranted disregard for their beneficial impacts, thus resulting in a simplified, if not misleading, understanding of impact dynamics (Goodenough 2010; Boltovskoy et al. 2018). As a result, there has been some disagreement over the use of terminology and the interpretation of data among invasion scientists (Boltovskoy et al. 2018). Guerin et al. (2018), for example, suggested that meta-analyses quantifying the impact of alien species might not be fully objective, as these studies are often characterised by selection bias toward highly deleterious taxa (but see also Kuebbing and Nuñez 2018, who argued that potential publication biases do not necessarily invalidate findings). Another potential consequence is the risk of implementing controversial management policies: management decisions based only on deleterious impacts ignore the fact that there might be conflicts of interest among stakeholders (Zengeya et al. 2017; Potgieter et al. 2019a; Kumschick et al. 2020a).

The general tendency to focus mainly on the deleterious impacts of alien taxa can also be observed in the impact assessment frameworks developed over the last decades. These frameworks adopt science-based approaches to estimate impact magnitude, describe mechanisms underlying impacts and facilitate comparisons across different taxonomic groups and geographic regions. However, only a subset of these impact assessment frameworks evaluate beneficial impacts. Of nine impact assessment frameworks developed in the last two decades, only three frameworks include strategies to incorporate beneficial impacts of alien species into the impact assessment process (Table 1). Frameworks focusing exclusively on deleterious impacts have been cited more often than those incorporating beneficial impacts, which may indicate that the latter are relatively less applied in the scientific community. Although we acknowledge that using the number of citations as a proxy for frequency of application might not always be appropriate, we found that this index reflects well with how often the different frameworks have been applied.

The conceptual framework proposed by Kumschick et al. (2012) uses a bidirectional ranking scale to estimate socio-economic and environmental impacts of alien taxa. In such a scheme, negative and positive socio-economic impacts mirror each other, with the former describing decreases in a measured variable that is relevant to humans (such as forestry and animal production) and the latter describing increases of the same variable. Environmental benefits, on the contrary, are evaluated by assessing the capacity of alien taxa to modify the ecosystem towards a hypothesised historical functional state. Despite the novel approach and insights provided, this framework is less frequently cited (Table 1), and applied than other schemes that exclusively assess negative impacts such as GISS (Generic Impact Scoring System, Nentwig et al. 2016) and EICAT (Environmental Impact Classification for Alien Taxa, Blackburn et al. 2014). This relatively low number of citations can be due to a variety of factors, including the high structural complexity of the framework, which requires to weigh impacts according to their importance for various stakeholders, or the successive development of other, more detailed, impact assessment frameworks such as EICAT. The framework proposed by Katsanevakis et al. (2014) describes multiple mechanisms by which marine alien species affect biodiversity (e.g. by habitat engineering) and ecosystem services (e.g. by ocean nourishment), both beneficially and deleteriously. Although the impact magnitude was not considered (i.e. local-, small-, and large-scale impacts were all treated equally) such a framework allowed the screening of a high number of marine species (87), finding most (67) cause both deleterious and beneficial impacts. Although the framework is highly cited within the scientific community (Table 1), most of the citations arise because of the large documentation on impact variation of alien species in the European seas. On the contrary, the same framework has been very rarely applied to assess deleterious and beneficial impacts of

Table 1. List of impact assessment frameworks which assess environmental and/or socio-economic impacts developed in the last 30 years. The list has been compiled following Roy et al. 2007, Bartz and Kowarik 2019, Srebaliene et al. 2019, Strubbe et al. 2019 and Vilà et al. 2019. The total number of citations per article corrected by year has been obtained from Google Scholar in June 2020.

General name	Target spatial area	Target taxa	References	Explicit assessment of beneficial impacts	Type of impact (E = Environmental, SE = Socio-Economic)	Number of citations / year (total number of citations)
Invasive species assessment protocol: evaluating non-native plants for their impact on biodiversity	USA	Plants	Morse et al. (2004)	No	E	2.6 (42)
Biopollution assessment scheme	Baltic Sea	Aquatic taxa	Olenin et al. (2007)	No	E	16.2 (211)
Conceptual framework for prioritisation of invasive alien species for management according to their impact	Global	Generic	Kumschick et al. (2012)	Yes	E /SE	14.1 (113)
Generic ecological impact assessments of alien species in Norway	Norway	Generic	Sandvik et al. (2013)	No	E	5.9 (41)
Review of impacts of invasive alien marine species on ecosystem services and biodiversity	Europe	Marine taxa	Katsanevakis et al. (2014)	Yes	E / SE	55.3 (332)
EICAT (Environmental Impact Classification for Alien Taxa)	Global	Generic	Blackburn et al. (2014), Hawkins et al. (2015)	No	E	81.2 (487)
GISS (Generic Impact Scoring System)	Europe	Generic	Nentwig et al. (2016)	No	E / SE	16.8 (67)
SEICAT (Socio-Economic Impact Classification of Alien Taxa)	Global	Generic	Bacher et al. (2018)	No	SE	39.5 (79)
InSEAT (INvasive Species Effects Assessment Tool)	Global	Generic	Martinez-Cillero et al. (2019)	Yes	E / SE	4 (4)

alien species on other ecosystems or geographic areas. The INSEAT framework (INvasive Species Effects Assessment Tool) developed by Martinez-Cillero et al. (2019) adopts a bidirectional scoring system to quantify ecosystem service gains and losses caused by alien species. To date, the INSEAT scheme has been tested on 18 alien species in Great Britain (Martinez-Cillero et al. 2019). The renewed attention paid toward ecosystem services and disservices linked to alien species (Vaz et al. 2017; Vilà and Hulme 2017; Potgieter et al. 2019b; Shackleton et al. 2019a; Milanović et al. 2020) might promote the future application of the scheme across different regions and taxonomic groups.

Several frameworks focusing on deleterious impacts still explicitly recognise the existence of beneficial impacts caused by alien species (Bomford et al. 2008; Blackburn et al. 2014; Copp et al. 2016). For instance, the EFSA risk assessment framework developed by the European Food Safety Authority (2011) suggests identifying and describing any beneficial effect caused by aliens on the provisioning and regulation of ecosystem services but specifies that such impacts should not be scored. The absence of a scoring system for beneficial impacts was not only motivated by the intrinsic scope of risk assessment frameworks, which consider multiple factors, such as introduction pathways or establishment probability, to estimate whether an alien species can become deleterious (Leung et al. 2012; Kumschick et al. 2020b). The EFSA members also stressed that "assessing positive impacts is extremely difficult and may also be inappropriate or cause a potential conflict of interest for risk assessors if introductions are intentional". Both conceptual and methodological reasons could thus explain why frameworks assessing both beneficial and deleterious impacts are less frequently cited, and applied, than those assessing deleterious impacts only. The latter are used to a greater extent not only because they specifically help to prioritise alien species according to the magnitude of deleterious impacts, but also because unidirectional frameworks might have reached a higher level of acceptance, clarity and understanding over time. The relatively limited attention given to beneficial effects of alien species across impact assessment frameworks seems thus to reflect a general tendency in invasion science to consciously exclude beneficial impacts for various reasons rather than an attempt to deny their existence.

Below we review arguments for a greater consideration of positive and beneficial impacts caused by alien species. We collected the arguments from a set of 47 papers and illustrate each argument with examples. We grouped the arguments into two categories (value-free and value-laden) that reflect whether each argument has been formulated independently from, or in combination with, ethical and societal values. Arguments grouped in the value-free category consider negative and positive impacts as numerical decrease or increase of an attribute (e.g. the concentration of soil nutrients; Jeschke et al. 2014). Positive and negative impacts do not denote human values (Kumschick et al. 2012), but rather quantify bi-directional changes caused by alien species "as neutrally as possible" (Jeschke et al. 2014). In accordance with this value-free perspective, in our manuscript we strictly define positive impacts as quantitative increases in attributes of the recipient systems. Arguments grouped in the value-laden category, on the contrary, refer to how impacts are perceived according to ethical and societal values (Jeschke et al. 2014). Impacts are generally considered deleterious or beneficial if they damage or benefit attributes linked to ethical and societal values (human well-being). In accordance to this value-laden perspective, in our manuscript we strictly define beneficial impacts as bi-directional quantitative changes (i.e. including both increases and decreases) in attributes of the recipient systems that are associated with benefits based on human values. Therefore, although negative and positive impacts are often considered as deleterious and beneficial, respectively (examples 1, 3 and 4 in Fig. 1), under our definitions, some negative impacts can less intuitively be perceived as beneficial (example 2 in Fig. 1), and some positive impacts as deleterious (example 3 in Fig. 1).

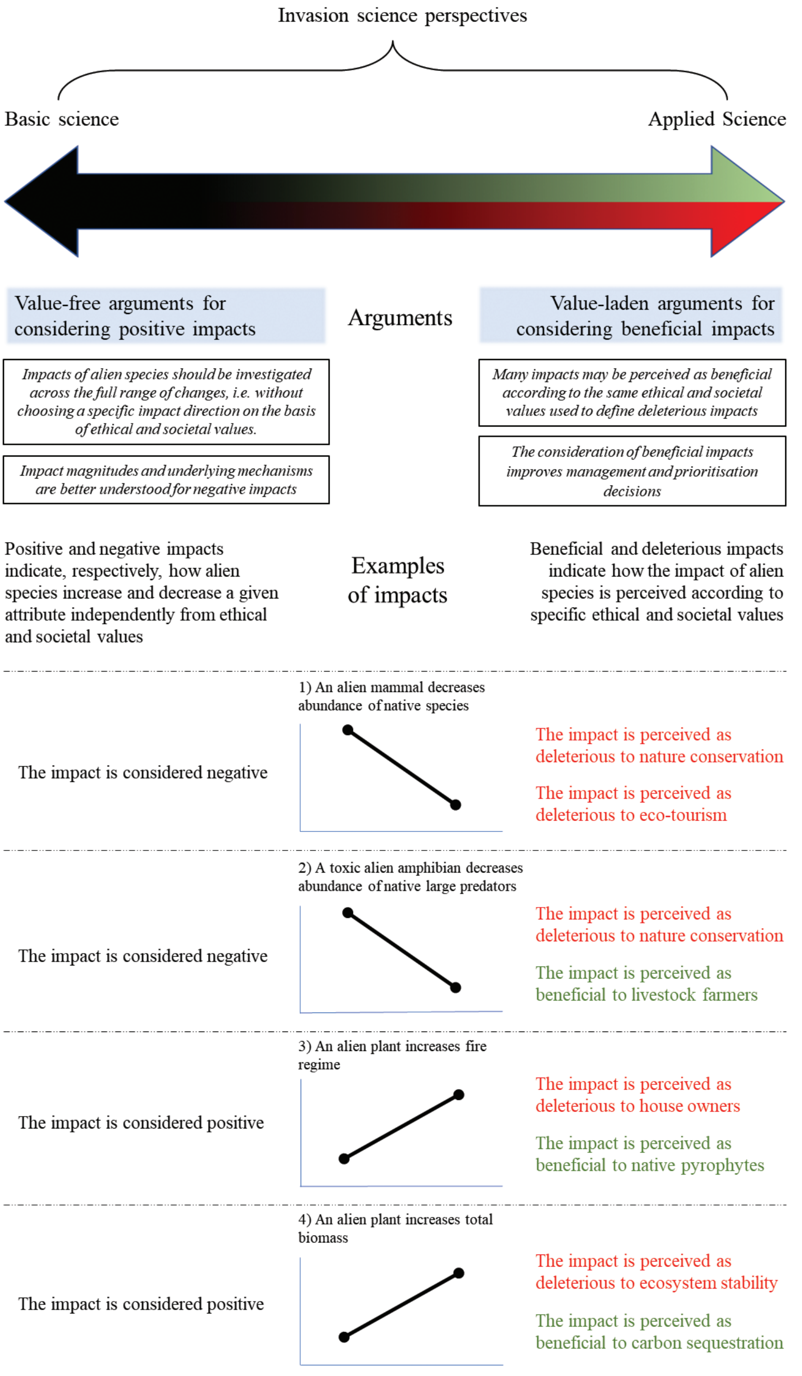


Figure 1. Schematic representation of the gradient of perspectives in invasion science. These perspectives i) contribute to the formulation of general arguments that invoke a greater consideration of positive and beneficial impacts; ii) help to distinguish between negative/positive impacts and deleterious/beneficial impacts. Four examples (1–4) are also provided to illustrate a conceptual distinction between positive/negative impacts (black text) and beneficial/deleterious impacts (red and green text).

We show how the development of impact assessment frameworks assessing positive and beneficial impacts can benefit the field of invasion science and we offer suggestions on how this development should be carried out.

Collection and value-based classification of arguments

We conducted a thorough, but non-exhaustive, literature review to identify arguments for considering positive and beneficial impacts of alien species. We started with papers on the topic that were already known to us and followed up on other papers that referred to them or were cited in them. Articles were selected only if they had broad aims, i.e. they were not restricted to a single case study or taxonomic group. The purpose of this review was to exemplify arguments why authors invoke greater consideration of positive and beneficial impacts in invasion science. However, we do not aim to make quantitative statements about the frequency of these arguments in the field.

In the papers selected, arguments stem from the different perspectives and interests of authors. Like in related disciplines, such as conservation biology (Scott et al. 2007), invasion scientists have disparate standpoints and interests that span from a basic science perspective to an applied science perspective (Humair et al. 2014; Estévez et al. 2015). The former perspective suggests that similarly to any other natural phenomenon, impacts of alien species should be investigated as neutrally as possible (Slobodkin 2001; Brown and Sax 2005). Therefore, the influence of ethical and societal values on the investigation of impacts needs to be minimised in order to adopt a value-free, scientific approach (Slobodkin 2001; Brown and Sax 2005; Sagoff 2018). At the other extreme, the applied science perspective recommends that invasion science "must serve and be relevant to communities" (Munro et al. 2019). Thus, since invasion science concerns, among others, "costs and benefits of the presence and abundance of introduced organisms with reference to human value systems" (Richardson et al. 2007), a value-laden scientific approach could be adopted in the study of alien species. We are aware that a complete distinction between these two perspectives is a simplification of the broad spectrum of the existing views in invasion science (Fig.1) (Humair et al. 2014; Estévez et al. 2015; Bartz and Kowarik 2019). However, such a distinction is still useful here for illustrating the key arguments (Fig. 1) that invoke a greater consideration of positive impacts (value-free arguments), and those which invoke a greater consideration of beneficial impacts (value-laden arguments).

Value-free arguments for considering positive impacts

Impacts of alien species should be investigated across the full range of changes, i.e. without choosing a specific impact direction on the basis of ethical and societal values.

All alien species will cause changes, i.e. impacts, to some attributes of their recipient systems (Ricciardi et al. 2013; Jeschke et al. 2014). These attributes may describe different aspects of the recipient ecosystem, such as species diversity, total biomass, carbon sequestration capacity, fire intensity, pollination frequency, etc. Impacted attributes may also be associated with both human well-being and socio-economic aspects, such as the number of people employed in forestry or fishing, food security, livelihood and human connection to nature. Basic scientific arguments advocate that changes in attributes should be investigated independently from ethical values in order to be objective (Slobodkin 2001). Authors strictly supporting these arguments state that value judgements cannot be empirically tested and that some ecologists fallaciously confuse these judgements with descriptions of environmental changes (Brown and Sax 2005; Sagoff 2018). In other words, one should measure the increase of a given attribute (positive impact) and the decrease of the same attribute (negative impact) along the full spectrum of changes, without any specific focus on one of the two directions (Jeschke et al. 2014, Fig.1). Value-laden terms such as “beneficial” or “deleterious” should be avoided whereas terms such as “positive” or “negative” should be only used from a numerical standpoint, as in the increase or decrease in the value of a property (Brown and Sax 2005). Furthermore, this argument posits that invasion scientists should act similarly to astronomers or particle physicists, who analyse scientific phenomena without considering moral values or practical consequences of their scientific research (Slobodkin 2001; Brown and Sax 2004).

Impact magnitudes and underlying mechanisms are better understood for negative impacts

Under a value-free perspective, value judgement should not interfere with the study of impacts; it is theoretically expected that studies targeting alien species assess their impacts on the recipient system independently and unbiasedly from impact directions (e.g. meta-analyses which use effect size, such as in Castro-Díez et al. 2019). However, biases towards negative impacts on native biota have been reported, i.e. predominantly reporting on native biota suffering from aliens and ignoring native biota that profit from the presence of alien species (Goodenough 2010; Schlaepfer et al. 2011; Fig.2). Furthermore, it is difficult to judge how large this alleged bias is because it is unknown if alien species more often cause a decrease (i.e. generate negative impacts), rather than an increase (i.e. generate positive impacts), to the attributes of their recipient systems (Charles and Dukes 2007; Vitule et al. 2012). An example of a negative impact may be the decrease of species diversity caused by alien populations of rodents introduced to islands (see also example 1, Fig.1), whereas an example of a positive impact may be the increase of local species diversity caused by the establishment of an alien invertebrate that acts as ecosystem engineer (Castilla et al. 2004).

Alternatively, there may be a bias toward studying and reporting negative impacts (Guerin et al. 2018). Multiple negative impacts of alien species (e.g. decrease in native population size) were considered as deleterious based on ethical and societal values (Jeschke et al. 2014; Bartz and Kowarik 2019). The urgency to investigate the conspicuous deleterious impacts that some aliens cause to native communities and human activities

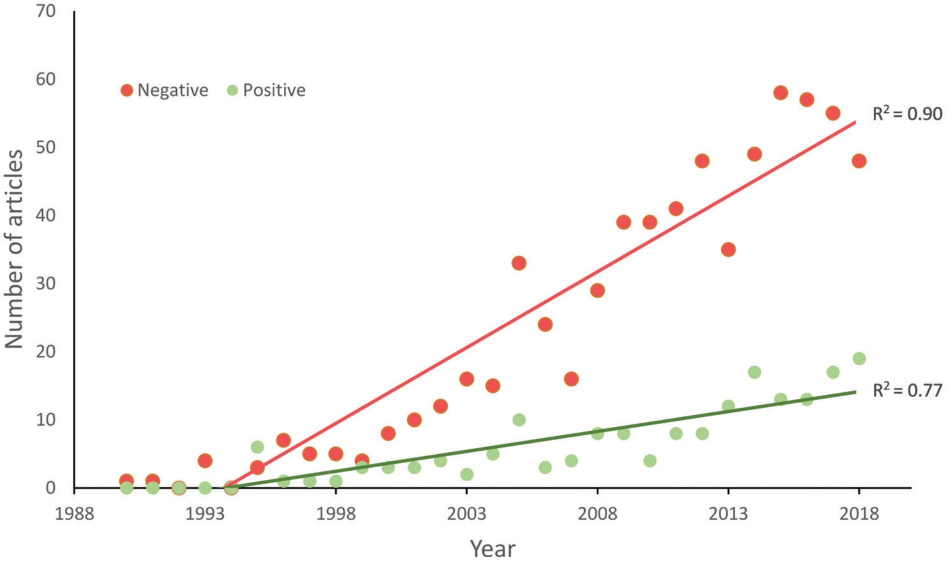


Figure 2. Plot reporting the number of articles and fitted linear regression obtained using the following search strings in Google Scholar at the end of October 2019: ***In red***: "negative * of alien species " OR "negative * of non-native species " OR "negative * of exotic species" OR "costs of alien species " OR "costs of non-native species " OR "costs of exotic species"; ***In green***: "positive * of alien species " OR "positive * of non-native species " OR "positive * of exotic species" OR "benefits of alien species " OR "benefits of non-native species " OR "benefits of exotic species".

(Richardson et al. 2000; Pyšek et al. 2008; Simberloff et al. 2012) might have contributed to this bias even among natural scientists. Such urgency was, for instance, emphasised during the Fourth Meeting of the Conference of the Parties to the Convention on Biological Diversity held in Slovakia in 1998, which first considered "including the subject of alien invasive species in its longer-term programme of work". The report of the meeting specifically noted "the significant adverse ecological and economic effects of certain alien species on biological diversity and human health" and "the importance of taking a precautionary and ecosystem approach when dealing with issues related to alien species" (UNEP 1998). The following editions of the conference considered "alien species that threaten ecosystems, habitat or species" as a cross-cutting and priority issue relevant to biological diversity, and advocated for the prevention and mitigation of their deleterious impacts, which has become a major cornerstone of invasion science. In addition to this, since many alien species were deliberately introduced to provide benefits to humans, such benefits might have seemed obvious, thereby preventing their systematic study. Many invasion scientists might also have investigated the unwanted deleterious consequences of alien taxa introductions in order to counterbalance a favourable attitude from many stakeholders towards alien taxa intentionally introduced for agriculture and forestry (Simberloff and Stiling 1996; Louda et al. 2003; Pyšek et al. 2008).

As most research assessing the impacts of alien species has been directed toward negative impacts, the magnitude of positive impacts has been rarely systematically assessed and quantified by using statistical or semi-quantitative tools (Goodenough 2010). Instead, the literature record of positive impacts seems rather anecdotal, with impacts usually defined according to human values (Vilà et al 2010; Schlaepfer et al. 2011). Thus, there are not only fewer studies that report positive impacts, but these studies often lack a systematic and evidence-based approach to classify and compare these impacts (Vilà et al 2010). Consequently, detailed descriptions of the mechanisms by which alien species can benefit their recipient ecological and the socio-economic systems are also scarce. Some mechanisms by which aliens positively affect the diversity and abundance of native taxa by providing food and refuge have been identified by Robinson et al. (2007), Goodenough (2010), Schlaepfer et al. (2011), McQuaid and Griffiths (2014) and Tassin and Kull (2015). Additionally, Kumschick et al. (2012) described mechanisms such as herbivory, competition or predation by which aliens may affect species that are degrading the ecosystem and thereby restore its historical functional state. Further studies on these underlying mechanisms may provide eco-evolutionary insights around alien-native coevolution, rapid adaptation, biotic resistance and niche vacancy. Greater knowledge has probably been gained around socio-economic benefits to human-well-being, as multiple authors identified mechanisms by which aliens increase ecosystem services and decrease ecosystem disservices (Katsanevakis et al. 2014; Vaz et al. 2017; Knapp et al. 2019; Shackleton et al. 2019a; Milanović et al. 2020). Despite these efforts, unified systematic approaches to capture the diversity of positive and beneficial impacts of aliens across taxa and geographic regions are still lacking.

Value-laden arguments for considering beneficial impacts

Many impacts may be perceived as beneficial according to the same ethical and societal values used to define deleterious impacts

Although impacts cannot be defined as deleterious or beneficial in an absolute way, changes caused by alien species may still be perceived as deleterious or beneficial according to societal and ethical values (Fig.1, Vilà et al. 2010; Kumschick et al. 2012; Jeschke et al. 2014; Bartz and Kowarik 2019). Alien species can alter the demography of endangered populations and permanently modify native communities (Doherty et al. 2008, Gurevitch and Padilla 2004). Since native populations and communities have high conservation value, their decrease (i.e. negative impact) can be considered deleterious from a value-laden perspective (example 1, Fig.1). This nature conservation perspective guided the development of some impact assessment frameworks frequently used (Vilà et al. 2019), such as the GISS framework (Nentwig et al. 2016) and the EICAT framework (Blackburn et al. 2014; Hawkins et al 2015; IUCN 2020), which both assess the deleterious impacts of alien species on native taxa. Alien species may also be perceived as deleterious to socio-economic systems and human well-being. For example, when alien species impede human activities such as fishing and farming or impair human health (Mazza et al. 2014; Rai and Singh 2020), personal safety or material and immaterial assets (Bacher et. al. 2018). Deleterious impacts on the social and economic sectors have been captured in the SEICAT framework (Socio-Economic Impact Classification of Alien Taxa), which adopts a scoring system analogous to EICAT to assess how human activities are affected by alien species (Bacher et al. 2018). Some impact assessment frameworks such as GISS (Nentwig et al. 2016) and INSEAT (Martinez-Cillero 2019), and many risk assessment frameworks, evaluate deleterious socio-economic impacts (for a review of impact assessment frameworks see Strubbe et al. 2019 and Vilà et al. 2019; for a review of risk assessment frameworks see Leung et al. 2012 and Kumschick and Richardson 2013).

Analogously to negative impacts that are perceived as deleterious to native communities and humans, many positive impacts can be considered beneficial according to values associated with nature conservation and human well-being. For example, some alien species may moderately increase fire frequency in their introduced range, thus providing benefits to native pyrophytes which require fire for germination (example 3 in Fig. 1). Alien plants can also increase the biomass of a recipient ecosystem, thus being beneficial to global carbon sequestration (example 4 in Fig. 1). Additionally, many alien species increase attributes that are relevant to societal values and human well-being. In other words, they increase existent, or provide additional, ecosystem services or beneficial contributions to people's quality of life (Díaz et al. 2018) such as food and water provision, soil and sand stabilisation and nitrogen fixation (Vaz et al. 2017; Milanović et al. 2019; Shackleton et al. 2019a). In a world of increasing environmental issues, aliens can also help to reduce the impact of other stressors. Examples include alien plants which mitigate the effects of climate change by facilitating coastal protection from erosion and favouring carbon sequestration (example 4 in Fig. 1, Essl. et al. 2017, in Castro-Díez et al. 2019). However, not all environmental and socio-economic beneficial impacts coincide with positive impacts; for example, in the impact scoring framework proposed by Kumschick et al. (2012), beneficial impacts of alien animals are quantified by measuring to what extent they reduce the population density of species degrading the ecosystem (e.g. pest species). In other words, a negative impact (e.g. decrease of pest species abundance), may thus be considered beneficial from a nature conservation standpoint or according to other values and interests (example 2, Fig.1). An alien bio-control agent (e.g. a parasitoid wasp) that reduces the abundance of an agricultural pest can be similarly considered beneficial to farmers and other stakeholders. Such species can thus provide additional benefits to humans by reducing ecosystem disservices (Vaz et al. 2017; Knapp et al. 2019; Milanović et al. 2019).

The consideration of beneficial impacts improves management and prioritisation decisions

Human values and interests associated with the impacts of alien species affect whether and how these species can be managed. Some alien species have been intentionally introduced because of the benefits they can provide to people (Castro-Díez et al. 2019). Additionally, many aliens cause low or insignificant impacts to their recipient systems and can be simply considered inconsequential for ecosystems and society (Zengeya et al. 2017). Beneficial and inconsequential species do not generally require management interventions, and their prompt identification facilitates the allocation of management resources elsewhere (van Wilgen and Richardson 2004; Zengeya et al. 2017). Aliens that provide beneficial impacts to human well-being might, however, decrease the demography of native populations, thus being deleterious from a nature conservation standpoint (Doherty et al. 2008). More generally, stakeholders may have such disparate values and interests that their perception toward alien species can be simultaneously favourable and unfavourable (Novoa et al. 2018; Shackleton et al 2019b). Such disparate values (examples 2,3 and 4, Fig.1) may cause a conflict of interests among different stakeholders and hamper management implementation (Jeschke et al. 2014; Crowley et al. 2017; Essl et al. 2017; Zengeya et al. 2017). For instance, van Wilgen and Wilson (2018) showed that control and regulation of a few alien taxa such as pine trees (*Pinus* spp.) and the rainbow trout (*Oncorhynchus mykiss*) were extremely controversial in South Africa, given these species cause both beneficial and deleterious impacts on different sectors of society. Analogously, the control of Paterson's curse (*Echium plantagineum*), an alien plant that is highly toxic to livestock, has generated conflicts between Australian farmers and beekeepers, with the latter benefiting from the nectar produced by the plant (Messing 2000). Transparent and evidence-based descriptions of beneficial and deleterious impacts of alien species may thus help to support prioritisation, clarify and motivate values underlying management, identify conflicts of interests and advance dialogue among stakeholders.

Reasons and suggestions to develop frameworks assessing positive and beneficial impacts

We show that arguments from different perspectives invoke a greater consideration of positive and beneficial impacts in invasion science. The development of assessment frameworks that classify deleterious and negative impacts through a standardised and evidence-based approach (e.g. EICAT and SEICAT) has improved our understanding of such impacts. These frameworks describe the different ways in which alien taxa deleteriously interact with native taxa (impact mechanisms), and quantify the severity of such interactions (impact magnitude) (Blackburn et al. 2014; Nentwig et al. 2016; Bacher et al. 2018). The application of these frameworks to different taxa and ecosystems has allowed for the investigation of factors driving impact magnitude (e.g., Kumschick et al. 2013; Measey et al. 2016; Novoa et al. 2016; Evans et al. 2018) and the ranking of hundreds of alien species based on their deleterious impacts (e.g. Kumschick et al. 2015; Nentwig et al. 2018). Given the above considerations, some of these frameworks might be adapted to assess beneficial impacts. Detailed descriptions provided by these frameworks around mechanisms by which alien species cause deleterious impacts can be extended to capture mechanisms linked to beneficial impacts (i.e. Blackburn et al. 2014; Nentwig et al. 2016). Approaches adopted by existing frameworks to evaluate assessment uncertainty can also be followed because they might help to overcome methodological limitations associated with transparency, clarity and reproducibility (Vilà et al. 2019; Probert et al. 2020). However, some conceptual and methodological aspects should be considered when developing frameworks that assess positive and beneficial impacts.

Impact assessment frameworks classify deleterious impacts according to their magnitudes, i.e. by measuring to what extent alien taxa affect reference attributes. This facilitates comparison among taxonomically distant alien species and across spatial scale and habitats. However, several different strategies have been adopted to measure impact magnitudes. Frameworks such as those proposed by Sandvik et al. (2013) and Martinez-Cillero et al. (2019) use ranking scales which distinguish between low (or noticeable), substantial (or medium), and high (intense) impacts. The scales may be associated with parameters that can be numerically quantified such as the spatial extent of the non-native range, genetic diversity, fitness and abundance of native individuals or provision of ecosystem services (Bartz and Kowarik 2019; Crystal-Ornelas and Lockwood 2020). As a consequence, such scoring scales could be easily adapted to assess bidirectional changes (Martinez-Cillero et al. 2019). Although general scaling approaches may allow the assessment of many alien species and adopt a fully symmetrical bidirectional approach (Zengeya et al. 2017), they may still be prone to subjectivity, especially when the distinction between the magnitude levels is not accurately described. The EICAT framework (Blackburn et al. 2014), on the contrary, clarifies differences between magnitude levels by assuming that with each level of impact magnitude (from minimal concern to massive), a different level of organisation is affected (from native individuals to native communities). Clarity in describing distinct levels of impact magnitude might have contributed to the increasing use of EICAT among scientists and practitioners (Kumschick et al. 2020a). An analogous scoring approach that assesses ecological impacts based on organisation level has been also developed by Olenin et al. (2007). Such approaches, however, define the highest levels of impact magnitude according to the capacity of alien species to cause the extinction of a native species (Olenin et al. 2007; Blackburn et al. 2014). As extinction cannot be exactly mirrored by any other positive ecological phenomenon, the development of a perfectly symmetrical bidirectional adaptation of these schemes might be difficult to achieve. As a consequence, not all impact assessment frameworks can, or need to, adopt a fully symmetric bidirectional scoring scale to assess impact magnitudes. This limitation should be recognised in any conceptual attempt to adapt existing frameworks in order to assess the benefits of alien species.

Impact assessment frameworks are generally developed based on different values that should be recognised and explicitly stated. Values and perspectives influence how we select the attributes of ecosystems or human activities that will be assessed (Bartz and Kowarik 2019; Strubbe et al. 2019) and must be considered when making management recommendations and in final decision making (Probert et al. 2020). However, values and perspectives also define the aims and the intrinsic limitations of each framework. For example, when evaluating the changes caused by an alien species to the community of the recipient environment, we should choose and specify which taxa are taken into consideration. Scientists embracing a conservation standpoint might consider only native, or even endangered taxa, as they aim to quantify alien impacts on species of conservation interest. Scientists who follow a more basic science approach, however, could consider all taxa independently of their origin, as their aim is to measure the negative or positive impacts of aliens from a value-free perspective. The development of a framework that assesses deleterious and beneficial impacts should thus disclose which values underlie the framework and whether the framework distinguishes between deleterious/beneficial impacts and negative/positive impacts. Such a disclosure of values can also be facilitated by the development, and adoption, of a more neutral and transparent terminology in invasion science. The distinction we have drawn in our manuscript between positive/negative and beneficial/deleterious impacts, for example, has been instrumental in defining impacts regardless of whether they were associated with human values. Both terms "positive" and "negative", however, have in general an intrinsic value connotation and are often used as synonyms of "beneficial" or "favourable" and "detrimental" or "deleterious" in invasion science and other scientific disciplines. Given this lack of linguistic consistency, there might be the necessity to develop a more neutral and transparent terminology in invasion science that unequivocally clarifies whether an impact is defined in accordance to human values or only from a mathematical and value-free perspective.

Conclusion

When underlying values are explicitly stated and intrinsic limitations are openly recognised, the development of frameworks that assess positive and beneficial impacts might advance our scientific understanding of impact dynamics and generate reliable information for management and prioritisation. Adapting existing or developing novel frameworks to quantify these impacts should not be seen as an attempt to outweigh or discount deleterious impacts of alien taxa (EFSA 2011) but rather as an opportunity to provide an additional piece of information for scientists, managers and policymakers.

Acknowledgments

This paper emerged from a workshop on 'Frameworks used in Invasion Science' hosted by the DSI-NRF Centre of Excellence for Invasion Biology in Stellenbosch, South Africa, 11–13 November 2019, that was supported by the National Research Foundation of South Africa and Stellenbosch University. We thank the handling editor and reviewers for their helpful comments and suggestions, which improved the quality of the manuscript. We thank Ingolf Kühn, Belinda Gallardo, Ross Shackleton and Louisa Wood for fruitful discussions around the evaluation of positive and beneficial impacts of alien species through impact assessment frameworks. GV, LV, AFP and SB acknowledge funding from the Swiss National Science Foundation (grant numbers 31003A_179491 and 31BD30_184114) and the Belmont Forum – BiodivERsA International joint call project InvasiBES (PCI2018-092939). SK acknowledges the support of the DSI-NRF Centre of Excellence for Invasion Biology (CIB) and Stellenbosch University, and the South African Department of Forestry, Fisheries and the Environment (DFFtE) noting that this publication does not necessarily represent the views or opinions of DFFtE or its employees.

References

Bacher S, Blackburn TM, Essl F, Genovesi P, Heikkilä J, Jeschke JM, Jones G, Keller R, Kenis M, Kueffer C, Martinou AF, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Roy HE, Saul WC, Scalera R, Vilà M, Wilson JRU, Kumschick S (2018) Socio-economic impact classification of alien taxa (SEICAT). Methods in Ecology and Evolution 9: 159–168. https://doi.org/10.1111/2041-210X.12844

Bartz R, Kowarik I (2019) Assessing the environmental impacts of invasive alien plants: A review of assessment approaches. NeoBiota 43: 69–99. https://doi.org/10.3897/neobiota.43.30122

Blackburn TM, Essl F, Evans T, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Marková Z, Mrugała A, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Wilson JRU, Winter M, Genovesi P, Bacher S (2014) A Unified Classification of Alien Species Based on the Magnitude of their Environmental Impacts. PLoS Biology 12. https://doi.org/10.1371/journal.pbio.1001850

Boltovskoy D, Sylvester F, Paolucci EM (2018) Invasive species denialism: Sorting out facts, beliefs, and definitions. Ecology and Evolution 8: 11190–11198. https://doi.org/10.1002/ece3.4588

Bomford M, Glover J (2004) Risk assessment model for the import and keeping of exotic freshwater and estuarine finfish A report produced by the Bureau of Rural Sciences for The Department of Environment and Heritage. http://www.dcita.gov.au/cca [March 31, 2020]

Brown JH, Sax DF (2005) Biological invasions and scientific objectivity: Reply to Cassey et al. (2005). Austral Ecology 30: 481–483. https://doi.org/10.1111/j.1442-9993.2005.01504.x

Castilla JC, Lagos NA, Cerda M (2004) Marine ecosystem engineering by the alien ascidian Pyura praeputialis on a mid-intertidal rocky shore. Marine Ecology Progress Series 268: 119–130. https://doi.org/10.3354/meps268119

Castro-Díez P, Vaz AS, Silva JS, van Loo M, Alonso Á, Aponte C, Bayón Á, Bellingham PJ, Chiuffo MC, DiManno N, Julian K, Kandert S, La Porta N, Marchante H, Maule HG, Mayfield MM, Metcalfe D, Monteverdi MC, Núñez MA, Ostertag R, Parker IM, Peltzer DA, Potgieter LJ, Raymundo M, Rayome D, Reisman-Berman O, Richardson DM, Roos RE, Saldaña A, Shackleton RT, Torres A, Trudgen M, Urban J, Vicente JR, Vilà M, Ylioja T, Zenni RD, Godoy O (2019) Global effects of non-native tree species on multiple ecosystem services. Biological Reviews 94: 1477–1501. https://doi.org/10.1111/brv.12511

Charles H, Dukes JS (2007) Impacts of invasive species on ecosystem services. Biological Invasions 193: 217–237. https://doi.org/10.1007/978-3-540-36920-2_13

Copp GH, Russell IC, Peeler EJ, Gherardi F, Tricarico E, Macleod A, Cowx IG, Nunn AD, Occhipinti-Ambrogi A, Savini D, Mumford J, Britton JR (2016) European Non-native Species in Aquaculture Risk Analysis Scheme – a summary of assessment protocols and decision support tools for use of alien species in aquaculture. Fisheries Management and Ecology 23: 1–11. https://doi.org/10.1111/fme.12074

Crowley SL, Hinchliffe S, McDonald RA (2017) Invasive species management will benefit from social impact assessment. Journal of Applied Ecology 54: 351–357. https://doi.org/10.1111/1365-2664.12817

Crystal-Ornelas R, Lockwood JL (2020) The "known unknowns" of invasive species impact measurement. Biological Invasions 22: 1513–1525. https://doi.org/10.1007/s10530-020-02200-0

Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMA, Baste IA, Brauman KA, Polasky S, Church A, Lonsdale M, Larigauderie A, Leadley PW, van Oudenhoven APE, van der Plaat F, Schröter M, Lavorel S, Aumeeruddy-Thomas Y, Bukvareva E, Davies K, Demissew S, Erpul G, Failler P, Guerra CA, Hewitt CL, Keune H, Lindley S, Shirayama Y (2018) Assessing nature's contributions to people. Science 359: 270–272. https://doi.org/10.1126/science.aap8826

Doherty TS, Glen AS, Nimmo DG, Ritchie EG, Dickman CR (2016) Invasive predators and global biodiversity loss. Proceedings of the National Academy of Sciences of the United States of America 113: 11261–11265. https://doi.org/10.1073/pnas.1602480113

EFSA Panel on Plant Health (2011) Guidance on the environmental risk assessment of plant pests. EFSA Journal 9: 1–121. https://doi.org/10.2903/j.efsa.2011.2460

Essl F, Hulme PE, Jeschke JM, Keller R, Pyšek P, Richardson DM, Saul WC, Bacher S, Dullinger S, Estévez RA, Kueffer C, Roy HE, Seebens H, Rabitsch W (2017) Scientific and normative foundations for the valuation of alien-species impacts: Thirteen core principles. BioScience 67: 166–178. https://doi.org/10.1093/biosci/biw160

Essl F, Dullinger S, Rabitsch W, Hulme PE, Hülber K, Jarošík V, Kleinbauer I, Krausmann F, Kühn I, Nentwig W, Vilà M, Genovesi P, Gherardi F, Desprez-Loustau ML, Roques A, Pyšek P (2011) Socioeconomic legacy yields an invasion debt. Proceedings of the National Academy of Sciences of the United States of America 108: 203–207. https://doi.org/10.1073/pnas.1011728108

Estévez RA, Anderson CB, Pizarro JC, Burgman MA (2015) Clarifying values, risk perceptions, and attitudes to resolve or avoid social conflicts in invasive species management. Conservation Biology 29: 19–30. https://doi.org/10.1111/cobi.12359

Evans T, Kumschick S, Şekercioğlu ÇH, Blackburn TM (2018) Identifying the factors that determine the severity and type of alien bird impacts. Diversity and Distributions 24: 800–810. https://doi.org/10.1111/ddi.12721

Goodenough A (2010) Are the ecological impacts of alien species misrepresented? A review of the "native good, alien bad" philosophy. Community Ecology 11: 13–21. https://doi.org/10.1556/ComEc.11.2010.1.3

Guerin GR, Martín-Forés I, Sparrow B, Lowe AJ (2018) The biodiversity impacts of non-native species should not be extrapolated from biased single-species studies. Biodiversity and Conservation 27: 785–790. https://doi.org/10.1007/s10531-017-1439-0

Gurevitch J, Padilla DK (2004) Are invasive species a major cause of extinctions? Trends in Ecology and Evolution 19: 470–474. https://doi.org/10.1016/j.tree.2004.07.005

Hawkins CL, Bacher S, Essl F, Hulme PE, Jeschke JM, Kühn I, Kumschick S, Nentwig W, Pergl J, Pyšek P, Rabitsch W, Richardson DM, Vilà M, Wilson JRU, Genovesi P, Blackburn TM (2015) Framework and guidelines for implementing the proposed IUCN Environmental Impact Classification for Alien Taxa (EICAT). Diversity and Distributions 21: 1360–1363. https://doi.org/10.1111/ddi.12379

Humair F, Edwards PJ, Siegrist M, Kueffer C (2014) Understanding misunderstandings in invasion science: why experts don't agree on common concepts and risk assessments. NeoBiota 20: 1–30. https://doi.org/10.3897/neobiota.20.6043

IUCN (2020) IUCN EICAT Categories and Criteria. The Environmental Impact Classification for Alien Taxa (EICAT): First edition. Gland, Switzerland and Cambridge, UK: IUCN. https://doi.org/10.2305/IUCN.CH.2020.05.en

Jeschke JM, Bacher S, Blackburn TM, Dick JTA, Essl F, Evans T, Gaertner M, Hulme PE, Kühn I, Mrugała A, Pergl J, Pyšek P, Rabitsch W, Ricciardi A, Richardson DM, Sendek A, Vilà M, Winter M, Kumschick S (2014) Defining the impact of non-native species. Conservation Biology 28: 1188–1194. https://doi.org/10.1111/cobi.12299

Katsanevakis S, Wallentinus I, Zenetos A, Leppäkoski E, Çinar ME, Oztürk B, Grabowski M, Golani D, Cardoso AC (2014) Impacts of invasive alien marine species on ecosystem services and biodiversity: A pan-European review. Aquatic Invasions 9: 391–423. https://doi.org/10.3391/ai.2014.9.4.01

Knapp S, Winter M, Zehnsdorf A, Kühn I (2019) How Good Are Bad Species? Atlas of Ecosystem Services. https://doi.org/10.1007/978-3-319-96229-0_34

Kuebbing SE, Nuñez MA (2018) Current understanding of invasive species impacts cannot be ignored: potential publication biases do not invalidate findings. Biodiversity and Conservation 27: 1545–1548. https://doi.org/10.1007/s10531-018-1527-9

Kumar Rai P, Singh JS (2020) Invasive alien plant species: Their impact on environment, ecosystem services and human health. Ecological Indicators 111: 106020. https://doi.org/10.1016/j.ecolind.2019.106020

Kumschick S, Richardson DM (2013) Species-based risk assessments for biological invasions: Advances and challenges. Diversity and Distributions 19: 1095–1105. https://doi.org/10.1111/ddi.12110

Kumschick S, Bacher S, Blackburn TM (2013) What determines the impact of alien birds and mammals in Europe? Biological Invasions 15: 785–797. https://doi.org/10.1007/s10530-012-0326-6

Kumschick S, Bacher S, Dawson W, Heikkilä J, Sendek A, Pluess T, Robinson T, Kühn I (2012) A conceptual framework for prioritization of invasive alien species for management according to their impact. NeoBiota 15: 69–100. https://doi.org/10.3897/neobiota.15.3323

Kumschick S, Bacher S, Evans T, Marková Z, Pergl J, Pyšek P, Vaes-Petignat S, van der Veer G, Vilà M, Nentwig W (2015) Comparing impacts of alien plants and animals in Europe using a standard scoring system. Journal of Applied Ecology 52: 552–561. https://doi.org/10.1111/1365-2664.12427

Kumschick S, Bacher S, Bertolino S, Blackburn TM, Evans T, Roy HE, Smith K (2020) Appropriate uses of EICAT protocol, data and classifications. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 193–212. https://doi.org/10.3897/neobiota.62.51574

Kumschick S, Wilson JRU, Foxcroft LC (2020) A framework to support alien species regulation: the Risk Analysis for Alien Taxa (RAAT). NeoBiota 62: 213–239. https://doi.org/10.3897/neobiota.62.51031

Leung B, Roura-Pascual N, Bacher S, Heikkilä J, Brotons L, Burgman MA, Dehnen-Schmutz K, Essl F, Hulme PE, Richardson DM, Sol D, Vilà M (2012) TEASIng apart alien species risk assessments: A framework for best practices. Ecology Letters 15: 1475–1493. https://doi.org/10.1111/ele.12003

Louda SM, Pemberton RW, Johnson MT, Follett PA (2003) Nontarget effects – The achille's heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Annual Review of Entomology 48: 365–396. https://doi.org/10.1146/annurev.ento.48.060402.102800

Martinez-Cillero R, Willcock S, Perez-Diaz A, Joslin E, Vergeer P, Peh KSH (2019) A practical tool for assessing ecosystem services enhancement and degradation associated with invasive alien species. Ecology and Evolution 9: 3918–3936. https://doi.org/10.1002/ece3.5020

Mazza G, Tricarico E, Genovesi P, Gherardi F (2014) Biological invaders are threats to human health: An overview. Ethology Ecology and Evolution 26: 112–129. https://doi.org/10.1080/03949370.2013.863225

McGeoch MA, Genovesi P, Bellingham PJ, Costello MJ, McGrannachan C, Sheppard A (2016) Prioritizing species, pathways, and sites to achieve conservation targets for biological invasion. Biological Invasions 18: 299–314. https://doi.org/10.1007/s10530-015-1013-1

McQuaid KA, Griffiths CL (2014) Alien reef-building polychaete drives long-term changes in invertebrate biomass and diversity in a small, urban estuary. Estuarine, Coastal and Shelf Science 138: 101–106. https://doi.org/10.1016/j.ecss.2013.12.016

Measey GJ, Vimercati G, de Villiers FA, Mokhatla M, Davies SJ, Thorp CJ, Rebelo AD, Kumschick S (2016) A global assessment of alien amphibian impacts in a formal framework. Diversity and Distributions 22: 970–981. https://doi.org/10.1111/ddi.12462

Messing RH (2000) The Impact of Nontarget Concerns on the Practice of Biological Control. Nontarget Effects of Biological Control. Springer, US, 45–55. https://doi.org/10.1007/978-1-4615-4577-4_4

Milanović M, Knapp S, Pyšek P, Kühn I (2020) Linking traits of invasive plants with ecosystem services and disservices. Ecosystem Services 42: 101072. https://doi.org/10.1016/j.ecoser.2020.101072

Morse LE, Randall JM, Benton N, Hiebert R, Lu S (2004) An invasive species assessment protocol: evaluating non-native plants for their impact on biodiversity. Version 1. 42 pp.

Munro D, Steer J, Linklater W (2019) On allegations of invasive species denialism. Conservation Biology 33: 797–802. https://doi.org/10.1111/cobi.13278

Nentwig W, Bacher S, Kumschick S, Pyšek P, Vilà M (2018) More than "100 worst" alien species in Europe. Biological Invasions 20: 1611–1621. https://doi.org/10.1007/s10530-017-1651-6

Nentwig W, Bacher S, Pyšek P, Vilà M, Kumschick S (2016) The generic impact scoring system (GISS): a standardized tool to quantify the impacts of alien species. Environmental Monitoring and Assessment 188. https://doi.org/10.1007/s10661-016-5321-4

Novoa A, Kumschick S, Richardson DM, Rouget M, Wilson JRU (2016) Native range size and growth form in Cactaceae predict invasiveness and impact. NeoBiota 30: 75–90. https://doi.org/10.3897/neobiota.30.7253

Novoa A, Shackleton R, Canavan S, Cybèle C, Davies SJ, Dehnen-Schmutz K, Fried J, Gaertner M, Geerts S, Griffiths CL, Kaplan H, Kumschick S, Le Maitre DC, Measey GJ, Nunes AL, Richardson DM, Robinson TB, Touza J, Wilson JRU (2018) A framework for engaging stakeholders on the management of alien species. Journal of Environmental Management 205: 286–297. https://doi.org/10.1016/j.jenvman.2017.09.059

Olenin S, Minchin D, Daunys D (2007) Assessment of biopollution in aquatic ecosystems. Marine Pollution Bulletin 55: 379–394. https://doi.org/10.1016/j.marpolbul.2007.01.010

Oreska MPJ, Aldridge DC (2011) Estimating the economic costs of invasive alien species as a tool for prioritization. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 6. https://doi.org/10.1079/PAVSNNR20116049

Pimentel D, McNair S, Janecka J, Wightman J, Simmonds C, O'Connell C, Wong E, Russel L, Zern J, Aquino T, Tsomondo T (2001) Economic and environmental threats of alien plant, animal, and microbe invasions. Agriculture, Ecosystems and Environment 84: 1–20. https://doi.org/10.1016/S0167-8809(00)00178-X

Potgieter LJ, Gaertner M, O'Farrell PJ, Richardson DM (2019a) A fine-scale assessment of the ecosystem service-disservice dichotomy in the context of urban ecosystems affected by alien plant invasions. Forest Ecosystems 6: 1–16. https://doi.org/10.1186/s40663-019-0200-4

Potgieter LJ, Gaertner M, O'Farrell PJ, Richardson DM (2019b) Perceptions of impact: Invasive alien plants in the urban environment. Journal of Environmental Management 229: 76–87. https://doi.org/10.1016/j.jenvman.2018.05.080

Probert AF, Volery L, Kumschick S, Vimercati G, Bacher S (2020) Understanding uncertainty in the Impact Classification for Alien Taxa (ICAT) assessments. In: Wilson JR, Bacher S, Daehler CC, Groom QJ, Kumschick S, Lockwood JL, Robinson TB, Zengeya TA, Richardson DM (Eds) Frameworks used in Invasion Science. NeoBiota 62: 387–405. https://doi.org/10.3897/neobiota.62.52010

Probert AF, Ward DF, Beggs JR, Lin S-L, Stanley MC (2020) Conceptual Risk Framework: Integrating Ecological Risk of Introduced Species with Recipient Ecosystems. BioScience 70: 71–79. https://doi.org/10.1093/biosci/biz131

Pyšek P, Richardson DM, Pergl J, Jarošík V, Sixtová Z, Weber E (2008) Geographical and taxonomic biases in invasion ecology. Trends in Ecology and Evolution 23: 237–244. https://doi.org/10.1016/j.tree.2008.02.002

Ricciardi A, Hoopes MF, Marchetti MP, Lockwood JL (2013) Progress toward understanding the ecological impacts of nonnative species. Ecological Monographs 83: 263–282. https://doi.org/10.1890/13-0183.1

Richardson DM, Pyšek P (2008) Fifty years of invasion ecology – the legacy of Charles Elton. Diversity and Distributions 14: 161–168. https://doi.org/10.1111/j.1472-4642.2007.00464.x

Richardson DM, Pyšek P, Rejmánek M, Barbour MG, Dane Panetta F, West CJ (2000) Naturalization and invasion of alien plants: Concepts and definitions. Diversity and Distributions 6: 93–107. https://doi.org/10.1046/j.1472-4642.2000.00083.x

Robinson TB, Branch GM, Griffiths CL, Govender A, Hockey PAR (2007) Changes in South African rocky intertidal invertebrate community structure associated with the invasion of the mussel *Mytilus galloprovincialis*. Marine Ecology Progress Series 340: 163–171. https://doi.org/10.3354/meps340163

Roy HE, Rabitsch W, Scalera R, Stewart A, Gallardo B, Genovesi P, Essl F, Adriaens T, Bacher S, Booy O, Branquart E, Brunel S, Copp GH, Dean H, D'hondt B, Josefsson M, Kenis M, Kettunen M, Linnamagi M, Lucy F, Martinou A, Moore N, Nentwig W, Nieto A, Pergl J, Peyton J, Roques A, Schindler S, Schönrogge K, Solarz W, Stebbing PD, Trichkova T, Vanderhoeven S, van Valkenburg J, Zenetos A (2018) Developing a framework of minimum standards for the risk assessment of alien species. Journal of Applied Ecology 55: 526–538. https://doi.org/10.1111/1365-2664.13025

Sagoff M (2018) What Is Invasion Biology? Ecological Economics 154: 22–30. https://doi.org/10.1016/j.ecolecon.2018.07.023

Sandvik H, Sæther BE, Holmern T, Tufto J, Engen S, Roy HE (2013) Generic ecological impact assessments of alien species in Norway: A semi-quantitative set of criteria. Biodiversity and Conservation 22: 37–62. https://doi.org/10.1007/s10531-012-0394-z

Schlaepfer MA, Sax DF, Olden JD (2011) The potential conservation value of non-native species. Conservation Biology 25: 428–437. https://doi.org/10.1111/j.1523-1739.2010.01646.x

Scott JM, Rachlow JL, Lackey RT, Pidgorna AB, Aycrigg JL, Feldman GR, Svancara LK, Rupp DA, Stanish DI, Steinhorst RK (2007) Policy advocacy in science: Prevalence, perspectives, and implications for conservation biologists. Conservation Biology 21: 29–35. https://doi.org/10.1111/j.1523-1739.2006.00641.x

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, Van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nature Communications 8: 1–9. https://doi.org/10.1038/ncomms14435

Shackleton RT, Shackleton CM, Kull CA (2019a) The role of invasive alien species in shaping local livelihoods and human well-being: A review. Journal of Environmental Management 229: 145–157. https://doi.org/10.1016/j.jenvman.2018.05.007

Shackleton RT, Richardson DM, Shackleton CM, Bennett B, Crowley SL, Dehnen-Schmutz K, Estévez RA, Fischer A, Kueffer C, Kull CA, Marchante E, Novoa A, Potgieter LJ, Vaas J, Vaz AS, Larson BMH (2019b) Explaining people's perceptions of invasive alien species: A conceptual framework. Journal of Environmental Management 229: 10–26. https://doi.org/10.1016/j.jenvman.2018.04.045

Simberloff D, Stiling P (1996) How risky is biological control? Ecology 77: 1965–1974. https://doi.org/10.2307/2265693

Simberloff D, Souza L, Nũnez MA, Barrios-Garcia MN, Bunn W (2012) The natives are restless, but not often and mostly when disturbed. Ecology 93: 598–607. https://doi.org/10.1890/11-1232.1

Slobodkin LB (2001) The good, the bad and the reified. Evolutionary Ecology Research 3: 1–13.

Srebaliene G, Olenin S, Minchin D, Narščius A (2019) A comparison of impact and risk assessment methods based on the IMO Guidelines and EU invasive alien species risk assessment frameworks. PeerJ 2019. https://doi.org/10.7717/peerj.6965

Strubbe D, White R, Edelaar P, Rahbek C, Shwartz A (2019) Advancing impact assessments of non-native species: Strategies for strengthening the evidence-base. NeoBiota 51: 41–64. https://doi.org/10.3897/neobiota.51.35940

Tassin J, Kull CA (2015) Facing the broader dimensions of biological invasions. Land Use Policy 42: 165–169. https://doi.org/10.1016/j.landusepol.2014.07.014

UNEP (1998) Report of the Fourth Meeting of the Conference of the Parties to the Convention on Biological Diversity. In: Conference of the Parties to the Convention on Biological Diversity, Fourth meeting. UNEP/CBD/COP/4/27, Bratislava, Slovakia.

Vaz AS, Kueffer C, Kull CA, Richardson DM, Vicente JR, Kühn I, Schröter M, Hauck J, Bonn A, Honrado JP (2017) Integrating ecosystem services and disservices: insights from plant invasions. Ecosystem Services 23: 94–107. https://doi.org/10.1016/j.ecoser.2016.11.017

Vilà M, Basnou C, Pyšek P, Josefsson M, Genovesi P, Gollasch S, Nentwig W, Olenin S, Roques A, Roy D, Hulme PE, Andriopoulos P, Arianoutsou M, Bazos I, Kokkoris I, Yannitsaros A, Zikos A, Augustin S, Cochard PO, Lopez-Vaamonde C, Sauvard D, Yart A, Bacher S, Bretagnolle F, Gasquez J, Chiron F, Kark S, Shirley S, Clergeau P, Cocquempot C, Coeur d'Acier A, Dorkeld F, Migeon A, Navajas M, David M, Delipetrou P, Georghiou K, Desprez-Loustau ML, Didziulis V, Essl F, Galil BS, Hejda M, Jarosik V, Pergl J, Perglová I, Kühn I, Winter M, Kühn PW, Marcer A, Pino J, McLoughlin M, Minchin D, Panov VE, Pascal M, Poboljsaj K, Scalera R, Sedlácek O, Zagatti P (2010) How well do we understand the impacts of alien species on ecosystem services? A pan-European, cross-taxa assessment. Frontiers in Ecology and the Environment 8: 135–144. https://doi.org/10.1890/080083

Vilà M, Hulme PE (2017) Non-native Species, Ecosystem Services, and Human Well-Being. In: Impact of Biological Invasions on Ecosystem Services. Springer International Publishing, 1–14. https://doi.org/10.1007/978-3-319-45121-3_1

Vilà M, Gallardo B, Preda C, García-Berthou E, Essl F, Kenis M, Roy HE, González-Moreno P (2019) A review of impact assessment protocols of non-native plants. Biological Invasions 21: 709–723. https://doi.org/10.1007/s10530-018-1872-3

Vitule JRS, Freire CA, Vazquez DP, Nuñez MA, Simberloff D (2012) Revisiting the Potential Conservation Value of Non-Native Species. Conservation Biology 26: 1153–1155. https://doi.org/10.1111/j.1523-1739.2012.01950.x

van Wilgen BW, Richardson DM (2014) Challenges and trade-offs in the management of invasive alien trees. Biological Invasions 16: 721–734. https://doi.org/10.1007/s10530-013-0615-8

van Wilgen BW, Wilson JR (2018) The status of biological invasions and their management in South Africa in 2017. South African National Biodiversity Institute, Kirstenbosch and DST-NRF Centre of Excellence for Invasion Biology, Stellenbosch. https://doi.org/10.13140/RG.2.2.31003.52002

Zengeya T, Ivey P, Woodford DJ, Weyl O, Novoa A, Shackleton R, Richardson D, van Wilgen B (2017) Managing conflict-generating invasive species in South Africa: Challenges and trade-offs. Bothalia 47: 1–11. https://doi.org/10.4102/abc.v47i2.2160

Identifying, reducing, and communicating uncertainty in citizen science: a focus on alien species

Anna F. Probert[1], Daniel Wegmann[1], Lara Volery[1], Tim Adriaens[2], Rigers Bakiu[3], Sandro Bertolino[4], Franz Essl[5,6], Eugenio Gervasini[7], Quentin Groom[8], Guillaume Latombe[5,9], Dragana Marisavljevic[10], John Mumford[11], Jan Pergl[12], Cristina Preda[13], Helen E. Roy[14], Riccardo Scalera[15], Heliana Teixeira[16], Elena Tricarico[17], Sonia Vanderhoeven[18], Sven Bacher[1]

1. Department of Biology, University of Fribourg, Chemin du Musée 10, 1700, Fribourg, Switzerland.

2. Research Institute for Nature and Forest (INBO), Herman Teirlinckgebouw, Havenlaan 88 bus 73, B-1000 Brussels, Belgium.

3. Agricultural University of Tirana, Faculty of Agriculture and Environment, Department of Aquaculture and Fisheries, Koder-Kamez, Tirane, Albania.

4. Department of Life Sciences and Systems Biology, University of Turin, 10123 Torino, Italy

5. Bioinvasions, Global Change, Macroecology-Group, Department of Botany and Biodiversity Research, University Vienna, Rennweg 14, 1030 Vienna, Austria.

6. Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, South Africa

7. European Commission, Joint Research Centre, Ispra, Italy

8. Meise Botanic Garden, Meise, Belgium

9. Institute of Evolutionary Biology, University of Edinburgh, Edinburgh, EH9 3JT UK

10. Institute for Plant Protection and Environment, Belgrade, Serbia

11. Centre for Environmental Policy, Imperial College London, Silwood Park Campus, Buckhurst Road, Ascot, SL5 7PY, United Kingdom

12. Czech Academy of Sciences, Institute of Botany, CZ-252 43 Průhonice, Czech Republic

13. Ovidius University of Constanta, Al. Universitatii nr.1, Corp B, 900470 Constanta, Romania

14. UK Centre for Ecology & Hydrology, Benson Lane, Crowmarsh Gifford, OX10 8BB, United Kingdom

15. IUCN/SSC Invasive Species Specialist Group, Rome, Italy

16. CESAM - Centre for Environmental and Marine Studies, Department of Biology, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal

17. Department of Biology, University of Florence, Sesto Fiorentino (FI), Italy

18. Belgian Biodiversity Platform - Département du Milieu Naturel et Agricole – Service Public de Wallonie, Avenue Maréchal Juin 23 B-5030 Gembloux, Belgium

Anna F. Probert ORCID 0000-0003-4288-4716
Daniel Wegmann ORCID 0000-0003-2866-6739
Lara Volery ORCID 0000-0002-1876-4119
Tim Adriaens ORCID 0000-0001-7268-4200
Rigers Bakiu ORCID 0000-0002-9613-4606
Sandro Bertolino ORCID 0000-0002-1063-8281
Franz Essl ORCID 0000-0001-8253-2112
Eugenio Gervasini
Quentin Groom ORCID 0000-0002-0596-5376
Guillaume Latombe ORCID 0000-0002-8589-8387
Dragana Marisavljevic ORCID 0000-0002-1123-2427
John Mumford ORCID 0000-0001-8964-1784
Jan Pergl ORCID 0000-0002-0045-1974
Cristina Preda ORCID 0000-0002-3513-7344
Helen E. Roy ORCID 0000-0001-6050-679X
Riccardo Scalera ORCID 0000-0002-4100-3959
Heliana Teixeira ORCID 0000-0001-8525-9967
Elena Tricarico ORCID 0000-0002-7392-0794
Sonia Vanderhoeven ORCID 0000-0002-6298-5373
Sven Bacher ORCID 0000-0001-5147-7165

Abstract

1. Citizen science provides a unique opportunity to address questions beyond the scope of traditional research methods whilst simultaneously engaging communities in the scientific process. This leads to broad educational benefits, empowers people and can increase public awareness of societally relevant issues such as the biodiversity crisis. Given this, citizen science has become a particularly attractive framework for researching alien species where data on the presence, absence, abundance, phenology and impact of species is important in informing management decisions. However, uncertainties arising at different stages can limit the interpretation of data and lead to projects failing to achieve their intended outcomes.
2. We reviewed the literature and practices commonly performed in citizen science projects that address alien species, identifying the key research questions and the relevant uncertainties that arise during the process of developing the study design, i.e., collecting the data, and the statistical analyses. Additionally, we assessed uncertainties from a linguistic perspective, and how the communication stages among project coordinators, participants and other stakeholders can alter the way in which information may be interpreted.
3. Here, we identify major sources of epistemic and linguistic uncertainty aligning with the key research questions to guide future citizen science projects focused on alien species. We review existing methods for reducing uncertainty and suggest further solutions to improve data reliability. Specifically, we address uncertainty stemming from inaccurate data related to species detection and abundance data, including changes in their temporal trends. Overall, we make suggestions to reduce the uncertainties that emerge at each project step and provide guidance and recommendations that can be readily applied in practice.
4. We advocate that reducing uncertainties through appropriate project design and stages of communication is essential and necessary to strengthen the scientific and community outcomes of citizen science. This is of particular importance to ensure the success of projects aimed at detecting novel alien species and monitoring their dynamics across space and time.

Keywords: biodiversity monitoring; biological invasions; community science; data quality; epistemic uncertainty; linguistic uncertainty; non-native species

Introduction

Citizen science (also sometimes termed 'community science' or 'volunteer biological recording') refers to the form of scientific inquiry involving public participation, usually through collaborative initiatives between volunteers and professional scientists (Jordan et al., 2015). For most citizen science projects, the aims are broadly twofold: to generate scientific data, whilst simultaneously engaging and educating citizens with science and their environment. From a research perspective, public participation can benefit science, particularly in the stages of data collection and analysis, when practical caveats, such as lack of time, and economic or human resources, would represent a major constraint. This means that citizen science provides an alternative or complementary approach to address ecological questions that otherwise would be logistically challenging or unfeasible under the traditional scientific framework (Dickinson et al., 2012; Newman et al., 2012; Pergl et al., 2020). The scope and design of projects is usually determined by the primary objective, which may be more or less focused on generating scientific data or increasing education and community engagement, with the ultimate aim to lead to advances in both science and public understanding of science through a collaborative partnership between multiple sectors of society. The level of public participation can be considered a spectrum: whilst some projects are conceptualised and completed entirely by members of the public who may lack scientific backgrounds—such as community conservation groups (Peters et al., 2016)—others rely on a close partnership between citizens and professional scientists, or alternatively, may be driven by professional scientists, involving the public only in the data collection stage (Haklay, 2013; Pocock et al., 2015). These different models of project design, the respective levels of involvement of citizens and experts, and the skills and experience of participants can result in varying types and degrees of uncertainty, which has led to questions about the reliability of citizen science datasets (Aceves-Bueno et al., 2017).

Uncertainty is an inherent part of scientific research; however, the way it is identified, understood and handled can strongly influence the degree to which data may be interpreted and used (van der Bles et al., 2019). It manifests due to limited knowledge—usually from incomplete information in the data collection stage and subsequent analysis of data—as well as through imprecise language. Uncertainties in citizen science projects are often overlooked, sometimes completely ignored, and previous attempts to provide solutions usually only consider them from an analytical perspective, concentrating on only certain types of uncertainty (e.g., measurement error) (Bird et al., 2014; Jiménez et al., 2019). Although the uncertainties that arise using a citizen science approach do not differ from those under the more traditional framework of science, they may vary in magnitude, either negatively or positively. For instance, as citizen science usually increases the “data collection power”, such projects may be expected to capture the natural variation of large-scale phenomena better than small-scale projects led by professional scientists (Baker et al., 2019). On the other hand, by favouring quantity, some citizen science projects have higher rates of measurement error or increased data collection bias compared to other approaches (Crall et al., 2011; Gardiner et al., 2012). Additionally, the bias and associated uncertainty resulting from poor experimental design is rarely quantified and considered in the analyses. Citizen science projects therefore may underestimate the importance of setting a testable hypothesis and appropriate experimental design, which should consider trade-offs between data quality and data quantity; the design of citizen science projects is often a compromise between participation and data quality (Lewandowski & Specht, 2015). These characteristics of citizen science can limit the conclusions that can be drawn from the data obtained or lead to its misinterpretation. Further, uncertainty is seldom properly communicated, leading to misunderstandings, mistrust, and limiting data use from citizen science projects in decision-making (Vanderhoeven et al., 2017).

Data generated by citizens are now widely employed to monitor biodiversity and detect biological invasions in all environmental realms (Bois et al., 2011; Pearson et al., 2019; Perdikaris et al., 2017; Pusceddu et al., 2019; Stuart-Smith et al., 2017). This has been largely facilitated by the development of online tools, dedicated websites and smartphone applications that provide a simple and engaging way for citizen scientists to record their data (Adriaens et al., 2015; Giovos et al., 2019; Johnson et al., 2020; Rowley et al., 2019; Santori et al., 2021). In many cases, engaging citizens in the data collection process may be the only practicable way to conduct large-scale or long-term studies or gain access to, and collect data in, difficult-to-access sites (Lepczyk, 2005). As such, citizen science projects provide a practical tool for addressing invasion-related questions, particularly for post-border surveillance (Thomas et al., 2017) that require spatial, temporal, and/or phenological information (Roy et al., 2018). For instance, citizen science has been used to delimit the distribution of alien species, during both the early (Eritja et al., 2019; Hourston et al., 2015) and late (Bois et al., 2011; Crall et al., 2015) stages of invasion, to understand alien species' range expansions (Grason et al., 2018), as well as temporal emergence patterns (Maistrello et al., 2016) and even to reveal impacts on native biodiversity (Mori et al., 2019; Roy et al., 2012). Given that citizen science projects often capture data opportunistically—particularly in the form of presence-only data—they may harbour large uncertainties that must be accounted for in downstream analyses (Bird et al., 2014; Isaac & Pocock, 2015; Petersen et al., 2021). Additionally, the overall spatial and temporal data coverage from citizen science initiatives may be uneven; thus, failing to account for this could make findings less robust for use in decision-making on the prevention and management of alien species.

The way uncertainty is communicated (or not) may affect trust in citizen science outcomes and ultimately decision-making relying on citizen science data (van der Bles et al., 2019). Indeed, additional uncertainties may be introduced during the stage of communication. Many citizen science projects—though often implicitly—aim to achieve learning outcomes and increase the scientific literacy of their participants, which partly accounts for the engagement and motivation of volunteers (Jennett et al., 2016). The project design and methods need to be explained to participants for a thorough understanding of their role and to ensure these learning outcomes are achieved. This inherently includes communication on how specific aspects of project design, such as the way data are collected, relate to methodology to overcome biases and uncertainty. Furthermore, the endorsement of project results by other parties and societal actors, the credibility of the research, and the uptake of citizen science project results in decision-making, equally requires open and transparent communication to these stakeholders in ways to reduce uncertainty as well as suit the target audience and their aims (Groom et al., 2019; van der Bles et al., 2019).

We argue that to produce scientifically robust and society-relevant conclusions, projects must be carefully designed to identify and reduce potential sources of uncertainties. The analysis of the resulting data must adequately account for the remaining uncertainty, and the uncertainty associated with the findings must be effectively communicated. Here, we provide specific recommendations to help increase the robustness of ongoing and future citizen science research projects and to increase the reliability of their research outcomes. Considering the importance of citizen science in alien species research, we focus on the application of citizen science to biological invasions in support of decision-making. We (1) outline four common research aims citizen science projects address when studying different aspects of alien species, then (2) identify the relevant sources of epistemic and linguistic uncertainty in the process of conducting a citizen science project, and (3) provide suggestions on how to reduce and account for epistemic uncertainties based on project aims. Finally, we (4) provide recommendations for effective communication explicitly addressing uncertainty towards participants, stakeholders, and end-users of project results.

In this manuscript we distinguish between professional scientists/experts and citizen scientists/volunteer recorders, adopting this terminology. However, we recognise that the expertise among participants of citizen science projects will vary greatly; some citizen scientists may possess extensive knowledge relating to the study system and can indeed be considered experts that make more accurate and reliable observations, reducing data uncertainty. Further, whilst we acknowledge that citizen scientists often play an important role in the management of alien species, we do not cover this here. Rather, we focus on the data collection and subsequent analysis and the communication of research findings.

(1) Project aims and key questions addressed in citizen science projects on alien species

Across the field of alien species research, we recognise four key aims for citizen science projects which are largely driven by the need for information in decision-making on alien species policy and management. To answer these research questions, certain types of data must be generated; each of these can be subject to certain types of uncertainty meaning appropriate measures to reduce these should be considered.

(i) Presence and Distribution: The first aim relates to verifying the presence of an alien species in a geographic area, addressing the question "does species A occur here"? This is relevant in terms of both species detection (i.e., detecting new incursions or confirming absence after a management intervention) and delimiting species distributions. Engaging citizens in the surveillance of alien species means 'many eyes on the ground' and may facilitate early detection of novel species incursions (Ministry for Primary Industries, 2016; Thomas et al., 2017), which can be a critical factor in eradication success (Vander Zanden et al., 2010; Wotton et al., 2004; but see Pluess et al., 2012). The early detection of alien species has been aided using smartphone and web applications allowing citizens to submit species occurrences and obtain taxonomic verification in real-time (Moulin, 2020). Additionally, delimiting the distributions of some alien species has only been possible due to public participants reporting sightings, which in certain cases may be more effective than traditional biological monitoring techniques (Goldstein et al., 2014).

(ii) Abundance: The second aim relates to evaluating the abundance of a specific alien taxon in areas in which it is known to occur. Estimates of abundance can be useful to understand the impact of alien species (Parker et al., 1999; Sofaer et al., 2018) and are important data to plan and evaluate management interventions. For harmful alien species for which eradication is no longer possible, maintaining populations below an ecological damage threshold might provide the most cost-effective management solution if feasible (Green et al., 2014; Robertson et al., 2020). Defining such thresholds requires some form of damage-density relationship and abundance data. Abundance estimates are therefore important to inform the management of alien species (Bradley et al., 2018). Measurements may be in terms of either the density (i.e., how many alien individuals are there in a given area?) or relative abundance (i.e., how many alien individuals are there in relation to native species of concern, e.g., parasites on a host or a plant). Information on relative abundance may also help understanding whether only vagrant/casual individuals are present, or whether an established population occurs. Citizen science projects that simultaneously assess the abundance of alien and native species are especially informative to assess impacts of alien species on biodiversity (see point iv).

(iii) Trend: The third aim relates to questions regarding a change—in either the abundance or the spatial distribution of a species—by ensuring some components of the temporal or spatial variation are captured in the data. Citizen science projects can be particularly useful for research addressing spread dynamics over large spatio-temporal scales (Preuss et al., 2014; Roy & Brown, 2015), which would otherwise be unattainable. For instance, in Britain and Belgium researchers have been able to track the spread of the harlequin ladybird (*Harmonia axyridis*) with a large-scale citizen science survey (Adriaens et al. 2008; Brown et al., 2018). In Portugal and Italy, citizen science data revealed expansion rates of the Asian hornet (*Vespa velutina nigrithorax*) and the brown marmorated stink bug (*Halyomorpha halys*), respectively, facilitating the development of appropriate management strategies at the regional level (Carvalho et al., 2020; Maistrello et al., 2016). Given the predicted general increase in the number of alien species worldwide (Seebens et al., 2020) and the way projected climate change is expected to alter species distributions (Essl et al., 2019), citizen science data will certainly play a central role in informing future predictive models (Kress et al., 2018).

(iv) Impact: The fourth aim is an extension of assessing trends and relates to identifying the impacts of alien species. In cases where impacts are investigated, they are usually inferred from correlations with affected native species in terms of population trends, namely abundance, and distributional changes, or in some cases, other indirect measures such as numbers of dead trees or water quality (Colléony & Shwartz, 2020; Diamond & Ross, 2019; Guyot et al., 2015; Koenig et al., 2013; Roy et al., 2012). Such trends should be interpreted with caution as multiple causative agents of the decline of native species and populations may not be captured in the study (Byers, 2002), potentially leading to an overestimation of alien species impact. However, information on spatio-temporally co-occurring species, including species from the same guilds, host or food plants, overlapping phenology etc., is useful to assess potential impact of an invader. For instance, Adriaens et al. (2008) calculated niche overlap indices which informed ecological risk assessment for an invasive alien ladybird (Kenis et al., 2017). Future focus on the interactions between native and alien species may be more informative for discerning impacts of alien species, particularly alongside mechanistic experimental studies.

(2) Identifying the different sources of uncertainty in citizen science projects

Most citizen science projects follow a generalised process of scientific inquiry (Fig. 1). First, the occurrence of a phenomenon related to an alien species will initiate the motivation to ask a scientific question. Identifying this question and developing a study to investigate the phenomenon may be done before the data collection step, either by professional scientists, citizen scientists or through co-creation. Alternatively, data may already exist, for example in online biodiversity databases, in which case considering the steps prior to the stage of data analyses become less relevant as fewer sources of uncertainty may be controlled. After data have been gathered, they are analysed and interpreted, and ultimately communicated, for instance in the form of a report. For projects spanning longer temporal scales, information learnt during the process may be integrated into subsequent actions allowing the refinement and improvement of the different stages via a feedback loop.

Using the taxonomy of uncertainty outlined by Regan et al. (2002)—where uncertainty sources are classified as either *linguistic* or *epistemic* (Table 1)—we identify where different sources of uncertainty emerge during the process of scientific inquiry, in the context of citizen science for alien species research (Fig. 1). It is important to note that uncertainties arising at each step can propagate to the other research steps, and thus become compounded at the subsequent stages.

Linguistic uncertainty

During any step of the project that requires communication, uncertainty can manifest through imprecise language (from the communicator(s)) or misunderstanding (audience), leading to confusion and misinterpretation of messages (Fig. 1; Regan et al., 2002). Linguistic uncertainties are not mutually exclusive; that is, words and phrases may comprise more than one of the different types of linguistic uncertainties (Table 1). For example, a phrase may be simultaneously vague and ambiguous, or ambiguous and contain uncertainty due to lack of specificity. It is important to note that linguistic uncertainty from communicators can amplify subjective judgement (see section on epistemic uncertainties below) which arises due to the individual interpretation of information by the audience. Given that subjectivity refers to personal feelings and opinions rather than facts it may be fair to expect that inputs of subjective judgement will be magnified through the inclusion of many individuals during data collection when compared to projects under the traditional scientific framework.

The first step where linguistic uncertainties will initially be introduced is during the ‘Communication for data collection’ stage, where project coordinators will specify information pertaining to the project, such as the rationale behind the research and the methods in which they require participants to collect data. Under more traditional scientific frameworks, communication is usually restricted to far fewer data collectors that would be recruited based on their level of expertise to collect data and are usually provided with in-person training. The leveled expertise acquired through training and the lower number of people involved makes it easier to control for linguistic uncertainties. The subsequent step involving communication where linguistic uncertainty can arise is at the ‘Communication of the results’ step, when the findings of the project are communicated either in the form of a report or directly to an audience. The types of linguistic uncertainty relevant here only differ from other scientific projects in the sense that they might require communication to a broader audience. For instance, findings from citizen science projects addressing alien species may be published in academic journals or communicated by other means to decision makers and stakeholders. Most importantly, results and project conclusions should be communicated to all participants in a way that can be clearly understood regardless of their individual level of expertise and scientific knowledge (see section four).

A key consideration is that scientific terminology may be unfamiliar and interpreted differently by citizen scientists due to the uncertainty associated with technical terms and phrases. Indeed, similar problems arise within the use of natural language where definitions can have varying meaning due to cultural differences. This is particularly applicable to the invasion science lexicon which is known for its value-laden terminology in some contexts (Verbrugge et al., 2016). For example, although the terms 'alien', 'exotic' and 'non-native' are frequently used interchangeably, research has demonstrated that 'exotic' is more often perceived more favourably and associated with beneficial impacts (Kapitza el al., 2019). Thus, carefully selecting the terminology used will be important to consider for projects that involve individuals from wider geographical scales and particularly if projects necessitate information being translated into additional languages.

Epistemic uncertainty

In any scientific project, epistemic uncertainty is always present as natural variation in the observed phenomenon (Fig. 1; Table 1). Because citizen science projects can facilitate the collection of data over greater spatial and temporal scales due to the increased 'people power', such uncertainties may be better accounted for compared to other less-intensive studies. Whilst experts are thought to consistently collect high quality data with reduced measurement error, numerous studies have demonstrated citizens can have similar capabilities in terms of both accuracy and reliability (Crall et al., 2011; Kallimanis et al., 2017). However, this is highly dependent on the study system and research question at hand, given that some species will inherently be more difficult to detect and/or identify than others (Brandon et al., 2003; Forrester et al., 2015). Additionally, poorly communicated background information and instructions may lead to confusion and inconsistencies among citizen scientists during the data collection stage.

In all studies, epistemic uncertainty arises during the data collection. Here, these uncertainties will most notably arise in the form of measurement error, systematic error and subjective judgement (Fig. 1; Table 1). Compared to studies conducted under the more traditional scientific framework it might be expected that such uncertainties are amplified given the increased number of individuals contributing to data collection. In citizen science projects, there are more chances for individual observer-level error to be introduced during the data collection (e.g., misidentification of a species) and recording (e.g., incorrectly entering data into a spreadsheet). This introduces additional variation when compared to traditional methods linked to when, where and what volunteers record (Boakes et al., 2016). Furthermore, the introduction of subjective judgement may lead to taxonomic, geographic, and temporal biases. For instance, observer preferences for particular taxa—which can be influenced by culturally related preferences or individual interests (Ressurreição et al., 2012)—result in detection biases. In this sense, subjective judgement can create systematic error whereby individuals will intentionally include or exclude observations. Such biases have been demonstrated by Caley et al. (2020), who found citizen scientists tended to preferentially log opportunistic insect occurrence reports for species with more striking physical features. Similarly, citizen scientists may be more likely to visit some localities over others for various reasons, such as their proximity to home, ease of access or preference of habitat type (Petersen et al., 2021; Tye et al., 2017), leading to data with strong spatial biases (Geldmann et al., 2016). There may also be biases in the weather conditions or time of day and year when citizens collect the data (Baker et al., 2019); these spatial and temporal biases can lead to natural variation being poorly captured in the data, creating knowledge gaps (Regan et al., 2002). Additionally, Boakes et al. (2016) showed the recording behaviour itself can introduce bias which is considered separately from volunteer’s natural preferences for taxa and places. This is certainly relevant for the recording of high-profile invasive alien species which receive a lot of media coverage, are often well known to everyone and therefore have a higher recordability.

Subsequent forms of epistemic uncertainty arising post data-collection include model uncertainty during the stage of data analyses and additional subjective judgement arising when research findings are interpreted and communicated. Model uncertainty is inherent to all scientific research given the necessity to describe biological phenomena using simplifications. Every time we collect data to make inferences to describe the true state, natural variation leads to model uncertainty (Regan et al., 2002). Once data have been analysed, subjective judgement is generated by the project coordinators when they interpret data and communicate findings and when the audience (e.g., citizen scientists) interprets this information.

(3) Reducing uncertainty

All research will inevitably be associated with various forms of uncertainty; however, if these are appropriately considered—in terms of where and why they arise—different approaches may be taken to reduce the overall uncertainties that may be relevant when designing a project and during the downstream data analyses. We recognise that linguistic forms of uncertainty (Table 1) are of great importance given their ability to contribute to the emergence of subjective judgement among participants (see section above). Thus, our overall recommendation to reduce forms of linguistic uncertainty and subjective judgement in this context is to be mindful of the language during any stages where communication is involved. Specifically, avoiding the use of jargon-laden language where possible and in cases where this is unavoidable, providing simple, clear and concise definitions for scientific terms. Ideally, a reciprocal dialogue between participants and project coordinators should be established to allow citizen scientists to ask questions and clarify aspects they may not initially understand. In doing so, the communication approach may be refined in the future as the feedback is integrated into the project (Fig. 1).

Below, we focus and discuss different ways to reduce epistemic uncertainty by: i) increasing the quality of data generated by participants, ii) choosing an appropriate experimental design to account for uncertainty in the analyses, while we provide ii) specific examples to account for uncertainty.

i) Increasing quality of data generated by participants

The ability of citizen scientists to accurately collect data will depend largely on the question to be addressed. Some projects require participants to have more specific identification skills that may be improved through training or practice alone (Gallo & Waitt, 2011; Kampen et al., 2015; Starr et al., 2014). One major issue is that, generally, novice citizen scientists are more likely to misidentify or overlook species compared to professional scientists (Austen et al., 2016; Falk et al., 2019; Galloway et al., 2006), which can lead to uncertainty in single observations regarding species identification and presence at specific locations. The ability to accurately detect and identify species may vary significantly among citizen scientists depending on the individual skills of volunteer participants; for instance, some individuals may be amateur experts with abilities equal to professional scientists. Importantly, however, it should be noted that some biases may become more, or less, prevalent as the skill-level increases among participants. For instance, Farmer et al. (2012) found a tendency for more false positives of rare species to be recorded by participants with higher expertise. In contrast, Groom & Whild (2017) found false positives to be uniformly distributed among observers of different expertise, yet both studies reported higher frequencies of false positive detections for rarer species when compared to more common species. Increasing participants' observational skills, in the aim of reducing false negative and false positive detections, may be directly addressed by providing training and feedback (but see Feldman et al., 2018), although such an option is often not feasible for many citizen science projects. In some cases, the development of online tools to support learning may provide an accessible way to improve citizen science skills as well as to promote engagement and reach educational goals. Online tools that provide citizen scientists a platform to interact may also help to increase individual competencies through peer feedback.

Currently, the majority of citizen science projects focusing on the recording of alien species have a verification step, whereby data collected by participants (most often images or specimens) are confirmed by experts (Schade et al., 2019; Wiggins et al., 2011). For example, during a survey on 103 alien species citizen science projects in Europe, 89 projects indicated using validation procedures (Alien-CSI consortium, unpublished data). Generally, the most prominent approaches for validation of citizen science data are expert- and peer-validation, most often aided by automatic filtering techniques (e.g., through data mining algorithms, artificial intelligence) which can address random variation, such as outlier detection (Balázs et al., 2021; Wiggins et al., 2011). Model-based quality assessment can tackle errors using an explicit model of variation in space and time. For example, Kelling et al. (2015) indexed eBird observers variability using species accumulation curves to account for observer skill and improve data quality post-hoc. The relatively labour-intensive step of data verification is often necessary to ensure data quality, but future identification will likely become more efficient through the use of machine learning based on imagery, acoustics, and environmental DNA at both the individual and landscape-level (Demertzis et al., 2018; Demertzis & Iliadis, 2017; Kganyago et al., 2018; Milián-García et al., 2021; Terry et al., 2020).

ii) Choosing an experimental design that allows to estimate and account for errors

When considering the experimental design for a project where a citizen scientist will survey a specific location (or site) for the presence of an alien species, we can distinguish two types of observation errors (Fig. 2): the alien species is present but is not detected/identified (i.e., a false negative detection), or the alien species is not present but recorded due to misidentification or false reporting (i.e., a false positive detection). Although proper training can minimise these errors, they are unlikely to be eliminated and therefore need to be accounted for statistically, especially for species and life stages not easily identifiable. This is possible if the rates at which these errors occur are either known or can be learned from the data, with the possibility of the latter depending on the experimental design.

Error rates of any kind may only be learned from replicate data points. Take, for example, a citizen scientist visiting the same location multiple times. If the alien species is present at that location, the fraction of visits at which it was not detected provides information about the rate of false negatives.

Similarly, if a citizen scientist reports the alien species at several locations from which no other citizen scientist has ever detected it, that individual must either be superior at detection or otherwise misidentifies the species frequently. A key realisation from this is that error rates can only be learned properly if absence data are collected: if a citizen scientist only reports visits that resulted in an observation, the data contains no information about the probability of detection. In cases where absence data (i.e., non-detections) cannot be collected directly, an effort should be made to estimate them, for instance by estimating an observer's activity through reports of common species (for which an error rate can be assumed), the number of visits to a location, the length of a species list or other covariates (Lele et al., 2012).

In the case of high error rates, uncertainty may be reduced by focusing on hierarchical parameters, i.e., model parameters that govern other parameters of the model (Box 1). The reason is that for hierarchical parameters, many data points are collectively informative, and this information can be exploited if error rates are either known or can be estimated accurately from the data. The fraction of locations at which an alien species is present, for instance, may be estimated accurately, even if the presence at individual locations is highly uncertain (Box 1). When designing citizen science projects, we thus recommend identifying the most relevant hierarchical parameters and to choose an experimental design most suitable for those.

iii) Accounting for uncertainty: specific examples

In the following section, we will discuss approaches to learn and account for detection errors when assessing the distribution, abundance and trends of alien species, related to each of the key project aims identified above.

Distribution: We distinguish two experimental designs of citizen science projects to delineate the distribution of alien species. In the first design, citizen scientists are asked to report potential sightings of the alien species without being instructed where to look. In the second design, citizen scientists are asked to survey specific locations and to report whether or not the alien species was detected. These designs differ fundamentally in the error rates that may be learned. Since non-detections are not reported in the first design, no information on search effort is available, meaning we cannot infer error rates from these data alone. This is a general problem of presence-only data, and existing methods to infer species distributions from such data assume that error rates are predicted well by ecological covariates (Guisan et al., 2017). For rare alien species, however, environmental covariates may not be good predictors: their relatively recent introduction means they have likely only covered a small part of their environmental niche space. Inferring the spatial distribution of an alien species under such an experimental design thus requires the verification of reports and evidence by experts unless search effort can be estimated from other covariates such as reports of more common species, the number of visits, or the species list length (Isaac et al., 2014; Szabo et al., 2010).

By contrast, when non-detections are reported along with detections, error rates and species distributions can be estimated jointly. Occupancy models (MacKenzie et al., 2002) are the most frequently applied method to achieve this using citizen science data (Altwegg & Nichols, 2019; Dennis et al., 2017; van Strien et al., 2013). The measure of interest under these models is the distribution of presences (occupancy) or absences of a species at surveyed locations, which are learned while accounting for false negatives by explicitly modelling and learning detection probabilities. Under the assumption of no false positive detections, these detection probabilities are readily learned if locations were surveyed multiple times: if the alien species was detected at a location at least once, all surveys at that location that did not result in detections must be false-negatives (Box 2, MacKenzie et al., 2002).

Occupancy models may also account for variation in detection rates among observers. To learn individual detection rates, observers should conduct surveys at different locations. This is because if an observer surveys only a single location but never detects the target alien species, it may be because the alien species is not present at this location, or because the probability of the observer detecting the species is low (i.e., a high false-negative error rate). The latter would be concluded if the same observer reported non-detections at locations where others did spot the alien species. If such a design is not feasible, variation in detection rates may still be accounted for by modelling them as a function of covariates correlated with an observer's level of training, the search effort spent at a location (if reported), or both (Box 2, Johnston et al., 2018).

If the number of surveys per location is too low to accurately infer local presences or absences, hierarchical parameters may be learned. These typically include the fraction of locations at which an alien species is present, and ecological covariates predicting local presences and absences (Johnston et al., 2018). Compared with other species, however, the latter may be less useful for recently introduced alien species as their distribution may be less determined by characteristics of the environment but more by their introduction history and patterns of dispersal.

Classic occupancy models generally assume no false-positives or that false-positive rates are known. The reason is that false positives cannot be distinguished from true positives from reported detections alone. However, false-positives are common in citizen science data, particularly for studies that aim at detecting recently introduced and hence rare alien species that are therefore easily misidentified (Groom & Whild, 2017). To learn false-positive rates in an occupancy setting, additional information must be available, either in the form of ground-truth at a subset of locations, or confirmed detections (e.g., by requesting to upload pictures of the observed individual(s) (Chambert et al., 2015; Vantieghem et al., 2017). The latter approach may be particularly appealing for citizen science data of recent invasions in which false-positive rates are likely high, but a fair number of reported detections can be confirmed by experts.

Abundance: Inferring abundance is generally more challenging than occupancy because, in the absence of false positives, a single detection is sufficient to identify a location as occupied, but a single detection may indicate a low abundance, a low detection probability, or both. If detection rates are low, however, variation in the frequency of detections at a location does provide information about variation in abundances between locations. The Royle-Nichols model (Royle & Nichols, 2003), for instance, captures this information by assuming detection rates to scale exponentially with abundances. These models require the same experimental design as classic occupancy models: observers must report absences and ideally survey multiple locations, including some also surveyed by others. If the latter is not possible, covariates indicative of the level of training of observers should be collected.

If an abundance survey is targeted to locations at which the alien species is expected to be common (i.e., there are numerous individuals), most visits might result in detections. In these cases, simple presence-absence data are not sufficient to distinguish locations. Rather, observers should provide an estimate of abundance. These estimates may be from direct observations such as the number of individuals or a measure of vegetation cover, biomass or density, or from indirect observations such as the number of nests, the presence or frequency of faeces or tracks, or a browsing index. The aforementioned count data, however, do not lend themselves easily to infer error rates as the parameters regarding abundances and detection probabilities are confounded: a low abundance location surveyed with a high detection probability may result in the exact same number of observations as a high abundance location surveyed with a low detection probability. As a result, joint estimates of abundances and detection probabilities are associated with large uncertainty, even from a large number of replicates (DasGupta & Rubin, 2005, Box 3, Fig. 5A). As we show in Box 3, it may therefore be advisable to infer relative abundances only, as these can be learned more accurately and jointly with relative detection probabilities if observers visit multiple locations or if relative detection probabilities are well characterised by covariates.

Trend: Of interest may be both trends in the distribution and trends in the abundance of an alien species. Common to both is that changes in the effective search effort between surveys must be accounted for. For instance, if a citizen science project is successful in acquiring new participants, or if the participants gained additional experience in detecting the target species, an increase in the number of reported detections may not necessarily reflect an increase in the abundance of that species. A statistical approach to infer population trends must thus account for temporal variation in the effective search effort, either by modelling it explicitly or through informative covariates such as the number of active citizen scientists or their rate in reporting more common species whose abundance is assumed not to change through time.

For repeated survey data resulting in reported detections and non-detections, occupancy models can be extended to trends in distributions explicitly with two additional parameters: the rate at which an alien species colonised previously non-occupied locations, and the rate at which it gets extinct at previously occupied locations (MacKenzie et al., 2003). Similarly, Royle-Nichols models can be extended to detect trends in species abundances by explicitly modelling population growth (Dail & Madsen, 2011; Hostetler & Chandler, 2015). These so-called multi-season models require generally similar experimental designs as their single-season analogues, but they differ in one key aspect: a design in which observers survey a single location is permissible, even if their level of training is not well reflected by covariates. The reason is that while observers vary in their detection probabilities, information about a change in occupancy state is contained also in the data of a single observer visiting the same location repeatedly, allowing for error rates to be integrated out (Link & Saur, 1997).

This is also true for surveys in which citizen scientists report direct or indirect estimates of abundances: regardless of the detection probability of an observer, a change in abundance translates into a change in the expected reported abundances (with the exception of a detection probability of 0). Link & Saur (1997) introduced such trend models for direct or indirect observations well characterised by Poisson processes (including the negative-binomial distribution for overdispersed data), for which Aebischer et al. (2020) recently introduced an analytical Bayesian solution. Most count data are well characterised by Poisson processes, and importantly including from surveys in which citizen scientists report all detections without surveying specific locations. While such a design does not allow for easy estimation of error rates (see above), it may still result in an accurate inference of population trends, as we discuss in Box 4. A common drawback of existing methods to infer trends in abundance is their assumption of no false-positives. While citizen science protocols involving expert or community-based validation procedures may reduce false-positives to a minimum (Schade et al., 2019; Wiggins et al., 2011), we identify the development of methods that explicitly account for false positives as an important area of future research.

(4) Communicating uncertainty to participants and other stakeholders

Effective communication should be considered a central component of all citizen science projects (Garbarino & Mason, 2016). It is necessary to achieve project objectives which will be different for the various actors involved (e.g., citizen scientists, professional scientists, managers, policymakers and other stakeholders). In the context of alien species, clearly communicating is not only important in the recruitment, engagement, motivation and retention of participants (Dickinson et al., 2012), but can be instrumental for the success of any management decisions (Falk et al., 2016). Highlighting the extent to which the data collected are used may be relevant to strengthen the engagement of citizens in such projects. In a complementary way, there is an interest in communicating towards stakeholders and decision-makers in particular, to make them understand how much added value there is in taking into account data from citizen science as an element of evidence. These two aspects can act in synergy and reinforce each other (Groom et al., 2019). Effective communication during the early stages (i.e., the recruitment of participants and data collection before it becomes routine) will require an explanation of the aims and importance of the project. Participants should be made aware about what their contribution may lead to (e.g., eradication or management of a species, research to underpin management decisions, research on invasion dynamics or impacts of alien species) given the potential for individual participants to oppose management methods and outcomes. Instructions for participants should be clearly explained to reduce the potential for miscommunication and improve data quality throughout the project. Importantly, by understanding the way in which messages can become misconstrued, we can minimise additional uncertainties that may emerge during communication.

Central to effective communication is establishing a reciprocal dialogue between project coordinators and participants, taking into account that this should ideally be based on a two-way process (Shackleton et al., 2019). Sustained engagement throughout the project, where participants are able to provide feedback and ask questions, enables project coordinators to refine their approach to identified issues, which need to be tackled to reach the intended educational, engagement and research outcomes (Druschke & Seltzer, 2012). In recent years a number of communication best practice guidelines have become available to project initiators (e.g., Veeckman et al., 2019).

Objective and efficient dissemination of research findings and the associated uncertainty (in a way that reduces the potential for the audience to misinterpret and potentially misuse information) should be a central aim of citizen science initiatives. Communicating with participants by providing feedback and presenting the research findings and their implications is an important obligation of project coordinators working within the citizen science framework (Vries et al., 2019). As project results, particularly regarding alien species, may be relevant to policymakers and managers (Groom et al., 2019; Lioy et al., 2019), the approach used to communicate findings and their uncertainty may require adaptation based on the intended audience (e.g., project participants, scientists, the general public or decision-makers).

Following a framework of uncertainty communication outlined in van der Bles et al. (2019), we identify the different components to consider when developing research and communication strategies in citizen science projects.

Who is communicating to whom?

A key element to acknowledge is how the relationship between communicator(s) and the audience can influence how uncertainty is perceived. The audience may come from culturally diverse backgrounds, hold different values and motivating factors, and have a varying degree of numerical and scientific literacy skills (Ganzevoort et al., 2017; Wright et al., 2015). Thus, although there may not be a one-size-fits-all approach to the form in which uncertainty is communicated, one should consider what is being communicated to whom. For instance, the relationship between the communicator(s) and the audience can be important from the perspective of whether the information being received and the person/organisation conveying it are considered trustworthy (van der Bles et al., 2019). Trust of the audience in the communicator is of utmost importance as the lack of trust will lead to a defensive stance or rejection even if the messages are true (Tuler & Kasperson, 2013). This highlights the importance of selecting communicators based on their reputation with the audience and their ability to effectively engage with participants. Some projects aimed at large-scale participation may warrant the use of professional science communicators, and/or public figures of endorsement, to be involved or consulted during the out-reach phases of projects to build rapport, encourage participation and continued involvement in the project. More targeted projects may benefit from involving individuals with greater relatability with participants during communication stages. For example, if an alien species has a much greater probability of establishing within agricultural landscapes, involving one or more local farmers to act alongside project coordinators in a communication role may facilitate improved project outcomes. This could be particularly important if implications of the research may lead to management actions that require landowner support. Another option is to use project ambassadors i.e., people from the citizen science community itself acting as role models for other participants and helping in promotion and community building (Druschke & Seltzer, 2012).

What is being communicated?

Identifying exactly what we are uncertain about is necessary to then determine the way in which it should be communicated (van der Bles et al., 2019). Here, it should be noted that both the information that we are uncertain about and how it is expressed can influence the effect of the communication to the audience. When the data has the potential to be used for a specific purpose in decision making processes, it is important to have a good understanding of the information needs, how and to what extent the consideration of uncertainty may influence the decision making and steer the decisions. This helps to identify what needs to be communicated.

For citizen science projects that address aspects of alien species, uncertainty will stem from whether the collected data adequately captures the information required to answer the specific research question(s). Effectively, identifying the types of uncertainty that need to be communicated can help to determine how best to do so. For instance, does the uncertainty arise because of sampling variation across space or time (i.e., the experimental design), or rather because there is a lack of knowledge around the biology and dynamics of a given species (i.e., there is a general knowledge gap)? Further, how large are these uncertainties and how does that affect our confidence in the results? Different analytical techniques can be applied to derive measures of certainty around the data that is usually expressed through probability distributions or qualitative statements and may be communicated through various forms of graphical visualisations such as error bars and confidence intervals (Padilla et al., 2021). Identifying exactly what the source of uncertainty is will help to guide appropriate ways to communicate it and can affect how information is perceived (see below). Communicating these identified uncertainties to participants/stakeholders in a clear and transparent manner is critical to create and maintain trust in the results and the people who participated in the project. Importantly, potential conflicts of interest should be explicitly stated as participants may be sceptical of findings if they perceive a biased agenda.

To what effect?

The effect to which uncertainty is communicated will vary among the audience. This is due to the strongly subjective nature of interpreting informing, based on not only what the message is but also in the medium of format in which it is conveyed (van der Bles et al., 2019). For instance, the various ways that uncertainty is visualised (e.g., error bars around a mean, boxplots etc.) are not consistently understood among people (Padilla et al., 2021). This can be shaped by the elements we previously mentioned; however, as subjective judgement arises due to the interpretation of information, we may reduce this form of uncertainty to some degree if messages are conveyed in a clear and understandable way. Again, having a good understanding of the knowledge needs and potential purpose of the data allows you to properly shape the communication and thus maximise its effects.

When communicating project findings, care must be taken to not present information in a misleading way, for example, with unfounded certainty (by downplaying the uncertainty) that may undermine project outcomes in the long term (e.g., engagement and empowerment of citizens) and produce public distrust. Given that citizen science projects on alien species may have management implications, which can be highly contentious (Crowley et al., 2019; Friedel et al., 2011; Zengeya et al., 2017), presenting an objective interpretation of research findings will produce the most beneficial outcomes for the project, but also ultimately for public trust in science in general. If the research findings lead to recommendations, it is also important to communicate the level of uncertainty that is relevant for the decision (Fischhoff & Davis 2014), e.g., if uncertainty around a measurement of alien species abundance does not affect the recommendation for its management. Although policies and practices related to the management of alien species are intrinsically value-driven and will therefore strongly influence how messages transmitted are received (Reaser, 2001), communicating transparently will establish and maintain trust to the benefit of citizen science in general. In dealing with uncertainty, communicators also grapple with the issue of credibility. Acknowledging uncertainty and explicitly communication on uncertainty will increase the perceived trustworthiness of the data (Lundgren & McMakin, 2018).

Conclusions

We recognise that citizen science plays a steadily growing role in the understanding, and ultimately in the prevention and management, of future biological invasions and in the ongoing monitoring of already established alien species. Citizen science projects provide opportunities to capture information that would otherwise be difficult to record, usually due to high costs and efforts associated with data collection. They mutually benefit science and society, expanding scientific knowledge and improving science literacy among the general public. However, data generated from citizen science projects may be associated with varying degrees of uncertainties. These should be adequately acknowledged and addressed in the project design. Neglecting to address these uncertainties, particularly when communicating with participants, stakeholders, managers, and policy- and decision-makers can decrease overall confidence in the results, leading to inappropriate management decisions and public scepticism. Effective uncertainty communication (Box 5) creates a more informed public, empowers citizens in the decision-making process and leads to better uptake of management decisions.

Box 1: Inferring hierarchical parameters

As an example, consider a project in which citizen scientists report detections and non-detections of an alien species at a large number of locations. Rather than inferring whether a location is occupied (i.e., the alien species is present) for each location individually, such data may be modelled using hierarchical parameters that govern the distribution of occupied locations. For instance, one might introduce the hierarchical parameter ψ that reflects the fraction of locations that are occupied.

To illustrate this, consider a project in which citizen scientists visit L locations m times each. Let d_i reflect the number of visits at location $l = 1, \dots, L$ that resulted in a detection, and the remaining $m - d_l$ in a non-detection. Let us further denote by z_l wheter location l is occupied ($z_l = 1$) or not ($z_l = 0$) and by ϵ_{10} and ϵ_{01} the false negative and false positive detection rates, respectively. Under this model,

$$P(d_l|z_l, \epsilon_{01}, \epsilon_{10}) = \begin{cases} \binom{m}{d_l} \epsilon_{10}^{d_l}(1-\epsilon_{10})^{m-d_l} & if\ z_l = 0, \\ \binom{m}{d_l} (1-\epsilon_{01})^{d_l}\epsilon_{01}^{m-d_l} & if\ z_l = 1. \end{cases}$$

As an example, we consider the case with $m = 5$ visits per location, $\epsilon_{01} = 0.1$ and $\epsilon_{10} = 0.7$. As shown in Fig. 4, accurately identifying occupied locations is difficult under these parameters: the most likely data at occupied locations is $d_l = 1$, which is almost equally likely to get at non-occupied locations as well.

To infer the hierarchical parameters ψ, ϵ_{01} and ϵ_{10}, we integrate out z_l to obtain the relevant likelihood

$$P(d|\psi, \epsilon_{01}, \epsilon_{10}) = \prod_{l=1}^{L}[P(d_l|z_l = 0, \epsilon_{01}, \epsilon_{10})(1-\psi) + P(d_l|z_l, = 1\epsilon_{01}, \epsilon_{10})\psi].$$

In Fig. 4, we show Bayesian estimates of the parameters ψ, ϵ_{01} and ϵ_{10} from data simulated at $L = 100$, $L = 1{,}000$ or $L = 10{,}000$ locations, confirming that these hierarchical parameters can be inferred rather accurately if sufficient locations were surveyed.

Box 2: Occupancy models for citizen science data

Let z_l denote whether site $l = 1, \ldots, L$ is occupied ($z_l = 1$) or not ($z_l = 0$) and y_{lv}whether the species was detected ($y_{lv} = 1$) or not ($y_{lv} = 0$) during visit $v = 1, \ldots, V$ at site l. If the site is occupied, the species is detected with probability p_{lv} such that $P(y_{lv} = 1|z_l, p_{lv}) = p_{lv} z_l$.

The detection probability p_{lv} cannot be estimated for each site and visit individually, but it can be estimated if data from multiple visits are pooled. One way to achieve this is by modeling p_{lv} as a function of site and observer specific covariates:

$$\text{logit}(p_{lv}) = \beta_{o_v} + \boldsymbol{\beta}\boldsymbol{x}_l,$$

where β_{o_v} is the observer specific intercept of observer o_v that conducted visit v, $\boldsymbol{x}_l$ a vector of sites-specific covariates with associated coefficients $\boldsymbol{\beta}$. To pool information about occupancy across sites, it is further often assumed that the probability of occupancy $P(z_l = 1|\psi_l) = \psi_l$ is a function of environmental covariates

$$\text{logit}(\psi_l) = \alpha_0 + \boldsymbol{\alpha}\boldsymbol{y}_l \text{ ,}$$

where $\alpha_0$is an intercept, $\boldsymbol{y}_l$ a vector of site-specific covariates with associated coefficients $\boldsymbol{\alpha}$**.** Here, α_0, $\boldsymbol{\alpha}$**,** β_O and $\boldsymbol{\beta}$ are parameters estimated from the data.

Many alternative choices of covariates are possible. If individual observers conducted too few visits to learn their detection probabilities individually, p_{lv} may be modelled as a function of observer covariates related to expertise (e.g., Johnston et al., 2018).

Box 3: Estimating relative abundances

Consider a survey designed to quantify the abundances N_l at locations $l = 1, \dots, L$ from abundances reported by observers $j = 1, \dots, J$ from a total of V visits. Let d_v denote the reported abundance during visit $v = 1, \dots, V$ conducted at location l_v by observer o_v. Here, d_v is affected by both the abundance N_{l_v} at location l_v as well as by the detection probability p_{o_v} of observer o_v such that

$$P\left(d_v \middle| N_{l_v}, p_{o_v}\right) = \binom{N_{l_v}}{d_v} {p_{o_v}}^{d_v} (1 - p_{o_v})^{N_{l_v} - d_v}$$

is given by binomial sampling. Since N_{l_v} and p_{o_v} are confounded, estimating them individually is difficult (DasGupta & Rubin, 2005). To illustrate this, consider a case with two locations with $N_1 = 100$ and $N_2 = 200$ surveyed $m = 5$ times each by a single observer with detection probability $p = 0.2$. As shown in Fig. 5A, the uncertainty associated with abundance estimated from that data under mild priors $N_1, N_2 \sim \mathrm{Exp}(0.001)$ spans about two orders of magnitude. This is because the data is well explained by pretty much any abundance if paired with a corresponding detection probability and more informative priors would be required to constrain the range of possible values. However, there is considerable evidence that N_2 is about twice N_1 (Fig. 5B), illustrating that relative abundances may be learned accurately from such surveys.

To generalize the inference of relative abundances to many locations, let us assume that the abundances $N_l = N_0 e^{\rho_l}$ are scaled by location-specific factors $\rho_l \sim N(0, \sigma_\rho^2)$ that are themselves normally distributed with mean zero variance σ_ρ^2. Similarly, we assume that the detection probabilities $p_j = \mathrm{logistic}(\pi_0 + \pi_j)$ are scaled by observer-specific effects $\pi_j \sim N(0, \sigma_\pi^2)$ that are also normally distributed with mean zero and variance σ_π^2. Here, the logistic transformation ensures $0 \leq p_j \leq 1$. We further enforce the conditions $\frac{1}{L}\sum_i \rho_l = 0$ and $\frac{1}{J}\sum_j \pi_j = 0$ by scaling N_0 and p_0 accordingly. If observers do not visit multiple locations, the π_j need to be modelled using informative covariates.

We conducted simulations with $N_0 = 100$, $\sigma_\rho^2 = 0.2$, $\pi_0 = -1$ and $\sigma_\pi^2 = 0.5$, corresponding to an average detection probability $p_0 = \mathrm{logistic}(\pi_0) = 0.27$. As shown in Figs. 5C and 5D neither N_0 nor p_0 can be inferred accurately, regardless of whether $L = 20$ or $L = 100$ locations were surveyed by $J = 20$ or $J = 100$ observers visiting $m = 5$ different locations each, corresponding to $V = 100$ and $V = 500$ visits, respectively. In contrast, the relative abundances are estimated well, and easily distinguish locations with high from those with low abundances (Figs. 5E and 5F).

Box 4: Inferring trends in abundances

We consider a design in which citizen scientists are reporting GPS locations of all detections. We further assume that there exists some information proportional to the spent search effort, such as the time citizen scientists spend looking for the alien species or the number of reports of a commonly detected species. Let us denote by $d_{lj}(t)$ the number of detections reported by observer $j = 1, \dots, J$ during survey t in a specific area $l = 1, \dots, L$, for instance a specific cell of a geographic grid, and let $s_{lj}(t)$ be a measure proportional to the search effort spent by observer j in that area. Under such a design, n_{lj} is likely well characterized by a Poisson distribution $n_{lj} \sim \text{Pois}(\lambda_{lj}(t)s_{lj})$ with unknown rates $\lambda_{lj}(t)$. Note that these rates are affected by the abundance at location i as well as the detection probability of observer j at that location, itself a potentially complex function of the training of an observer as well as characteristics of the location (e.g. vegetation).

Assuming that the detection probabilities are constant across surveys ($\lambda_{lj}(t_1) = \lambda_{lj}(t_2)$), a change in the rates is reflective of a change in abundances. The interest therefore lies in inferring changes in the rates, which are independent of location or observer-specific characteristics. For a case of two surveys at t_1, t_2, we thus have $\lambda_{lj}(t_2) = \phi\lambda_{lj}(t_1)$ and wish to infer ϕ from the data of all observers and all locations. Following Aebischer *et al.* (2020), conditioning on the number of observations $n_{lj} = d_{lj}(1) + d_{lj}(2)$ leads to the likelihood

$$P(\boldsymbol{d}|\phi, \boldsymbol{n}) \propto \prod_{l=1}^{L}\prod_{j=1}^{J} p_{lj}(\phi)^{d_{lj}(t_1)}(1 - p_{lj}(\phi))^{d_{lj}(t_2)}$$

with $\boldsymbol{d} = (d_{11}, \dots, d_{1J}, \dots d_{LJ})$, $\boldsymbol{n} = (n_{11}, \dots, n_{1J}, \dots, n_{LJ})$ and

$$p_{lj}(\phi) = \frac{\lambda_{lj}(1)s_{lj}(1)}{\lambda_{lj}(1)s_{lj}(1) + \phi\lambda_{lj}(1)s_{lj}(1)} = \left(1 + \frac{s_{lj}(2)}{s_{lj}(1)}\phi\right)^{-1}$$

Box 4 cont:

Importantly, this formulation gets rid of the nuisance parameters $\lambda_{ij}(t)$. Note further that no absolute estimates of search efforts are required: since only their ratio is relevant, any quantity proportional to the search effort will do. The posterior distribution of ϕ is readily inferred under Jeffrey's prior (Aebischer et al. 2020).

To illustrate this approach, we simulated data for observers that each surveyed a unique location during two consecutive surveys. As each location was surveyed by a single observer, detection probabilities and the abundances cannot be inferred individually without strong assumptions about their distribution (there are less data points than unknowns). However, a trend in abundance may still be identified. To show that, we simulated observers $j = 1, \dots, J$ with detection probabilities $p_j \sim \mathrm{Beta}(0.01, 10)$, their search efforts as $s_j(t) \sim \mathrm{Exp}(0.1)$ and the abundances at their location as $N_j(t_1) \sim \mathrm{Pois}(10)$. Data simulated this way resulted in reported abundances $d_j(t_1) = 0$ in $> 99\%$ of all surveys, representative for citizen science projects targeting rare alien species. We then identified the power to detect a decreasing trend with $\phi = 0.5$, 0.9 or 0.95 for different number of observers (and corresponding locations). As shown in Fig. 6, trends are reliably identified if sufficient observers participate, with stronger declines generally easier to identify. Obviously, higher detection probabilities, higher abundances or larger search efforts would all result in higher reported abundances and render trend identification easier. In case the assumption of constant detection rates it not possible, covariates accounting for variation can be folded into $s_{lj}(t)$ (Link & Saur 1997).

Box 5: Key messages for effective uncertainty communication

Uncertainty is an inherent part of the scientific process and will persist to some degree regardless of the approach. The understanding and extent of uncertainty, particularly in relation to our confidence in the results, is critical to open and transparent communication of scientific findings.

Set up your aims: Establish and communicate a clear objective and indicators of success.

Know your audience: Define the target audiences, understand their values and motivations, identify their needs and potential agenda, and understand how uncertainty may steer the decision-making process and the decisions. Adapt your message and communication approach accordingly.

Avoid jargon: Keep the usage of jargon to a minimum and explain scientific terms clearly.

Train participants: Ensure participants have adequate instructions and understanding so providing benefits through democratisation of science by increasing scientific literacy while also reducing errors and uncertainty.

Develop a reciprocal dialogue: Communication should occur between project coordinators and citizen scientists. Channels for easy communication should be set up and encouraged by project organisers.

Ask for feedback: Actively seek discussion and feedback throughout the communication effort. This will help determine where potential misunderstandings may be arising.

Acknowledge uncertainty and communicate about it explicitly: Discuss the sources of uncertainty, explain why it exists, describe what, if anything, can be done to manage it better. Explain the level of uncertainty that is relevant for decision-making.

Build trust with your audience: Be honest, transparent and unbiased in communicating with your audience. Trust between communicator and audience is essential for effective communication.

Share your stories: We can improve our application of citizen science to biodiversity studies by highlighting the successes and, importantly, failures of projects while also sharing the excitement of the collaborative outcomes.

Acknowledgements: This article is based upon results from a workshop supported by COST Action CA17122 (Increasing understanding of alien species through citizen science), supported by COST (European Cooperation in Science and Technology). We thank Anne Marthe van der Bles for her participation and contribution to the workshop. SB, AFP and LV acknowledge funding from the Swiss National Science Foundation (grant number 31003A_179491) and SB acknowledges additional funding by the Swiss National Science Foundation (grant number 31BD30_184114) and by the Belmont Forum—BiodivERsA International joint call project InvasiBES (PCI2018-092939). JP was partly supported by 19-28807X (Czech Science Foundation) and long-term research development project RVO 67985939 (Czech Academy of Sciences). QG and TA acknowledge funding from the Belgian Science Policy Office's Brain program (BelSPO BR/165/A1/TrIAS). HT thanks FCT/MCTES for financial support to host institution CESAM (UIDB/50017/2020+UIDP/50017/2020). FE and GL acknowledge funding by the 2017-2018 Belmont Forum and BiodivERsA joint call for research proposals, under the BiodivScen ERA-Net COFUND programme, and with the funding organisation FWF ("AlienScenarios", project no I 4011-B32). HER was supported by the Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCAPE programme delivering National Capability.

Authors' contribution statement:

AFP, DW, LV and SB organized the workshop from which this manuscript derived. All authors contributed to the development of concepts and ideas during the workshop. AFP, DW, LV and SB developed the initial manuscript. AFP and DW led the writing. All authors contributed critically to all the drafts and gave final approval for publication.

Conflict of interest statement:

The authors declare no conflict of interest.

Data availability statement:

There is no data associated with this paper.

References:

Aceves-Bueno, E., Adeleye, A. S., Feraud, M., Huang, Y., Tao, M., Yang, Y., & Anderson, S. E. (2017). The Accuracy of Citizen Science Data: A Quantitative Review. *The Bulletin of the Ecological Society of America*, *98*(4), 278–290. https://doi.org/10.1002/bes2.1336

Adriaens, T., G. Gomez, and D. Maes. 2008. Invasion history, habitat preferences and phenology of the invasive ladybird *Harmonia axyridis* in Belgium. BioControl 53:69-88. https://doi.org/10.1007/s10526-007-9137-6

Adriaens, T., Sutton-Croft, M., Owen, K., Brosens, D., van Valkenburg, J., Kilbey, D., Groom, Q., Ehmig, C., Thürkow, F., Van Hende, P., & Schneider, K. (2015). *Trying to engage the crowd in recording invasive alien species in Europe: Experiences from two smartphone applications in northwest Europe*. https://doi.org/10.3391/mbi.2015.6.2.12

Aebischer, T., Ibrahim, T., Hickisch, R., Furrer, R. D., Leuenberger, C., & Wegmann, D. (2020). Apex predators decline after an influx of pastoralists in former Central African Republic hunting zones. *Biological Conservation*, *241*, 108326. https://doi.org/10.1016/j.biocon.2019.108326

Altwegg, R., & Nichols, J. D. (2019). Occupancy models for citizen-science data. *Methods in Ecology and Evolution*, *10*(1), 8–21. https://doi.org/10.1111/2041-210X.13090

Austen, G. E., Bindemann, M., Griffiths, R. A., & Roberts, D. L. (2016). Species identification by experts and non-experts: Comparing images from field guides. *Scientific Reports*, *6*(1), 33634. https://doi.org/10.1038/srep33634

Baker, E., Jeger, M. J., Mumford, J. D., & Brown, N. (2019). Enhancing plant biosecurity with citizen science monitoring: Comparing methodologies using reports of acute oak decline. *Journal of Geographical Systems*, *21*(1), 111–131. https://doi.org/10.1007/s10109-018-0285-2

Balázs, B., Mooney, P., Novákov, E., Bastin, L., & Arsanjani, J. J. (2021). Data Quality in Citizen Science. In K. Vohland, A. Land-Zandstra, L. Ceccaroni, R. Lemmens, J. Perelló, M. Ponti, R. Samson, & K. Wagenknecht (Eds.), *The Science of Citizen Science*. Springer International Publishing.

Bird, T. J., Bates, A. E., Lefcheck, J. S., Hill, N. A., Thomson, R. J., Edgar, G. J., Stuart-Smith, R. D., Wotherspoon, S., Krkosek, M., Stuart-Smith, J. F., Pecl, G. T., Barrett, N., & Frusher, S. (2014). Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation*, *173*, 144–154. https://doi.org/10.1016/j.biocon.2013.07.037

Boakes, E. H., Gliozzo, G., Seymour, V., Harvey, M., Smith, C., Roy, D.B., Haklay, M. (2016). Patterns of contribution to citizen science biodiversity projects increase understanding of volunteers' recording behaviour. Sci. Rep. 6, 33051; doi: 10.1038/srep33051 (2016).

Bois, S. T., Silander, J. A., & Mehrhoff, L. J. (2011). Invasive plant atlas of New England: the role of citizens in the science of invasive alien species detection. *BioScience*, *61*(10), 763–770. https://doi.org/10.1525/bio.2011.61.10.6

Bradley, B. A., Allen, J. M., O'Neill, M. W., Wallace, R. D., Bargeron, C. T., Richburg, J. A., & Stinson, K. (2018). Invasive species risk assessments need more consistent spatial abundance data. *Ecosphere*, *9*(7), e02302. https://doi.org/10.1002/ecs2.2302

Brandon, A., Spyreas, G. R., Molano-Flores, B., Carroll, C., & Ellis, J. (2003). Can volunteers provide reliable data for forest vegetation surveys? *Natural Areas Journal*, *23*(3), 254–261.

Brown, P. M. J., Roy, D. B., Harrower, C., Dean, H. J., Rorke, S. L., & Roy, H. E. (2018). Spread of a model invasive alien species, the harlequin ladybird *Harmonia axyridis* in Britain and Ireland. *Scientific Data*, *5*(1), 1–8. https://doi.org/10.1038/sdata.2018.239

Byers, J. E. (2002). Impact of non-indigenous species on natives enhanced by anthropogenic alteration of selection regimes. *Oikos*, *97*(3), 449–458. https://doi.org/10.1034/j.1600-0706.2002.970316.x

Caley, P., Welvaert, M., & Barry, S. C. (2020). Crowd surveillance: Estimating citizen science reporting probabilities for insects of biosecurity concern. *Journal of Pest Science*, *93*(1), 543–550. https://doi.org/10.1007/s10340-019-01115-7

Cardoso, A. C., Tsiamis, K., Gervasini, E., Schade, S., Taucer, F., Adriaens, T., Copas, K., Flevaris, S., Galiay, P., Jennings, E., Josefsson, M., López, B., Magan, J., Marchante, E., Montani, E., Roy, H., Schomberg, R. von, See, L., & Quintas, M. (2017). Citizen science and open data: a model for invasive alien species in Europe. *Research Ideas and Outcomes*, *3*, e14811. https://doi.org/10.3897/rio.3.e14811

Carvalho, J., Hipólito, D., Santarém, F., Martins, R., Gomes, A., Carmo, P., Rodrigues, R., Grosso-Silva, J., & Fonseca, C. (2020). Patterns of *Vespa velutina i*nvasion in Portugal using crowdsourced data. *Insect Conservation and Diversity*, *13*(5), 501–507. https://doi.org/10.1111/icad.12418

Chambert, T., Miller, D. A. W., & Nichols, J. D. (2015). Modeling false positive detections in species occurrence data under different study designs. *Ecology*, *96*(2), 332–339. https://doi.org/10.1890/14-1507.1

Christie, A. P., Amano, T., Martin, P. A., Shackelford, G. E., Simmons, B. I., & Sutherland, W. J. (2019). Simple study designs in ecology produce inaccurate estimates of biodiversity responses. *Journal of Applied Ecology*, *56*(12), 2742–2754. https://doi.org/10.1111/1365-2664.13499

Colléony, A., & Shwartz, A. (2020). When the winners are the losers: Invasive alien bird species outcompete the native winners in the biotic homogenization process. *Biological Conservation*, *241*, 108314. https://doi.org/10.1016/j.biocon.2019.108314

Crall, A. W., Jarnevich, C. S., Young, N. E., Panke, B. J., Renz, M., & Stohlgren, T. J. (2015). Citizen science contributes to our knowledge of invasive plant species distributions. *Biological Invasions*, *17*(8), 2415–2427. https://doi.org/10.1007/s10530-015-0885-4

Crall, A. W., Newman, G. J., Stohlgren, T. J., Holfelder, K. A., Graham, J., & Waller, D. M. (2011). Assessing citizen science data quality: An invasive species case study. *Conservation Letters*, *4*(6), 433–442. https://doi.org/10.1111/j.1755-263X.2011.00196.x

Crowley, S. L., Hinchliffe, S., & McDonald, R. A. (2019). The parakeet protectors: Understanding opposition to introduced species management. *Journal of Environmental Management*, *229*, 120–132. https://doi.org/10.1016/j.jenvman.2017.11.036

Dail, D., & Madsen, L. (2011). Models for estimating abundance from repeated counts of an open metapopulation. *Biometrics*, *67*(2), 577–587. https://doi.org/10.1111/j.1541-0420.2010.01465.x

DasGupta, A., & Rubin, H. (2005). Estimation of binomial parameters when both n, p are unknown. *Journal of Statistical Planning and Inference*, *130*(1), 391–404. https://doi.org/10.1016/j.jspi.2004.02.019

Demertzis, K., & Iliadis, L. (2017). Detecting invasive species with a bio-inspired semi-supervised neurocomputing approach: The case of *Lagocephalus sceleratus*. *Neural Computing and Applications*, *28*(6), 1225–1234. https://doi.org/10.1007/s00521-016-2591-2

Demertzis, K., Iliadis, L. S., & Anezakis, V.-D. (2018). Extreme deep learning in biosecurity: The case of machine hearing for marine species identification. *Journal of Information and Telecommunication*, *2*(4), 492–510. https://doi.org/10.1080/24751839.2018.1501542

Dennis, E. B., Morgan, B. J. T., Freeman, S. N., Ridout, M. S., Brereton, T. M., Fox, R., Powney, G. D., & Roy, D. B. (2017). Efficient occupancy model-fitting for extensive citizen-science data. *PLOS ONE*, *12*(3), e0174433. https://doi.org/10.1371/journal.pone.0174433

Diamond, J. M., & Ross, M. S. (2019). Exotic parrots breeding in urban tree cavities: Nesting requirements, geographic distribution, and potential impacts on cavity nesting birds in southeast Florida. *Avian Research*, *10*(1), 39. https://doi.org/10.1186/s40657-019-0176-3

Dickinson, J. L., Shirk, J., Bonter, D., Bonney, R., Crain, R. L., Martin, J., Phillips, T., & Purcell, K. (2012). The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment*, *10*(6), 291–297. https://doi.org/10.1890/110236

Druschke, C. G., & Seltzer, C. E. (2012). Failures of engagement: lessons learned from a citizen science pilot study. *Applied Environmental Education & Communication*, *11*(3–4), 178–188. https://doi.org/10.1080/1533015X.2012.777224

Eritja, R., Ruiz-Arrondo, I., Delacour-Estrella, S., Schaffner, F., Álvarez-Chachero, J., Bengoa, M., Puig, M.-Á., Melero-Alcíbar, R., Oltra, A., & Bartumeus, F. (2019). First detection of *Aedes japonicus* in Spain: An unexpected finding triggered by citizen science. *Parasites & Vectors*, *12*(1), 1–9. https://doi.org/10.1186/s13071-019-3317-y

Essl, F., Dullinger, S., Genovesi, P., Hulme, P. E., Jeschke, J. M., Katsanevakis, S., Kühn, I., Lenzner, B., Pauchard, A., Pyšek, P., Rabitsch, W., Richardson, D. M., Seebens, H., van Kleunen, M., van der Putten, W. H., Vilà, M., & Bacher, S. (2019). A conceptual framework for range-expanding species that track human-induced environmental change. *BioScience*, *69*(11), 908–919. https://doi.org/10.1093/biosci/biz101

Falk, B. G., Snow, R. W., & Reed, R. N. (2016). Prospects and limitations of citizen science in invasive species management: a case study with Burmese pythons in Everglades National Park. *Southeastern Naturalist*, *15*(sp8), 89–102. https://doi.org/10.1656/058.015.sp806

Falk, S., Foster, G., Comont, R., Conroy, J., Bostock, H., Salisbury, A., Kilbey, D., Bennett, J., & Smith, B. (2019). Evaluating the ability of citizen scientists to identify bumblebee (*Bombus*) species. *PLOS ONE*, *14*(6), e0218614. https://doi.org/10.1371/journal.pone.0218614

Farmer, R. G., Leonard, M. L., & Horn, A. G. (2012). Observer effects and avian-call-count survey quality: rare-species biases and overconfidence. *The Auk*, *129*(1), 76–86. https://doi.org/10.1525/auk.2012.11129

Feldman, R. E., Žemaitė, I., & Miller-Rushing, A. J. (2018). How training citizen scientists affects the accuracy and precision of phenological data. *International Journal of Biometeorology*, *62*(8), 1421–1435. https://doi.org/10.1007/s00484-018-1540-4

Fischhoff, B., & Davis, A. L. (2014). Communicating scientific uncertainty. *Proceedings of the National Academy of Sciences*, *111*(Supplement 4), 13664–13671. https://doi.org/10.1073/pnas.1317504111

Forrester, G., Baily, P., Conetta, D., Forrester, L., Kintzing, E., & Jarecki, L. (2015). Comparing monitoring data collected by volunteers and professionals shows that citizen scientists can detect long-term change on coral reefs. *Journal for Nature Conservation*, *24*, 1–9. https://doi.org/10.1016/j.jnc.2015.01.002

Friedel, M. H., Grice, A. C., Marshall, N. A., & van Klinken, R. D. (2011). Reducing contention amongst organisations dealing with commercially valuable but invasive plants: The case of buffel grass. *Environmental Science & Policy*, *14*(8), 1205–1218. https://doi.org/10.1016/j.envsci.2011.08.001

Gallo, T., & Waitt, D. (2011). Creating a successful citizen science model to detect and report invasive species. *BioScience*, *61*(6), 459–465. https://doi.org/10.1525/bio.2011.61.6.8

Galloway, A. W. E., Tudor, M. T., & Haegen, W. M. V. (2006). The reliability of citizen science: a case study of Oregon White Oak stand surveys. *Wildlife Society Bulletin*, *34*(5), 1425–1429. https://doi.org/10.2193/0091-7648(2006)34[1425:TROCSA]2.0.CO;2

Ganzevoort, W., van den Born, R. J. G., Halffman, W., & Turnhout, S. (2017). Sharing biodiversity data: Citizen scientists' concerns and motivations. *Biodiversity and Conservation*, *26*(12), 2821–2837. https://doi.org/10.1007/s10531-017-1391-z

Garbarino, J., & Mason, C. E. (2016). The power of engaging citizen scientists for scientific progress. *Journal of Microbiology & Biology Education*, *17*(1), 7–12. https://doi.org/10.1128/jmbe.v17i1.1052

Gardiner, M. M., Allee, L. L., Brown, P. M., Losey, J. E., Roy, H. E., & Smyth, R. R. (2012). Lessons from lady beetles: Accuracy of monitoring data from US and UK citizen-science programs. *Frontiers in Ecology and the Environment*, *10*(9), 471–476. https://doi.org/10.1890/110185

Geldmann, J., Heilmann-Clausen, J., Holm, T. E., Levinsky, I., Markussen, B., Olsen, K., Rahbek, C., & Tøttrup, A. P. (2016). What determines spatial bias in citizen science? Exploring four recording schemes with different proficiency requirements. *Diversity and Distributions*, *22*(11), 1139–1149. https://doi.org/10.1111/ddi.12477

Giovos, I., Kleitou, P., Poursanidis, D., Batjakas, I., Bernardi, G., Crocetta, F., Doumpas, N., Kalogirou, S., Kampouris, T. E., Keramidas, I., Langeneck, J., Maximiadi, M., Mitsou, E., Stoilas, V.-O., Tiralongo, F., Romanidis-Kyriakidis, G., Xentidis, N.-J., Zenetos, A., & Katsanevakis, S. (2019). Citizen-science for monitoring marine invasions and stimulating public engagement: A case project from the eastern Mediterranean. *Biological Invasions*. https://doi.org/10.1007/s10530-019-02083-w

Goldstein, E. A., Lawton, C., Sheehy, E., & Butler, F. (2014). Locating species range frontiers: A cost and efficiency comparison of citizen science and hair-tube survey methods for use in tracking an invasive squirrel. *Wildlife Research*, *41*(1), 64–75. https://doi.org/10.1071/WR13197

Grason, E., McDonald, S., Adams, J., Litle, K., Apple, J., & Pleus, A. (2018). Citizen science program detects range expansion of the globally invasive European green crab in Washington State (USA). *Management of Biological Invasions*, *9*(1), 39–47. https://doi.org/10.3391/mbi.2018.9.1.04

Green, S. J., Dulvy, N. K., Brooks, A. M. L., Akins, J. L., Cooper, A. B., Miller, S., & Côté, I. M. (2014). Linking removal targets to the ecological effects of invaders: A predictive model and field test. *Ecological Applications*, *24*(6), 1311–1322. https://doi.org/10.1890/13-0979.1

Groom, Q. J., & Whild, S. J. (2017). Characterisation of false-positive observations in botanical surveys. *PeerJ*, *5*, e3324. https://doi.org/10.7717/peerj.3324

Groom, Q., Strubbe, D., Adriaens, T., Davis, A. J. S., Desmet, P., Oldoni, D., Reyserhove, L., Roy, H. E., & Vanderhoeven, S. (2019). Empowering citizens to inform decision-making as a way forward to support invasive alien species policy. *Citizen Science: Theory and Practice*, *4*(1), 33. https://doi.org/10.5334/cstp.238

Guisan, A., Thuiller, W., & Zimmermann, N. E. (2017). *Habitat Suitability and Distribution Models: With Applications in R*. Cambridge University Press. https://doi.org/10.1017/9781139028271

Guyot, V., Castagneyrol, B., Vialatte, A., Deconchat, M., Selvi, F., Bussotti, F., & Jactel, H. (2015). Tree diversity limits the impact of an invasive forest pest. *PLOS ONE*, *10*(9), e0136469. https://doi.org/10.1371/journal.pone.0136469

Haklay, M. (2013). Citizen science and volunteered geographic information: overview and typology of participation. In D. Sui, S. Elwood, & M. Goodchild (Eds.), *Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice* (pp. 105–122). Springer Netherlands. https://doi.org/10.1007/978-94-007-4587-2_7

Hostetler, J. A., & Chandler, R. B. (2015). Improved state-space models for inference about spatial and temporal variation in abundance from count data. *Ecology*, *96*(6), 1713–1723. https://doi.org/10.1890/14-1487.1

Hourston, M., McDonald, J., & Hewitt, M. (2015). Public engagement for the detection of the introduced marine species *Charybdis japonica* in Western Australia. *Management of Biological Invasions*, *6*(3), 243–252. https://doi.org/10.3391/mbi.2015.6.3.03

Isaac, N. J. B., & Pocock, M. J. O. (2015). Bias and information in biological records. *Biological Journal of the Linnean Society*, *115*(3), 522–531. https://doi.org/10.1111/bij.12532

Isaac, N. J. B., Strien, A. J. van, August, T. A., Zeeuw, M. P. de, & Roy, D. B. (2014). Statistics for citizen science: Extracting signals of change from noisy ecological data. *Methods in Ecology and Evolution*, *5*(10), 1052–1060. https://doi.org/10.1111/2041-210X.12254

Jennett, C., Kloetzer, L., Schneider, D., Iacovides, I., Cox, A., Gold, M., Fuchs, B., Eveleigh, A., Mathieu, K., Ajani, Z., & Talsi, Y. (2016). Motivations, learning and creativity in online citizen science. *Journal of Science Communication*, *15*(3), A05. https://doi.org/10.22323/2.15030205

Jiménez, M., Triguero, I., & John, R. (2019). Handling uncertainty in citizen science data: Towards an improved amateur-based large-scale classification. *Information Sciences*, *479*, 301–320. https://doi.org/10.1016/j.ins.2018.12.011

Johnson, B. A., Mader, A. D., Dasgupta, R., & Kumar, P. (2020). Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations. *Global Ecology and Conservation*, *21*, e00812. https://doi.org/10.1016/j.gecco.2019.e00812

Johnston, A., Fink, D., Hochachka, W. M., & Kelling, S. (2018). Estimates of observer expertise improve species distributions from citizen science data. *Methods in Ecology and Evolution*, *9*(1), 88–97. https://doi.org/10.1111/2041-210X.12838

Jordan, R., Crall, A., Gray, S., Phillips, T., & Mellor, D. (2015). Citizen science as a distinct field of inquiry. *BioScience*, *65*(2), 208–211. https://doi.org/10.1093/biosci/biu217

Kallimanis, A. S., Panitsa, M., & Dimopoulos, P. (2017). Quality of non-expert citizen science data collected for habitat type conservation status assessment in Natura 2000 protected areas. *Scientific Reports*, *7*(1), 8873. https://doi.org/10.1038/s41598-017-09316-9

Kampen, H., Medlock, J. M., Vaux, A., Koenraadt, C., van Vliet, A., Bartumeus, F., Oltra, A., Sousa, C. A., Chouin, S., & Werner, D. (2015). Approaches to passive mosquito surveillance in the EU. *Parasites & Vectors*, *8*(1), 9. https://doi.org/10.1186/s13071-014-0604-5

Kapitza, K., Zimmermann, H., Martín-López, B., & Wehrden, H. von. (2019). Research on the social perception of invasive species: A systematic literature review. *NeoBiota*, *43*, 47–68. https://doi.org/10.3897/neobiota.43.31619

Kelling, S., Johnston, A., Hochachka, W. M., Iliff, M., Fink, D., Gerbracht, J., Lagoze, C., Sorte, F. A. L., Moore, T., Wiggins, A., Wong, W.-K., Wood, C., & Yu, J. (2015). Can observation skills of citizen scientists be estimated using species accumulation curves? *PLOS ONE*, *10*(10), e0139600. https://doi.org/10.1371/journal.pone.0139600

Kenis M., Adriaens T., Brown P.M., Katsanis A., San Martin G., Branquart E., Maes D., Eschen R., Zindel R., Van Vlaenderen J. (2017). Assessing the ecological risk posed by a recently established invasive alien predator: *Harmonia axyridis* as a case study. BioControl 62(3):341-354. https://doi.org/10.1007/s10526-016-9764-x

Kganyago, M., Odindi, J., Adjorlolo, C., & Mhangara, P. (2018). Evaluating the capability of Landsat 8 OLI and SPOT 6 for discriminating invasive alien species in the African Savanna landscape. *International Journal of Applied Earth Observation and Geoinformation*, *67*, 10–19. https://doi.org/10.1016/j.jag.2017.12.008

Kobori, H., Dickinson, J. L., Washitani, I., Sakurai, R., Amano, T., Komatsu, N., Kitamura, W., Takagawa, S., Koyama, K., Ogawara, T., & Miller-Rushing, A. J. (2016). Citizen science: A new approach to advance ecology, education, and conservation. *Ecological Research*, *31*(1), 1–19. https://doi.org/10.1007/s11284-015-1314-y

Koenig, W. D., Liebhold, A. M., Bonter, D. N., Hochachka, W. M., & Dickinson, J. L. (2013). Effects of the emerald ash borer invasion on four species of birds. *Biological Invasions*, *15*(9), 2095–2103. https://doi.org/10.1007/s10530-013-0435-x

Kress, W. J., Garcia-Robledo, C., Soares, J. V. B., Jacobs, D., Wilson, K., Lopez, I. C., & Belhumeur, P. N. (2018). Citizen science and climate change: mapping the range expansions of native and exotic plants with the mobile app Leafsnap. *BioScience*, *68*(5), 348–358. https://doi.org/10.1093/biosci/biy019

Latombe, G., Canavan, S., Hirsch, H., Hui, C., Kumschick, S., Nsikani, M. M., Potgieter, L. J., Robinson, T. B., Saul, W.-C., Turner, S. C., Wilson, J. R. U., Yannelli, F. A., & Richardson, D. M. (2019). A four-component classification of uncertainties in biological invasions: Implications for management. *Ecosphere*, *10*(4), e02669.

Latombe, G., Pyšek, P., Jeschke, J. M., Blackburn, T. M., Bacher, S., Capinha, C., Costello, M. J., Fernández, M., Gregory, R. D., Hobern, D., Hui, C., Jetz, W., Kumschick, S., McGrannachan, C., Pergl, J., Roy, H. E., Scalera, R., Squires, Z. E., Wilson, J. R. U., … McGeoch, M. A. (2017). A vision for global monitoring of biological invasions. *Biological Conservation*, *213*, 295–308. https://doi.org/10.1016/j.biocon.2016.06.013

Lele, S. R., Moreno, M., & Bayne, E. (2012). Dealing with detection error in site occupancy surveys: What can we do with a single survey? *Journal of Plant Ecology*, *5*(1), 22–31. https://doi.org/10.1093/jpe/rtr042

Lepczyk, C. A. (2005). Integrating published data and citizen science to describe bird diversity across a landscape. *Journal of Applied Ecology*, *42*(4), 672–677. https://doi.org/10.1111/j.1365-2664.2005.01059.x
Lewandowski, E., & Specht, H. (2015). Influence of volunteer and project characteristics on data quality of biological surveys. *Conservation Biology*, *29*(3), 713–723. https://doi.org/10.1111/cobi.12481
Link, W. A., & Sauer, J. R. (1997). Estimation of population trajectories from count data. *Biometrics*, *53*(2), 488–497. https://doi.org/10.2307/2533952
Lioy, S., Manino, A., Porporato, M., Laurino, D., Romano, A., Capello, M., & Bertolino, S. (2019). Establishing surveillance areas for tackling the invasion of *Vespa velutina* in outbreaks and over the border of its expanding range. *NeoBiota*, *46*, 51–69. https://doi.org/10.3897/neobiota.46.33099
Lundgren, R. E., & McMakin, A. H. (2018). *Risk Communication: A Handbook for Communicating Environmental, Safety, and Health Risks, 6th Edition | Wiley* (6th ed.). John Wiley & Sons. https://www.wiley.com/en-us/Risk+Communication%3A+A+Handbook+for+Communicating+Environmental%2C+Safety%2C+and+Health+Risks%2C+6th+Edition-p-9781119456155
MacKenzie, D. I., Nichols, J. D., Hines, J. E., Knutson, M. G., & Franklin, A. B. (2003). Estimating site occupancy, colonization, and local extinction when a species is detected imperfectly. *Ecology*, *84*(8), 2200–2207. https://doi.org/10.1890/02-3090
MacKenzie, D. I., Nichols, J. D., Lachman, G. B., Droege, S., Royle, J. A., & Langtimm, C. A. (2002). Estimating site occupancy rates when detection probabilities are less than one. *Ecology*, *83*(8), 2248–2255. https://doi.org/10.1890/0012-9658(2002)083[2248:ESORWD]2.0.CO;2
MacLeod, C. J., & Scott, K. (2021). Mechanisms for enhancing public engagement with citizen science results. *People and Nature*, *3*(1), 32–50. https://doi.org/10.1002/pan3.10152
Maistrello, L., Dioli, P., Bariselli, M., Mazzoli, G. L., & Giacalone-Forini, I. (2016). Citizen science and early detection of invasive species: Phenology of first occurrences of *Halyomorpha halys* in Southern Europe. *Biological Invasions*, *18*(11), 3109–3116. https://doi.org/10.1007/s10530-016-1217-z
Milián-García, Y., Young, R., Madden, M., Bullas-Appleton, E., & Hanner, R. H. (2021). Optimization and validation of a cost-effective protocol for biosurveillance of invasive alien species. *Ecology and Evolution*, *11*(5), 1999–2014. https://doi.org/10.1002/ece3.7139
Ministry for Primary Industries. (2016). *Biosecurity 2025 Direction Statement for New Zealand's biosecurity system* (No. 978-1-77665-424–6; p. 32). https://www.biosecurity.govt.nz/dmsdocument/14857-biosecurity-2025-direction-statement-for-new-zealands-biosecurity-system
Mori, E., Menchetti, M., Camporesi, A., Cavigioli, L., Tabarelli de Fatis, K., & Girardello, M. (2019). License to kill? Domestic cats affect a wide range of native fauna in a highly biodiverse Mediterranean country. *Frontiers in Ecology and Evolution*, *7*, 477. https://doi.org/10.3389/fevo.2019.00477
Moulin, N. (2020). When Citizen Science highlights alien invasive species in France: The case of Indochina mantis, *Hierodula patellifera* (Insecta, Mantodea, Mantidae). *Biodiversity Data Journal*, *8*. https://doi.org/10.3897/BDJ.8.e46989
Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., & Crowston, K. (2012). The future of citizen science: Emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment*, *10*(6), 298–304. https://doi.org/10.1890/110294
Parker, I. M., Simberloff, D., Lonsdale, W. M., Goodell, K., Wonham, M., Kareiva, P. M., Williamson, M. H., Von Holle, B., Moyle, P. B., Byers, J. E., & Goldwasser, L. (1999). Impact: Toward a framework for understanding the ecological effects of invaders. *Biological Invasions*, *1*(1), 3–19.

Pearson, J. M. N., Kidd, J. A., Knysh, K. M., Van den Heuvel, M. R., Gagnon, J.-M., & Courtenay, S. C. (2019). Identification of native and non-native grass shrimps *Palaemon* spp. (Decapoda: Palaemonidae) by citizen science monitoring programs in Atlantic Canada. *Journal of Crustacean Biology*, *39*(2), 189–192. https://doi.org/10.1093/jcbiol/ruy116

Perdikaris, C., Konstantinidis, E., Georgiadis, C., & Kouba, A. (2017). Freshwater crayfish distribution update and maps for Greece: Combining literature and citizen-science data. *Knowledge & Management of Aquatic Ecosystems*, *418*, 51. https://doi.org/10.1051/kmae/2017042

Pergl, J., Pyšek, P., Essl, F., Jeschke, J. M., Courchamp, F., Geist, J., Hejda, M., Kowarik, I., Mill, A., Musseau, C., Pipek, P., Saul, W.-C., Schmalensee, M. von, & Strayer, D. (2020). Need for routine tracking of biological invasions. *Conservation Biology*, *34*(5), 1311–1314. https://doi.org/10.1111/cobi.13445

Peters, M. A., Hamilton, D., Eames, C., Innes, J., & Mason, N. W. H. (2016). The current state of community-based environmental monitoring in New Zealand. *New Zealand Journal of Ecology*, *40*(3), 279–288.

Petersen, T. K., Speed, J. D. M., Grøtan, V., & Austrheim, G. (2021). Species data for understanding biodiversity dynamics: The what, where and when of species occurrence data collection. *Ecological Solutions and Evidence*, *2*(1), e12048. https://doi.org/10.1002/2688-8319.12048

Pluess, T., Cannon, R., Jarošík, V., Pergl, J., Pyšek, P., & Bacher, S. (2012). When are eradication campaigns successful? A test of common assumptions. *Biological Invasions*, *14*(7), 1365–1378. https://doi.org/10.1007/s10530-011-0160-2

Pocock, M. J. O., Roy, H. E., Preston, C. D., & Roy, D. B. (2015). The Biological Records Centre: A pioneer of citizen science. *Biological Journal of the Linnean Society*, *115*(3), 475–493. https://doi.org/10.1111/bij.12548

Preuss, S., Low, M., Cassel-Lundhagen, A., & Berggren, Å. (2014). Evaluating range-expansion models for calculating nonnative species' expansion rate. *Ecology and Evolution*, *4*(14), 2812–2822. https://doi.org/10.1002/ece3.1106

Pusceddu, M., Floris, I., Mannu, R., Cocco, A., & Satta, A. (2019). Using verified citizen science as a tool for monitoring the European hornet (*Vespa crabro*) in the island of Sardinia (Italy). *NeoBiota*, *50*, 97–108. https://doi.org/10.3897/neobiota.50.37587

Reaser, J. (2001). Invasive alien species prevention and control: The art and science of managing people. In *The great reshuffling: Human dimensions of invasive alien species*.

Regan, H. M., Colyvan, M., & Burgman, M. A. (2002). A taxonomy and treatment of uncertainty for ecology and conservation biology. *Ecological Applications*, *12*(2), 618–628. JSTOR. https://doi.org/10.2307/3060967

Ressurreição, A., Gibbons, J., Kaiser, M., Dentinho, T. P., Zarzycki, T., Bentley, C., Austen, M., Burdon, D., Atkins, J., Santos, R. S., & Edwards-Jones, G. (2012). Different cultures, different values: The role of cultural variation in public's WTP for marine species conservation. *Biological Conservation*, *145*(1), 148–159. https://doi.org/10.1016/j.biocon.2011.10.026

Robertson, P. A., Mill, A., Novoa, A., Jeschke, J. M., Essl, F., Gallardo, B., Geist, J., Jarić, I., Lambin, X., Musseau, C., Pergl, J., Pyšek, P., Rabitsch, W., von Schmalensee, M., Shirley, M., Strayer, D. L., Stefansson, R. A., Smith, K., & Booy, O. (2020). A proposed unified framework to describe the management of biological invasions. *Biological Invasions*, *22*(9), 2633–2645. https://doi.org/10.1007/s10530-020-02298-2

Rowley, J. J. L., Callaghan, C. T., & CutajaR, T. (2019). FrogID: Citizen scientists provide validated biodiversity data on frogs of Australia. *Herpetological Conservation and Biology*, *14*(1), 16.

Roy, H. E., Adriaens, T., Agnello, G., Antic, M., Archambeau, A.-S., Bacher, S., Bonn, A., Brown, P., Brundu, G., López, B., Cleary, M., Cogălniceanu, D., Groot, M. de, Sousa, T. D., Deidun, A., Essl, F., Pečnikar, Ž. F., Gazda, A., Gervasini, E., … Cardoso, A. C. (2018). Increasing understanding of alien species through citizen science (Alien-CSI). *Research Ideas and Outcomes*, *4*, e31412. https://doi.org/10.3897/rio.4.e31412

Roy, H. E., Adriaens, T., Isaac, N. J. B., Kenis, M., Onkelinx, T., Martin, G. S., Brown, P. M. J., Hautier, L., Poland, R., Roy, D. B., Comont, R., Eschen, R., Frost, R., Zindel, R., Vlaenderen, J. V., Nedvěd, O., Ravn, H. P., Grégoire, J.-C., Biseau, J.-C. de, & Maes, D. (2012). Invasive alien predator causes rapid declines of native European ladybirds. *Diversity and Distributions*, *18*(7), 717–725. https://doi.org/10.1111/j.1472-4642.2012.00883.x

Roy, H. E., & Brown, P. M. J. (2015). Ten years of invasion: *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae) in Britain. *Ecological Entomology*, *40*(4), 336–348. https://doi.org/10.1111/een.12203

Royle, J. A., & Nichols, J. D. (2003). Estimating abundance from repeated presence–absence data or point counts. *Ecology*, *84*(3), 777–790. https://doi.org/10.1890/0012-9658(2003)084[0777:EAFRPA]2.0.CO;2

Santori, C., Keith, R. J., Whittington, C. M., Thompson, M. B., Dyke, J. U. V., & Spencer, R.-J. (2021). Changes in participant behaviour and attitudes are associated with knowledge and skills gained by using a turtle conservation citizen science app. *People and Nature*, *3*(1), 66–76. https://doi.org/10.1002/pan3.10184

Schade, S., Kotsev, A., Cardoso, A. C., Tsiamis, K., Gervasini, E., Spinelli, F., Mitton, I., & Sgnaolin, R. (2019). Aliens in Europe. An open approach to involve more people in invasive species detection. *Computers, Environment and Urban Systems*, *78*, 101384. https://doi.org/10.1016/j.compenvurbsys.2019.101384

Seebens, H., Bacher, S., Blackburn, T. M., Capinha, C., Dawson, W., Dullinger, S., Genovesi, P., Hulme, P. E., Kleunen, M. van, Kühn, I., Jeschke, J. M., Lenzner, B., Liebhold, A. M., Pattison, Z., Pergl, J., Pyšek, P., Winter, M., & Essl, F. (2020). Projecting the continental accumulation of alien species through to 2050. *Global Change Biology*, *n/a*(n/a). https://doi.org/10.1111/gcb.15333

Shackleton, R. T., Adriaens, T., Brundu, G., Dehnen-Schmutz, K., Estévez, R. A., Fried, J., Larson, B. M. H., Liu, S., Marchante, E., Marchante, H., Moshobane, M. C., Novoa, A., Reed, M., & Richardson, D. M. (2019). Stakeholder engagement in the study and management of invasive alien species. *Journal of Environmental Management*, *229*, 88–101. https://doi.org/10.1016/j.jenvman.2018.04.044

Shirk, J., Ballard, H., Wilderman, C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B., Krasny, M., & Bonney, R. (2012). Public participation in scientific research: a framework for deliberate design. *Ecology and Society*, *17*(2). https://doi.org/10.5751/ES-04705-170229

Sofaer, H. R., Jarnevich, C. S., & Pearse, I. S. (2018). The relationship between invader abundance and impact. *Ecosphere*, *9*(9), e02415. https://doi.org/10.1002/ecs2.2415

Starr, J., Schweik, C. M., Bush, N., Fletcher, L., Finn, J., Fish, J., & Bargeron, C. T. (2014). Lights, camera…Citizen science: assessing the effectiveness of smartphone-based video training in invasive plant identification. *PLoS ONE*, *9*(11), e111433. https://doi.org/10.1371/journal.pone.0111433

Stuart-Smith, R. D., Edgar, G. J., Barrett, N. S., Bates, A. E., Baker, S. C., Bax, N. J., Becerro, M. A., Berkhout, J., Blanchard, J. L., Brock, D. J., Clark, G. F., Cooper, A. T., Davis, T. R., Day, P. B., Duffy, J. E., Holmes, T. H., Howe, S. A., Jordan, A., Kininmonth, S., … Thomson, R. (2017). Assessing national biodiversity trends for rocky and coral reefs through the integration of citizen science and scientific monitoring programs. *BioScience*, *67*(2), 134–146. https://doi.org/10.1093/biosci/biw180

Szabo, J. K., Vesk, P. A., Baxter, P. W. J., & Possingham, H. P. (2010). Regional avian species declines estimated from volunteer-collected long-term data using List Length Analysis. *Ecological Applications*, *20*(8), 2157–2169. https://doi.org/10.1890/09-0877.1

Terry, J. C. D., Roy, H. E., & August, T. A. (2020). Thinking like a naturalist: enhancing computer vision of citizen science images by harnessing contextual data. *Methods in Ecology and Evolution*, *11*(2), 303–315. https://doi.org/10.1111/2041-210X.13335

Thiel, M., Penna-Díaz, M., Luna-Jorquera, G., Salas, S., Sellanes, J., & Stotz, W. (2014). Citizen scientists and marine research: volunteer participants, their contributions, and projection for the future. *Oceanography and Marine Biology: An Annual Review*, *52*, 257–314. https://doi.org/10.1201/b17143-6

Thomas, M. L., Gunawardene, N., Horton, K., Williams, A., O'Connor, S., McKirdy, S., & Merwe, J. van der. (2017). Many eyes on the ground: Citizen science is an effective early detection tool for biosecurity. *Biological Invasions*, *19*(9), 2751–2765. https://doi.org/10.1007/s10530-017-1481-6

Tuler, S. P., & Kasperson, R. E. (2013). Social distrust and its implications for risk communication: An example from high level radioactive waste management. In J. Arvai & L. Rivers III (Eds.), *Effective Risk Communication* (pp. 91–107). Routledge.

Tye, C. A., McCleery, R. A., Fletcher, R. J., Greene, D. U., & Butryn, R. S. (2017). Evaluating citizen vs. Professional data for modelling distributions of a rare squirrel. *Journal of Applied Ecology*, *54*(2), 628–637. https://doi.org/10.1111/1365-2664.12682

van der Bles, A. M., Freeman, A. L. J., Mitchell, J., Galvao, A. B., Zaval, L., & Spiegelhalter, D. J. (2019). Communicating uncertainty about facts, numbers and science. *Royal Society Open Science*, *6*(5), 181870. https://doi.org/10.1098/rsos.181870

van Strien, A. J., Swaay, C. A. M. van, & Termaat, T. (2013). Opportunistic citizen science data of animal species produce reliable estimates of distribution trends if analysed with occupancy models. *Journal of Applied Ecology*, *50*(6), 1450–1458. https://doi.org/10.1111/1365-2664.12158

Vander Zanden, M. J., Hansen, G. J. A., Higgins, S. N., & Kornis, M. S. (2010). A pound of prevention, plus a pound of cure: Early detection and eradication of invasive species in the Laurentian Great Lakes. *Journal of Great Lakes Research*, *36*(1), 199–205. https://doi.org/10.1016/j.jglr.2009.11.002

Vanderhoeven, S., Branquart, E., Casaer, J., D'hondt, B., Hulme, P. E., Shwartz, A., Strubbe, D., Turbé, A., Verreycken, H., & Adriaens, T. (2017). Beyond protocols: improving the reliability of expert-based risk analysis underpinning invasive species policies. *Biological Invasions*, *19*(9), 2507–2517. https://doi.org/10.1007/s10530-017-1434-0

Vantieghem, P., Maes, D., Kaiser, A., & Merckx, T. (2017). Quality of citizen science data and its consequences for the conservation of skipper butterflies (Hesperiidae) in Flanders (northern Belgium). *Journal of Insect Conservation*, *21*(3), 451–463. https://doi.org/10.1007/s10841-016-9924-4

Veeckman, C., Talboom, S., Gijsel, L., Devoghel, H., & Duerinckx, A. (2019). *Communication in Citizen Science. A practical guide to communication and engagement in citizen science.* SCIVIL.

Verbrugge, L. N. H., Leuven, R. S. E. W., & Zwart, H. A. E. (2016). Metaphors in invasion biology: implications for risk assessment and management of non-native species. *Ethics, Policy & Environment*, *19*(3), 273–284. https://doi.org/10.1080/21550085.2016.1226234

Vries, M. de, Land-Zandstra, A., & Smeets, I. (2019). Citizen scientists' preferences for communication of scientific output: a literature review. *Citizen Science: Theory and Practice*, *4*(1), 2. https://doi.org/10.5334/cstp.136

Wiggins, A., Newman, G., Stevenson, R. D., & Crowston, K. (2011). Mechanisms for data quality and validation in citizen science. *Proceedings - 7th IEEE International Conference on e-Science Workshops, EScienceW 2011*, 14–19. https://doi.org/10.1109/eScienceW.2011.27

Wotton, D. M., O'Brien, C., Stuart, M. D., & Fergus, D. J. (2004). Eradication success down under: Heat treatment of a sunken trawler to kill the invasive seaweed *Undaria pinnatifida*. *Marine Pollution Bulletin*, *49*(9), 844–849. https://doi.org/10.1016/j.marpolbul.2004.05.001

Wright, D. R., Underhill, L. G., Keene, M., & Knight, A. T. (2015). Understanding the motivations and satisfactions of volunteers to improve the effectiveness of citizen science programs. *Society & Natural Resources*, *28*(9), 1013–1029. https://doi.org/10.1080/08941920.2015.1054976

Zengeya, T., Ivey, P., Woodford, D. J., Weyl, O., Novoa, A., Shackleton, R., Richardson, D., & van Wilgen, B. (2017). Managing conflict-generating invasive species in South Africa: Challenges and trade-offs. *Bothalia - African Biodiversity & Conservation*, *47*(2), 1–11. https://doi.org/10.4102/abc.v47i2.2160

Zurell, D., Berger, U., Cabral, J. S., Jeltsch, F., Meynard, C. N., Münkemüller, T., Nehrbass, N., Pagel, J., Reineking, B., Schröder, B., & Grimm, V. (2010). The virtual ecologist approach: Simulating data and observers. *Oikos*, *119*(4), 622–635. https://doi.org/10.1111/j.1600-0706.2009.18284.x

Table 1: Epistemic and linguistic uncertainties (Regan et al., 2002) relevant to citizen science in context of research addressing alien species.

Epistemic uncertainties
Natural variation Relates to the changes (usually related to space and time) which are naturally and inherently present but often difficult to predict. Citizen science projects may be able to help reduce such biases, particularly related to natural spatial variation, by upscaling data collection. <u>Example:</u> Populations of alien species vary in different demographic attributes due to natural changes in fecundity and mortality.
Measurement error Occurs due to imperfect measuring equipment and observation techniques, including when the individual and/or equipment causes the error. <u>Example:</u> A participant under- or overestimates the number of individuals of a species on site. The Global Positioning Satellite (GPS) of a smartphone is slow and records an observation in a different kilometre square or with high associated coordinate uncertainty.
Systematic error Arises due to biases in sampling procedure or measuring equipment. <u>Example:</u> For example, two species A and B look relatively similar. A citizen scientist consistently records the presence of species A as the presence of species B as they do not realise that there are two different species; or, a citizen scientist incorrectly sets up a GPS device and now all locations that the citizen scientists record are systematically wrong.
Model uncertainty Results from the necessity to represent the 'true' situation through the use of simplified models. Model uncertainty is generated from the fact there are a multitude of drivers that affect a process, and we will never capture the true scenario. Model uncertainty may be reduced through model validation methods (Zurell et al., 2010) and ensuring that findings are interpreted within the limits of the model.
Subjective judgement Arises through the interpretation of information. This is relevant from the perspective of both the project co-ordinators and the audience (e.g., citizen scientists) receiving the information. Linguistic uncertainties may exacerbate subjective judgement. <u>Example:</u> A scientist believes that changes caused by an alien species in an ecosystem (e.g., soil pH) are generally deleterious for native species and therefore describes them in the report as detrimental for the ecosystem.
Linguistic uncertainties
Vagueness Language that permits borderline cases; common when using linguistic categories that underpin continuous measurements. <u>Example:</u> Asking citizen scientists to provide linguistic size class categories, such as small, medium and large, for a specific species observation, may lead to inconsistencies.

Context dependence When the context under which something is required to be completely understood is absent. Example: Species may be thought of as either native or alien, depending on their geographical range. For instance, species translocated within a country may be perceived as native by some yet alien by others. Understanding the native range is necessary for context to determine if it is alien.
Ambiguity Where more than one meaning for a word or phrase may be interpreted and it is not clear which meaning is correct. Example: The term 'invasive' can be interpreted differently as current definitions use it to refer to alien species that are established and widespread across a landscape with no reference to impact, or alternatively, alien species that are perceived to have deleterious impacts.
Under specificity When there is an unwanted generalism and information is not clear due to the lack of detail. Example: Failure to clearly explain to citizen scientists the level of details necessary for each species observation may lead to incomplete records and data gaps.
Indeterminacy of theoretical terms Occurs because language is imprecise, and words can change meaning with time. Example: Species names (both their scientific nomenclature and common names) can change over time, causing confusion to those who were aware of their previous names.

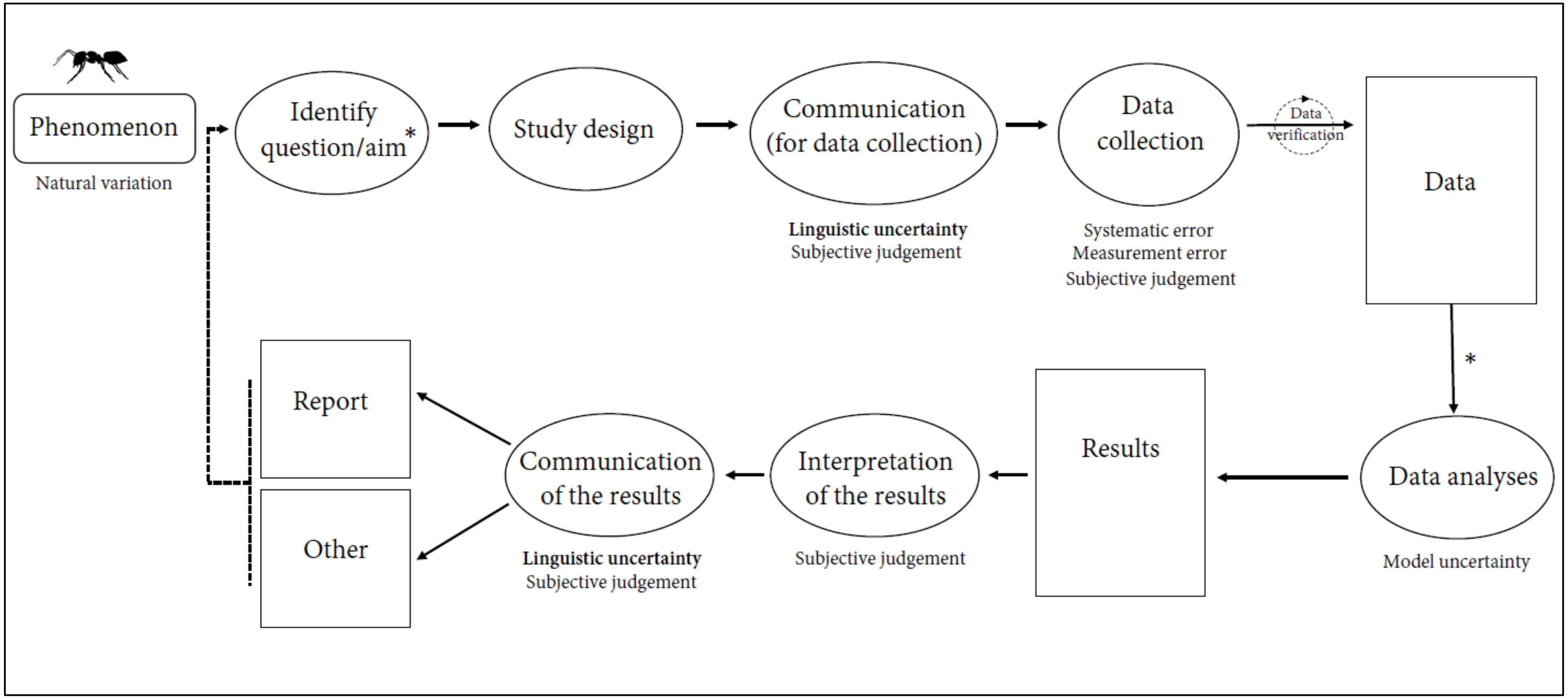


Figure 1: Schematic of a generalised scientific process in context of citizen science, beginning with the occurrence of some phenomenon (e.g., arrival, spread) of an alien species to be investigated. Sources of uncertainty (Regan et al., 2002), and where they arise, have been mapped along the process. The specific types of epistemic uncertainty are listed, with linguistic uncertainties presented in general. During the communication of both the project aims and the results, subjective judgement is relevant as it may influence the message made by the communicator(s) and thus the way the recipient audience perceives the information. Text in ovals indicate actions, whereas text in rectangles indicate outcomes. The asterisk between the 'Data' and 'Data analyses' stages indicates that some projects utilise data generated by citizen scientists and thus for some projects the research question may be identified post-data collection (e.g., projects that data mine biological databases). The dashed lines represent the potential for information learnt during the process to be integrated into subsequent actions for longer-term projects allowing the process to become refined and improved as information is learnt.

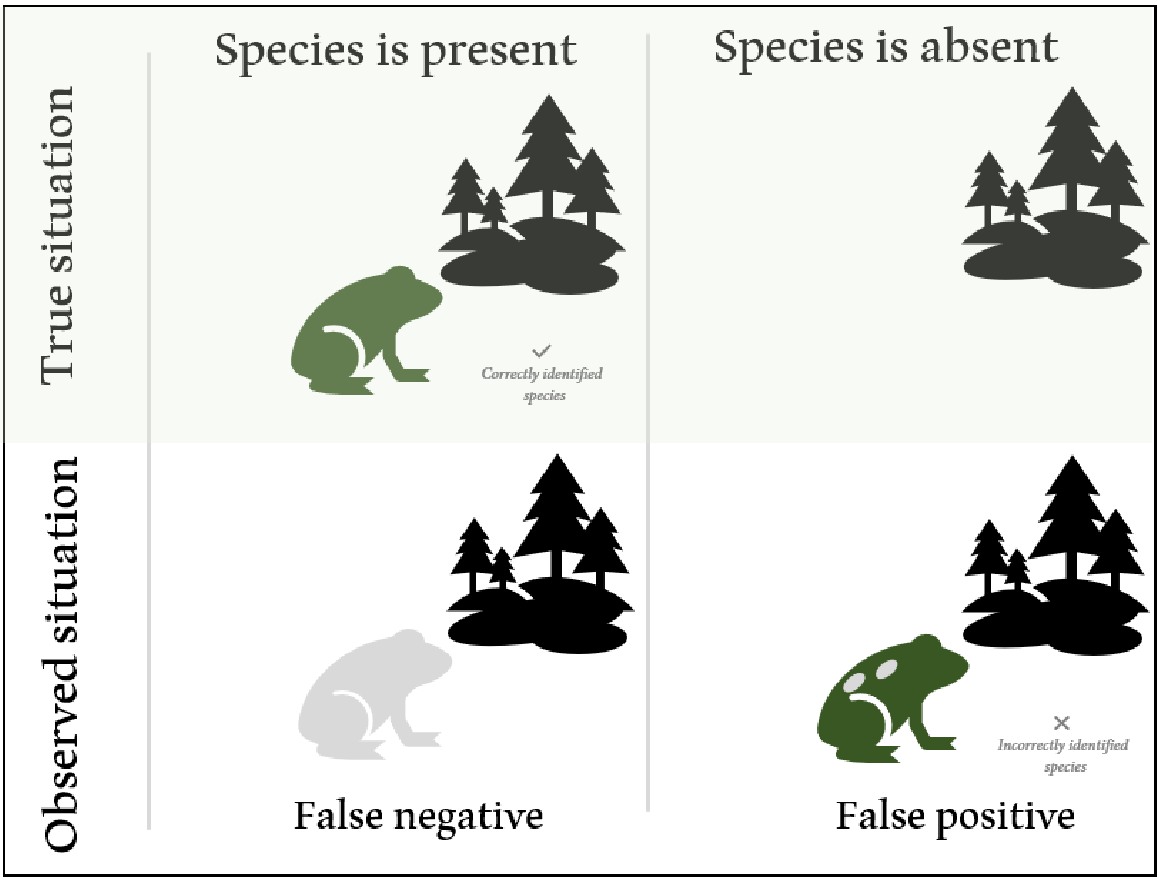


Figure 2: The two forms of detection errors are illustrated using the example of a frog at a specific location. False negatives (Type II error) occur when an observer does not detect the alien species that was indeed present. This may arise because observers are i) either looking in the wrong place (e.g., the species occurs on plant A, but the observer only looks on plant B) ii) the species is cryptic or hidden, or, iii) is seen, but incorrectly identified (in our example here, the spotted frog is misidentified as our frog species of interest). False positives (Type I error) occurs when an observer incorrectly detects the alien species (usually based on an inaccurate species identification).

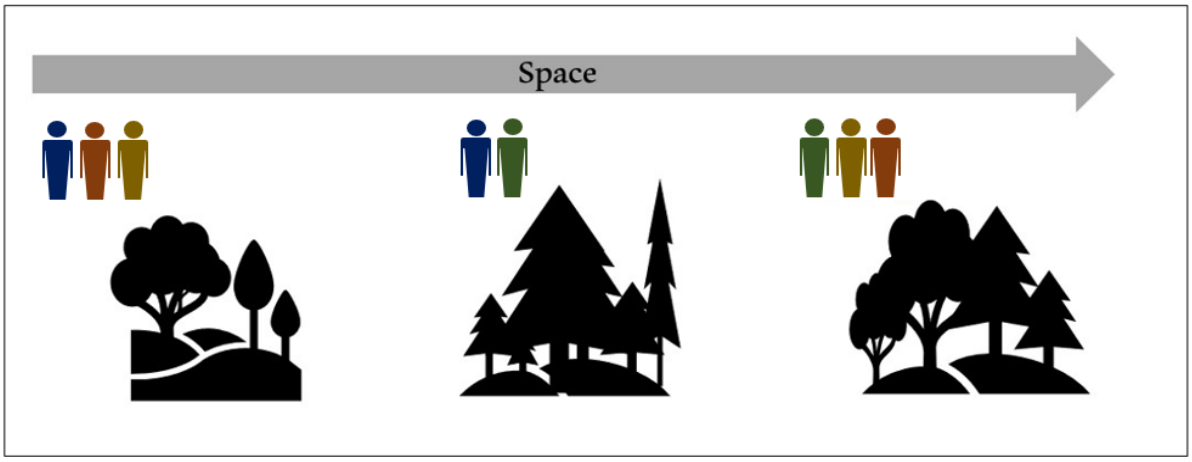


Figure 3: Detection biases may be accounted for by obtaining information about individual observer's detection rates. Some observers may be more likely to detect a species. To learn error rates, studies should be designed such that different locations are visited by more than one observer (illustrated by figures of different colours). Not all projects will lend themselves to such a design; there may be few participants and/or participants may be unable to visit multiple locations.

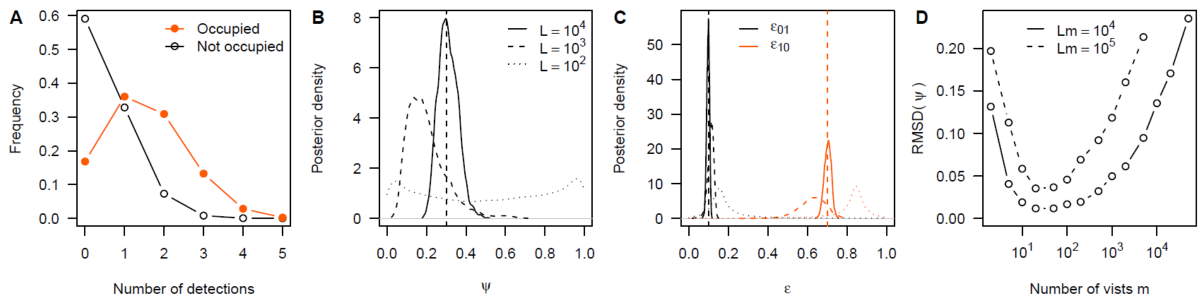


Figure 4: Illustration of the hierarchical model from Box 1 with parameters $\psi = 0.3$, $\epsilon_{01} = 0.1$ and $\epsilon_{10} = 0.7$. A: expected distributions of the number of reported detections at occupied (filled, orange) and not occupied locations (open, black) for $m = 5$ visits per location. B and C: Posterior distributions on ψ (B), ϵ_{01} (C, black) and ϵ_{10} (C, orange) for data simulated at $L = 10^4$ (solid), L (dashed) and $L = 10^2$ (dotted) locations with $m = 5$ visits each. D: Accuracy of inferring ψ as quantified by the root mean squared deviation (RMSD) of the posterior means of ψ across 100 replicate simulations for different combinations of locations L and visits m for $Lm = 10^5$ (solid), $Lm = 10^4$ (dashed) and $Lm = 10^3$ (dotted) the total number of visits.

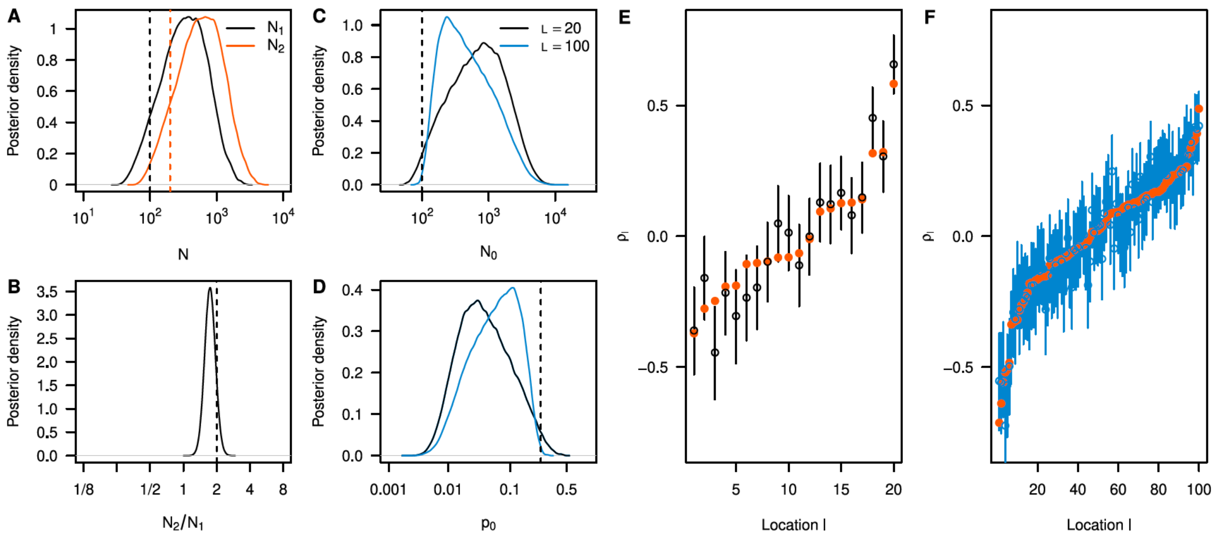


Figure 5: Inferring relative abundances under the models presented in Box 3. A-B: Posterior estimates of abundances from data simulated for five visits per location with $N_1 = 100$ and $N_2 = 200$ (dashed vertical lines) and detection probability $p = 0.2$. B: Posterior distribution of the relative abundance of N_2/N_1 from the data of A. C-F: Posterior distributions on N_0 (C), p_0 (D) and the relative abundances ρ_i (E and F, mean and 90% quantile) under the multi-location model to estimate relative abundances as outlined in Box 3 from data simulated with $N_0 = 100$, $\sigma_\rho^2 = 0.2$, $p_0 = -1$ and $\sigma_\pi^2 = 0.5$ and either $L = J = 20$ (black, E) or $L = J = 100$ (blue, F).

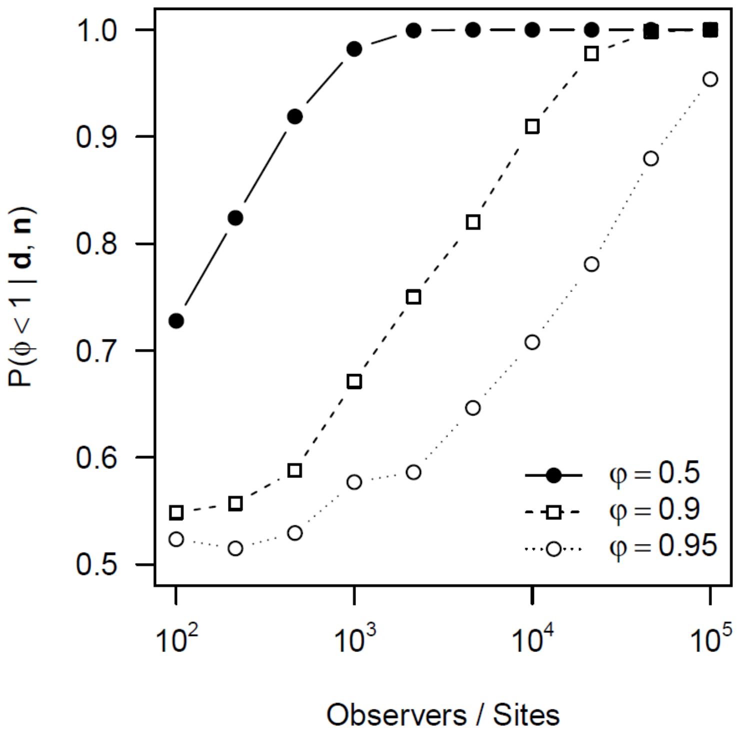


Figure 6: Power to identify trends in abundances. Shown are the mean posterior probabilities $P(\phi < 1|d,n)$ reflecting the certainty that abundances declined across 1,000 replicate simulations for different trends $\phi = 0.5$, 0.9 or 0.95 as a function of the number of observers that each surveyed a single location with observer-specific detection probabilities and location-specific abundances as described in Box 4.

Chapter 4 – Supplementary Material 1

a. Additional information about the EICAT assessment procedure

Uncertainty rationales

Confidence levels (high, medium or low) are assigned to each observation to indicate how confident the assessor is that the assigned magnitude is the 'true' one: the assessor therefore evaluates the chances that the 'true' impact magnitude is different from the one assigned (IUCN, 2020b; Volery et al., 2020). A *High* confidence level is assigned to an impact observation only when the assessor is confident that the assigned magnitude is the true one, i.e. that higher or lower impact magnitudes are unlikely according to the impact description and methodology of the study. A *Medium* confidence level is assigned when evidence indicates that the true impact magnitude is likely to be the one assigned, but that be a higher or lower magnitude is also possible. When the assessor did not find evidence indicating that the true impact magnitude is likely to be the assigned one, a *Low* confidence level was assigned. A *Low* confidence level can be assigned to vague impact observations with few or no details on the experimental or observational set-up, but also to well-designed studies testing effects not easily transferrable into EICAT criteria.

In our study, to increase transparency on how the confidence levels were assigned and to highlight where uncertainty occurs in each observation, the assessor evaluated if the true impact could be higher or lower than the one described, based on the described impact in the report and considering the methodology for observing it (see Sheet 4 in Supp. 2). For example, if a field study finds decreases in performance of individuals of a native species (observed impact = MN), but did not look at changes in its population density, it is possible that the true impact might even have led to a population decrease (MO) (IUCN, 2020b; Probert et al., 2020; Volery et al., 2020). It is however unlikely that the impact is negligible (MC) as the decrease in the performance of native individuals was observed; it is also unlikely that the alien led to a local extinction (MR/MV) as individuals were observed. This approach led to higher consistency among the three assessors.

Species guilds

Deer are often forming guilds of several species, making it difficult to evaluate the impact of a species independently from the others (e.g. Wardle, Barker, Yeates, Bonner, & Ghani, 2001). When the experimental set-up did not allow distinguishing the individual impacts of each species, we assigned the described impact to all alien species in the guild and decreased the confidence level. For instance, if a species was the most abundant in the guild, it is likely that this species was contributing to the described impacts (no decrease in the confidence level), whereas if a species comprised only a small part of the guild, it is less clear whether it contributed to the described impact or whether the same impact would have been occurring in its absence (decrease in confidence level).

Complementary studies

In a few cases where multiple studies where explicitly complementing each other, the assessor combined them into one impact observation (see Sheet 4 in Supp. 2). For instance, one study was observing the change in the native population (e.g. a decline in the population size), and another study was establishing the link between this change and the alien (e.g. by showing the mechanism through which the alien is acting on the native population). This was to avoid double counting of impacts. When the link between two studies was not explicitly made in the reports, we did not combine studies.

b. R code for the significance test of pairwise comparisons between impact risks

To compare the impact risk of $Species_a$ with the impact risk of $Species_b$:

Generating beta distributions for $Species_a$ and $Species_b$, based on the frequency at which they caused their highest impact

a <- rbeta(*number_of_simulations,* (*$Species_a$_number_of_successes + 1*), (*$Species_a$_number_of_failures + 1*)) (where "successes" indicate the number of regions in which $Species_a$ caused its highest impact magnitudes, and "failures" indicate the number of regions in which it caused lower impacts)

b <- rbeta(*number_of_simulations*, (*$Species_b$_number_of_successes + 1*), (*$Species_b$_number_of_failures + 1*))

Comparing the two distributions by calculating their overlap

sum((a-b)>0)/*number_of_simulations*

sum((b-a)>0)/*number_of_simulations*

We used 100'000 simulations to generate random beta distributions. The lowest overlap measure is taken as the p-value: values around 0.5 indicate a complete overlap of the two probability distributions, whereas values around 0 indicate almost no overlap and allow to reject the null hypothesis that the two probability distributions are not different.

Table S1. Species classified as Data Deficient (DD). To test whether more widely ungulates were more often studied (see Table S8), we added the numbers of countries each species has been introduced to (no re-introductions) (extracted from Sheet 3 in Supp. 2).

Species	*Order*	*Family*	*Number of countries of introduction*
Addax nasomaculatus	Cetartiodactyla	Bovidae	**1**
Aepyceros melampus	Cetartiodactyla	Bovidae	**3**
Antilope cervicapra	Cetartiodactyla	Bovidae	**6**
Bison bonasus	Cetartiodactyla	Bovidae	**4**
Boselaphus tragocamelus	Cetartiodactyla	Bovidae	**6**
Capra ibex	Cetartiodactyla	Bovidae	**9**
Capra nubiana	Cetartiodactyla	Bovidae	**3**
Capra pyrenaica	Cetartiodactyla	Bovidae	**2**
Gazella subgutturosa	Cetartiodactyla	Bovidae	**7**
Hippotragus equinus	Cetartiodactyla	Bovidae	**4**
Kobus ellipsiprymnus	Cetartiodactyla	Bovidae	**1**
Kobus leche	Cetartiodactyla	Bovidae	**2**
Kobus vardonii	Cetartiodactyla	Bovidae	**1**
Madoqua kirkii	Cetartiodactyla	Bovidae	**1**
Oryx dammah	Cetartiodactyla	Bovidae	**1**
Oryx leucoryx	Cetartiodactyla	Bovidae	**2**
Ovibos moschatus	Cetartiodactyla	Bovidae	**9**
Ovis canadensis	Cetartiodactyla	Bovidae	**2**
Rupicapra rupicapra	Cetartiodactyla	Bovidae	**7**
Syncerus caffer	Cetartiodactyla	Bovidae	**1**
Taurotragus derbianus (syn. *Tragelaphus derbianus*)	Cetartiodactyla	Bovidae	**2**
Tragelaphus euryceros	Cetartiodactyla	Bovidae	**1**
Tragelaphus imberbis	Cetartiodactyla	Bovidae	**1**
Tragelaphus oryx	Cetartiodactyla	Bovidae	**1**
Tragelaphus spekii	Cetartiodactyla	Bovidae	**1**
Lama pacos (syn. *Vicugna pacos*)	Cetartiodactyla	Camelidae	**1**
Vicugna vicugna	Cetartiodactyla	Camelidae	**3**
Alces alces	Cetartiodactyla	Cervidae	**9**
Axis porcinus	Cetartiodactyla	Cervidae	**6**
Capreolus capreolus	Cetartiodactyla	Cervidae	**7**
Capreolus pygargus	Cetartiodactyla	Cervidae	**10**
Dama mesopotamica	Cetartiodactyla	Cervidae	**1**
Elaphurus davidianus	Cetartiodactyla	Cervidae	**3**
Hydropotes inermis	Cetartiodactyla	Cervidae	**4**
Rusa marianna	Cetartiodactyla	Cervidae	**4**
Hippopotamus amphibius	Cetartiodactyla	Hippopotamidae	**2**
Equus africanus	Perissodactyla	Equidae	**2**
Equus hemionus	Perissodactyla	Equidae	**2**
Diceros bicornis	Perissodactyla	Rhinocerotidae	**3**

Table S2. Locations of impact observations. We list the 34 countries for which impact observations were available (white lines). To test whether impacts of ungulates were more often studied in countries with more introduced ungulate species (see Table S11), we added the numbers of introduced ungulate species per country (no re-introductions; extracted from Sheet 3 in Supp. 2). We completed the list with countries without impact observation, but with > 6 introduced ungulate species (grey lines and italic).

Continent/Country	***Number of impact observations***	***Number of introduced ungulate species***
Africa	**3**	**99**
Mauritius	1	3
Seychelles	2	4
South Africa	*0*	*34*
Madagascar	*0*	*6*
Sao Tomé and Principe	*0*	*6*
Antarctica	**1**	**6**
French Southern Territories	1	5
Asia	**11**	**151**
India	8	8
Russian Federation	1	14
Japan	1	10
Israel	1	4
Ukraine	*0*	*10*
China	*0*	*7*
Kyrgyzstan	*0*	*7*
Malaysia	*0*	*7*
Indonesia	*0*	*6*
Kazakhstan	*0*	*6*
Sri Lanka	*0*	*6*
Yemen	*0*	*6*
Europe	**87**	**232**
United Kingdom	50	22
Ireland	14	10
Spain	5	8
Greece	4	4
Czech Republic	3	13
Italy	3	9
Poland	2	10
France	1	20
Lithuania	1	5
Netherlands	1	6

Portugal	1	7
Germany	*0*	*15*
Sweden	*0*	*10*
Austria	*0*	*8*
Belgium	*0*	*7*
Slovakia	*0*	*7*
Denmark	*0*	*6*
Finland	*0*	*6*
Latvia	*0*	*6*
Slovenia	*0*	*6*
Switzerland	*0*	*6*
North and Central America	**170**	**159**
United States	119	33
Canada	41	16
Mexico	9	14
Saint Pierre and Miquelon	3	1
Saint Vincent and the Grenadines	1	1
Cuba	*0*	*12*
Antigua and Barbuda	*0*	*7*
Grenada	*0*	*6*
Haiti	*0*	*6*
Saint Kitts and Nevis	*0*	*6*
Oceania	**123**	**110**
New Zealand	61	18
Australia	49	21
Northern Mariana Islands	7	5
Fiji	3	5
New Caledonia	2	6
Papua New Guinea	1	11
Vanuatu	*0*	*6*
South America	**47**	**104**
Argentina	23	23
Ecuador	14	8
Brazil	6	9
Chile	2	10
Falkland Islands	2	6
Colombia	*0*	*11*
Peru	*0*	*10*
Bolivia	*0*	*6*
Venezuela	*0*	*6*

Table S3. Distribution of impact magnitudes per species. To test whether more widely introduced ungulates were more often studied (see Table S8), we added the numbers of countries each species has been introduced to (no re-introductions) (extracted from Sheet 3 in Supp. 2).

Alien species	MC	MN	MO	MR	MV	*Total number of impact observations*	*Number of countries of introduction*
Ammotragus lervia	0	2	1	0	0	**3**	**10**
Axis axis	1	4	6	0	0	**11**	**25**
Bison bison	0	1	0	0	0	**1**	**4**
Bos taurus	1	6	5	1	0	**13**	**62**
Bubalus bubalis	3	0	10	0	0	**13**	**43**
Camelus dromedarius	0	3	1	1	0	**5**	**4**
Capra hircus	2	20	25	1	0	**48**	**83**
Cervus canadensis	0	4	2	0	0	**6**	**9**
Cervus elaphus	1	14	9	0	0	**24**	**33**
Cervus nippon	9	13	17	5	0	**44**	**34**
Dama dama	0	11	14	0	0	**25**	**55**
Elephas maximus	0	1	2	0	0	**3**	**3**
Equus asinus	1	8	1	0	0	**10**	**41**
Equus caballus	1	15	18	0	0	**34**	**42**
Hemitragus jemlahicus	0	0	3	0	0	**3**	**6**
Lama guanicoe	0	1	1	0	0	**2**	**7**
Muntiacus reevesi	0	6	8	0	0	**14**	**8**
Odocoileus hemionus	0	11	9	0	0	**20**	**6**
Odocoileus virginianus	1	18	15	2	0	**36**	**22**
Oreamnos americanus	2	1	5	0	0	**8**	**2**
Oryx gazella	0	1	1	0	0	**2**	**2**
Ovis aries	2	5	8	1	0	**16**	**66**
Ovis orientalis	2	5	11	2	0	**20**	**31**
Rangifer tarandus	0	0	4	0	0	**4**	**16**
Rusa timorensis	0	1	2	1	0	**4**	**14**
Rusa unicolor	1	6	2	0	0	**9**	**10**
Sus scrofa	5	36	22	0	0	**63**	**89**

Table S4. Impact magnitudes. Total numbers of impact observations classified in each impact magnitude.

Impact magnitude	**Count**
Minimal Concern (**MC**)	32
Minor (**MN**)	193
Moderate (**MO**)	202
Major (**MR**)	14
Massive (**MV**)	0
	441

Table S5. Confidence scores. Total numbers of impact observations classified in each impact magnitude and with each confidence score.

Confidence score	**MC**	**MN**	**MO**	**MR**	**MV**	***Total***
High	5	8	20	1	0	**34**
Medium	15	86	84	2	0	**187**
Low	12	99	98	11	0	**220**

Table S6. Are harmful impacts associated with lower or higher confidence scores? Contingency table (Pearson's Chi-squared test) showing observed and expected (in italic) numbers of harmful (MO, MR and MV) and lower (MC and MN) impacts by confidence score.

Confidence score	**Harmful impacts**	**Lower impacts**	**Total**
High	21 *16.65*	13 *17.35*	**34**
Medium	86 *91.59*	101 *95.41*	**187**
Low	109 *107.76*	111 *121.24*	**220**
Total	**216**	**225**	**441**

X-squared = 2.92, parameter = 2, p = 0.23

Table S7. Impact mechanisms. Total numbers of impact observations classified by impact magnitude and mechanism (some impact observations are recorded multiple times because they occurred through multiple mechanisms).

Impact mechanism	*Mechanism type*	MC	MN	MO	MR	MV	*Total*
Grazing/herbivory/browsing	Direct	7	135	112	6	0	**260**
Direct physical disturbance	Direct	2	41	36	0	0	**79**
Chemical, physical or structural impact on ecosystems	Indirect	10	5	50	3	0	**68**
Hybridisation	Direct	8	5	6	5	0	**24**
Competition	Indirect	3	3	12	0	0	**18**
Predation	Direct	1	13	4	0	0	**18**
Indirect impact through interaction with other species	Indirect	0	1	5	0	0	**6**
Transmission of diseases	Indirect	2	1	1	0	0	**4**

Table S8. Are indirect mechanisms or direct mechanisms associated with higher impact magnitudes? We tested whether direct or indirect mechanisms were associated with harmful impacts on all 441 impact observations (see Sheet 4 in Supp. 2), except impact observations occurring through both direct and indirect mechanisms.

Model: glmer(harmful/lower impacts ~ direct/indirect mechanisms + (1|Region), family=binomial)

	Estimate	**Std. Error**	***p***
Fixed effect: indirect mechanisms	-1.41	0.31	< 0.001
	Variance	**Std. Dev.**	
Random effect	1.07	1.03	

AICc: 574.3; AICc of null model: 595.2 (ΔAICc= 20.9)

Table S9. Impacted native species. Total numbers of impact observations classified in each impact magnitude, and in which animals or plants were affected. One impact observation is recorded twice because it affected both kingdoms.

Impacted kingdom	MC	MN	MO	MR	MV	*Total*
Animals	22	31	72	8	0	**133**
Plants	10	162	131	6	0	**309**

Table S10. Is native fauna or native flora associated with higher impact magnitudes? We tested whether native fauna or flora was associated with harmful impacts on all 441 impact observations (see Sheet 4 in Supp. 2), except the impact observation occurring on both native fauna and flora.

Model: glmer(harmful/lower impacts ~ native fauna/native flora + (1|Region), family=binomial)

	Estimate	**Std. Error**	***p***
Fixed effect: native flora	0.73	0.25	0.005
	Variance	**Std. Dev.**	
Random effect: Region	1.10	1.05	

AICc: 594; AICc of null model: 600 (ΔAICc= 6)

Table S11. Is the impact of ungulates more often studied in countries with more introductions? The numbers of impact observations and of introduced ungulate species for each country are given in the Table S2. We tested this on all 34 countries which had impact observations available, as well as on countries with no impact observations but at least six introduced ungulate species.

Model: lmer(log(number of impact observations for the country+1) ~ log(number of introduced ungulate species to the country+1) + (1|Continent))

	Estimate	**Std. Error**
Fixed effect	0.55	0.14
	Variance	**Std. Dev.**
Random effect: Continent	0.12	0.35
Residual	1.15	1.07

AICc: 208; AICc of null model: 218.4 (ΔAICc= 10.4)

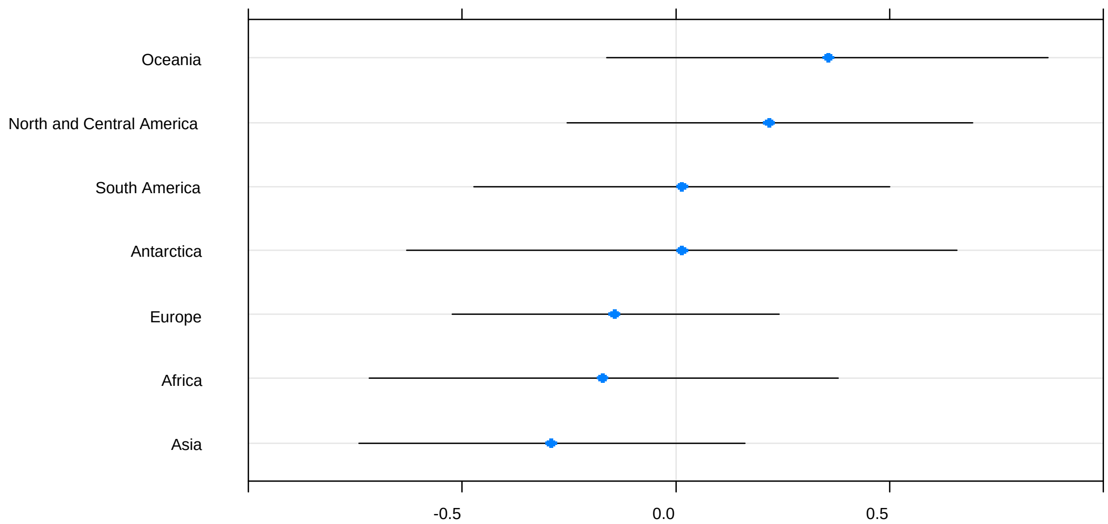


Figure S1. Caterpillar plot showing the variability in the increase of the number of impact observations per continent with the increase of introduced ungulate species.

Table S12. Are more widely introduced species more studied? To test whether more widely introduced species were more studied, we tested, on all 66 ungulate species, whether the number of impact observations per species increased with the number of countries each species has been introduced to (see Table S1 for DD species and Table S3 for assessed species; DD species were assigned 0 impact observation).

Model: lm(log(number of impact observations per species+1) ~ scale(log(number of countries the species has been introduced to+1))

Estimate	**Std. Error**	***p***	**Residual standard error**	**Adjusted R-squared**	**F-statistic**
1.10	0.09	< 0.001	0.78 on 64 DF	0.67	130.9 on 64 DF

AICc: 159; AICc of null model: 230.2 (ΔAICc= 71.2)

Table S13. Are species causing higher impacts more studied? We excluded DD species and the American bison (the only assessed species not causing higher impacts than MN impacts) and tested, on the remaining 26 species, whether the species having caused local extinctions (MR impacts) were more studied than species causing population declines (MO impacts) (see Table S3).

Model: lm(log(species' total number of impact observations+1) ~ MO/MR impact)

Estimate	**Std. Error**	***p***	**Residual standard error**	**Adjusted R-squared**	**F-statistic**
0.58	0.38	0.14	0.89 on 24 DF	0.05	2.33 on 24 DF

AICc: 72.7; AICc of null model: 72.5 (ΔAICc= - 0.2)

Table S14. Are more widely introduced species causing higher impacts? We excluded DD species and the American bison (the only assessed species not causing higher impacts than MN impacts) and tested, on the remaining 26 species, whether the more widely introduced species were the ones causing higher impacts (local extinctions, MR impacts) (see Table S3).

Model: glm(MO/MR impact ~ scale(log(number of countries in which the species have been introduced+1), family=binomial)

Estimate	**Std. Error**	***p***	**Null deviance**	**Residual deviance**
0.72	0.46	0.12	32.1 on 25 DF	29.14 on 24 DF

AICc: 33.7; AICc of null model: 34.3 (ΔAICc= 0.6)

Table S15. Pairwise comparisons between the impact risks of the species classified in the Major category. When the impact risks of two species are significantly different from each other, they are shown in black and bold.

Alien species	*Ovis orientalis*	*Camelus dromedarius*	*Rusa timorensis*	*Odocoileus virginianus*	*Ovis aries*	*Bos taurus*	*Cervus nippon*	*Capra hircus*
Ovis orientalis		0.29	0.19	0.20	0.10	0.064	**0.046**	**0.013**
Camelus dromedarius	0.29		0.37	0.37	0.22	0.15	0.11	**0.034**
Rusa timorensis	0.19	0.37		0.49	0.33	0.23	0.19	0.056
Odocoileus virginianus	0.20	0.37	0.49		0.33	0.23	0.19	0.056
Ovis aries	0.10	0.22	0.33	0.33		0.38	0.34	0.11
Bos taurus	0.066	0.15	0.23	0.23	0.38		0.47	0.17
Cervus nippon	**0.046**	0.11	0.19	0.19	0.34	0.47		0.12
Capra hircus	**0.013**	**0.034**	0.056	0.056	0.11	0.17	0.12	

Table S16. Pairwise comparisons between the impact risks of the species classified in the Moderate category. When the impact risks of two species are significantly different from each other, they are shown in black and bold.

	Rang_tar	*Hemi_jem Elep_max Oryx_gaz Lama_gua*	*Buba_bub Axis_axi*	*Orea_ame*	*Munt_ree*	*Dama_dam*	*Equu_cab*	*Odoc_hem Ammo_ler Cerv_can Rusa_uni*	*Cervu_ela*	*Sus_scro*	*Equu_asi*
Rang_tar		0.40	0.42	0.17	0.21	0.29	0.20	0.19	0.41	0.12	**0.047**
Hemi_jem Elep_max Oryx_gaz Lama_gua	0.40		0.33	0.28	0.33	0.42	0.33	0.29	0.46	0.24	0.10
Buba_bub Axis_axi	0.42	0.33		0.11	0.14	0.20	0.12	0.14	0.33	0.066	**0.023**
Orea_ame	0.17	0.28	0.11		0.41	0.27	0.39	0.49	0.19	0.46	0.19
Munt_ree	0.21	0.33	0.14	0.41		0.33	0.48	0.42	0.23	0.34	0.12
Dama_dam	0.29	0.42	0.20	0.27	0.33		0.32	0.30	0.34	0.15	**0.049**
Equu_cab	0.20	0.33	0.12	0.39	0.48	0.32		0.41	0.22	0.29	0.093
Odoc_hem Ammo_ler Cerv_can Rusa_uni	0.19	0.29	0.14	0.49	0.42	0.30	0.41		0.22	0.47	0.22
Cervu_ela	0.41	0.46	0.33	0.19	0.23	0.34	0.22	0.22		0.11	**0.040**
Sus_scro	0.12	0.24	0.066	0.46	0.34	0.15	0.29	0.47	0.11		0.15
Equu_asi	**0.047**	0.10	**0.023**	0.19	0.12	**0.049**	0.093	0.22	**0.040**	0.15	

(Rang_tar: Rangifer tarandus; Hemi_jem: Hemitragus jemlahicus; Elep_max: Elephas maximus; Oryx_gaz: Oryx gazella; Lama_gua: Lama guanicoe; Buba_bub: Bubalus bubalis; Axis_axi: Axis axis; Orea_ame: Oreamnos americanus; Munt_ree: Muntiacus reevesi; Dama_dam: Dama dama; Equu_cab: Equus caballus; Odoc_hem: Odocoileus hemionus; Ammo_ler: Ammotragus lervia; Cerv_can : Cervus canadensis; Rusa_uni : Rusa unicolor; Cervu_ela : Cervus elaphus; Sus_scro : Sus scrofa; Equu_asi: Equus asinus)

Table S17. Comparison with the impacts of alien amphibians (Kumschick et al. 2017) and birds (Evans et al. 2016). Contingency table (unconditional Exact functional test) showing observed and expected (in italic) numbers of harmful (MO, MR and MV) and lower (MC and MN) impacts by alien taxa.

	Harmful impacts	**Lower impacts**	**Total**
Alien ungulates	26 *11.47*	1 *15.53*	**27**
Alien birds	37 *50.54*	82 *68.46*	**119**
Alien amphibians	16 *16.99*	24 *23.01*	**40**
Total	**63**	**83**	**146**

Statistic = 37.5, parameter = 2, $p < 0.001$, estimate = 0.44

LARA VOLERY
Research Associate in Invasion Biology

Adress:	Rue Pierre-Aeby 23, 1700 Fribourg
Phone:	079 680 66 19
Email:	Lara.Volery@unifr.ch
D.O.B.:	18 October 1989

CURRENT POSITION

2021 **Post-doctoral researcher in invasion biology** – ***University of Fribourg***

EDUCATION

2021 **Doctor of Philosophy in Biology (ecology & evolution)** – ***University of Fribourg***
Topic: The impacts of alien species

2016 **Master of Science in Biology (ecology & evolution)** – ***University of Fribourg***
Topic: Effects of soil management on biodiversity in Swiss vineyards

2013 **Bachelor of Science in Biology** – ***University of Fribourg***
Minor: Environmental sciences

2009 **High School Certificate** – ***Collège St-Croix, Fribourg***

AWARDS & DISTINCTIONS

2020 Best Poster Award (2nd place) – *Neobiota 2020 (11th International Conference on Biological Invasions)*, Vodice (Croatia)

TECHNICAL SKILLS

Expert in the application of international frameworks for quantifying the impacts of alien species on the environment (the IUCN ***Environmental Impact Classification of Alien Taxa*** – ***EICAT***) and the society (the ***Socio-Economic Impact Classification of Alien Taxa*** – ***SEICAT***); Proficient in **data analyses** using **R**; Proficient in the set-up of **experimental designs**; Experienced in **plant** and **carabid surveys**; **Proficient** with the **Microsoft** software suite (Microsoft Word, Excel, Powerpoint)

WORK EXPERIENCE

Teaching & supervision

2019, 2020 Co-supervision of Bachelor students – University of Fribourg
Contribution in the design of projects, supervision during the analyses and the written work

2018, 2019 Presenter at two workshops on EICAT – Organised by *InfoSpecies* (Neuchâtel)
Presentation of the EICAT systems and their application, preparation of practical exercises

2016, 2017 Assistant for ecology practical courses – University of Fribourg
Insect determination

Grant application

2017 Successful application for funding with the Swiss National Science Foundation (SNSF)
*Important contribution in writing the proposal on '**Uncertainty in alien species impacts**'*

Services

2019 Co-organizer of the workshop '***Uncertainty in citizen science***' – 'European commission COST action working group - Increasing understanding of alien species through citizen science' (Ljubljana, Slovenia)
Important contribution in the development of the content and program of the workshop

2017 Co-organizer of the workshop '***Biological invasion: Challenges for science and society***' – University of Fribourg
Contribution in the organisation of social activities and of logistics of the workshop

Public administration

2014 - 2016 Administrative assistant (part-time) – Nature and Landscape Department of the Canton of Fribourg, Switzerland

2013 - 2014 Internship (6 months) – Nature and Landscape Department of the Canton of Fribourg, Switzerland
Development of documents for the implementation of a new Cantonal Law for nature protection

Other

Reviewer for the scientific journals *Biological Invasions* and *Mammal Research*

PUBLICATIONS

Volery, L., Jatavallabhula, D., Scillitani, L., Bertolino, S., & Bacher, S. (2021). Ranking alien species based on their risks of causing environmental impacts: a global assessment of alien ungulates. *Global Change Biology*. doi: 10.1111/gcb.15467

Volery, L., Bacher, S., Blackburn, T. M., Bertolino, S., Evans, T., Genovesi, P., ... & Smith, K. G. (2020). Improving the Environmental Impact Classification for Alien Taxa (EICAT): a summary of revisions to the framework and guidelines. *NeoBiota*, 62, 547-567. doi: 10.3897/neobiota.62.52723

Vimercati, G., Kumschick, S., Probert, A. F., **Volery, L.**, & Bacher, S. (2020). The importance of assessing positive and beneficial impacts of alien species. *NeoBiota*, 62, 525-545. doi: 10.3897/neobiota.62.52793

Probert, A. F., **Volery, L.**, Kumschick, S., Vimercati, G., & Bacher, S. (2020). Understanding uncertainty in the Impact Classification for Alien Taxa (ICAT) assessments. *NeoBiota*, 62, 387. doi: 10.3897/neobiota.62.52010

IUCN. (2020a). IUCN EICAT categories and criteria. The Environmental Impact Classification for Alien Taxa (EICAT) (1st ed.). *IUCN*. doi: 10.2305/IUCN.CH.2020.05.en

IUCN. (2020b). Guidelines for using the IUCN Environmental Impact Classification for Alien Taxa (EICAT) categories and criteria (1st ed.). *IUCN*.

Under review

Probert, A. F., Wegmann, D., **Volery, L.**, Adriaens, T., Bakiu, R., Bertolino, S., … & Bacher, S. (*under review*). Identifying, reducing, and communicating uncertainty in citizen science: a focus on alien species. *Biological invasions.*

Vimercati, G., Probert, A. F., **Volery, L.**, … & Bacher, S. (*under review*). EICAT+, a framework to classify positive impacts of alien taxa on native biodiversity. *Nature Ecology & Evolution.*

In preparation

Volery, L., Wegmann D. & Bacher, S. (*In prep.*). A general framework to quantify and compare ecological impacts under temporal dynamics.

Volery, L., Probert, A. F., Vimercati, G., Kumschick, S. & Bacher, S. (*In prep.*). A framework for indirect impact mechanisms of alien species.

PRESENTATIONS

International conferences and workshops

2020 *Neobiota 2020:* **Volery, L.**, Jatavallabhula, D., Scillitani, L., Sandro, B., Bacher, S. Adding risk of impacts to IUCN EICAT assessments improves prioritization of alien ungulates; Volery, L., Wegmann, D., Bacher, S. Temporal trends in alien species impacts (Poster) – Vodice, Croatia.

2019 *Frameworks used in Invasion Science:* **Volery, L.**, Bacher, S., Blackburn, T. M., Bertolino, S., Evans, T., Genovesi, P., ... & Smith, K. G. Improving the Environmental Impact Classification for Alien Taxa (EICAT) – Stellenbosch, South Africa.

2018 *Neobiota 2018:* **Volery, L.**, Jatavallabhula, D., Scillitani, L., Bertolino, S., Kumschick, S., Bacher, S. Improving our understanding of impacts – Dublin, Ireland.

2016 *Ecology of Soil Microorganisms:* **Volery, L.**, Fragnière, A.-F., Mène-Saffrané, L., Bacher, S. Effects of management on soil microorganism communities in Swiss vineyards (Poster) – Prague, Czech Republic.

Swiss conferences

2020 *Biology 20:* **Volery, L.**, Jatavallabhula, D., Scillitani, L., Bertolino, S., Bacher, S. Which are the worst alien species? The case of alien ungulates (Poster) – Fribourg.

2018 *Biology 20:* **Volery, L.**, Jatavallabhula, D., Bacher, S. Which are the worst aliens? (Poster) – Neuchâtel (2018).

Department seminars in Ecology & Evolution (University of Fribourg)

2020 **Volery, L.**, Jatavallabhula, D., Scillitani, L., Bertolino, S., Bacher, S. Adding risk of impacts to IUCN EICAT assessments improves prioritization of alien ungulates.

2019 **Volery, L.** & Bacher, S. Quantifying the impacts of alien species – Concepts.

2018 **Volery, L.** & Bacher, S. Uncertainty in impact assessments of alien species.

PROFESSIONAL DEVELOPMENT

2019 **GIS workshop.** Taught by Dr. Daniel Scherrer (Swiss National Institute of Forest, Snow and Landscape-WSL) – University of Fribourg

2019 **Structural Equation Modelling workshop.** Taught by Dr. James Grace (United States Geological Survey) – University of Fribourg

LANGUAGES

French – Native
German – Good knowledge (High School level)
English – Fluent (written and oral)