Extinction potential from invasive alien species

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Abstract

Biological invasions pose significant threats to biodiversity, while impacting ecosystem services, human health, and cultural heritage. Despite these far-ranging effects, their impacts are generally underappreciated by both the public and policymakers, resulting in insufficient management and inadequate conservation outcomes. Recognizing the gap in effective quantitative measurement tools, we introduce the Extinction Potential Metric (EPM) and its derivative, EPM for Unique species (EPM-U; adjusted for phylogenetic uniqueness) to quantify the ecological damage caused by invasive alien species (IAS). These metrics estimate the number of current and projected extinct species within a 50-year horizon under a business-as-usual scenario due to specific IAS.

We applied EPM and EPM-U to assess threats to native terrestrial vertebrates from IAS, examining impacts on 2178 amphibians, 920 birds, 865 reptiles, and 473 mammals. The analysis identified that damage mostly stems from a limited number of IAS, notably two pathogenic fungi affecting amphibians (up to 380 equivalent extinct species) and primarily cats (139 equivalent extinct species) and rats (50 equivalent extinct species) impacting other groups, through mechanisms such as predation, disease, and reduced reproductive success in birds.

The proposed metrics not only provide a standardised measure of ecological impacts but are sufficiently versatile to be tailored for specific spatial and temporal scales or taxonomic groups. Furthermore, EPM could serve as a model for developing unified indicators to monitor global biodiversity targets, such as those defined in the Kunming-Montreal Global Biodiversity Framework (GBF), by assessing the ecological effects of various individual and combined anthropogenic stresses. Also, EPM and EPM-U could support the enforcement of Target 6 of the GBF, by establishing lists of IAS requiring urgent prevention and control.

Thus, EPM and EPM-U offer critical tools for improving the management of biological invasions and enhancing global conservation strategies.

Keywords: Conservation, Extinction, Biological invasion, Ecological impact, Metric, Phylogeny, Red List

Introduction

Biological invasions are a major threat to biodiversity and cause impacts across all aspects of the natural and human world, including reduced ecosystem services, increased human health hazards, and loss of indigenous and cultural practices (Roy et al., 2024). The number of newly introduced alien species has been steadily increasing since the 1800's (Seebens et al., 2017), and the number of established alien species is expected to increase by 36% between 2005 and 2050 under a business-as-usual scenario (Seebens et al., 2021). The subset of these species that have negative impacts, so-called invasive alien species (IAS), have contributed to 60% of known species extinctions, cost hundreds of billions of $US each year (increasing four-fold every decade and reaching $423 billion in 2019), and adversely impact quality of life in 85% of cases (Roy et al., 2024). Despite these figures, the impacts of biological invasions remain underestimated and poorly understood by both the public and policy-makers, leading to hindered public support and participation, inadequate management actions, and hampered conservation outcomes (Courchamp et al., 2017).

The recent *InvaCost* database, which compiles the economic costs of IAS (including management- and damage-related costs), provides a quantitative metric documenting the economic impacts of IAS (i.e. monetary costs in a standardised currency and year; Diagne et al., 2020, 2021). As such, it succeeded in facilitating public and policy awareness (Ahmed et al., 2023). For ecological impacts, multiple metrics have also been proposed, primarily based on impact categories. For example, the Environmental Impact Classification for Alien Taxa scheme (EICAT; Blackburn et al., 2014; Hawkins et al., 2015) categorises the maximum impact an IAS has had globally into four categories above minimal (undetected) impact, and has been adopted by the IUCN (IUCN, 2020b, 2020a). These EICAT scores range from impacts on individual fitness to the local extinction of species and irreversible changes in community composition (see Bernardo-Madrid et al., 2022 for an assessment of the consistency of seven impact classification schemes).

However, to our knowledge, there is no fully quantitative, continuous impact metric that would allow for comparison of the ecological impacts of IAS across taxa and scales. Such a metric would allow for more granular impact comparisons among contexts and taxa with more detailed analyses and predictions, such as spatial and temporal trends of derived indicators, quantitative links with invasion drivers and alien species traits, or disentangling the demographic and per-unit or per-capita components of impact, therefore allowing for more targeted management actions (Latombe et al., 2022). Since managing biological invasions is often the most effective conservation action (Langhammer et al., 2024), robust and comparable quantitative metrics would permit prioritisation of action as requested from Target 6 of the Kunming-Montreal Global Biodiversity Framework (GBF), which aims to “eliminate, minimise, reduce and or mitigate the impacts of invasive alien species on biodiversity and ecosystem services” (CBD, 2022). It would also underpin indicators appropriate for risk identification and prioritisation efforts to meet global biodiversity targets (Butchart et al., 2005; Vicente et al., 2022). The lack of such standardised metrics capable of capturing the severity of IAS impacts to ecosystems and their services has been a major impediment, not only to action, but also to effective communication between scientists, stakeholders and policy-makers.

Here, we propose the Extinction Potential Metric (EPM) as a measure of impact of individual IAS. The EPM of an IAS can be conceptualised as the number of species that have already been led to extinction plus those that are expected to go extinct within a 50-year time frame under a business-as-usual scenario because of this IAS. It can also be seen as the equivalent number of extinct species, allowing for the comparison of IAS with different current levels of impacts on multiple native species, from complete extinction to population decrease or range contraction. The EPM uses the existing IUCN Red List of Threatened

Species framework (IUCN, 2024), quantifying the threats posed by IAS to native fauna to compute a risk of extinction within 50 years for each native species threatened by IAS. Moreover, since native species extinctions are unequal in terms of evolutionary distinctiveness among taxa, we introduce an additional metric, namely EPM-U, representing the number of 'unique' native species that have and would go extinct within a 50-year time frame. Species uniqueness accounts for the evolutionary history of the impacted native species. EPM-U therefore compares IAS with impacts on phylogenetically related vs unrelated species. Below, we present the EPM and EPM-U metrics and their computations in detail. We showcase both metrics with a proof of concept on native terrestrial vertebrate species threatened by IAS (amphibians, reptiles, birds and mammals). We also show how EPM and EPM-U can be used to identify which impact mechanisms are most detrimental to native species. EPM and EPM-U complement other methodologies to measure the impact of IAS, and in particular EICAT (Blackburn et al., 2014; Hawkins et al., 2015).

Method

Data: Native species impacted by identified invasive alien species

We utilised the IUCN Red List data (IUCN, 2024) to catalogue terrestrial vertebrate species impacted by IAS, i.e. those associated with Threat 8.1 (Invasive non-native/alien species/diseases). We identified 2178 amphibians, 920 birds, 865 reptiles, and 473 mammals in categories Least Concern (LC), Near-Threatened (NT), Vulnerable (VU), Critically Endangered (CR), Extinct in the Wild (EW), Extinct (EX), and Data Deficient (DD) for which at least one IAS was listed as a threat. DD species were discarded from the analyses. Invasive organisms threatening these native species were identified at the species level when possible (73%), but some were only identified at the genus (7%), family (1%), or order and class (0.6%) level. For 19% of the threats, the invasive organism was not identified and was recorded as “Unspecified species”. We refer to entries in the database as IAS hereafter for simplicity, and to genus, family, or order when specifically addressing these categories. For each of the native species previously identified, we also distinguished between species endemic to islands and other species, using data from Marino et al. (2022).

We also extracted information on the scope (proportion of population affected) and severity (speed of population decline) of the IAS threat to these native species from the database. Those with over 50% of their population witnessing a very rapid (>30% over 10 years or three generations; whichever is the longer), rapid (20–30% over 10 years or three generations; whichever is the longer), or slow and significant (<20% over 10 years or three generations; whichever is the longer) decline due to IAS were deemed to experience a high impact, while the other species were considered to experience a low impact (definitions from IUCN & CMP, 2012a). When neither the extent nor the severity was available, impact level was considered as ‘not available’ (NA). In addition, we extracted the mechanism by which each native species was affected by IAS, using the IUCN Red List stress classification scheme (IUCN & CMP, 2012b).

In addition to tabular information summarising the threat details on native species described above, the IUCN Red List website provides more detailed textual descriptions of the threats affecting native species, including from IAS, interlinking data with the Global Invasive Species Database implemented by the IUCN Invasive Species Specialist Group. Examination of these textual descriptions revealed that species included in the description are often missing from the tabular information. To assess the effects of this difference of information content, we manually examined the description for the 473 mammals in the LC, NT, VU, CR, EW, and EX categories, and generated an extended database including all species mentioned both in the text and in the table. Comparison between the extended dataset and the tabular dataset for mammals showed that the tabular information could miss up to 10 native species impacted by a given IAS with a mean value of 0.89 ± 1.12 (Supp. Fig. 1).

Computing the probability of extinction of each native species

To convert IUCN Red List categories into probabilities of extinction, we followed the EDGE2 and FUSE approaches (Gumbs et al., 2023; Pimiento et al., 2023) (Fig. 1). These approaches first assign the following species extinction probabilities within 50 years based on their IUCN Red List category: 0.06 for LC, 0.12 for NT, 0.24 for VU, 0.49 for EN, and 0.97 for Critically Endangered CR. EX and EW were attributed a probability of 1. To mitigate potential biases resulting from the discrete categorisation of species extinction risk, we then applied probabilistic draws for VU to CR species. These five IUCN Red List categories were first transformed into ordinal values from 1 to 5, and a quartic distribution was then applied to link these ordinal values and the extinction probabilities using the `polyfit` function from the pracma R package V 2.4.4 (Borchers, 2023) (Figure 1). For each species, a value was randomly chosen from a uniform distribution spanning the range of its ordinal category value +/- 0.5, using the `runif` function in R. We then computed its probability of extinction based on the previously established quartic distribution (Figure 1). This process was replicated 10 times for each native species, generating a set of 10 extinction probabilities per species according to their IUCN Red List category, enabling us to generate confidence intervals and account for uncertainty.

Translating the extinction risks of native species into future number of species extinct due to IAS

We calculated the extinction potential of each IAS by summing the probabilities of extinction (including EX and EW species) for all native species impacted by this specific IAS. However, the contribution of an IAS to the extinction risk or to the past extinction of a native species can vary. According to the IUCN Red List, the impact of IAS on a native species can be classified as high or low (Fig. 1), but these data can also be missing (hereafter NA). To account for these different levels of impact of IAS on the decline of native species population globally (low, high, or NA—as described above), we divided the probability of extinction of native species by a factor 2 for low impacts. For IAS whose impacts were classified as NA on some native species, we performed two sets of analyses to account for different uncertainty scenarios. First, assuming that NAs potentially reflect very small impacts, we excluded the corresponding native species in the computation of EPM values, providing a conservative value. As a result, 10 EPM values were computed for each IAS, based on the 10 extinction probabilities generated for each native species, as described above, adjusted for the level of impact of IAS.

Second, assuming NAs may simply represent a gap in how impacts were reported rather than a level of impact, we randomly selected between low and high impact categories, and repeated this process 100 times to assess the uncertainty linked to data deficiency. As a result, for each original set of 10 probabilities of extinction generated for each native species, we calculated 100 scores when the impact level of an IAS was NA, corresponding to their probability of extinction adjusted for the impact level. Consequently, to each of these IAS corresponded 1000 sets of extinction probabilities for the native species they impacted (10 extinction probabilities drawn from the quartic function x 100 potential impact levels). For each IAS, we therefore obtained a distribution of the number of native extinct species. We then computed the EPM for all native species together, but also for each native taxonomic group separately (i.e. each IAS had an impact distribution for amphibians, birds, mammals, and reptiles).

Considering unspecified IAS

As some IAS were only identified at the genus and family levels in the IUCN Red List database, we also used information on unspecified species to compute the maximum possible EPM value for an IAS based on the available data, by assuming unspecified species included all species in the reported genus or family. In other words, we considered a given IAS to be responsible for all the threats for which it is identified, but also for all the threats imposed by unspecified IAS of the same genus or family. For example, the maximum EPM of *Rattus rattus* was computed by aggregating the EPM of *Rattus rattus*, the EPM of Unspecified Rodentia and the EPM of Unspecified *Rattus*. The maximum EPM of the other *Rattus* species, i.e. *Rattus norvegicus*, and *Rattus exulans*, was computed in the same way. Conversely, doing so implies that native species impacted by unspecified *Rattus* species were considered as affected by all *Rattus* species (i.e. *Rattus rattus*, *Rattus norvegicus*, and *Rattus exulans*).

Accounting for evolutionary distinctiveness

Evolutionary distinctiveness is an important component of biodiversity that can be incorporated into our approach by following an approach similar to that used to compute the EDGE2 metric (Gumbs et al., 2023). The EDGE2 score of a species represents the number of millions of years of evolutionary history lost if a species goes extinct. It is the product of the heightened evolutionary distinctiveness (ED2) of a species and of its risk of extinction (GE2, for global endangerment). ED2 accounts for the phylogenetic distance of a species from other species (its “raw” evolutionary distinctiveness ED), but also the extinction risk of these other species. A species with an intermediate ED whose phylogenetically related species are endangered will therefore have a higher ED2, as the risk of losing the whole clade is then higher.

To account for evolutionary history in measuring the impact of IAS, we propose an additional metric, the Extinction Potential Metric for Unique species due to an IAS (EPM-U), which incorporates ED2 scores into EPM. As ED2 values are only available for mammals (Gumbs et al. 2023), we only computed EPM-U of IAS on native mammals. To do so, we propose to use the maximum ED2 score of all mammals to determine the most unique species in the database, with a value of 1. We then rescaled all ED2 values by dividing them by this maximum value, to generate a “uniqueness score” for each impacted native species in [0,1]. In addition, Gumbs et al. (2023) account for uncertainty in the calculations of ED2 values and provide a median value, with the corresponding lower and upper interquartile ranges for each species. We sampled 10 ED2 values per native species from a normal distribution where the mean is the median ED2 value and the standard deviation is the lower interquartile interval divided by 1.35. These 10 ED2 values for each native species were rescaled between 0 and 1 after dividing them by the maximum ED2 value. We then computed the number of unique extinct species due to an IAS as the sum of the probabilities of extinction for each native species impacted by the IAS multiplied by their uniqueness score. Following the same methods as for the EPM, we generated 100 scores per IAS.

Linking impact strength to impact mechanisms

We assessed the importance of the 11 impact mechanisms listed in the IUCN Red List through which IAS affect native species, using EPM values. For each of these 11 mechanisms—competition, ecosystem conversion, ecosystem degradation, hybridisation, inbreeding, indirect ecosystem effects, reduced reproductive success, skewed sex ratios, species disturbance, species mortality, and species stresses—we extracted the native species impacted by any IAS (identified or not). We then computed the corresponding EPM score based on the IUCN Red List category of the native species, the severity, and the scope of the threats, generating an EPM score for each impact mechanism following the same framework as detailed above. This was done for all native species and for each taxonomic group separately.

Results

Global impacts of IAS on native taxa

Considering all native species for which the impact level of IAS was known, we observed from the 196 IAS that median EPM values (all EPM values hereafter correspond to median values) ranged from 0.02 (*Pavo cristatus*) to 89.8 (*Batrachochytrium dendrobatidis*) extinct species, with a mean value of 2.4$\pm$9.64 (hereafter corresponding to the standard deviation). EPM values followed a log-normal distribution, with a few species having high values and most having low values and 47 IAS with a value above 1 extinct species (Fig. 2.A, Supp. Table 1). When including native species with an impact level defined as 'NA' (i.e. randomly assigned to low or high 100 times), 357 IAS were included, and mean EPM values increased by 38% with 80 IAS above 1 extinct species. The EPM values of IAS with the greatest impact were particularly affected, with *B. dendrobatidis* rising from 89.8 to 380.7, *Felis catus* from 87.2 to 138.8, and *Batrachochytrium salamandrivorans* from 15.1 to 88.5 (Supp. Fig. 2.A).

When computing EPM values of IAS for the different native taxonomic groups separately (i.e. the equivalent number of extinct native amphibians, birds, mammals or reptiles) we observed different rankings across taxa (Fig. 2.B, Supp. Table 2). Five IAS had an EPM higher than 1 extinct amphibian species. Two pathogenic fungi were particularly impactful, *B. dendrobatidis* (the pathogen causing chytridiomycosis in frogs; EPM = 89.8.0), followed by *B. salamandrivorans* (EPM = 15.1). Twenty-six IAS had an EPM above 1 extinct bird species, and three IAS above 10: *Felis catus* with (EPM = 40.1), *Rattus rattus* (EPM = 27.2), and *Canis familiaris* (EPM = 10.7) (Fig. 2.B). Five IAS had an EPM score above one extinct mammal species, but one was particularly impactful: *Felis catus* (EPM = 22.6) (Fig. 2.B). Finally, 15 IAS had an EPM score above 1 extinct reptile species, and 3 had a score above 10: *F. catus* (EPM = 25.0), *Wasmannia auropunctatus* (EPM = 12.2), and *Herpestes auropunctatus* (EPM = 11.3) (Fig. 2.B). When we included native species with an impact defined as 'NA', EPM values increased particularly for amphibians, for which the number of IAS with a score above 1 rose from 5 to 19 (a 280% increase). The number of IAS above 1 rose by 30% for birds (34 *vs* 26), 100% for mammals (10 *vs* 5) and 60% for reptiles (25 *vs* 15) (Supp. Fig. 2.B, Supp. Table 3). Similarly, we observed substantial increases in EPM values for the most impacting IAS for amphibians (*B. dendrobatidis* EPM = 380.5 and *B. salamandrivorans* = 87.0) but also for reptiles (*F. catus* EPM = 51.8, *R. rattus* EPM = 21.3, and *H. auropunctatus* EPM = 19.8) and to a lesser extent for birds (*F. catus* with EPM = 54.1, *R. rattus* EPM = 32.3, and *C. familiaris* EPM = 14.4) and mammals (*F. catus* EPM = 31.7) (Supp. Fig. 2.B, Supp. Table 4).

Results were similar for maximum EPM scores considering unspecified genera or families, with *Rattus* species seeing the main increase, due to many impacts being reported for unspecified *Rattus* and rodents in the IUCN Red List database (Supp. Fig. 3). *Mus musculus* and *H. auropunctatus* had a substantive increase in their score when considering unspecified rodents and unspecified *Herpestes*.

Insular endemic species accounted for 82.0±25.7% of the previously computed EPM scores across all native species. Specifically, the impact of IAS was highest for island endemic amphibians and reptiles, with mean changes of -92.4±27.2% and -88.7±16.6%, respectively. The effect was slightly less pronounced in birds, at -80.6±27.8%, and was the weakest in mammals, at -62.0±37.0% (Fig. 3). Adding native species with 'NA' impact did not broadly affect these results (Supp. Fig. 4).

Impacts of IAS on mammal species: tabular vs. textual information and number of unique extinct species

When considering the extended database comprising the tabular (high, low, and 'NA' threats) and textual information (only 'NA' threats), 29 IAS had an EPM score of more than 1 extinct mammal species (Fig. 4). *F. catus* had the largest impacts (EPM = 64.2), followed by *C. familiaris* (EPM = 30.6), *R. rattus* (EPM = 20.0), and *Vulpes vulpes* (EPM = 19.3). When considering the evolutionary distinctiveness of impacted mammals, the same 4 species had the highest EPM values (*F. catus* = 3.9, *C. familiaris* = 2.2, *V. vulpes* = 1.9, and *R. rattus* = 0.98) (Supp. Fig. 6.B). The evolutionary distinctiveness of impacted mammals had little effect on the ranking of the four most impactful IAS, but had important effects on rankings for other IAS (Fig. 5).

Impacts caused through different mechanisms

When considering all taxa, 'Species mortality' was associated with the largest EPM value of 396.9, more than three times the second and third highest EPM value from 'reduced reproductive success' (EPM = 122.5) and 'ecosystem degradation' (EPM = 109.6) (Fig. 6.A). Furthermore, 'Species mortality' was the most consistent mechanism, showing a significant association with higher EPM scores for amphibians, birds, mammals, and reptiles (Fig. 6.B). For native birds, it was closely followed by 'reduced reproductive success,' and for native birds and reptiles, 'ecosystem degradation' also had a substantial effect (Fig. 6.B). Adding native species with 'NA' impact did not affect 'species mortality' which stayed largely the most impactful mechanism with EPM = 1018.7, but 'ecosystem degradation' became the second most important mechanisms with EPM = 235.3 above 'reduced reproductive success' EPM = 158.4 when considering all taxa (Supp. Fig. 6).

Discussion

We introduced and applied a new metric, the Extinction Potential Metric, which computes the ecological impacts of IAS as the equivalent number of native species that IAS have contributed to driving to extinction. The EPM uses the IUCN Red List assessments to compute extinction probabilities of native species impacted by IAS within 50 years, in addition to those species already extinct. A quantitative EPM value is then attributed to each IAS based on the number of species it is expected to drive to extinction, allowing for detailed comparison of the impacts of different IAS. We also introduced an alternative metric, EPM-U, the Extinction Potential Metric for Unique species, to account for differences in evolutionary history of impacted native species, and complement the information provided by EPM.

Most impacts on native tetrapods result from a few IAS

Birds, mammals, and reptiles were all mostly impacted by cats (*F. catus*), followed by dogs (*C. familiaris*) and rats (especially the black rat, *R. rattus*, but also other rat species, often unspecified or including *Rattus norvegicus* and *Rattus exulans* for birds), foxes (*V. vulpes*), the small Indian mongoose (*H. auropunctatus*), and domestic goats (*Capra hircus*). All these species belong to the IUCN list of 100 of the worst invasive species (Lowe et al., 2000; Luque et al., 2014). Results are nonetheless different for amphibians, which are mostly affected by two invasive pathogenic fungi, *B. dendrobatidis* and *B. salamandrivorans* (Fig. 2), with the former also appearing in the 100 of the worst list. The number of amphibian species affected by these two species is higher than the number of all tetrapod species affected by any other IAS (see also Bellard, Genovesi, et al., 2016). An important part of these impacts is recorded for species that are endemic to islands (Fig. 3), indicating the disproportionate impacts IAS have on species that are potentially evolutionarily distinct within insular habitats (Millien, 2006). In addition, for most IAS, the numbers of impacted native species in each Red List category are of the same order of magnitude (Fig. 7, Supp. Fig. 7). This means that EPM scores are mostly driven by past extinctions (EX and EW categories) or by decreases in native species populations and ranges that have driven them to the brink of extinction (CR category), rather than by expected future extinctions (LC to VU categories).

The evidence presented above confirms that controlling a limited number of IAS could effectively prevent and mitigate the impacts of biological invasions on biodiversity. This is consistent with the conclusions of the IPBES assessment that highlighted that, with sufficient resources, political will and long-term commitment, preventing and controlling IAS are attainable goals that will yield significant long-term benefits for nature (Roy et al., 2024). Also, the results of our analysis support the need to identify priority IAS for prevention and control, as requested from Target 6 of the GBF.

Considering the evolutionary distinctiveness of impacted native mammals, did not fundamentally change the ranking of the most impactful IAS (Fig. 5), but changed the score distribution, with a more gradual increase in EPM-U compared to EPM values (Supp. Fig. 5). Evolutionary distinctiveness, and more generally phylogenetic diversity, is a core component of conservation as it captures multiple concepts (Gumbs et al., 2023; Lean & Maclaurin, 2016; Winter et al., 2013). Evolutionarily distinct species may be considered to have a high intrinsic value on the basis of their uniqueness. Phylogenetic diversity (maximised by conserving the most unique species) has also been advanced as a proxy for functional diversity and evolutionary potential, whose maximisation is important for ecosystem services and for maintaining the benefits humans draw from nature, although these claims have been questioned (Mazel et al., 2018; Winter et al., 2013). The difference in EPM and EPM-U score distribution has implications for the design of management actions and IAS prioritisation. Although assessing the risk caused by IAS is insufficient to prioritise which IAS to manage, which should also account for management feasibility and costs (Robertson et al., 2021), it is an essential component of this process. Here, using EPM scores alone would give a greater weight to the few species with a disproportionately high score, whereas EPM-U scores would suggest considering a wider range of species.

“Species mortality” is the main mechanism through which IAS impact native species (Fig. 6). This occurs through predation for mammals, birds, and reptiles, and through two diseases for amphibians. Ranking of the other mechanisms varied substantially across the four taxonomic groups. Interestingly, birds were the only group for which reduced reproductive success was an important mechanism, ranking second. However, this is likely due to the fact that IAS consume native bird eggs before hatching, which is therefore similar to predation in the sense that this is linked to direct resource consumption. Aggregating the EPM scores of these two impact mechanisms for native birds would generate a profile similar to that of the other taxonomic groups. Other important but secondary, non-lethal impact mechanisms include ecosystem degradation, species disturbance, and competition. The predominance of direct predation over other impact mechanisms suggests that appropriate IAS management requires the removal of interactions between IAS predators and their prey. It may also suggest that increased attention is needed towards more subtle threat mechanisms which are less conspicuous than those driving direct mortality. While lethal control of predators may seem to be the most obvious approach, it may not be effective or even achievable, especially on the mainland (García-Díaz et al., 2021). IAS populations can recover quickly, preventing eradication success, and lethal control may need to be performed at levels that are not attainable with current techniques, or are financially unsustainable to see positive effects. Efficacy is also context-dependent, with studies on various native taxa showing effects of IAS control ranging from positive to negligible and even negative effects (García-Díaz et al., 2021). Context-specific alternative approaches to lethal control have been proposed, including IAS exclusion, for example using fences (D. Smith et al., 2020), nest cages to prevent egg consumption (Buzuleciu et al., 2015; R. K. Smith et al., 2011), translocation of native species (Miskelly & Powlesland, 2013), or prey training and harnessing natural selection to combat prey naivete (Moseby et al., 2016), although their efficacy has been questioned. Nevertheless, IAS eradications have had high success rates on islands (Spatz et al., 2022), which contributed the majority of extinction risk in those habitats.

The results presented here should be taken with some level of caution. First, the IUCN Red List, despite being a major conservation resource, is not fully comprehensive, and not all native nor invasive species have been assessed or are up-to-date (Cazalis et al., 2022, 2023). This is exemplified by the large shares of IAS with impacts classified as 'NA' towards particular native species in the current study. The resource is also more likely to report impacts from IAS when these have been long standing, and often uses observed and inferred impact through expert opinion rather than comprehensive, published evidence (e.g. Gula et al., 2023; Van der Colff et al., 2021). The figures we present are therefore conservative. The IUCN Red List is also of limited use in identifying future problematic IAS, given time lags to invasion and impact (Essl et al., 2011). Finally, and importantly, the IUCN Red List data is open access and can easily be extracted from the IUCN Red List website as text files containing data in a tabular format. However, examination of more detailed textual information provided on the webpage of each assessed native mammal revealed that this tabular information was incomplete, with up to 10 IAS missing in the list of threats (Supp. Fig. 1). Computing EPM scores for the extended database comprising the textual information revealed that impacts were largely under-estimated, even for the most impactful species, and that ranking differed for many species. We therefore advocate for an in-depth curation of the IUCN Red List database, to harmonise the information content on IAS threats on native species between tabular and textual information, to ensure consistency across taxa. Fostering knowledge on IAS impacts on native species is also paramount to improve these figures and develop an even more accurate application of EPM.

EPM as a measure of ecological impacts

The new metric we propose provides a bespoke quantitative measure of ecological impact of IAS and has many advantages compared to existing, mostly qualitative metrics. Using probabilities, the EPM links impacts at the population and species level. It uses species as a unit, which is the fundamental unit of conservation, as exemplified by the IUCN Red List of Threatened Species—arguably the most influential global conservation tool to date. As the IUCN Red List is open access, EPM assessments are transparent, readily applicable and reproducible. The EPM score of an IAS can be interpreted as the number of species that it will have driven to extinction in 50 years under a business-as-usual scenario, including past and future extinctions. Thus, EPM is easily conceptualised by policy-makers and the civil society, and will therefore foster communication about the impacts of biological invasions and the design of management actions, such as native conservation prioritisation.

In addition, EPM offers the possibility to be temporally and spatially downscaled. Red List statuses are ideally updated every few years for each species, which will enable us to generate estimates and track temporal changes in the impacts of IAS. EPM, as presented here, assesses ecological impacts of IAS at the global scale, because it is the scale for which the IUCN most commonly provides Red List categories and with the most complete level of details. However, Red List categories can also be assessed at national and regional levels (IUCN, 2012). EPM could therefore also be spatially explicit if the same level of information on the status and threats on native species is assessed at multiple spatial scales. This downscaling is particularly pertinent given that the impacts of IAS can differ substantially among populations occurring in different regions over time, undermining the efficacy of global species ‘watch lists’.

As demonstrated in our analyses, EPMs can be computed for different groups of impacted native species, allowing for the capture of multiple dimensions of impacts caused by IAS, rather than generating a single value or category for an IAS. Here, we showed that IAS impacts varied across four taxonomic groups of native tetrapods. In addition, although we applied the EPM at the IAS level, it would be straightforward to upscale the metric to the genus level or beyond, or for any group of IAS of interest. For example, here we also quantified the importance of each mechanism through which IAS impact native species, by computing EPM scores after grouping all IAS impacting native species through these threat mechanisms. Although the most important impacts occur through direct mortality, it also revealed that other, non-lethal impacts (e.g. competition or species disturbance, such as the disruption of critical lifecycle stages) or changes in the environment (e.g. ecosystem degradation) can also have important impacts. Doing so therefore enables us to capture the broader ecological impacts of biological invasions for different components of ecosystems, and how they cascade to *in fine* affect native species survival.

Note, however, that native species impacted by biological invasions are often threatened by multiple IAS simultaneously, as well as other anthropogenic pressures, and their effects can combine non-additively. Disentangling the relative impacts of different IAS on a single native species is not possible with the current granularity of IUCN data. It is consequently not possible to assess if an IAS could lead a native species to extinction in the absence of another IAS (e.g. cats are often associated with red foxes in Australia, but have led many native species to extinction by themselves in other regions). In the absence of a clearly identifiable rule to determine the contribution of each IAS, here we took a conservative, objective and reproducible approach, attributing the same probability to cause extinction to different IAS affecting a native species with the same level of impact. This follows precautionary principles, an approach already used by other impact classification schemes, including EICAT (Kumschick et al., 2024), to avoid irreversible impacts or high costs to the environment and society that would result from inaction.

The versatility of EPM offers avenues to derive indicators assessing the ecological impacts of biological invasions to inform international policy initiatives, in particular Target 6 of the GBF. This framework is lacking appropriate indicators that would allow tracking of policy performance regarding this target (Henriksen et al., 2024). Such indicators should capture spatial and temporal changes, be species-specific and allow for identification of the mechanisms through which IAS impact native species (Henriksen et al., 2024), which are all readily included in EPM. Different indicators have been developed, but are either qualitative (e.g. Genovesi et al., 2012), categorical (e.g. Kumschick & Nentwig, 2010), do not provide information on the IAS and their impact mechanisms (e.g. Butchart, 2008; Butchart et al., 2005), or focus on species extinction (i.e., extreme 'end-points') rather than combining multiple levels of earlier-stage impacts on different native species (e.g. Bellard, Cassey, et al., 2016). Indicators derived from EPM could be combined with other indicators of impacts (Van der Colff et al., 2021) but also with trends or projections in IAS numbers and ranges, trends in introduction and spread mechanisms, and trends in policy responses (McGeoch et al., 2006, 2010; Rabitsch et al., 2016), to provide a comprehensive description of the issue and analysis of its drivers.

Finally, the EPM could be used to assess the ecological impacts of other anthropogenic pressures listed as threats under the IUCN Red List classification scheme (e.g. residential & commercial development, agriculture & aquaculture, pollution, climate change & severe weather, etc., as per the IUCN Red List Threat Classification scheme V3.3; IUCN & CMP, 2012a). Doing so could lead to a set of harmonised indicators to assess progress towards different targets of the GBF (e.g. Target 7: Reduce Pollution to Levels That Are Not Harmful to Biodiversity; CBD, 2022). It could also permit analyses of synergies among global change drivers, by identifying which processes combine to create the highest threats, compared to where they occur individually. Indeed, specific native species are often impacted by multiple anthropogenic pressures simultaneously, which can reinforce each other.

Conclusion

We introduced the Extinction Potential Metric, a new quantitative metric to assess the ecological impacts of invasive alien species. The EPM computes the equivalent number of native species driven to extinction by an IAS using the IUCN Red List categories to assign probabilities of extinction within 50 years. Doing so enables us to incorporate IAS impacts at the population and species levels into a single metric, and also to account for evolutionary distinctiveness between impacted native species. Applying this metric to native terrestrial vertebrates shows that a few IAS disproportionately affect native species populations through direct mortality, suggesting that controlling a limited number of IAS could effectively prevent and mitigate the impacts of biological invasions on biodiversity. The metric is versatile and transparent, and can be applied to different groups of native species and IAS, to permit prioritisation of conservation action and to provide a detailed and more comprehensive assessment of IAS ecological impacts than existing approaches. We argue it can be the basis to derive spatio-temporal indicators that will improve our capacity to assess the efficacy of global and regional conservation policies.

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Data availability

The data on which this paper is based are freely available on the IUCN Red List website (www.redlist.org). A list of the native and invasive alien species used in the analyses is given in the electronic supplementary material.

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FIGURES

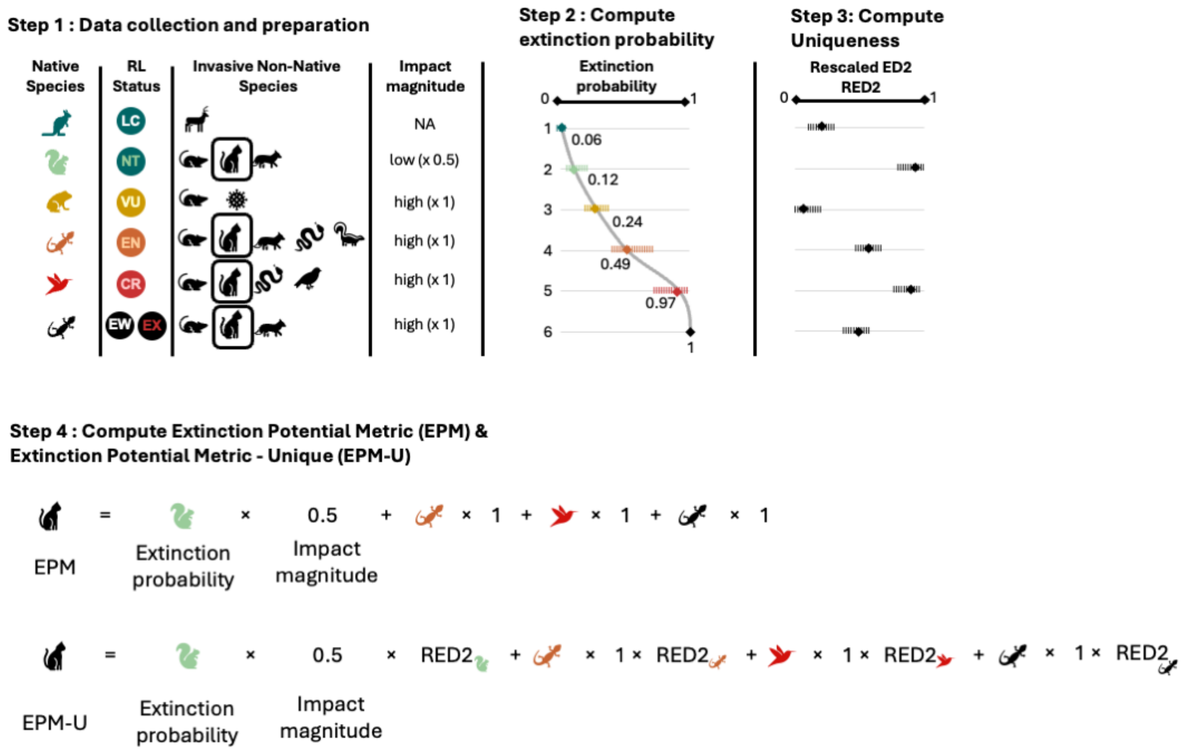

Figure 1. Workflow used to compute the Extinction Potential Metric. Species uniqueness was computed by rescaling ED2 scores from Gumbs et al. (2023); although they are indicated for all species here to show the general principle, ED2 scores were only available for native mammals. For impact magnitude, NAs were either considered as no impact (x 0) or randomly drawn as low or high impacts. Rug plots depict random draws along the quartic function for extinction probabilities and between lower and upper interquartiles from Gumbs et al. (2023) for ED2 scores.

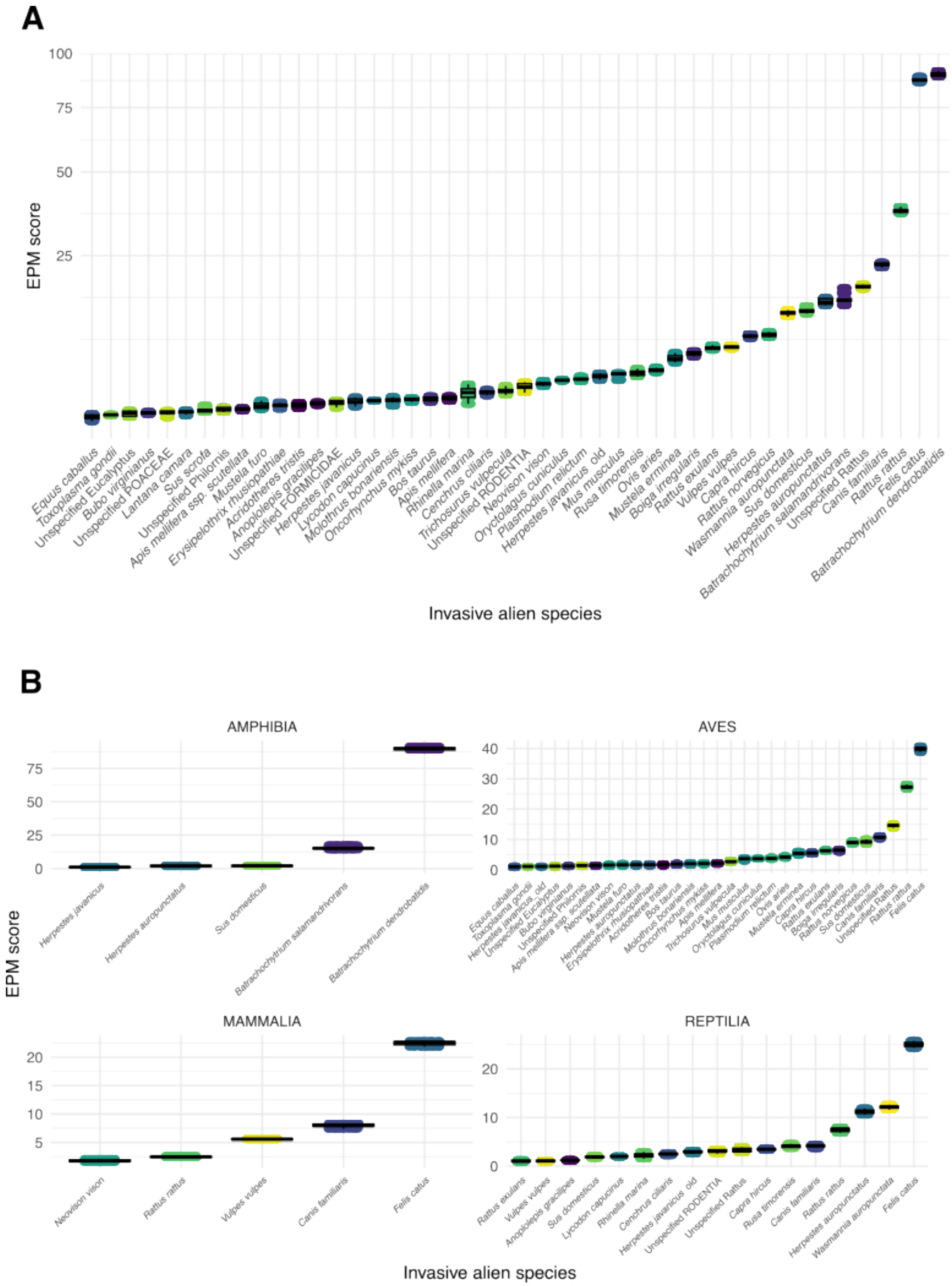

Figure 2. Extinction Potential Metric (EPM) scores of invasive alien species (IAS) impacting native tetrapods globally. Only IAS with a score above 1 are displayed. Panel A shows EPM scores based on the impacts of IAS on all native tetrapods combined. Panel B shows EPM scores based on the impacts of IAS on each taxonomic group (amphibians, birds, mammals, and reptiles) separately.

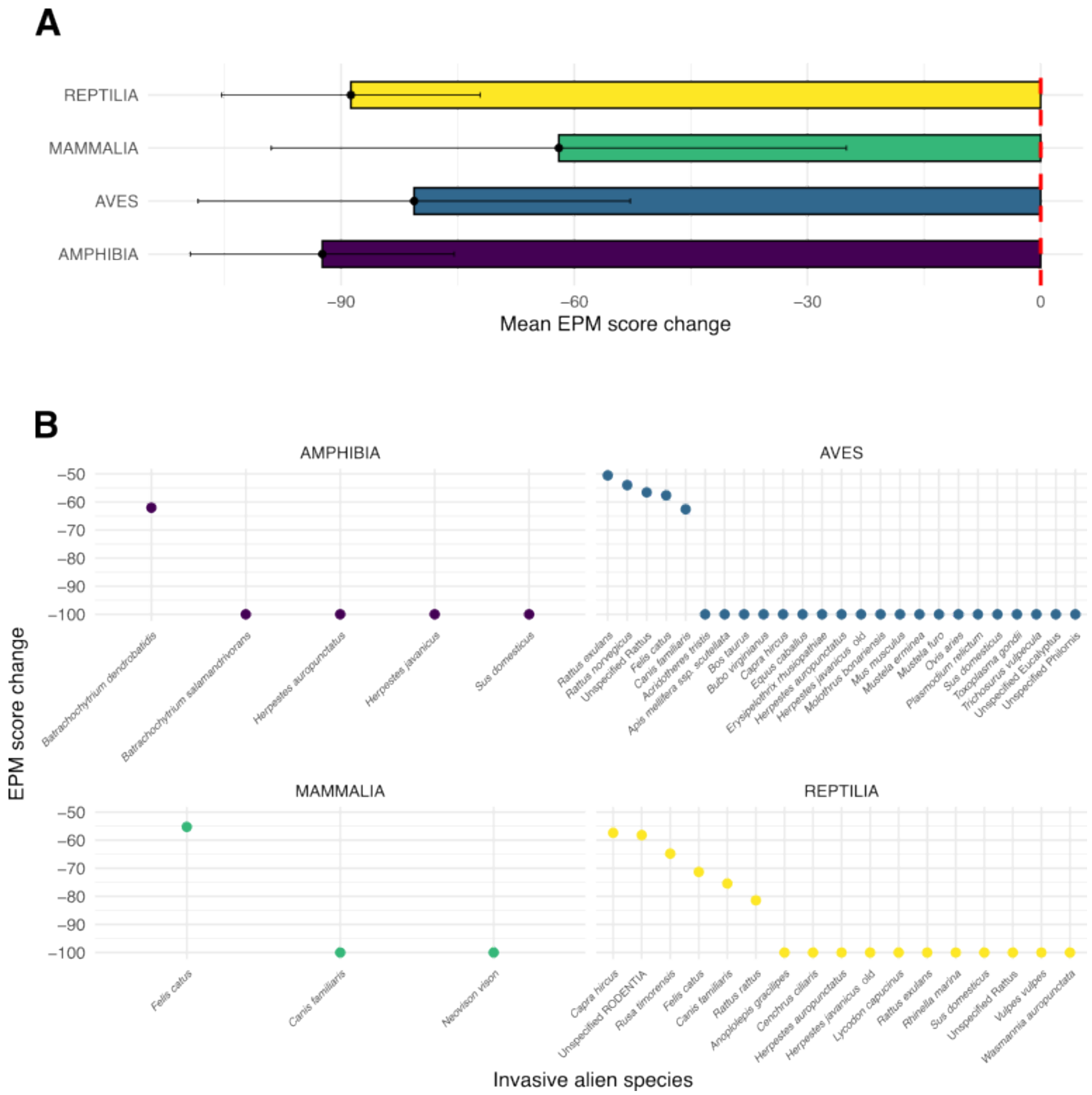

Figure 3. Contribution of insular endemic species to the EPM scores. EPM scores reflect the impact of IAS on native tetrapods globally, considering insular endemic species. Panel A shows the change in EPM scores (in %) when excluding insular endemic species for each of the four native taxonomic groups. Panel B highlights IAS with a difference in score of more than 50% when excluding insular endemic specie

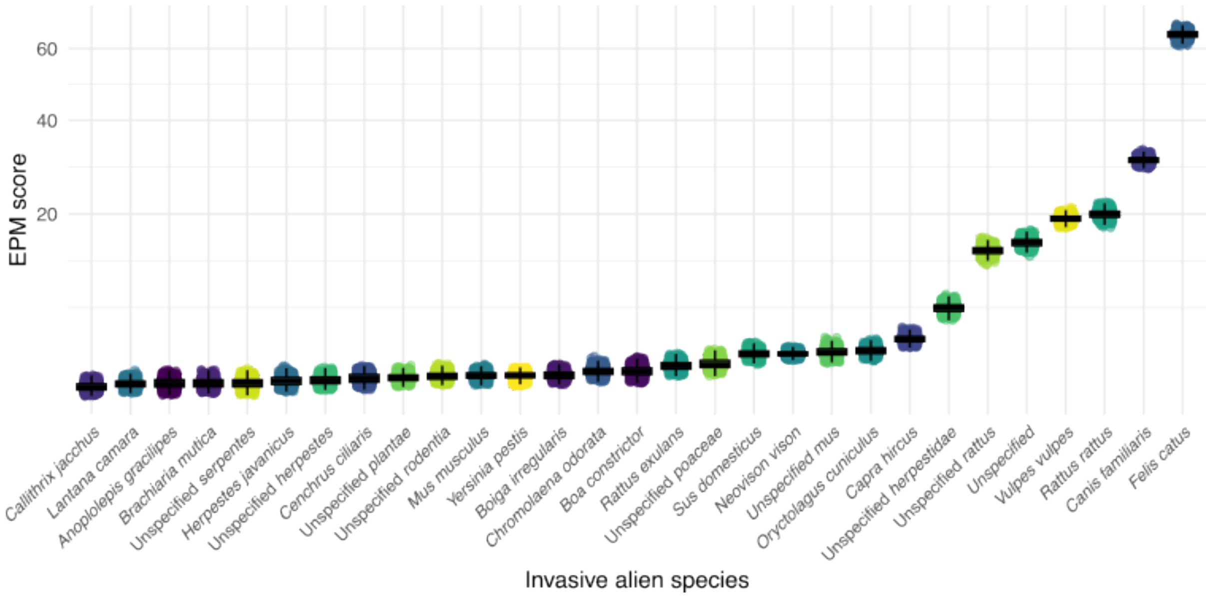

Figure 4. EPM scores of IAS impacting native mammals globally using textual and tabular data from the IUCN Red List. EPM scores were computed using both textual and tabular data from the IUCN Red List, including all impacts on native species, even when the severity or scope of the impact was not assessed.

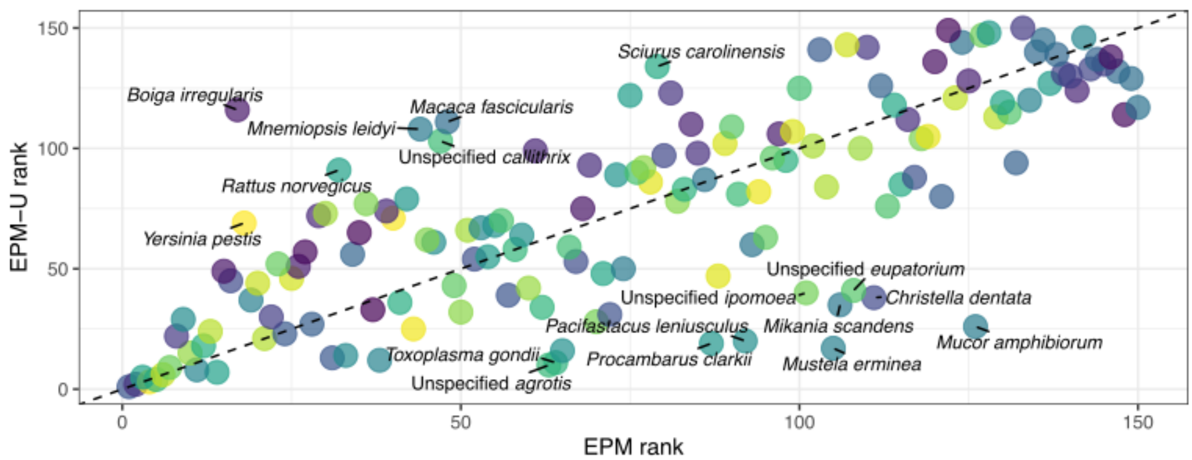

Figure 5. Comparison of EPM-U and EPM scores of IAS according to rank. The lower an IAS's rank, the higher its score, and vice versa. Species close to the diagonal have similar ranks for both approaches. IAS whose absolute difference between the two metrics is greater than 50 are displayed with their scientific name.

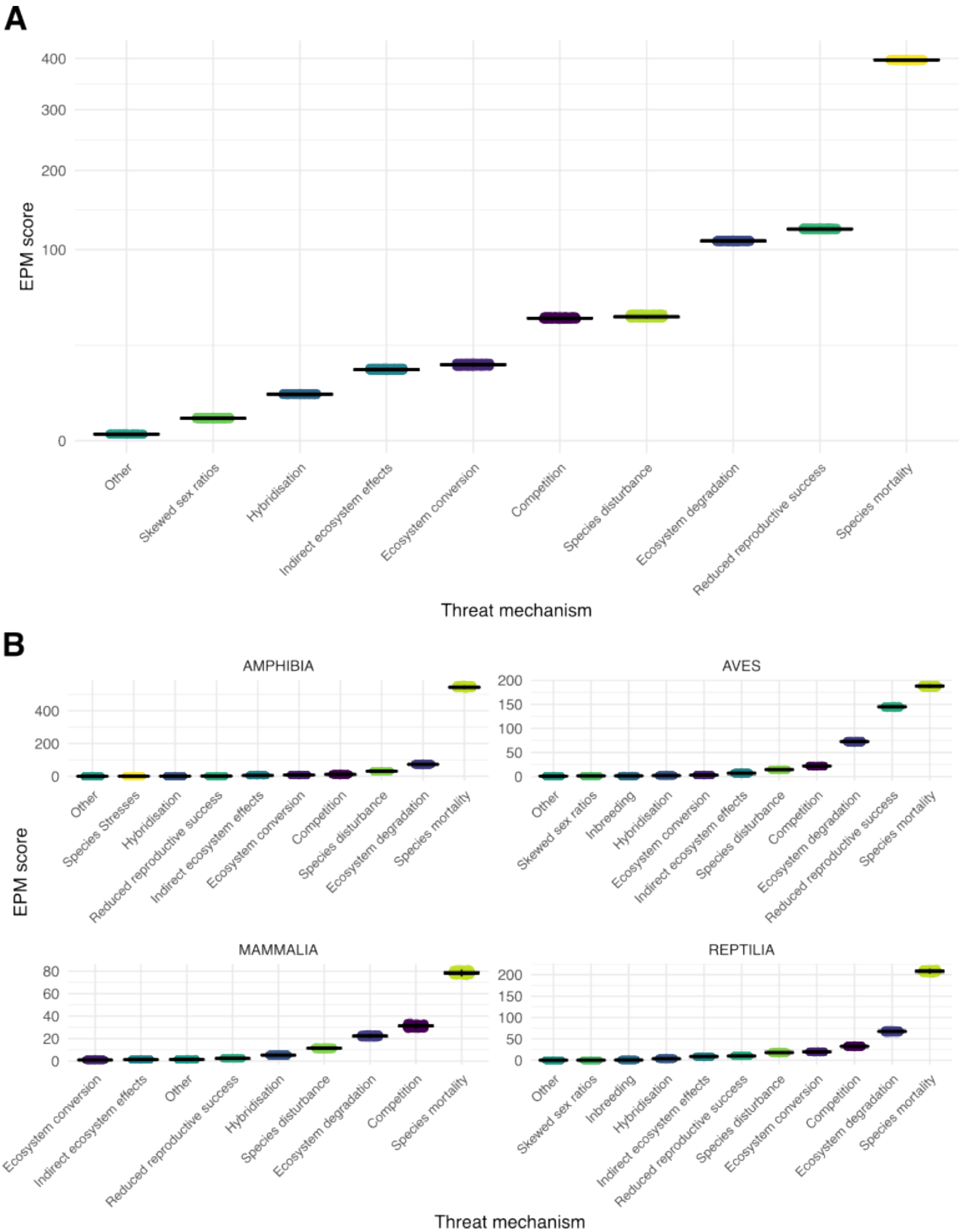

Figure 6. EPM scores of threat mechanisms impacting native tetrapods globally. Only IAS with a score above 1 are displayed. Panel A shows EPM scores based on the impacts of mechanisms on all native tetrapods combined. Panel B shows EPM scores based on the impacts of mechanisms on each taxonomic group (amphibians, birds, mammals, and reptiles) separately.

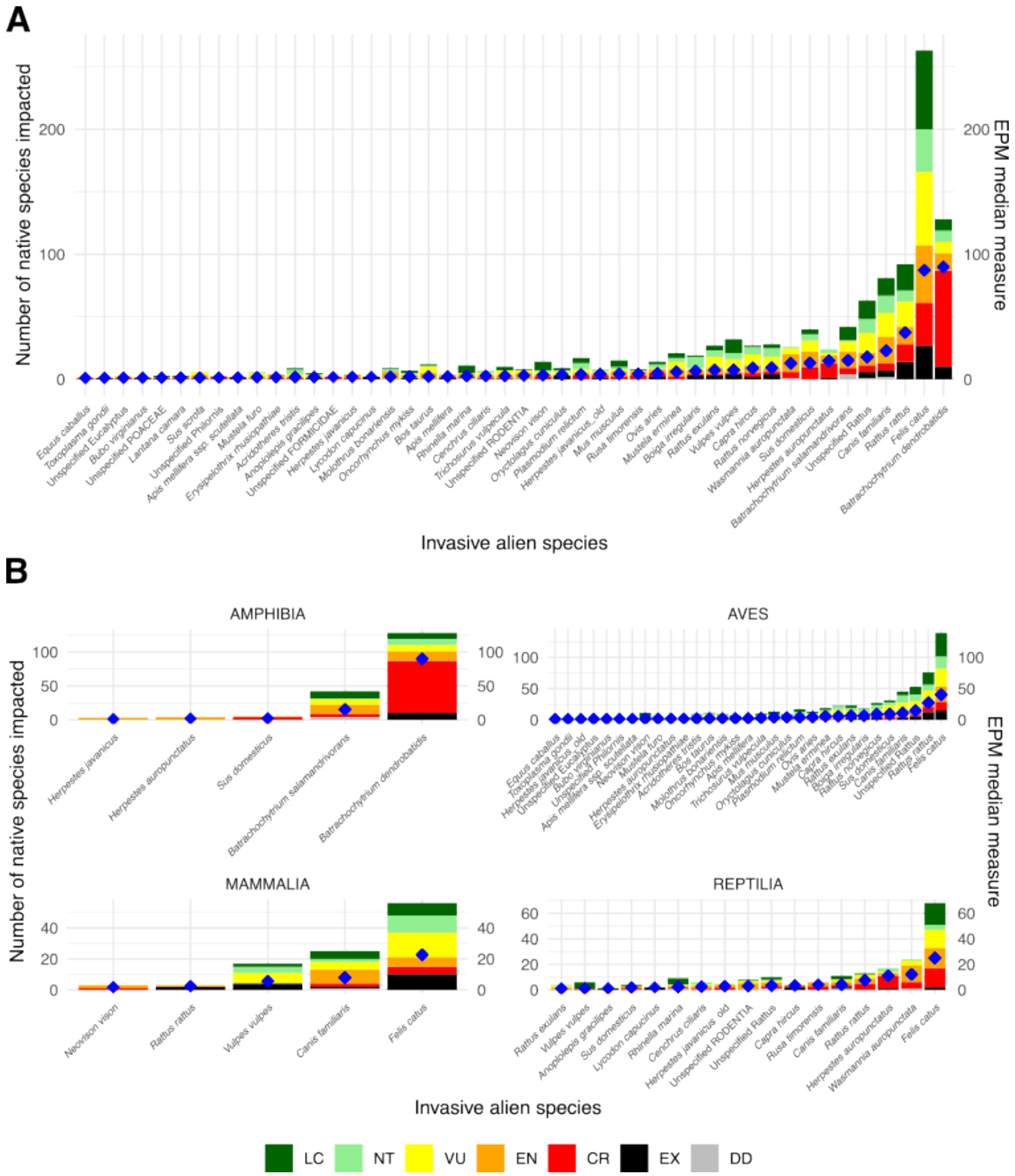

Figure 7. IUCN categories of native tetrapods impacted by IAS globally and their associated EPM scores. Only IAS with an EPM score above 1 are displayed. Panel A shows EPM median measure (blue diamonds) and the number of native species per IUCN category, based on the impacts of IAS on all native tetrapods combined. Panel B shows EPM median measure (blue diamonds) and the number of native species per IUCN category, based on the impacts of IAS on each taxonomic group (amphibians, birds, mammals, and reptiles) separately.