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The threat of invasive species to IUCN-listed critically endangered species: A systematic review

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ABSTRACT

We conducted a comprehensive review of the research literature on interactions between invasive species and species included in the critically endangered category of the International Union for Conservation of Nature (IUCN) Red List. This review reveals that, globally, invasive species threaten 14% (28% on islands) of critically endangered terrestrial vertebrate species (birds, mammals and reptiles), with critically endangered birds (25%; 47% on islands) the most affected, threatened predominantly by a few invasive mammal predators (mainly rodents and feral cat). The chytrid fungal pathogen is the main threat for critically endangered amphibians. The control and management of the invasive species identified in this study should be a high priority for global biological conservation, thereby contributing towards the achievement of the goals of the Post-2020 Framework of the Convention on Biological Diversity. Further research on the impacts of invasive species and interactions with other drivers will be essential for the conservation of highly threatened species.

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1. Introduction

The loss of biodiversity is a major environmental issue globally (Dirzo and Raven, 2003; Ceballos et al., 2010). Current and projected rates for the extinction of species exceed normal geological background rates by several orders of magnitude, and are considered to constitute the ongoing sixth major extinction event (e.g. Barnosky et al., 2011; Dirzo et al., 2014; Ceballos et al., 2017). Identification of the drivers of biodiversity loss and extinction-prone taxa is one of the most important tasks in conservation biology (Didham et al., 2007). The main drivers of biodiversity loss are habitat alteration, overexploitation and invasive species, along with other lower-ranked threats (Gurevitch and Padilla, 2004; Maxwell et al., 2016; WWF, 2016); the same rankings also apply to threatened vertebrates globally (Hoffmann et al., 2010; Ducatez and Shine, 2017). Invasive species are often considered the second most important threat (but see Dueñas et al., 2018).

Invasive species are listed as a driver of extinction, along with other threats, for half of species extinctions since 1500 CE for which any information exists. The cause of extinction is known for one quarter of current species extinctions. Invasive species are recorded as the sole driver of extinction in about 20% of species extinctions (Clavero and García-Berthou, 2005; Bellard

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et al., 2016a). In the case of terrestrial vertebrates, overexploitation and invasive species are identified as the main drivers (Loehle and Eschenbach, 2012; Bellard et al., 2016a). More than 80% of the species affected are island-endemic (Doherty et al., 2016; Bellard et al., 2016b). It is estimated that 27% of the currently threatened terrestrial vertebrate species worldwide included on the IUCN (International Union for the Conservation of Nature) Red List (mammals, birds and reptiles), and 40% of the critically endangered species in particular, are threatened by invasive species, amongst other threats (Bellard et al., 2016b).

The IUCN Red List is recognized as the most comprehensive list of threatened species worldwide (Rodrigues et al., 2006; Mace et al., 2008). The classification of the species listed according to their extinction risk is based on an explicit, scientifically strict framework (IUCN, 2017). By contrast, the information on the threats to these species relies on observation and expert opinion and less on quantitative assessment, as has been suggested (e.g., Hayward, 2009); and some is not based on reliable information (Gurevitch and Padilla, 2004), thereby increasing the degree of uncertainty regarding the threat. In order to overcome these limitations, species-specific knowledge of the individual drivers contributing to species decline is critical for the development of efficient and successful conservation strategies.

A scientific evidence-based approach has been suggested (Gurevitch and Padilla, 2004). Despite extensive efforts to assess the impacts of invasive species on biodiversity, there has been no global comprehensive synthesis of the current state of research.

The aim of this study was to find the science-based evidence in published scientific literature of the interactions between invasive species and species included in the IUCN Red List's critically endangered category (which face an extremely high risk of extinction in the near future) (IUCN, 2014). It was possible to ascertain whether some taxonomic groups were more affected than others and which invasive species were mainly involved, along with the mechanism of the impact and the geographical location.

2. Methods

The method followed a systematic review framework to search available literature and identify reliable sources of evidence. Unlike conventional reviewing, systematic reviewing involves a method that minimises bias and improves transparency, repeatability and reliability (Roberts et al., 2006). This systematic review was carried out following the guidelines specific to conservation interventions developed by Pullin and Stewart (2006). The search for relevant research literature was undertaken using the following electronic databases: ISI Web of Science, Scopus and CAB Direct, covering the period 1900−2015. Our search terms (see appendix, supplement S1 for searching method) were designed to retrieve references that focused on the interactions of invasive species with threatened species. Additional searches for grey literature were undertaken using Google Scholar. Further references cited in retrieved publications and review studies on the impacts of invasive species were examined for relevant sources.

The selection of references followed the PRISMA flow diagram (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines adopted from Moher et al. (2009). We used the following inclusion/exclusion criteria for the selection of references: (1) only species listed in the critically endangered category (4,635 species) as downloaded from the IUCN Red List of Threatened Species (version 2014.3; IUCN, 2014) were included. These species were classified as either island-endemic or mainland using the information provided by the IUCN Red List. (2) any interactions between invasive species and critically endangered species, in respect of population size, species range, growth, interference with reproduction, and alteration of gene pools were included. (3) crops, livestock and commercial trees (timber) were not accepted as being invasive species. (4) both experimental (e.g. exclosure or controlled and replicated manipulation) and observational (e.g. time-series data, geographical comparisons) study designs were included. (5) we did not retrieve literature written in languages other than English. For each case study, the following data were recorded: scientific name of the critically endangered species and the invasive species; taxonomic group; location of the study (mainland or island); country; environment (marine, freshwater or terrestrial); and mechanisms of interaction (predation, competition, hybridization, disease, herbivory or habitat alteration), according to the classification by Blackburn et al. (2014).

This systematic review did not attempt to quantify the impacts of invasive species, nor did it compare the direction of the impacts. The main aim was to identify the number of highly threatened species impacted by invasive species based on published scientific evidence. We used a chi-squared test to assess the proportion of impacted species among taxonomic groups and location (mainland versus island); and to compare the principal mechanism of impact and geographical distribution of the threatened species.

3. Results

This review selected 193 research papers with evidence of interactions between invasive species and critically endangered species (see appendix, Fig. S1 and supplement S2), with a total of 304 case studies (appendix, Table S1), as some references contained more than one species. Of these, 269 case studies were unique (after the duplicates were removed). The total number of critically endangered species researched in the references selected was 189 (4% of critically endangered species), of which 176 species were reported as being impacted negatively (3.8% of critically endangered species). It should be noted that the selection of these species found in the review did not mean that they were solely impacted by invasive species, as the majority of them were also impacted by other drivers.

The number of affected terrestrial species was higher on islands (107) than of those located on continents (67), ($\chi 2 = 44.1$, df = 1, $p < 0.001$); the remaining one was a marine species. The impacts of invasive species differed across taxa between islands and continents ($\chi 2 = 93.3$, df = 6, $p < 0.001$) (Fig. 1). The majority of impacted species were terrestrial vertebrates (124 species, 71% of which were on islands), and the most affected groups were birds (54 species, 98% on islands), and amphibians (40 species, 80% on continents). According to this study, 14% (84 species, n=594, with 28% on islands; 78 species, n=283) of bird, mammal and reptile species included in the critically endangered category were affected by invasive species, with critically endangered birds (25%; 54, n=213, with 47% on islands; 53, n=113) the most affected.

Mammals was the group of invasive species that threatened the highest number of species (affecting 45% of the total number of species identified in this study). The main mammals included in this group were rodents (mainly black rat (*Rattus rattus*)), and feral cat (*Felis catus*), which impacted mainly bird species. The next group of mammal predators in terms of threat were two species of Asian mongoose: the Javan mongoose (*Herpetes javanica*) and the small Indian mongoose (*H. auropunctata*) (hereafter *Herpetes* spp.), (see appendix, supplement S3 for further information), impacting reptile and bird taxa.

After mammal predators, another group that threatened a significant number of species was the disease chytridiomycosis, caused by the chytrid fungal pathogen *Batrachochytrium dendrobatidis* (Bd), affecting mainly amphibian species. The freshwater fish group impacted mainly freshwater native species, with a hotspot in Lake Victoria (Africa), where the invasive fish species Nile perch (*Lates niloticus*) impacted a significant number of haplochromine cichlid fish species. The next group was invertebrate invasive taxa (mainly the snail species, *Euglandina rosea*), followed by herbivores, mainly goats (*Capra hircus*), and feral pigs (*Sus scrofa*) (Fig. 2).

The mechanism of impact by invasive species was not evenly distributed among the different types of species interactions (appendix, Fig. S2). Predation alone was the principal interaction, mainly by mammal predators, followed by disease (associated exclusively with chytridiomycosis disease), affecting mainly amphibian species. Regarding geographical location, the majority of species identified in the literature review that were impacted negatively by invasive species were located on islands worldwide, mainly the Pacific islands (29%), and the Caribbean islands (17%), and in continental North and Central America (27%) (Fig. 3).

4. Discussion

Biological invasions are widely recognized as a key driver of current global change (e.g. Vitousek et al., 1997). In contrast, invasive species as a threat to biodiversity ranks lower compared with overexploitation and habitat change (Maxwell et al., 2016). For example, based on the information contained in the IUCN Red List, Gurevitch and Padilla (2004) determined that invasive species threaten 6% of threatened species; WWF (2016) reported a similar percentage (5%); and Duenas et al. (2018) found that invasive species threatened 6.2% of endangered and threatened species on the ESA list (USA). According to the published scientific evidence reviewed in this study, the proportion of species identified is 3.8%, albeit this percentage relates to critically endangered species, a subset of threatened species on the IUCN Red List.

However, the number of species affected is non-random across taxa: the study shows that invasive species are responsible or co-responsible globally for extinction risks to 14% (28% on islands) of critically endangered terrestrial vertebrate species (birds, mammals and reptiles), which are threatened predominantly by invasive mammal predators (rodents and feral cat). A previous assessment found that 26% of critically endangered birds, mammals and reptiles are impacted by invasive species (Bellard et al., 2016b), and 20% are impacted exclusively by invasive mammal predators on islands (Bellard et al., 2017; Doherty et al., 2016; McCreless et al., 2016).

This group of invasive species has been responsible for more documented terrestrial vertebrate extinctions on islands worldwide than any other invasive species (Bellard et al., 2016a). In general, most extinctions have been on islands as opposed to continents. In respect of the specific threat of invasive species (Sax et al., 2002), the main mechanism of impact is predation, which has caused the extinction of a disproportionate number of terrestrial vertebrates on islands (Sax and Gaines, 2008).

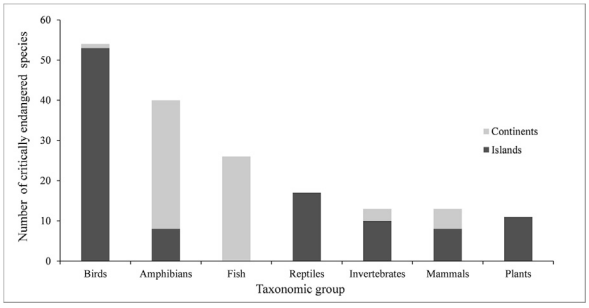

Fig. 1. Number of critically endangered species across taxonomic groups (marine species not included) that are impacted by invasive species on continents and islands.

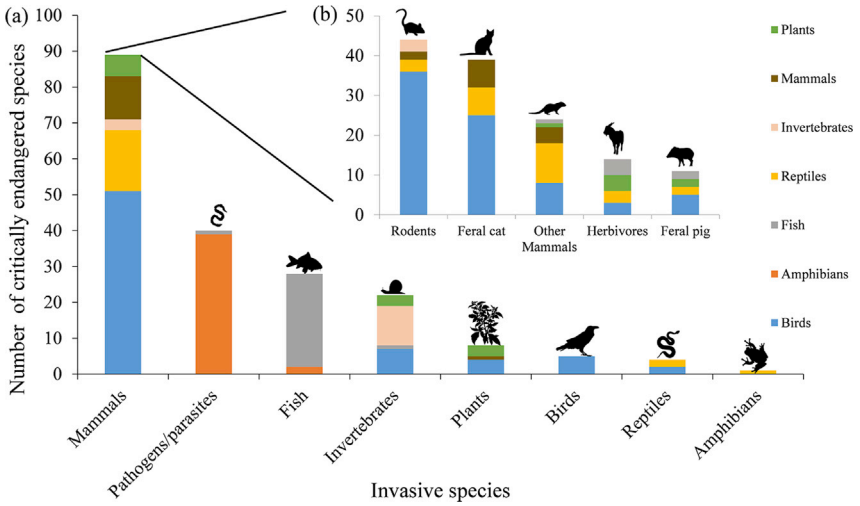

Fig. 2. (a) Number of critically endangered species impacted by invasive species across taxonomic groups; (b) Invasive mammal taxa are shown separately, split into the more common invasive groups referred to in biological invasion literature.

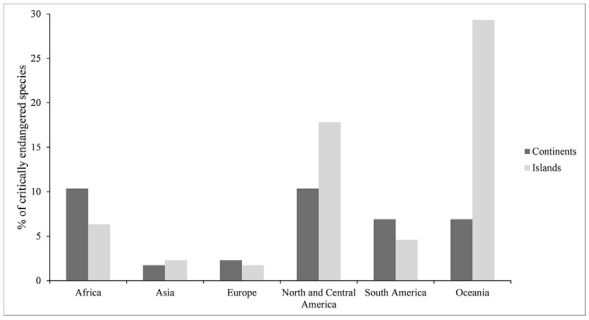

Fig. 3. Distribution of critically endangered species impacted by invasive species on continents versus islands.

The group most affected by invasive species is birds. The review shows that 25% (47% on islands) of critically endangered birds are chiefly affected by mammal predators. The majority of bird extinctions since 1600 have been on islands (Bellard et al., 2016a; Johnson and Stattersfield, 1990), with a continuing steady decline (Blackburn, 2004; Clavero et al., 2009; Harper and Bunbury, 2015; Bellard et al., 2016b, 2017), especially of seabirds (Jones et al., 2008; Spatz et al., 2014), although other drivers such as overexploitation also affect their decline and extinction (Owens and Bennett, 2000; Bellard et al., 2016a).

The other invasive mammal predator identified in this study is the mongoose (*Herpetes* spp.), mainly threatening reptiles on Caribbean islands. Mongooses have been introduced to many different parts of the world, chiefly onto islands for the biological control of rats and snakes in plantations (Barun et al., 2013), and they are responsible for the decline of many reptile species (Hays and Conant, 2007), mainly island-endemic reptiles in the Caribbean islands (Doherty et al., 2016). Globally, however, the main drivers are habitat alteration and overexploitation (Böhm et al., 2013). In contrast, other invasive mammal predators (mustelids, dogs and foxes) are known to affect island species and ecosystems in some situations, but their global impacts are not well studied or reported (Hays and Conant, 2007). Another invasive mammal group, herbivores such as feral pigs (*Sus scrofa*), are an important threat to endangered species on islands by predation (Spear and Chown, 2009), but our results suggest that they are not the most important drivers of extinction risk at a global scale.

After birds, this study identified that amphibians is the next group most affected by invasive species. The infectious chytridiomycosis panzootic, caused by the chytrid fungal pathogen, is the main cause of amphibian declines. This disease has caused the decline of at least 6.5% of described amphibian species across the globe (Stuart et al., 2004), and it is implicated in recent extinction events (Skerratt et al., 2007; Wake and Vredenburg, 2008; Bellard et al., 2016a), and represents the greatest loss of biodiversity attributable to a disease affecting amphibians worldwide (Scheele et al., 2019).

For global fish taxa, this review found that the main group impacted is freshwater species, which are threatened by different drivers, especially harvesting (Olden et al., 2007). This study retrieved a negligible number of marine species with some evidence of impact by invasive species; this is as corroborated by recent studies (Anton et al., 2019). There are no documented global extinctions attributed to marine exotic species (Gurevitch and Padilla, 2004). This can be explained by the fact that the main drivers leading extinctions of marine species are harvesting and pollution (Olden et al., 2007).

The research effort identified in this review shows that few critically endangered insect species are threatened by invasive species. This group shows a high decline, with more than half of the species affected by habitat loss and pollution; invasive species are considered a lesser threat (Sánchez-Bayo and Wyckhuys, 2019), although there is no documented research on the causes of extinction of a large number of insects (Dunn, 2005). The terrestrial mollusc taxon is identified in the review as being impacted mainly by the snail, *Euglandina rosea,* in the oceanic islands. The introduction of this predatory mollusc species on islands for the purposes of biological control is responsible for one-third of known mollusc extinction (Régnier et al., 2009).

The review found that very few critically endangered plants are impacted by invasive species, and that these were mainly on islands. It has been argued that this is in part because of the existence of time-lags between invader introduction and impacts, and the existence of extinction debts has been hypothesized (Gilbert and Levine, 2013). It has also been suggested that extinctions of invasive plants should be seen as a trajectory rather than as an end-point process (Downey and Richardson, 2016). Nevertheless, the main driver of plant extinctions globally is habitat alteration (Bellard et al., 2016a).

The geographical focus of research efforts has been mainly on the oceanic islands, where the highest declines and the highest risks of extinction by invasive species have been identified in previous studies (Pacific Ocean, including New Zealand, the islands of Hawaii and the Caribbean islands, as well as mainland Central America and Australia) (Bellard et al., 2016b, 2017; Doherty et al., 2016). In these geographical areas, 87% of terrestrial vertebrates have become extinct (Bellard et al., 2016a; Doherty et al., 2016). Most amphibian declines have occurred in the tropics of Mesoamerica and South America – geographical areas that have a greater richness of amphibian species than elsewhere in the world (Wake and Vredenburg, 2008) – and in Australia (Scheele et al., 2019). As regards Australia, in contrast to other continents, the general pattern of extinction of land mammals is most likely due to the introduction of mammal predators and changed fire regimes (Woinarski et al., 2015; Kearney et al., 2019). Australia's terrestrial mammals are the most distinctive in the world (Holt et al., 2013) because their long evolution in isolation has made an imprint on these species' susceptibility to the impact of invasive species (Cox and Lima, 2006).

In general, extinction rates have been higher on islands than on continents (Sax and Gaines, 2002). These extinctions have been unevenly distributed among taxonomic groups: a disproportionate number of birds have become extinct by predation whereas comparatively few plants have become extinct by competition (Sax et al., 2008). It has been asserted that the risk of extinction is greater on islands because they have more endemic species, small population sizes, reduced geographical ranges; and species on islands have low rates of reproduction, and lack of anti-predator behaviour (Blumstein and Daniel, 2005; Kier et al., 2009). In particular, islands harbour nearly 41% of critically endangered species and represent 4% of the world's threatened species, which are distributed on 0.3% of all islands worldwide (Spatz et al., 2017).

There are limitations to our systematic review approach. It is likely that the number of critically endangered species impacted by invasive species is underestimated, as some of the research documents (e.g. grey literature) are not widely accessible by conventional means. It is difficult to obtain quantitative and experimental data that evaluate the impact of invasions on highly threatened species in low abundance, and the time-lag phenomenon in invasions implies that many introduced species remain harmless for long periods before becoming invasive (Crooks, 2005). It is also difficult to distinguish threats from other synergistic drivers (Didham et al., 2007). Moreover, research is biased towards some taxa (e.g. birds and mammals) (Hulme et al., 2013): whereas the majority of vertebrates have been assessed (Baillie et al., 2004), data for invertebrate species are less comprehensive.

This systematic review, and others (e.g. Medina et al., 2011), found that many publications based on observational studies did not quantify the magnitude of interaction and that estimates of invasive species' abundance are biased (e.g. rodents, Ruffino et al., 2015). In general, the quantification of the impact of invasive species is not well represented in biological invasion literature (Esler et al., 2010), and there is therefore a high degree of uncertainty about such impacts. Nevertheless, invasive species with the greatest impact are most likely to be studied (Pyšek et al., 2008). Despite these limitations, the research undertaken on the impact of invasive species on critically endangered species largely mirrors the pattern of invasive-caused extinction identified in previous studies, in that invasive species have their greatest impact on islands, where the majority of species extinctions have occurred (Bellard et al., 2016a).

This systematic review supports the assertion that the management of invasive vertebrates, mainly invasive mammal predators on islands, is a prerequisite for conserving global biodiversity (Loehle and Eschenbach, 2012; Jones et al., 2016; McCreless et al., 2016). An important strategy for preventing the introduction of non-native species on islands is the implementation of biosecurity measures (Russell et al., 2017); this is the most cost-effective long-term strategy (Moore et al., 2010), although control and eradication is the most widespread method currently used in conservation management (Courchamp et al., 2003). Eradication has been demonstrated to be a successful conservation measure in recovering more than 200 threatened vertebrate species. It is predicted that 6% of highly threatened birds, mammals and reptiles are likely to have benefited from the eradication of invasive mammals from islands (Jones et al., 2016). There is some level of public opposition to eradication measures (Temple, 1990; Towns et al., 2006), and the implementation of these control projects can be very costly (Helmstedt et al., 2016). Alternative conservation measures have been proposed, such as enhanced restoration and an increase in conservation areas (Linklater and Steer, 2018).

5. Conclusion

This study provides a more comprehensive global review than has been available previously of research efforts undertaken on the impact of invasive species that potentially contribute to the decline of critically endangered species globally. This

systematic review reveals that a small number of invasive species are leading extinction risks: invasive mammal predators threatening terrestrial vertebrates mainly on islands, with chytrid fungus pathogen representing the main extinction threat to amphibians. This study provides valuable information in support of the aims of the Post-2020 Framework of the Convention on Biological Diversity (CBD, 2020), which calls for the identification and management of invasive species in order to reduce extinction risks. We call for more rigorous studies investigating the impacts of invasive species, and a better understanding of interactions with other drivers. This will be essential for the mitigation of biodiversity loss by invasive species.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2021.e01476.

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