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Perspective

Managing the risk of biological invasions

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SUMMARY

The large environmental impacts and enormous economic costs caused by biological invasions provide a strong impetus for managing invasion risks. Understanding the factors driving the invasion process and their consequences will raise awareness of invasions among the general public, stakeholders, and policymakers and inform effective management strategies. The identification of priority species and introduction pathways and sites and the development of national capabilities for prevention and preparedness, early detection, monitoring, and rapid response will reduce the impacts of invasive species in terms of effectiveness and cost efficiency.

WHAT CHANGES DO INVASIVE ALIEN SPECIES BRING TO THE ENVIRONMENT AND ECONOMY?

With increasing trade globalization, we are witnessing an accelerating number of alien species established in new areas outside their native range and increasing negative impacts of invasive alien species on the environment, economy, and society.[1,2] Here, alien species refer to those that are transported to new areas beyond the borders of their natural range by human activities, whether they are established or spread,[1,2] while established alien species are a subset of alien species that have a self-sustaining population in the wild and may spread. Invasive alien species, also commonly referred to as invasive species, represent established alien species that spread in new ranges and cause ecological, environmental, economic, and/or social problems.[1,2] Based on underestimated Figures, there are more than 37,000 established alien species and 3,500 invasive species worldwide (Table 1).[2] The invasive species include 1,061 alien plants, 1,852 alien invertebrates, 461 alien vertebrates, and 141 microbes. New established alien species are recorded at an unprecedented rate of about 200 each year. Approximately 1–16% of species on Earth, depending on taxonomic group, qualify as potential established alien species.[3] The number of established alien species is projected to increase by 36% from 2005 to 2050.[4] The alien species, as new components of invaded areas, may have positive (social and economic benefits, and enriching diversity), negative (economic cost, species extinction, altering ecosystem functioning and transmitting diseases, Figure 1) or neutral effects on environments, economy, and society in the recipient ecosystems. These effects vary greatly across taxa and at different spatial scales. For example, a recent study systematically reviewed the impacts of 103 alien species in the Mediterranean Sea.[5] They revealed that 59 of these species were associated with both negative and positive impacts, 17 to only negative, and 13 to only positive, while no impacts were found for 14 species.

There have been increased concerns about the negative impacts of invasive species on the environment, economy, and society in recent decades.[6,7] Invasive species are identified as a leading driver of biodiversity loss.[8] They have contributed to known or reported extinction of 261 of the 782 (33.4%) extinct animal species and 39 of the 153 (25.5%) extinct plant species, listed as primary cause of recent global extinctions. Invasive species have contributed solely to or alongside other drivers to 60% of recorded global extinctions.[2] Most of these extinctions (90%) occur on islands. Approximately 9.1% of protected areas across the world have been invaded by alien animals.[9] Furthermore, there is at least one established population within 10–100 km of the boundaries of 89–99% of protected areas, suggesting a significant threat of invasion to protected areas. Biological invasions can also cause great economic damage. A recent study revealed that the global annual mean economic costs (including control costs and management costs) of alien species reached US$ 26.8 billion from 1970 to 2017.[7] It was estimated that global economic costs of invasive species reached more than $423 billion in 2019,[2] with 4-fold increases in cost every decade. Alien mosquitoes, rats, and mice are among the top-cost invasive species.[7]

Both the environmental impacts and economic costs caused by invasive species are strongly underestimated and have large gaps at regional and taxonomic scales. Major studies on alien species have been carried out in developed countries in Europe, North America, and Australia. As biodiversity is less studied in most developing countries, data on the impacts of many invasive species are lacking in these countries. We probably only see the tip of the iceberg with regard to these negative impacts.

The impacts and costs of biological invasions provide a strong impetus for managing invasion risks. Understanding the factors driving biological invasions and their consequences will raise awareness of biological invasions among the general public, stakeholders, and policymakers and inform effective management strategies. This would also help to develop international policies for biodiversity conservation, biosecurity and sustainable development.

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Table 1. The numbers of established alien species and invasive alien species worldwide based on the Intergovernmental Platform on Biodiversity and Ecosystem Services

Taxa[2]	Number of Established alien species	Number of invasive alien species with impacts	Proportion of the invasive species in the established species
Total	37,000	3,500	9.45%
Plants	17,683	1,061	6%
Invertebrates	8418	1,852	22%
Vertebrates	3293	461	14%
Microbes	1282	141	11%

WHICH FACTORS DRIVE BIOLOGICAL INVASIONS?

A united framework of biological invasions divides the invasion process into four stages[1]: transportation (from the native range to areas outside the range), introduction (from captivity or transportation vectors to the wild), establishment (survival and establishment of self-breeding populations in the wild), and spread (range expansion of established populations). Each previous stage has important implications for subsequent stages. The species pool in source areas, introduction pathways (e.g., transportation pathways), species traits associated with introduction pathways, and socioeconomic factors in destination areas will have important effects on how many species are transported to new areas. Effective prevention and management of alien species requires a detailed knowledge of introduction pathways for alien species,[10] and a number of pathways have been identified. Introduction events (e.g., propagule pressure, number of release events, and number of released individuals), species traits and evolutionary processes, and invaded site characteristics (climate suitability and biotic resistance) likely influence the establishment likelihood of an alien species and the spread rate of an established population. There is a consensus on propagule pressure as an important determinant of establishment for animals and plants[11] and on islands as hotspots for establishment. Establishment success most critically depends on propagule pressure in the range of 10–100 individuals.[11] Recent studies hypothesized that colonization pressure (number of species introduced to an area) is the main determinant of established species richness in the area.[12] This hypothesis is key to understanding the geographical patterns of global alien richness and identifying the hotspots for establishment and areas vulnerable to invaders. However, the hypothesis remains to be tested. Data on invasion success are rapidly accumulating, while data on species that failed to establish are badly needed. To produce a better prediction of which species are more likely to establish in areas outside their natural range, several key questions still need to be resolved:

What species constitute potential species pools for a specific introduction pathway?
How many species have been transported to new areas outside the natural range along the introduction pathway?
Which species or how many species have been introduced into the wild along the pathway?
How do genetic diversity and adaptive evolution contribute to invasion success?

Ecologists and evolutionary biologists have long viewed biological invasions as natural ecological and evolutionary experiments in a recent historical time frame.[13] While DNA sequences and museum samples can only provide indirect inferences about evolutionary history, invasions provide a window to observe ecological and evolutionary processes in real time. Invasive species are exposed to genetic drift, founder effects, and population bottlenecks and often show rapid adaptation to new biotic and abiotic environments over short timescales.[13] The genetic paradox of invasions refers to invasive species successfully establishing and spreading in new environments despite reduced genetic diversity resulting from genetic bottlenecks.[13] Major studies on neutral loci (microsatellites, allozymes, mitochondrial genes, and nuclear sequences) identify reductions in genetic variations in invasive populations relative to source populations,[13] although some cases show increased genetic diversity in invasive populations due to the admixture of multiple introductions. However, such studies only include a small number of loci. Genomic data are increasingly used in invasion science to resolve taxonomic issues, to detect cryptic invasions, to track origins and pathways, to identify if single or multiple introductions have occurred, and to assess hybridization and introgression.[14] Understanding how genome-driven processes facilitate invasion will help to resolve the paradox and clarify the role of evolutionary processes driving the establishment or spread of invasive species.[15] Adaptive genetic variations promote the survival and adaptive potential of natural populations under environmental change. However, few studies have investigated how adaptive genetic diversity and relevant functional diversity respond to new environments in invasive species.[16]

IS THERE A WAY FORWARD TO MANAGE INVASION RISK?

Invasive species can be costly to manage, and resources are limited. Therefore, resources must be allocated to where they are likely to be most cost-effective. Species, pathways, or sites must be ranked based on their relative environmental and socioeconomic impacts to prioritize measures to prevent or mitigate the impacts at each stage of the invasion process.[17] At the transportation and introduction stages, the main pathways must be identified and prioritized for the purpose of preventing the introduction of invasive species. At the stages of establishment or spread, a number of measures, such as eradication and containment, control or prevention of spread, and protection of high priority sites, need to be ranked based on their effectiveness and efficiency. Prioritization schemes (or models) must be data-based. A number of schemes for prioritizing species, pathways and sites have been developed at regional or global scales.[17]

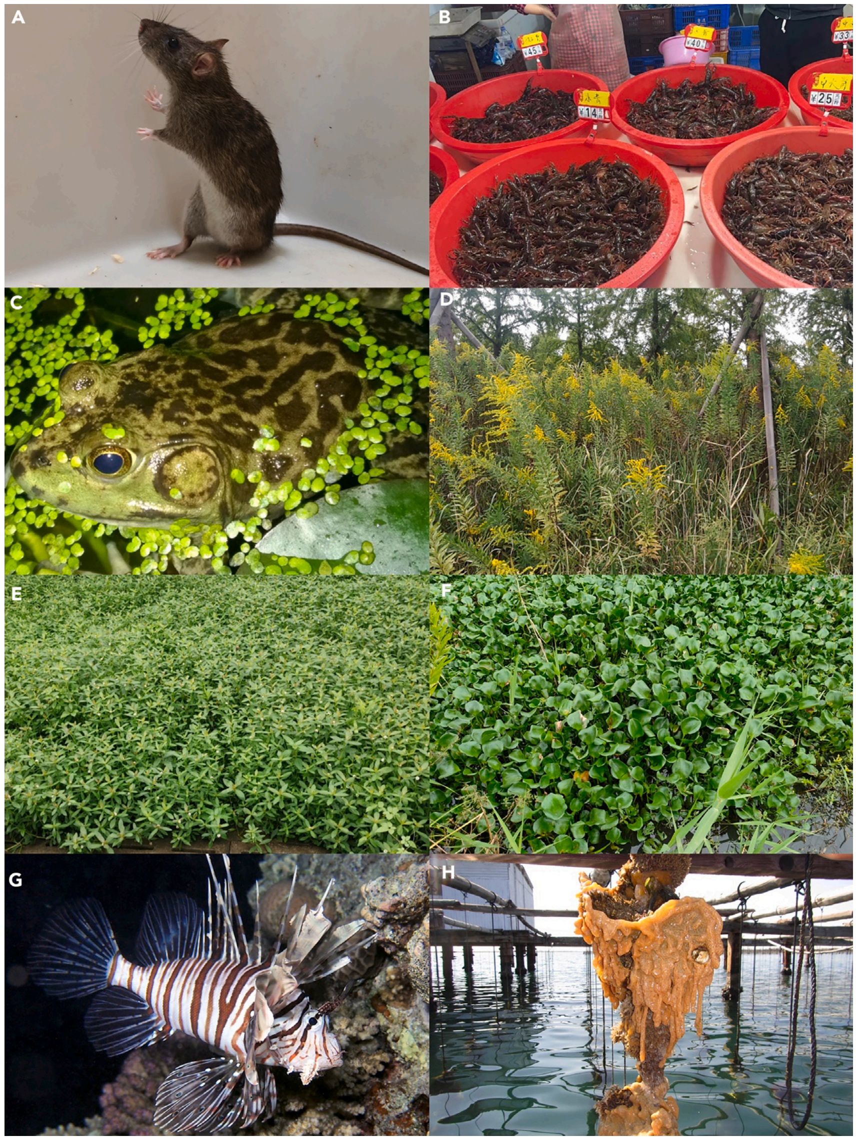

Figure 1. Some invasive species with negative impacts on ecosystems and economic

(A) Brown rat (*Rattus norvegicus*, photo by Zhimin Li) is one of the most invasive species. It damages the regeneration of many plant species by eating seeds and seedlings, destroys food crops, and spoils human food stores. Additionally, it can prey upon most animal species smaller than itself and transmit the plague bacterium (*Yersinia pestis*) via fleas.

(B) Red swamp crayfish (*Procambarus clarkia*, the photo (by Jun Zhang) shows the crayfish sold in Si Ji Mei in Wuhan City, China) has caused a dramatic decline in native crayfish in Europe through transmission of the crayfish plague and direct competition.

(C) American bullfrog (*Lithobates catesbeianus*, photo by Xianping Li) is one of the 100 worst invasive species in the world, affecting native frogs through direct predation and interference competition and spread of diseases.

(D) Canadian goldenrod (*Solidago canadensis*, photo by Fei-Hai Yu) can grow over 1.5 m tall and reproduces both sexually by producing plenty of small, wind-dispersed seeds and asexually by producing ramets from its underground rhizomes. It has a strong competitive ability and can displace native plants, especially in habitats disturbed by human activities.

(E) Alligator weed (*Alternanthera philoxeroides*, photo by Fei-Hai Yu) is amphibious and grows vigorously in both aquatic and terrestrial environments. It can displace native vegetation and form mono-species stands.

(F) Water hyacinth (*Eichhornia crassipes*, photo by Fei-Hai Yu) is one of the 100 worst invasive species in the world and can form extensive floating mats and displace native vegetation.

(G) Common lionfish (*Pterois miles*, photo by Xavier Turon) is one of the most badly invasive fishes in oceans, damaging ecosystems through aggressive predation and niche occupation.

(H) Carpet ascidian (*Didemnum vexillum*, photo by Xavier Turon) is a pest in many temperate regions, living in artificial habitats but also carpeting natural fishing ground.

For priority species, Blackburn and colleagues[18] developed an objective and transparent category for classifying alien taxa based on the magnitude of detrimental environmental impacts in the invaded range. This category is modified and refers to the Environmental Impact Classification for Alien Taxa (EICAT).[19] EICAT classified alien taxa into five impact categories from minimal to massive impact (Minimal Concern [MC], Minor [MN], Moderate [MO], Major [MR], and Massive [MV]), based on the level of biological organization (individual, population, or community) impacted. To support priority introduction pathways, the Convention on Biological Diversity recently adopted the standard pathway categorization for managing and priority pathways.[10] This standard categorization includes six broad categories (Release in nature, Escape from confinement, Transport–Contaminant, Transport–Stowaway, Corridor and Unaided) and 44 subcategories.[10]

Priority sites include two categories[17]: susceptible sites, which experience the greatest exposure to propagule pressures of invasive species and a high probability that these propagules will establish populations, and sensitive sites, which experience the greatest environmental, economic or social impact if invaded. Susceptible sites include ports and harbors, densely human-populated areas, road verges, tracks and paths,[17] while sensitive sites cover islands, protected areas and parks, freshwater systems, and water catchments. Global susceptible sites with high potential richness of invasive species (potential invasion hotspots) could be identified using species distribution models.[9,20]

Prevention and preparedness, early detection and monitoring and rapid response are effective and cost-efficient approaches to minimize the impact of invasive species.[2,7,21,22] Currently, policies for managing invasive species are fragmented within and across countries,[2] with 45% of countries actually having no investment in management of invasive species. National capacity building for prevention and preparedness, early detection and monitoring and rapid response to invasive species should become a crucial component of biosecurity policies. Developing emerging technologies, such as environmental DNA, citizen science based on the Internet, remote sensing, and chemical ecology, will facilitate the national capacity for such goals. Integrating diverse online data sources, including information, images, videos, social awareness and attitudes on alien species, will provide insights into mapping and monitoring the spatiotemporal distribution, spread and impacts of invasive species at a large spatial scale and inform biosecurity measures for prevention, early detection and warning, rapid response, control and eradication in a more effective and efficient manner.

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AUTHOR CONTRIBUTIONS

Conceptualization: Y.L. and F.H.Y.; Investigation: Y.L. and F.H.Y.; Writing – Original Draft: Y.L. and F.H.Y.; Visualization: Y.L. and F.H.Y.; Supervision: Y.L.; Project Administration: Y.L.; Funding Acquisition: Y.L.

DECLARATION OF INTERESTS

Authors declare that they have no competing interests.

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