The Link Between Invasive Alien Species and Extinction

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Abstract

Invasive alien species (IAS) can cause the extinction of a taxon. However, debate continues over the significance of IAS as drivers of extinction globally, the level of threat they pose to endangered species, and whether conservation efforts against IAS should take priority over other factors, such as habitat loss or climate change. We provide new insights from the IUCN Red List, focusing on species classified as extinct or extinct in the wild that are linked exclusively to IAS. Many extinction events are also caused by multiple synergistic threats, including IAS, but the relative contributions of these threats remain uncertain. We suggest using Structural Equation Models (SEMs) to tease out the effects of IAS and other interacting factors on threatened species, to better understand the role of IAS in potential extinctions.

Keywords: drivers; introduced species; non-indigenous species; non-native species; threats

1. Introduction

Invasive alien species (IAS) are recognised globally as ecologically destructive due to their role in driving declines in native floral and faunal populations. The impacts of IAS on native species can be either direct (e.g., through predation without natural control) or indirect (e.g., through competition for resources), but both can ultimately lead to species extinction [1]. Even before a species is driven to global extinction, short-term local extinctions can severely affect local ecosystems [2] by altering species composition [3], reducing ecosystem function, and accelerating population declines [4].

However, the effects of most IAS are not well understood due to a lack of quantitative data, with most available data being limited to a small number of taxonomic groups, regions, and habitats [4]. This has resulted in scepticism about the importance of IAS as drivers of ecological change and their capacity to drive native species to extinction [5]. The variation in data analysis methods, as seen throughout the literature, has also sparked debate over the significance of IAS as drivers of extinction. For example, Clavero and García-Berthou [6] challenged and reanalysed data used by Gurevitch and Padilla [5], revealing an increase from 2% to 25% in extinction events linked to IAS. This occurred after a closer examination and re-evaluation of the extinction drivers for each species. Variations in results will also likely occur between databases due to differences in data availability and the threat classification system used.

Many studies also focus solely on the impact of IAS on threatened species or regional biodiversity, rather than extinction [7–12]. One of the earliest and most widely cited IAS studies [13] found that habitat loss was the highest-ranked threat, followed by IAS, which affected 85% and 49% of threatened species, respectively. However, predicting

the likelihood of extinction for threatened species is nearly impossible, and evaluating biodiversity loss generally does not help us understand trends in extinction across different species groups or taxa [14]. Changes in human activities over time will also inevitably lead to corresponding changes in the level of threat posed by IAS [13]. Therefore, even after more than two decades of discussion surrounding IAS, their role as drivers of species extinction remains poorly understood [15].

Despite ongoing debates, it is widely accepted that anthropogenic activities are responsible for a significant proportion of biological invasions [16]. Humans have always played and continue to play a crucial role in enabling many non-native species to cross biogeographical barriers, whether intentionally or accidentally [17,18]. Given the rapid global changes, understanding the impact of IAS on species extinction and implementing relevant conservation measures is increasingly vital to prevent further species loss and ecological damage [19].

The relationship between IAS and species extinction has previously been assessed by comparing the number of extinctions or threatened species affected by each type of threat. However, this has shifted the focus towards identifying which threat is most significant, rather than understanding the trends of IAS impact on extinction, as we aim to do in this study. One of the main challenges in evaluating the importance of IAS as drivers of species extinction stems from context-dependent variation [20].
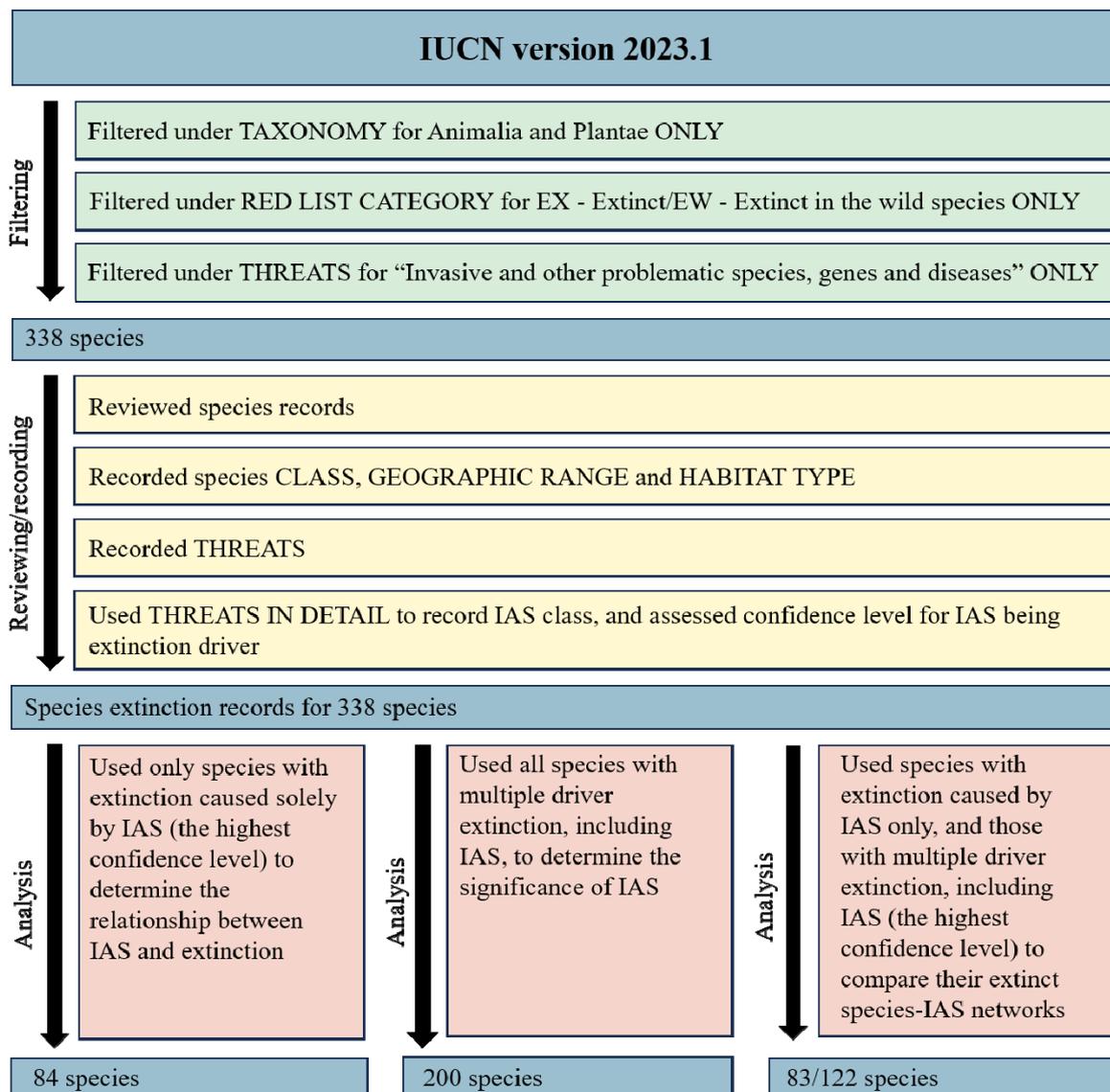
The role of IAS as a driver of species extinction is further complicated by the fact that most endangered species face multiple threats, many of which act synergistically [5]. Habitat destruction and disturbance often create conditions that facilitate the invasion or spread of IAS and increase the likelihood of interactions between native and non-native species [17]. For example, urban habitats are well recognised as hotspots for alien plant colonisation [17]. Habitat loss also diminishes available refugia for native species, making them more vulnerable to predation or competition effects from IAS [21]. The most common co-occurring drivers with IAS are biological resource use and agriculture [22]. According to the IUCN, 80% of species are subject to more than one threat [21]. When IAS are identified as drivers of species extinction, they are usually associated with 1.00 ± 1.24 other extinction drivers [22]. The cumulative impact of multiple threats can exacerbate the damage caused by IAS [23].

Here, we aim to examine the relationship between invasive alien species and species extinction. First, we provide a synthesis of IUCN data on IAS as the sole cause of extinction to better understand the link between IAS and extinction events. Specifically, our goal was to identify which taxonomic groups, regions, and habitats are most susceptible to extinction driven by IAS. Secondly, we assess the importance of IAS in cases where multiple threats have caused extinction. We aim to investigate how multiple synergistic threats, including IAS, contribute to species extinction and to identify the most common co-occurring drivers. We also aimed to analyse how the patterns of extinct species, by taxonomic group, region, and habitat, change when multiple threats are considered. Finally, we examine how the effects of IAS can be better understood when multiple threats are present. The comparison between extinctions caused solely by invaders and those influenced by multiple drivers is a novel contribution, as previous studies have generally combined these types of extinctions without distinguishing between them (e.g., Refs. [11,18]).

2. Methods

The IUCN Red List of Threatened Species is regarded as the most comprehensive database for assessing species' extinction risk [9,18]. The database has been compiled by hundreds of global expert volunteer contributors, and over 100,000 species have been evaluated using the IUCN Red List threat level classification scheme [24].

We conducted a novel synthesis of the IUCN database. The species records were first filtered for all Animalia and Plantae species classified as Extinct or Extinct in the Wild and linked to IAS as an extinction driver (338 species, as of October 2023, IUCN version 2023.1; Figure 1). Extinct species are defined as those with no reasonable doubt that the last individual has died, following failure to detect individuals across their historic range and suitable seasons [25]. Extinct in the wild species are defined as species known to survive only in captivity outside their native range, where they are otherwise considered extinct [25]. During the review, we recorded the taxonomic class of each extinct species and the related IAS, as well as the geographic region, insularity (island versus mainland), and habitat type. We then categorised species based on whether their extinctions were solely caused by IAS or by multiple drivers, including IAS. To assess the relationship between IAS and extinction caused solely by them, we included only species whose extinctions were confirmed or highly likely to have been driven by IAS, totalling 84 species. We excluded species if the IUCN record suggested the threats of IAS were uncertain, unknown, or possible.

IUCN version 2023.1

Filtering
- Filtered under TAXONOMY for Animalia and Plantae ONLY
- Filtered under RED LIST CATEGORY for EX - Extinct/EW - Extinct in the wild species ONLY
- Filtered under THREATS for "Invasive and other problematic species, genes and diseases" ONLY

338 species

Reviewing/recording
- Reviewed species records
- Recorded species CLASS, GEOGRAPHIC RANGE and HABITAT TYPE
- Recorded THREATS
- Used THREATS IN DETAIL to record IAS class, and assessed confidence level for IAS being extinction driver

Species extinction records for 338 species

Analysis
Used only species with extinction caused solely by IAS (the highest confidence level) to determine the relationship between IAS and extinction → 84 species

Analysis
Used all species with multiple driver extinction, including IAS, to determine the significance of IAS → 200 species

Analysis
Used species with extinction caused by IAS only, and those with multiple driver extinction, including IAS (the highest confidence level) to compare their extinct species-IAS networks → 83/122 species

Figure 1. Workflow diagram illustrating the methodological process for selecting and recording the data used in this study. Data accessed via the IUCN Red List was first filtered into three categories. All species records were then reviewed, and the data needed for the analysis was recorded.

To assess the significance of IAS within the context of multiple drivers, we included all species whose extinctions were linked to multiple threats, including IAS, totalling 200 species. For each species, we documented all identified causes of extinction. Since the precise roles and contributions of these drivers to extinction are often uncertain, we included all species in this analysis, even when the details of the threats remained unclear.

To map networks showing links between extinct species classes and IAS classes for all extinct and extinct in the wild species, we only included species where extinction drivers and the class of IAS were confirmed or highly likely to be driven by IAS. This included 83 species for extinctions driven by IAS only and 122 species for extinctions caused by multiple drivers, including IAS. Using the bipartite package in R (version 4.3.2) [26], we generated two networks: one for IAS-only extinctions and another for those caused by multiple drivers, for comparison. Each species and its IAS driver represent one interaction within the interaction matrix, with the proportional frequency of each class also indicated by the size of the bar.

3. Results

3.1. The Relationship Between IAS and Extinction

Molluscs (51%) were the most common species class among all extinct and extinct in the wild species whose extinctions were caused solely by IAS (χ^2 = 150.66, df = 9, $p < 0.001$; Figure 2a). Molluscs (52%) were also the most common class of IAS responsible for extinction events, followed by mammals (23%) and plants (9%) (χ^2 = 145.04, df = 7, $p < 0.001$; Figure 2b). Oceania (70%) was identified as the largest hotspot for IAS-driven extinctions, followed by Africa and Asia (χ^2 = 180.29, df = 5, $p < 0.001$; Figure 2c). Island territories accounted for 91% of extinction events caused solely by IAS (χ^2 = 58.33, df = 1, $p < 0.001$; Figure 2d). Most extinct species were found in tree-dominated habitats (83%) (χ^2 = 210.26, df = 4, $p < 0.001$; Figure 2e).

3.2. The Significance of IAS for Cases Where There Is More than One Threat

Out of the 981 recorded species extinctions, only 9% were caused solely by IAS (Figure 3a). In contrast, 13% of extinctions were caused by multiple drivers, including IAS, while 10% were associated with multiple drivers likely including IAS, and 3% involved multiple drivers that possibly included IAS. The remaining 66% of extinctions were attributed to factors unrelated to IAS (χ^2 = 1295.20, df = 4, $p < 0.001$). For multiple-threat extinctions, including IAS, biological resource use such as hunting and logging was the most common driver occurring alongside IAS (Figure 3b). Agriculture, including land conversion for farming, was the second most common co-occurring driver, followed by modifications to natural systems, such as changes to waterways and fire management (Figure 3b).

3.3. The Comparison of Extinct Species-Invasive Alien Species Networks

Figure 4a presents a network analysis of extinction events where IAS were the sole drivers of extinction (83 species). The network highlights that molluscs were the most affected taxonomic group, with their extinctions mostly driven by invasive molluscs. It also reveals that mammals and plants were the most common IAS groups responsible for the extinctions.

Figure 4b shows a more complex network of extinction events involving several drivers, including IAS, affecting 122 species. In this network, birds were the most affected taxonomic group, mainly due to interactions with invasive mammals, which are known to have caused a significant proportion of extinctions among birds, plants, reptiles, and mammals. Fish also appeared as a highly impacted group in this network. Mammals

accounted for the largest proportion of IAS in this multi-driver network. The network also shows that birds faced more extinction-driving taxonomic groups when multiple drivers were involved.
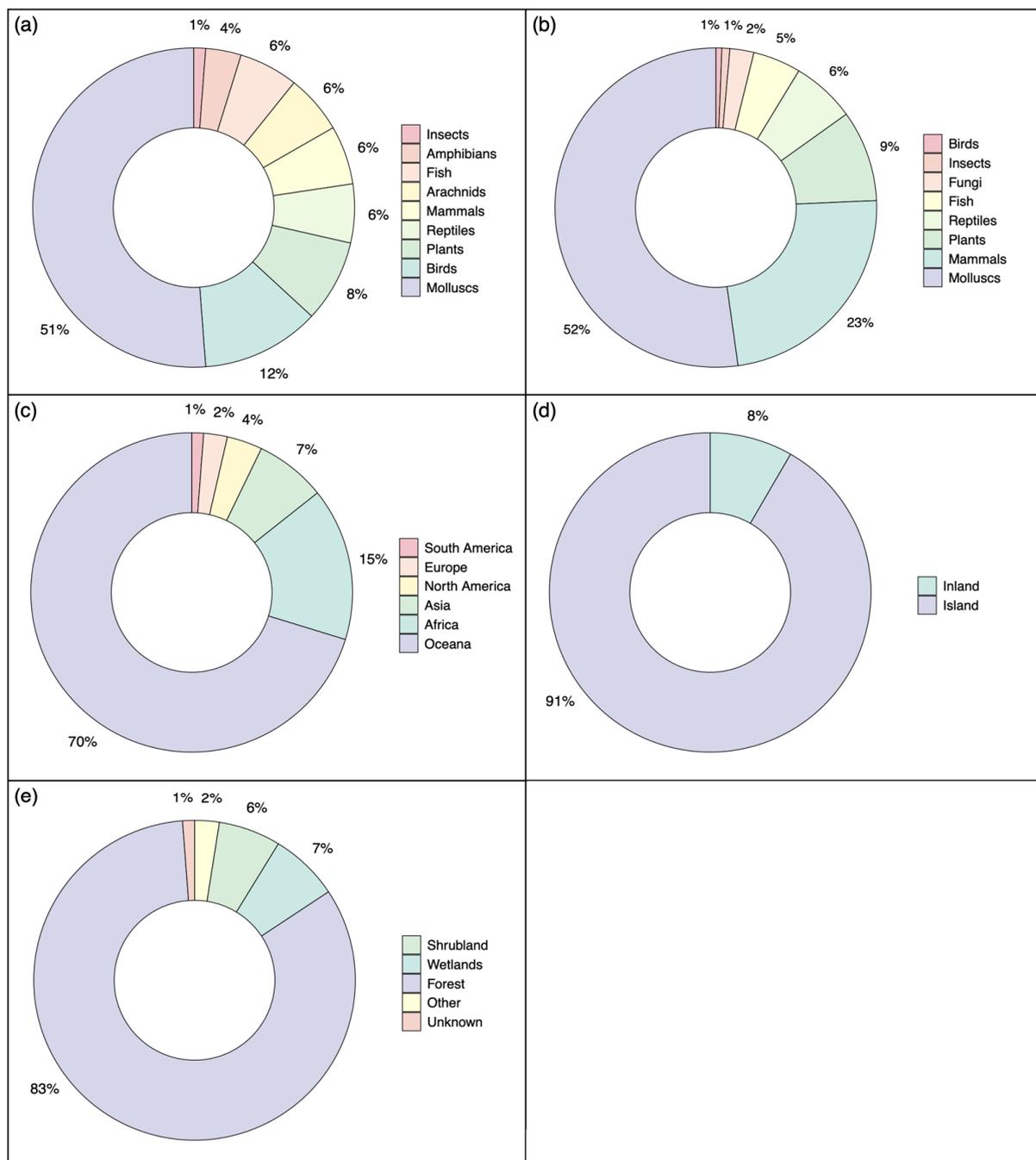
Figure 2. (**a**) Proportions of species classes for all extinct and extinct in the wild species whose extinctions were caused exclusively by IAS. (**b**) Proportions of IAS classes for the extinction events of all extinct and extinct in the wild species where the IAS class was known, and IAS was the sole extinction driver. (**c**) Proportions of native geographic regions for all extinct and extinct in the wild species whose extinctions were caused exclusively by IAS. (**d**) Proportions of island vs. inland species for all extinct and extinct in the wild species whose extinctions were caused exclusively by IAS. (**e**) Proportions of native habitat types for all extinct and extinct in the wild species whose extinctions were caused exclusively by IAS. All data were collected from the IUCN Red List (2023) and include only reports on species whose extinction was caused solely by IAS (84 species). Percentages may not total 100% due to rounding.
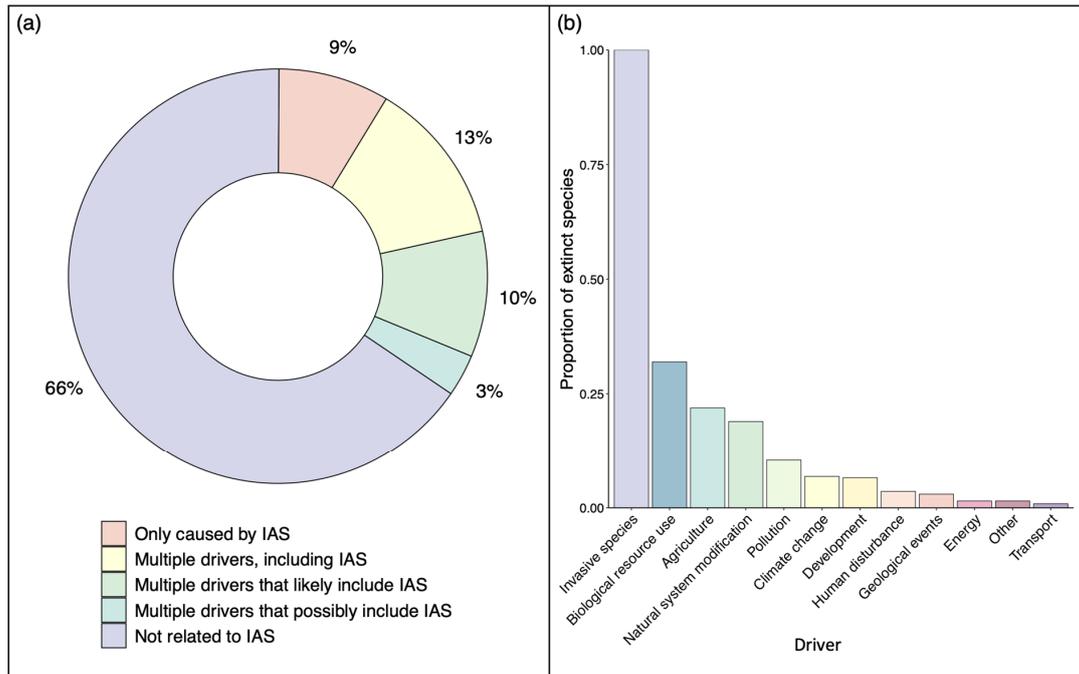
Figure 3. (**a**) Proportions of extinct and extinct in the wild species (total 981 species as of October 2023), categorised as: (i) only caused by IAS, (ii) caused by multiple drivers including IAS, (iii) caused by multiple drivers likely including IAS, (iv) caused by multiple drivers possibly including IAS, and (v) caused by other factors not including IAS. (**b**) Proportions of other drivers linked to the extinction of species that were also caused by or associated with IAS (200 species). Percentages may not total 100% due to rounding.
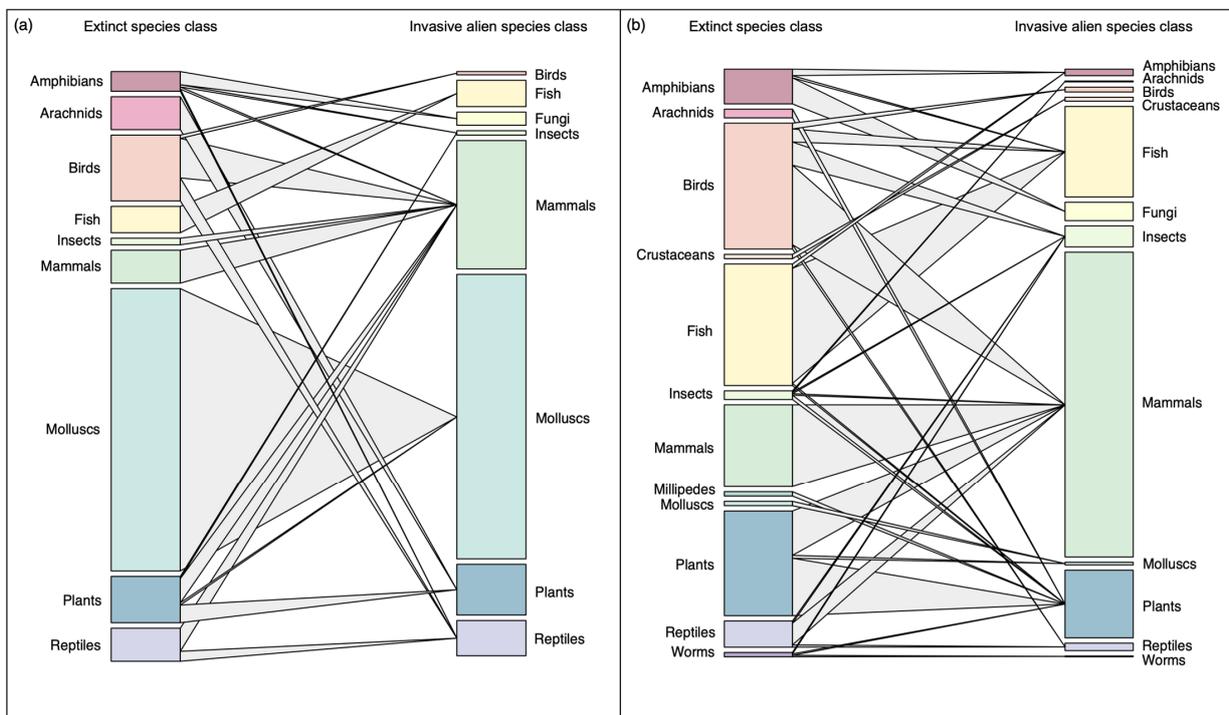
Figure 4. (**a**) Network illustrating links between extinct species classes (**left**) and IAS classes (**right**) for all extinct and extinct in the wild species whose extinctions were solely caused by IAS (83 species). The size of bars and links between extinct and IAS classes are proportional to the number of species and interactions, respectively. (**b**) Network illustrating links between extinct species classes (**left**) and IAS classes (**right**) for all extinct and extinct in the wild species whose extinctions were caused by multiple drivers, including IAS (122 species). The size of bars and links between extinct and IAS species classes are proportional to the number of species and interactions, respectively.

4. Discussion

4.1. Establishing the Relationship Between IAS and Extinction

4.1.1. A Synthesis of Extinction Linked Only to Invasive Alien Species

Considering the distribution of species classes across both extinct species and IAS, the most prevalent class was molluscs, largely due to the impact of the carnivorous Rosy Wolfsnail (*Euglandina rosea*) on Partula snails (Partulidae) [27]. This predatory snail was introduced to several Pacific islands as a biological control for the invasive Giant African Land Snail (*Lissachatina fulica*), but ultimately had a significant impact on native snails, including the eradication of 51 endemic Partulidae species in less than 10 years [27]. The devastating impact of the Rosy Wolfsnail highlights the destruction that a single IAS can cause. Although the effects of IAS on molluscs are well known, they are rarely recognised as the most affected group, especially given that most research focuses on vertebrates [8,18]. Another taxonomic group that is highly represented among extinct species is birds, as expected from the literature (see [28]). However, many bird extinctions, especially those of seabirds [4], are also driven by other factors, such as overexploitation. Since this first synthesis included only extinctions where IAS were recorded as the sole threat, they are not listed here as the most impacted group. Nonetheless, multiple-threat extinctions are addressed later in this report.

Mammals and plants were prevalent as IAS. Extinctions caused by invasive alien mammals are well documented, often linked to human colonisation and the arrival of black rats, cats, dogs, and livestock [8]. These taxa have been identified as affecting the greatest number of threatened species worldwide, after *Batrachochytrium dendrobatidis* (Bd), a chytrid fungus responsible for chytridiomycosis in amphibians [15]. This is likely because IAS originating from regions of historically intensive human land use will be better adapted for persistence as invaders in other human-disturbed landscapes [29]. Introduced rodents and cats are thought to be casual drivers in 44% of modern bird, mammal, and reptile extinctions [8]. Furthermore, grazing and trampling by livestock pose a much greater threat to native plants than herbivory by other non-native species [5]. Conversely, invasive plants are rarely cited as the primary cause of extinction, mainly leading to displacement and community changes rather than outright species extinctions [5]. For instance, nearly 20% of North America's vascular plant community consists of exotic species that have become naturalised, yet there is little to no evidence of resulting native species extinctions [30].

As most IAS plants exert competitive rather than predatory pressure on native plants, the mechanisms that will drive a native plant species to extinction will be saturation or competition based [5]. It is only at the saturation point for a given habitat (where the maximum number of species a habitat can support, based on resource availability, is reached [31]), that species turnover can be expected. Further colonisation by exotic species would then cause native species loss, with the extinction rate increasing as the colonisation rate increases [32]. Therefore, if exotic species continue to invade extinction-vulnerable areas such as islands, future significant increases in plant extinctions could occur [32]. Competition-driven extinctions are recorded far less often than predation-driven extinctions; however, it remains unclear whether competition-based extinctions are simply less common or whether they take longer to manifest [30]. Lastly, the primary hotspot for IAS-driven extinctions was Oceania, as previously documented [9,18]. Additionally, most IAS-driven extinction events occurred in island territories, aligning with the literature [17,33]. Interestingly, most species driven to extinction solely by IAS were forest inhabitants. Studies in European and tropical forests have documented local extinctions and declines in native species caused by IAS, but these are usually reversible or limited in spatial extent (e.g., Refs. [34,35]) and do not constitute global extinctions.

4.1.2. Limitations to Evaluation of the Threat of IAS

Several factors limit the precise assessment of IAS as drivers of extinction. First, we must address the issue of time lags, defined as the amount of time it takes for a species to become extinct after being affected (also known as the 'relaxation time') [36]. It can take many generations or even centuries for a species to go extinct [32], during which time, if the population becomes spatially isolated or unable to reproduce, it remains in extinction debt [37]. Since it is unlikely that all currently threatened species will ultimately go extinct, estimating the potential impact of the current extinction lag caused by IAS is challenging [11]. Nonetheless, it remains important to consider these species.

Numerous factors influence a species' extinction lag time, including intrinsic factors such as the longevity of individuals, the species' sensitivity to inbreeding depression, and the presence of a seed bank, as well as extrinsic factors such as the quality and extent of remaining natural habitat. For example, plants appear to have very few recorded extinctions caused by IAS, even on well-studied islands such as New Zealand [38]. This is likely because plants have a long extinction debt, which is attributed to their seed banks and long lifespans, especially in woody species, whose lifespans are rarely matched by those of animals [39].

The risk of plant extinction from IAS is greatly underestimated due to extinction debt, as demonstrated by multiple studies. Reduced seed bank size has been observed in many native species at sites invaded by Acacia [40], and community seed bank density and richness were significantly lowered by an invasive alien grass species (*Stenotaphrum secundatum*) [41]. Additionally, reduced seed production in native perennial herbs has been documented because of invasive honeysuckle (*Lonicera maackii*) [42]. Reduced recruitment directly reflects extinction debt in these populations. Despite recognising a significant extinction debt for plant species, estimating these time lags is impossible, so it is unclear whether ongoing invasions within native plant communities may eventually lead to a mass extinction event [32]. Time lags are likely to vary among taxonomic groups depending on how vulnerable a species is to extinction following population decline [38].

Another key factor to consider is the lack of knowledge about extinct species. Demonstrating a species' absence is much more challenging than confirming its existence, and for many species, determining and documenting extinction can take years of investigation [39]. Additionally, the cause of extinction is known for only about a quarter of current extinctions [4]. Even in cases where extinctions are better documented, there remains speculation about the responsible factors, as few species or populations have been closely monitored from invasion to extinction [32,43]. There is also ongoing debate regarding the accuracy of defining species' native ranges, identifying introduced species, and assessing the extent of ecosystem invasion [44].

Many species also remain unrecorded or are largely unknown. In 2016, only 40% of the world's reptile species had been assessed for the IUCN Red List [45]. Furthermore, data-deficient species account for 15% of the entire mammal dataset [11], despite there being disproportionate research effort and numbers of research scientists working on mammals and birds compared to other species groups, such as invertebrates [27]. Data biases, created by research focused on specific taxonomic groups, are evident across the literature [46]. Geographical bias can also occur in research due to limited information availability in developing countries [47]. For example, the biassed distribution of all mollusc extinctions can be partly attributed to where taxonomists are based, which often do not cover the most species-rich areas [27]. Consequently, there is always potential to underestimate the risk of extinction from IAS.

4.2. Establishing the Significance of IAS for Cases Where There Is More than One Threat

4.2.1. A Synthesis of the Importance of Invasive Alien Species Linked to Extinction

Our synthesis from the IUCN Red List showed that 25% of IAS-affected species classified as extinct or extinct in the wild had IAS listed as the sole driver of extinction. The remaining 75% of cases were caused by multiple factors, including IAS, or were likely to include IAS when the exact drivers were less clear. This is common due to a lack of monitoring before species loss, as these extinctions are often linked to invasive mammals introduced during human colonisation. In agreement with the literature [22], the most common drivers associated with IAS were biological resource use and agriculture, followed by natural system modification, such as changes to waterways and fire management.

4.2.2. Extinct Species-Invasive Alien Species Networks

For this study, networks were developed to compare the proportions of each taxonomic group involved in extinction events. The network approach, which is largely absent from IAS studies [33], can assist in visualising where the greatest threats lie within the IAS extinction framework and help identify where conservation efforts should be focused. Comparing the two networks—one for species in which IAS was the sole driver of extinction, and the other for species with multiple drivers—reveals differences in their structures. Mollusc extinctions in the network, driven solely by IAS, significantly influence the relative proportions of other taxonomic groups. Consequently, the network for species with multiple drivers shows a proportional increase in representation across taxonomic groups and a more complex interaction network. When multiple drivers are considered, birds are proportionally the most affected by IAS.

Furthermore, fish are the second most affected group by IAS in this multi-driver network, reflecting the widespread presence of invasive fish species in wetland systems introduced alongside other human impacts, such as aquaculture. Although the largest recent vertebrate extinction was the loss of about 300 endemic cichlid species in Lake Victoria following the introduction of the Nile perch (*Lates niloticus*), this was exacerbated by eutrophication and overexploitation [48]. This explains why fish were not well represented when considering only IAS-related extinctions.

When multiple drivers are recorded, mammals become the largest proportional class of IAS. This is probably because the threats most associated with IAS, such as biological resource use and agriculture, are often linked to human colonisation and the resulting common invasive mammals, such as black rats, cats, and livestock. For example, domestic cats have been found to contribute to at least 14% of all bird, reptile, and mammal extinctions [49]. Birds, which are rarely driven to extinction by other bird species, are a prime example of where invasive species linked with agriculture have largely contributed to species extinctions. This shows how some important interactions could be overlooked if only extinction events in which IAS are the sole driver are considered. Fortunately, eradication is possible for IAS, with 88% of black rat eradication programmes across islands having been successful [18].

4.2.3. Conservation Challenges

It is difficult to determine the independent effects and the value of threats as drivers of extinction because of the frequent correlations between them [50]. This can make it challenging to prioritise conservation efforts for IAS, as it is unclear which threat is the primary driver. For example, in some cases, IAS may be the final driver of extinction for a species whose population has already declined due to other threats, such as habitat loss [51]. In such situations, it can be debated which threat should take precedence in conservation efforts.

4.3. Elucidating the Effect of IAS Where There Is More than One Threat

Despite increased attention to the negative impacts of IAS, efforts to manage IAS are hindered by the lack of a comprehensive global strategy and targets. To effectively address this, it is essential to develop a unified strategy for data synthesis that integrates scientific research, policy making, and management practices [52,53]. Policies targeting IAS primarily focus on reducing global biodiversity loss [54]. For instance, in 2010, the United Nations Convention on Biological Diversity (CBD) established the "Strategic Plan for Biodiversity (2011–2020)", in which Aichi Target 9 aimed to identify, control or eradicate priority IAS and their pathways, and to establish management systems to prevent their further spread and establishment [55]. However, accurate global assessment of invasion pressure on biodiversity depends on reliable reporting of IAS across all countries and regions. It has been previously found that the number of reported IAS per country was negatively affected by a country's level of development and information availability, resulting in underreporting that obscures where conservation concern is greatest. Therefore, improving the global synthesis of IAS data and enabling more effective management of invasions and associated biodiversity loss requires increased research and monitoring capacity at local and regional levels, along with wider adoption of national IAS policies [47].

Due to limited progress in achieving the IAS targets by 2020 and increasing concern about invasive species, such as the arrival of the Murder Hornet in the US and Canada, the Convention on Biological Diversity (CBD) developed a new "Post-2020 Global Biodiversity Framework" [55]. This framework, which uses a new IUCN database on invasive species as one of its indicators, outlines a timeline for effectively managing significant introduction pathways, regulating harmful IAS, and restoring and recovering from their impacts [55]. While this framework considers key factors for understanding IAS, it is equally important to monitor the size and extent of the threat posed by IAS [47]. This prompts the question of how to assess the impact of IAS when multiple threats are present.

Assessing the impact of IAS can be improved by using a modelling framework, such as Structural Equation Models (SEM), to evaluate IAS as a driver of extinction for threatened and vulnerable species in the presence of multiple threats. SEM is a form of path analysis that enables the evaluation of complex relationships within ecological networks [56]. The strength of SEM lies in its ability to identify direct and indirect effects and to distinguish between related pathways that have a high potential to influence each other [57]. This ability to test hypotheses for multiple processes within the same system has made SEM of great interest to ecologists [58], with examples of its previous application in ecological studies including evaluating the direct and indirect causes of both habitat degradation [59] and growth inhibition [60].

Effective data collection is a critical step in building robust SEM. Conservation practitioners need to gather information on IAS presence, abundance, and traits through field surveys, the literature, or existing databases. Data on vulnerable native species populations, distribution range, and ecosystem metrics can be sourced from ecological studies, monitoring programmes, or historical records. Spatial and temporal data are also necessary to account for non-independence among observations, such as site proximity or temporal autocorrelation. If phylogenetic relationships among species are relevant, conservation practitioners can include phylogenetic distances using tools such as the APE package in R.

Once the data are collected, the PIECEWISESEM package in R can be used to construct a list of structured equations that represent the hypothesised causal network. Random effects can be incorporated to account for spatial and temporal non-independence, such as site-specific or year-specific variations. If applicable, phylogenetic relationships can be incorporated into the model to account for shared evolutionary history that may influence species' susceptibility to IAS. The model can then be evaluated using functions (such as

sem.fit) to test directed separation and to calculate Fisher's C statistic and AIC values for model comparison. Conservation practitioners can assess the significance of individual paths and indirect effects using standardised regression coefficients obtained (via sem.coefs). In addition, the fits of component models can be examined (using sem.model.fits) to ensure adequate explanatory power.

The results of this analysis can offer valuable insights into the direct and indirect impacts of IAS on native species abundance and ecosystem dynamics. Conservation practitioners can identify key pathways through which IAS influence native species and ecosystem functions and use partial correlation plots to visualise relationships and reveal potential non-linear effects. This approach enables a comprehensive understanding of the complex relationships driving species extinction and measures the relative strength and role of IAS within these systems.

SEM will enable the assessment of IAS contributions alongside other extinction drivers, such as climate change and habitat degradation. By improving understanding of the impacts of different drivers, the most damaging IAS and their pathways, as well as vulnerable regions, can be accurately identified as part of the new "Post-2020 Global Biodiversity Framework". This will also provide insights into which threats are most closely linked, and which should be targeted to enhance conservation outcomes for currently endangered and threatened species. Even if IAS is not the primary threat in some cases, addressing other threats, such as habitat loss, could also slow the impact of IAS. Developing a system to synthesise IAS data will be vital for informing policy and conservation strategies in a rapidly changing world. This modelling framework provides a method to establish such a system.

5. Conclusions

The threat posed by IAS to global ecosystems is alarming and cannot be ignored. In fact, it is estimated that IAS are impacting more than 60% of threatened species [9]. Although the magnitude of the threat varies by taxonomic group, region, and habitat, it is undeniable that IAS have contributed to numerous extinction events. The value of our unique native species and their role in maintaining ecosystem services make it crucial to understand regional and ecological trends in extinction events and explore ways to prevent future species losses. The comprehensive synthesis of data on IAS-driven extinctions provided by this study addresses the previous lack of consolidated information, enabling more targeted and effective conservation efforts. For example, using networks to identify where the greatest taxonomic threats lie within the extinction framework could help prioritise conservation actions. In the context of informing future conservation policies and strategies, SEM offers a promising approach to understanding the role of IAS in potential extinction events.

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