ANNUAL REVIEWS

Annual Review of Environment and Resources

Biological Invasions: Trends, Drivers, Impacts, Management, and Governance

David M. Richardson,[1] Sven Bacher,[2] Philip E. Hulme,[3] Laura A. Meyerson,[4] Helen E. Roy,[5,6] Ellen Ryan-Colton,[7] Hanno Seebens,[8,9] Evangelina Schwindt,[10] Montserrat Vilà,[11,12] John R.U. Wilson,[1,13] and Petr Pyšek[14,15]

[1]Centre for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Stellenbosch, South Africa; email: rich@sun.ac.za

[2]Department of Biology, University of Fribourg, Fribourg, Switzerland

[3]Bioprotection Aotearoa, Department of Pest-Management and Conservation, Lincoln University, Christchurch, New Zealand

[4]Department of Natural Resources Science, University of Rhode Island, Kingston, Rhode Island, USA

[5]UK Centre for Ecology and Hydrology, Wallingford, United Kingdom

[6]Centre for Ecology and Conservation, University of Exeter, Penryn, United Kingdom

[7]Fenner School of Environment and Society, Australian National University, Canberra, Australian Capital Territory, Australia

[8]Department of Animal Ecology and Systematics, Justus Liebig University Giessen, Giessen, Germany

[9]Senckenberg Biodiversity and Climate Research Centre, Frankfurt, Germany

[10]Instituto de Biología de Organismos Marinos (IBIOMAR-CONICET), Puerto Madryn, Argentina

[11]Estación Biológica de Doñana (EBD-CSIC), Sevilla, Spain

[12]Department of Plant Biology and Ecology, University of Sevilla, Sevilla, Spain

[13]South African National Biodiversity Institute, Kirstenbosch Research Centre, Cape Town, South Africa

[14]Czech Academy of Sciences, Institute of Botany, Průhonice, Czech Republic

[15]Department of Ecology, Faculty of Science, Charles University, Prague, Czech Republic

Annu. Rev. Environ. Resour. 2026. 51:19.1–19.36

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-121224-093418

Keywords

conceptual frameworks, early foundations, global patterns, integrated governance, invasion science

Abstract

Invasion science has matured rapidly into a vibrant interdisciplinary field addressing threats posed by biological invasions to people and nature. Nearly 40,000 species have established alien populations somewhere. For most taxonomic groups, numbers of alien species are increasing faster now than ever before, with introductions driven indirectly by economic development and human movement. Direct drivers (notably climate change and land- and sea-use change) facilitate alien species establishment and spread. Understanding the impacts of alien species has progressed from qualitative descriptions to structured quantification, culminating in the development of global frameworks. Negative impacts of invasive alien species on nature, ecosystem services, and people far outweigh their positive impacts. Many invasive species have been successfully controlled. While there is a notable invasion debt, the issue is tractable, but sustained resources are critical to achieve the coordination, contextual understanding, and outcome-based goal setting needed for Target 6 of the Global Biodiversity Framework.

Contents

1. THE ORIGINS AND DEVELOPMENT OF INVASION SCIENCE

1.1. Origins and Early Foundations

The study of biological invasions is evolving rapidly and has transformed, especially over the last three decades, into a formally defined interdisciplinary endeavor for addressing a major environmental crisis (1). This article first reviews the emergence of the discipline of invasion science, through major policy, program, and research initiatives. This becomes the foundation for exploring the most important advances, concepts, debates, and directions of invasion science, again with historical context, pertaining to trends, drivers, impacts, management, and governance of biological invasions.

Biological invasions are a consequence of the globalization of trade and transport. Although introductions of alien species occurred with the earliest human migrations, the extent and magnitude of invasions have grown rapidly with ever increasing global connectivity. Important groundwork for understanding biological invasions was laid down by nineteenth-century naturalists such as Charles Darwin, Alfred Russel Wallace, and Joseph Hooker (**Figure 1**). At that time alien species were mainly viewed as curiosities, and invasions were not seen as a portent of the homogenization of the world's biota or a driver of widescale ecosystem degradation. Nonetheless, such writings and many contributions in the early twentieth century laid foundations for concepts upon which the field of invasion science would later be built (2). However, these early works failed to trigger focused research on biological invasions in the absence of widely recognized major impacts and the lack of theoretical and conceptual frameworks.

Biological invasion: the phenomenon of, and suite of processes involved in, the transport of organisms through human activity to areas outside their potential range and the fate of such organisms in their new ranges

Invasion science: the discipline that addresses the full spectrum of fields of enquiry pertaining to biological invasions; it embraces invasion ecology but increasingly draws on nonbiological aspects of invasions, including economics, ethics, jurisprudence, sociology, and inter- and transdisciplinary studies

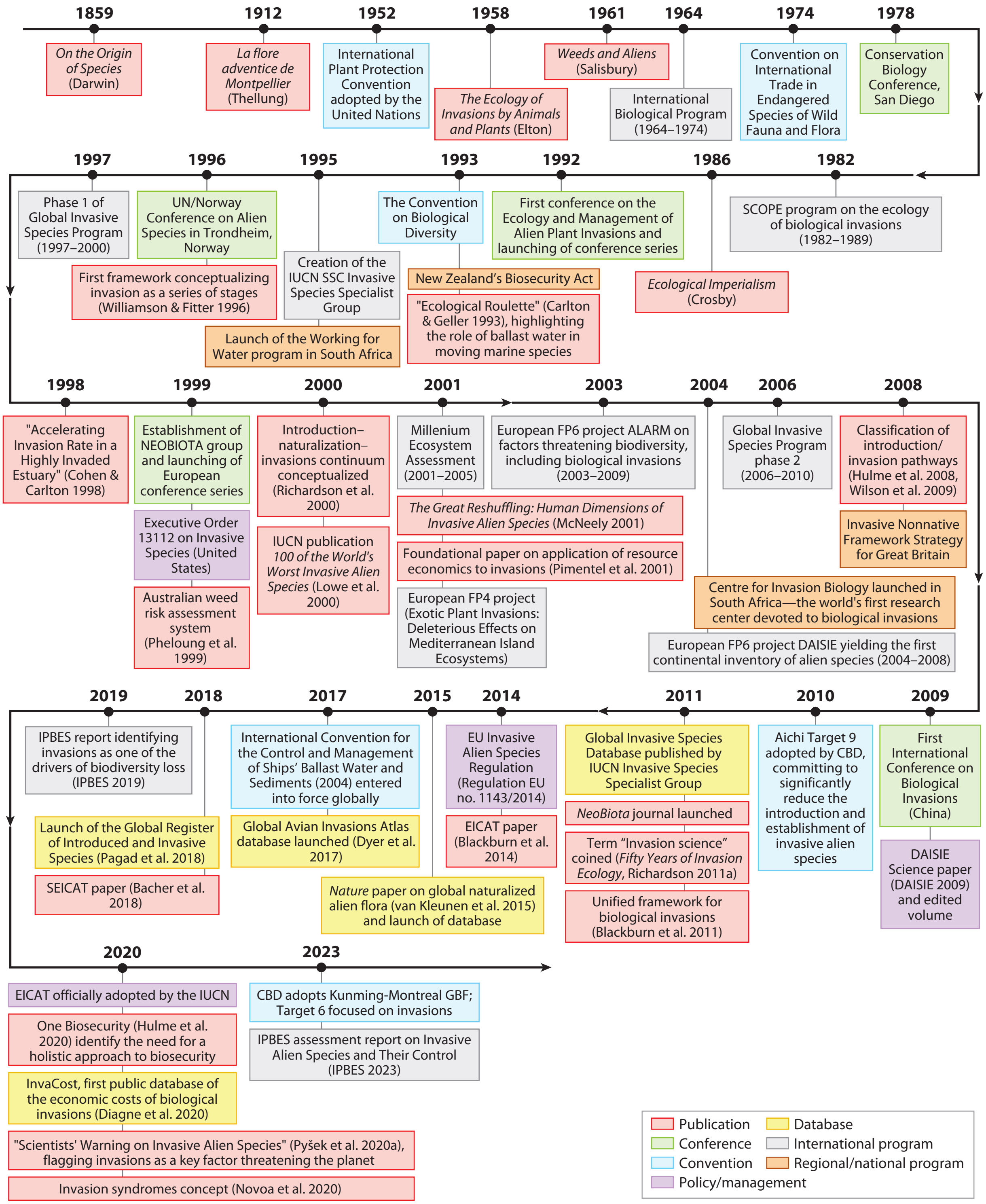
Impact: the measurable changes that alien species cause to any component of an ecological or sociocultural system

Introduction: movement of a species, intentionally or accidentally, through human activity from an area where it is native (or already present as an alien species) to a region outside that range

1.2. Formalization and Policy Integration (1958–2010)

Biological invasions surged in the wake of globalization after World War II (3), but research on the topic was still limited (**Figure 1**). Charles S. Elton's book *The Ecology of Invasions by Animals and Plants* (4) presented the first synthetic treatment of biological invasions to a general audience; it laid crucial conceptual foundations for what would become invasion science (5). Elton's work identified biological invasions as an issue of both scientific and societal concern. However, even Elton's treatment—the first blueprint for a research agenda for invasion science—failed to stimulate a surge in research on biological invasions. Richardson & Pyšek (6) suggested several reasons for this limited response. First, although there were many widespread biological invasions at that time, only decades later did biological invasions begin to be widely recognized as a major global environmental issue. Second, the field of ecology in the mid-twentieth century focused largely on natural ecosystems; biological invasions were mostly seen (if reported on at all) as background noise, as they did not fit in neatly to existing frameworks and paradigms of biogeography, ecology, and population biology. Parallel research into pathogens, pests, and weeds (7), as well as the spread of human diseases, was developing concurrently into distinct fields. Much of this research was, in essence, invasion science, but it was not clearly recognized as such.

Scientific research on biological invasions flourished in the 1980s thanks to an international program on the ecology of biological invasions launched by the Scientific Committee on Problems of the Environment (SCOPE) in 1982 (2). SCOPE explored why some species become invaders (the determinants of invasiveness), factors mediating susceptibility of sites to invasion (invasibility), and (in much less detail) options for management. SCOPE catalyzed invasion ecology to be viewed



(*Caption for **Figure 1** appears on following page*)

Figure 1 (*Figure appears on preceding page*)

Timeline of selected milestones in the emergence and development of invasion science. Further details of the entries are available in recent reviews (1–3, 19). Abbreviations: CBD, Convention on Biological Diversity; DAISIE, Delivering Alien Invasive Species in Europe; EICAT, Environmental Impact Classification of Alien Taxa; GBF, Global Biodiversity Framework; IPBES, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IUCN, International Union for Conservation of Nature; SCOPE, Scientific Committee on Problems of the Environment; SEICAT, Socio-Economic Impact Classification of Alien Taxa; SSC, Species Survival Commission; UN, United Nations.

as an urgent research topic. It launched the process of turning the largely qualitative concepts and hypotheses of Darwin, Elton, and others into quantitative treatments.

Concerns over biological invasions as a conservation issue intensified after SCOPE. The Convention on Biological Diversity (CBD), enacted in 1993, helped focus research on the conservation and sustainable use of biological diversity. Article 8(h) of the CBD committed many nations to implement measures to "prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats, or species." Following this development, the allocation of resources for managing invasions started to be justified. The 1995 launch of the Working for Water program in South Africa was a milestone; it was the first major national-scale initiative grounded explicitly on the goal of mitigating impacts of invasive alien species (IAS), in this case initially trees and shrubs, on ecosystem services, while simultaneously addressing crucial sociopolitical factors (8).

In 1996, the United Nations/Norway Conference on Alien Species in Trondheim, Norway, concluded that invasions were among the most significant threats to global biodiversity. The Global Invasive Species Program (GISP), launched in 1997, represented a step change, incorporating more interdisciplinary and transdisciplinary goals than SCOPE. GISP acknowledged the need to include economic valuation, stakeholder participation, pathway analysis, and management in the study of invasions. It sought practical solutions while recognizing the need for better understanding of fundamental ecological aspects (9), resulting in efforts to formalize the invasion process. In 1999 in the United States, President Clinton issued Executive Order 13112 on Invasive Species. This established a framework for preventing the introduction and spread invasive species and for their control. The order also mandated the creation of the National Invasive Species Council and the National Invasive Species Information Center to coordinate federal efforts to combat IAS that pose significant economic and environmental threats. The UN's Millennium Ecosystem Assessment (MEA) (2001–2005) provided further unifying focus on biological invasions as a crucial driver of biodiversity loss globally. The MEA was especially important in highlighting the need to quantify the impacts of biological invasions; it emphasized that many alien species can alter the structure and function of ecosystems and that this process can act synergistically with other global change drivers, resulting in amplified effects. The MEA also highlighted the impacts of alien species on regulating services of ecosystems (e.g., disease control, water purification) and the lack of global policy coordination, despite clear evidence of risk. In response, substantial research explored the policy implications of how alien species spread and their ecological impacts, as well as their synergies with drivers such as climate change and land-use change (10). Phase 2 of GISP (2006–2010) aimed to enhance the scientific basis for decision-making, assess invasion impacts on major economic sectors, and foster an environment conducive to improved management. Overall, the two phases of GISP inspired new research directions to clarify the multiple dimensions of impacts and integrate knowledge for management options (2).

Alien species: species whose presence in a region is attributable to human actions that allowed them to overcome biogeographical barriers; synonyms include exotic, introduced, non-indigenous, or non-native species

Invasive alien species (IAS): alien species that sustain self-replacing populations over several life cycles, produce reproductive offspring, often in very large numbers at considerable distances from the parent and/or site of introduction

1.3. Contemporary Advances and Global Governance (2011–2023)

The Aichi Biodiversity Targets were a set of 20 specific goals adopted by the CBD as part of their Strategic Plan for Biodiversity 2011–2020 (**Figure 1**). Aichi Target 9 mandated that "by 2020,

Biosecurity: the management of risks posed by organisms to the economy, environment, and human health through exclusion (the prevention of initial introduction of a species), mitigation, adaptation, control, and eradication

Invasion debt: a concept that posits that even if introductions cease (and/or other drivers of invasion are relaxed), new invasions will continue to emerge and already invasive species will continue to spread and cause greater impacts

Unified framework for biological invasions: a construct that reconciles and integrates key features of the most commonly used invasion frameworks into a single framework applicable to all biological invasions

invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment." Aichi Target 9 galvanized several nations to address biological invasions primarily through pathway management and biosecurity, helped focus the research community on enhancing understanding of pathways and sharing information through integrating databases (11–13), and brought about a major breakthrough in understanding global patterns in distribution and ecology of alien species. However, this target failed to generate substantial on-the-ground action (14). A major exception was the International Convention for the Control and Management of Ships' Ballast Water and Sediments. It entered into force globally in 2017 and was instrumental in reducing the global spread of invasive aquatic species by mandating the treatment and management of ballast water discharged by ships, which is a major vector for marine biological invasions (15, 16).

In 2023, the CBD adopted the Kunming-Montreal Global Biodiversity Framework (GBF), which also included a target specifically for biological invasions: GBF Target 6 mandates signatories to "reduce the introduction of invasive alien species by 50% and minimize their impact." Despite skepticism of the usefulness of such targets (e.g., 17), GBF Target 6 has been seen as setting useful aspirational goals and has triggered several studies that seek new directions or approaches for achieving more sustainable outcomes for managing invasions, for example, for protected areas (18). The GBF coincided with the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) *Thematic Assessment Report on Invasive Alien Species and Their Control* (19) (hereafter referred to as the IPBES Report). It drew together insights from more than 13,000 scientific publications and reports in 15 languages and Indigenous and local knowledge from all taxa, ecosystems, and global regions to provide "unequivocal evidence of the major and growing threat of invasive alien species." It emphasized that simple extrapolations from current observations likely underestimate future impacts due to considerable time lags and the concept of invasion debt (20). The IPBES Report confirmed human activities, particularly global trade and travel, as key drivers of introductions and spread. It also identified ambitious but realistic approaches for management and called for robust commitment at international and national levels. The IPBES Report sets the stage for more targeted actions to prevent new invasions and deal with existing ones—promising a new era of interdisciplinary study, policy, and challenges in invasion science.

1.4. Research on Biological Invasions and Key Conceptual Models

The development of global governance and integration into policy documents were closely related to research achievements (**Figure 1**). Systematic research on biological invasions started with the outputs of the SCOPE program that summarized the knowledge in several books (9, 21).

One of most highly cited contributions on biological invasions from the turn of the century proposed, for plant invasions, "a graphic scheme which conceptualizes the naturalization/invasion process" (22, p. 93), later refined as the "[introduction]naturalization-invasion continuum" (23, p. 411). This provided the basis for categorizing the status of species introduced by humans according to their success in negotiating a series of barriers an alien species needs to overcome to become casual, naturalized (established), or invasive (spreading widely). This linear conceptualization of aspects of the invasion process, later expanded as the "unified framework for biological invasions" (24) (hereafter referred to as the unified framework), has served as a road map for many theoretical and applied studies on invasions over the last two decades and has been pivotal in framing and defining biological invasions both in research and policy.

Substantial research effort was directed at identifying traits associated with taxa at different stages of the unified framework (e.g., 25). Many management-focused studies sought effective strategies to halt or slow progression along stages of the unified framework, for example, by clarifying introduction and invasion pathways (26–28). Formal risk assessment began to be integrated in management and policy agendas and research (29). The concepts inherent in the unified framework have also been central to the development and refinement of a plethora of hypotheses (30–32) and frameworks (33–36) pertaining to invasions.

Environmental Impact Classification of Alien Taxa (EICAT): a globally recognized standard, adopted by the IUCN, for classifying the severity of environmental impacts caused by alien species

The last decade has seen the rapid development of macroecological approaches that utilize increasingly accessible global databases on alien organisms and their distribution. Information on the global distributions of naturalized plants [the Global Naturalized Alien Flora (GloNAF) database (37, 38)], vertebrates, and invertebrates (for details, see 1) has improved dramatically, allowing for the identification of global hotspots of naturalized alien species (39, 40). The most significant progress has been made for plants; analyses using the GloNAF database have greatly enhanced the understanding of, for example, invasion mechanisms (41), historical legacy and cultural ties in shaping global invasion patterns (42), and biotic homogenization and biodiversity loss as a major outcome of biological invasions (43).

Increasing our understanding of the impacts of alien species, which is essential for assessing the risk and management of invasions, has been a strong focus of recent research. The last decade has seen major advances in the conceptualization of invasion-induced impact (44–46) and in the objective quantification of impacts of invasions on the environment (47), as well as on human well-being and good quality of life (48), including positive impacts (49), and in monetary terms (50). The Environmental Impact Classification of Alien Taxa (EICAT) scheme was adopted in 2020 as an official tool of the International Union for Conservation of Nature (IUCN) for assessing impacts of invasions, representing a major step toward cementing awareness of biological invasions among conservationists and aligning the objective approach for quantifying impacts of IAS with those of other drivers of global change.

Interdisciplinarity in the study of invasions has expanded rapidly to include many fields other than the natural sciences, drawing in insights and concepts that are needed to understand and manage the many drivers, implications, conflicts of interest, and potential management options for the burgeoning invasion contexts around the world (51). The term "invasion science" was coined to cover "the full spectrum of fields of enquiry that address issues pertaining to alien species and biological invasions" (3, p. 415). The definition thus "embraces invasion ecology, but increasingly involves nonbiological lines of enquiry, including economics, ethics, sociology, and inter- and transdisciplinary studies" (52). In turn, policy-oriented research pertaining to invasions has grown rapidly (53). Efforts to improve management systems have increasingly recognized the importance of prevention and risk assessment, used advanced data systems, and applied predictive modeling and cutting-edge technologies for detection and control (54, 55). There is increasing realization that progress in managing invasions must involve closer alignment with measures addressing human health, agricultural production systems, and conservation in general; seeking such alignment has been a productive area of research and is the cornerstone of One Biosecurity concept (56, 57).

2. TRENDS AND STATUS

2.1. Early History and Global Expansion of Alien Species (Pre-1800)

The introduction of alien species through human agency has a very long history (40). The earliest examples were likely almost all unintentional introductions associated with the human diaspora across the Earth. Many plant species and commensal rodents such as mice and rats were probably introduced thousands of years ago but went unnoticed. Most available records come from archaeobotany using seeds to reconstruct the introduction of, for example, crops in Central America and ancient Egypt and agricultural weeds in Europe (58). The discovery of sea routes connecting the Americas, Europe, Africa, and Asia in the late fifteenth century triggered a massive increase in trade and military activities, particularly by European empires. This marked the onset of the first truly global trade networks and was a pivotal moment in the history of the spread of alien species.

The increasing exchange of people and goods between continents, starting around 1500, particularly with transoceanic European colonization via ships, increased the frequency of movement of species across biogeographic barriers. Early explorers introduced European horses and other species to the Americas (59). Ships of seafarers and whalers reached nearly every coastal area in the world, carrying cats, mice, and rats to all corners of the globe, including very remote islands (2). Other animals, such as pigs, several species of deer and fish, and goats were intentionally introduced to establish familiar food resources for people. Once colonial or other settlements grew, trade intensified, resulting in the exchange and introduction of many alien species. Interest in alien species as commodities by people, companies, and governments increased rapidly with growing wealth and knowledge (40). The first botanical and zoological gardens were established in the sixteenth century, representing another source for introducing new species (58).

At a global scale and across all taxa, records on establishment (i.e., creating self-sustaining populations) are available for only 1,174 alien species between 1500 and 1800 (60); this equates to four newly recorded alien species per year on average. These numbers are severe underestimates because the arrival times of most introductions to new regions were not documented. Despite the many species introduced during this period, the intensity of these introductions was low compared to the deluge that followed (**Figure 2**). Dynamics changed in the late eighteenth century when documentation and the number of first records increased sharply. A combination of factors, mostly related to increases in Europe's human population and wealth, explains this rise. The rising and wealthier population in Europe resulted in a growing market and also associated demands for exotic products. Trading activities, but also the exploitation of resources by colonial empires, increased steadily, resulting in rising rates of alien species introductions. New migrants introduced plant and animal species for food production and to assist their survival; many species escaped from cultivation and captivity and established self-sustaining populations (2). Acclimatization societies in the colonies of European empires were established to identify and introduce species of interest for emigrants or to supply European markets.

The increase in first records between 1500 and 1800 was particularly pronounced for vascular plants (**Figure 2*b***), thanks in part to the increased activity of plant hunters, botanical gardens, and acclimatization societies. This period also saw a shift in documenting first records with the development and increasing application of a standardized typology for naming species published by Carl Linnaeus in 1758, which provided a more consistent way of reporting and exchanging information about species occurrences. Documenting new arrivals has become more common in recent years but still varies across regions and for different taxonomic groups.

2.2. Trends in Introductions Across Taxonomic Groups Since 1800

The number of new first records of alien species per period of time has increased continuously since around 1800 (**Figure 2**). This steady increase is particularly pronounced for insects but is also clear for birds, crustaceans, fungi, and mollusks. For amphibians and reptiles, rates are comparatively low, making it difficult to identify clear trends, particularly in the nineteenth century. Vascular plant introductions reached a high plateau in 1800, and numbers have remained high with only a slight increase. These long-term trends are likely affected by changes in research effort over time across countries and for different taxonomic groups. Particularly for invertebrates and fungi, and especially in early times, the numbers of first records are severely underreported (19). Mammals are the only group to show an apparent decline in the rate of new introductions since 1970,

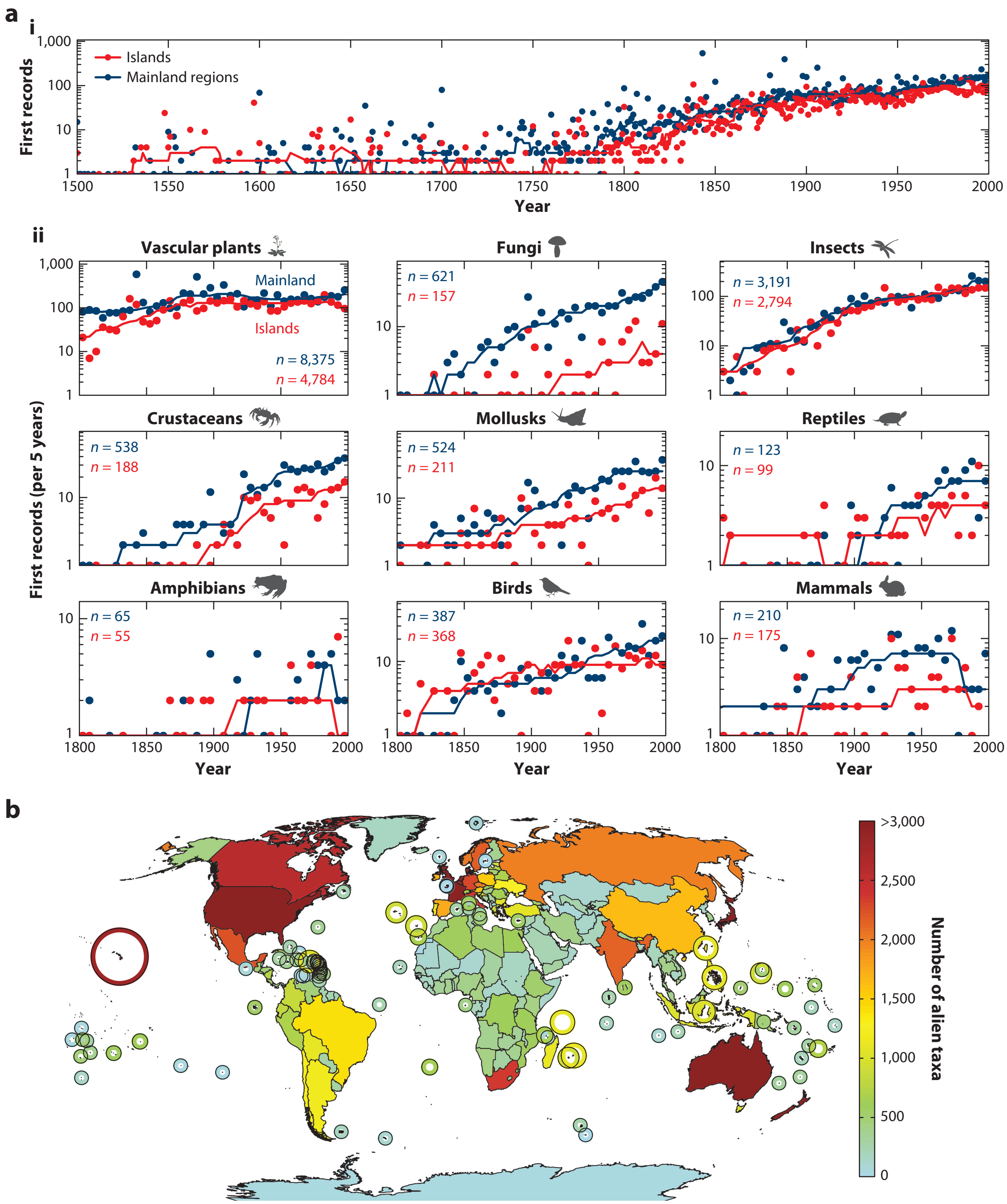


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Figure 2 (*Figure appears on preceding page*)

(*a*) Time series of the number of newly recorded alien species per year (i.e., first record rates) and (*b*) geographic distributions of the number of all alien species recorded per region. The time series show the number of newly recorded alien species per time interval either (*i*) for all alien species (annually) or (*ii*) for individual taxonomic groups (5-year intervals). Note the logarithmic scale on the *y*-axes. Red dots indicate first record rates on islands, while blue dots denote mainland regions. The map in panel *b* shows the number of alien species recorded per region. Small islands are represented by circles. Data from Reference 212.

and trends for other groups suggest a saturation in recent times (**Figure 2**). It is important to note that the reported trends over the last two decades are not fully reliable because lags between introduction, detection, and reporting render the data incomplete; the apparent universal decline in introduction rates over that period must therefore be interpreted with caution (60, 61). The decline in mammal introductions has, however, been consistent over multiple decades, suggesting that the trend is real. Likely reasons for this decline include a saturation effect (most mammals with utilitarian value have already been introduced), effective regulation of intentional introductions, and the lower probability of accidental introductions (given the relatively large body sizes of mammals) (19).

2.3. Global Distribution Hotspots and Islands

The highly uneven distribution of alien species across the globe (**Figure 2*c***) is largely a consequence of country-level economic development. Countries with long histories of international trading activities and economic development, particularly since 1950, currently harbor many alien species. Many global hotspots of alien species are therefore found in western Europe and North America, as well as in Australia and New Zealand, where the intense exchange of goods and people occurred over only the last few centuries via European colonization. Emerging economies such as Argentina, Brazil, China, India, Mexico, and South Africa have experienced pronounced increases in alien species numbers due to their strong recent economic development. Some islands and archipelagos, such as Hawaii, host surprisingly high numbers of alien species relative to their area.

Islands have received special attention in invasion science (19) because they seem to be especially severely affected by biological invasions (62). Although islands represent only 5.3% of the Earth's land area, the total number of alien species on islands worldwide is close to the number on mainlands for nearly all taxonomic groups (**Figure 2*c***), and several global hotspots of alien species are on islands (39). Only for fungi and aquatic species (crustaceans and mollusks) are reported numbers of alien species distinctly lower on islands compared to mainlands. Even very remote islands, such as those in the central Pacific or sub-Antarctic, host high numbers of alien species (63). Interestingly, the long-term trends of alien species introductions unfolded similarly for mainlands and islands in terms of the shape of the curves (number of first records), but often also in terms of absolute numbers (**Figure 2**). Islands are especially susceptible to biological invasions, in part because naive species assemblages may be unable to resist introduced predators and competitors, and because of limited area for escape (63). Another hypothesis is that islands have always been attractive for humans, resulting in sustained high propagule pressure on island ecosystems. The Hawaiian and the Galapagos archipelagos are prominent examples of remote islands with high anthropogenic pressures. Despite their remoteness, these archipelagos are hotspots of biological invasions, both hosting more alien than native plant species (64).

Propagule pressure: a concept that encompasses variation in the quantity, quality, composition, and rate of supply of alien organisms, including their propagules, resulting from the transport conditions and pathways between source and recipient regions

There is no reason to assume that rates of new alien species arrivals will decline in the next few decades compared to what has been observed to date. The main drivers of biological invasions, such as the transport of goods and people, land-use change, and climate change, are expected to intensify, resulting in new alien species introductions. Indeed, alien species numbers are predicted to increase by 36% on average globally until 2050 (65). Emerging economies such as Brazil, China, India, Mexico, and South Africa are especially expected to receive many alien species in the future (66). Even without new introductions, alien species already present are very likely to spread further. More than 50% of species introduced after 1950 are still found in a single region only, while >90% of species introduced before 1700 have been recorded in more than one region (67), suggesting a massive invasion debt. The introduction and spread of new alien species could be mitigated with extensive monitoring, management, and governance. However, since current efforts are clearly insufficient to halt the tide of intensifying biological invasions (19), the trend of alien species accumulation is projected to continue (65).

Monitoring: rapid and accurate assessment of occurrence, status, and impact of biological invasions across a region

3. DRIVERS

3.1. Definitions and Conceptual Framework

Following the conceptual frameworks of the MEA (68) and IPBES (69), the numerous processes that shape the nature and magnitude of biological invasions can be broadly classified into direct and indirect drivers (70). Direct drivers describe the explicit human influence on ecosystems and encompass five major biophysical processes: climate change, land-use and sea-use change, natural resource exploitation, pollution, and facilitation of one alien species by another. The scale and relative importance of the direct drivers acting on biological invasions are context specific and are shaped by attributes of human societies. The factors that shape the attributes of human societies, which in turn affect biological invasions, are termed indirect drivers; they act by altering one or more direct drivers. There are five broad classes of indirect drivers: sociocultural values, human demography, economic conditions, policies and governance, and science and technology. Recent decades have seen increases in economic development, human population growth, land-use and sea-use change, resource extraction, and pollution, as well as shifts in global temperatures and precipitation that have contributed to the acceleration of biological invasions worldwide (71). While the magnitude of many direct and indirect drivers has increased since 1950, largely due to globalization and the increase in the world's human population, the effects of each driver on the magnitude and rate of introductions of IAS vary. The relative importance of direct and indirect drivers on biological invasions can be visualized by examining their roles in the initial transport and introduction of alien species into a region, their subsequent successful establishment, and the ensuing wider spread. Such a process-based perspective offers insights into the roles of direct and indirect drivers on each stage of the unified framework for biological invasions (24) and the options available for management (**Figure 3**).

3.2. Transport

Economic development is the prime indirect driver of the transport of alien species worldwide (**Figure 3**), and international trade is the primary means of intentional or unintentional global movement of species to new regions (72). Species may be deliberately traded internationally, for example, through online marketplaces (73), arrive as contaminants of traded commodities such as weed seeds in grain shipments (74), or enter as stowaways on containers or vessels, as in the case of biofouling organisms (75). Not only has the volume of trade increased in the last two decades, but so has the rate of transport, with an increasing role of air freight in the global movement of goods (76). Airline travel has also become easier for tourists, and the growth of tourism as an important economic sector poses an increased risk of the inadvertent transport of species in passenger luggage (12). Humans also move around the world for reasons other than tourism. Longer-term demographic changes arising from an increase in the scale of international human migration because of conflict or climate change (77) are also expected to facilitate the intentional

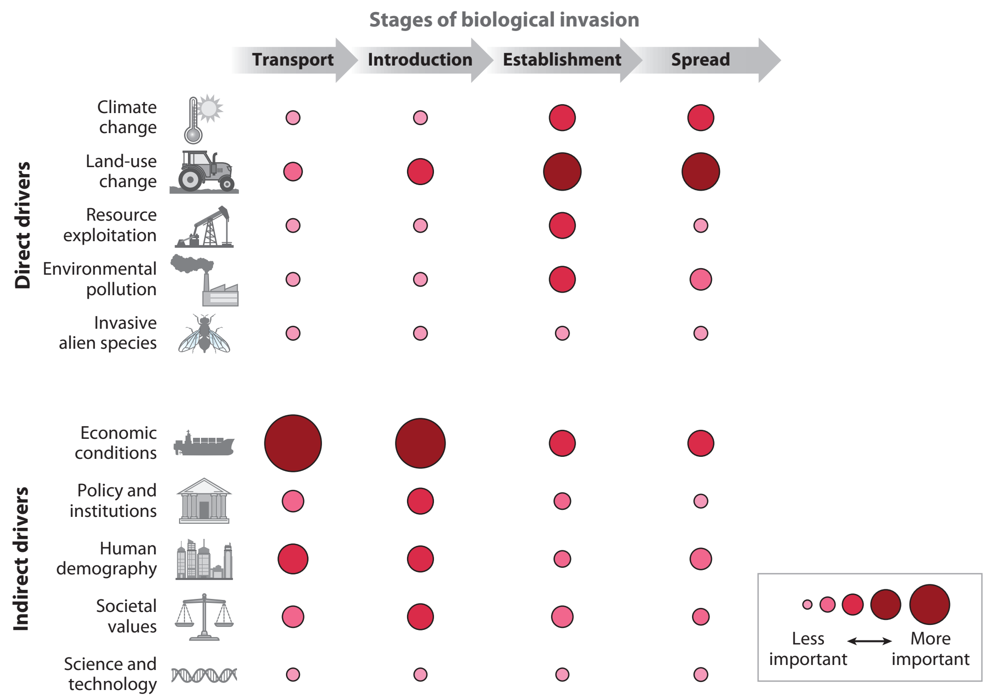


Figure 3

Schematic representation of the relative importance of different direct and indirect drivers of change in nature in facilitating invasive alien species across the four stages of biological invasion: transport, introduction, establishment, and spread of alien species. The size and shading of dots reflect the relative importance of each driver at each stage (larger and darker bubbles are more important). Data are drawn from an expert assessment of driver importance undertaken by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and are averaged across all taxa and biomes. Figure adapted from Reference 71.

or unintentional introduction of alien species as migrants move organisms deliberately or inadvertently (71). Direct drivers appear to play a smaller role in the international transport of species across borders (**Figure 3**). For example, environmental pollution in the form of marine plastics may facilitate the rafting of alien species on ocean currents from one region to another where they have previously been absent (78). It is also conceivable that extreme events such as cyclones or hurricanes associated with climate change may enhance long-distance transport of alien species from one region to another, particularly invertebrate pests and microbial pathogens (79). Nevertheless, despite examples of direct drivers facilitating the transport of species, the scale of these events is dwarfed by the economic and demographic indirect drivers.

3.3. Introduction

The outcome of the transport of a species to a new region depends on the interaction of several indirect drivers that include economic reasons to deliberately introduce alien species such as food or fiber production, as game animals, or as amenity species supporting the pet and ornamental plant industries (80) and the strength of regulatory and legislative instruments to prevent the entry of unwanted or high-risk organisms. The larger the human population and the higher its per capita wealth, the greater the consumer demand for alien species (81). The likelihood that such deliberate introductions occur will depend on their perceived risk to values that society regards as important, such as endemic biodiversity or the integrity of native ecosystems (82). The extent to which these values are protected will depend on the adequacy of legislation addressing species introductions, which will in turn reflect the strength of policy-making institutions at both national and international levels (83, 84). These institutional frameworks will also determine the effectiveness of border inspections, quarantine measures, and import health standards designed to prevent the unintentional introductions of alien pathogens, pests, and weeds. Direct drivers appear to be less important than indirect drivers in introducing alien species (**Figure 3**). The primary direct driver is thought to be changes in land use or sea use to accommodate alien species that are used in primary production, such as new crops, forestry plantations, or aquaculture species (85, 86). Some of these land-use and sea-use changes are also responses to mitigating climate change, as in the case of widespread planting of biofuel species or tree plantations for carbon sequestration (86).

3.4. Establishment

Many species transported and introduced to a region subsequently fail to establish because of unsuitable environmental conditions and/or insufficient propagule pressure (87). Direct drivers are generally more important than indirect ones in mediating the establishment of alien species in a new region (**Figure 3**). By disturbing and fragmenting native ecosystems, land-use and sea-use change can provide new opportunities for alien species establishment by changing the available resources (e.g., light, nutrients, space). Alien vascular plants, ants, spiders, birds, and mammals have been shown to exhibit a greater presence and frequency under disturbed land-use types compared to intact ecosystems (88). Although anthropogenic disturbance of marine ecosystems is common through such activities as bottom trawling, it is the creation of new habitats through the construction of artificial structures such as sea walls, piers, and pontoons that most commonly facilitates the establishment of alien species in coastal ecosystems (89).

By increasing ecosystem disturbance, natural resource exploitation (e.g., mining, deforestation) can aid the establishment of alien species in similar ways to land-use change by making ecosystems more vulnerable to invasions (90). Similarly, offshore oil and gas infrastructure create hard-surface environments in the open ocean that can act as settlement habitat or stepping stones for alien species in marine ecosystems (91). Mining and fossil fuel extraction generates pollutants, particularly heavy metals, and in some cases alien species can tolerate or even benefit more than native species from contamination of soils (92). Microplastics in soils may facilitate the establishment of alien plants (93, 94). Nitrogen, a major pollutant that leads to ecosystem eutrophication through terrestrial runoff or atmospheric deposition, has been found to benefit the establishment of alien plants and animals, particularly in aquatic ecosystems (95, 96). The importance of eutrophication in plant invasions can frustrate attempts to rehabilitate mireland soils since fertilization can accelerate the establishment of alien plant species (97).

Climate change caused by the emission of greenhouse gasses has been proposed as a mechanism facilitating alien species establishment by ameliorating climate conditions to the extent that species previously unable to reproduce successfully outside of captivity or cultivation now establish persistent populations (98). However, while warmer temperatures may favor cold-sensitive species, increasing aridity due to lower precipitation may act as a barrier to establishment for alien species adapted to mesic conditions. The net effect of climate change on alien species establishment depends strongly on the geographic region concerned and the identity of the species (99). The establishment of alien species can also be facilitated by other alien species, especially where these provide important mutualistic interactions (100) or additional resources (101). Direct drivers may appear more important in facilitating invader establishment (**Figure 3**), but indirect

Socio-Economic Impact Classification for Alien Taxa (SEICAT): a standardized framework for assessing the impacts of alien species on human well-being by focusing on how they change human activities

drivers are continually influencing more direct drivers and can have inherent time lags. For example, many national land-use policies consider the relative merits of economic development, social equity, and environmental protection (102). Where the balance favors agricultural expansion, urbanization, or natural resource exploitation over the environment, it follows that governments run the risk of increasing the probability of alien species establishment. Such risks are often ignored by those institutions responsible for governance of the environment, largely because impacts of land-use change on biological invasions are rarely immediate and evidence may become apparent only several decades after the implementation of policy resulting in an invasion debt (103, 104).

3.5. Spread

Following their establishment, many alien species become viewed as IAS simply due to their considerable natural dispersal potential (105). However, natural dispersal almost always interacts with several direct drivers to accelerate spread within a region. Changes in land use and sea use can make the environment more permeable to alien species due to the increase in linear infrastructures such as roads, railways, canals, pipelines, and coastal urbanization (106, 107) that favor both natural dispersal and unintentional spread by humans (26). Alien species are expected to exhibit larger range expansions than native species due to climate change with faster spread rates expected since many alien species have broader climatic tolerances (108). Economic growth, particularly urbanization and investment in transport infrastructure, underpins these changes in land use. However, economic activity can also encourage the spread of alien species within a country through commerce, particularly the online trade in ornamental plants and aquarium species (109, 110).

4. IMPACTS

4.1. Definitions and Conceptual Framework

The quantification of impacts of IAS has improved in recent years, allowing for more systematic input of information about impacts to risk assessments, management, and policy definitions. For example, only those alien species that cause a negative impact are considered invasive in definitions adopted by the IUCN (111), CBD (112), and IPBES (19). Here we focus on the impacts of IAS, for which conceptual frameworks now consider not only negative impacts, but also the benefits of some species.

In the late twentieth century, research on the impacts of IAS focused largely on qualitative descriptions of ecological disruptions (e.g., biodiversity loss and ecosystem alterations) and considered mechanisms such as competition or predation. These studies were mostly case-specific with limited standardization. In the first decade of the twenty-first century, the scope of impact was extended beyond ecology to recognize IAS as a multidimensional issue with effects on the economy, health, and culture (e.g., for Indigenous peoples and local communities). The last decade has seen substantial advances in quantifying impacts and developing standardized frameworks for impacts on ecosystems, such as EICAT (47), which was adopted by the IUCN as a global standard in 2020 (111), and on people, such as the Socio-Economic Impact Classification for Alien Taxa (SEICAT) (48). These frameworks categorize impacts by magnitude (minimal to massive), allow comparisons across taxa and regions, and facilitate objectivity in decision-making about seemingly intangible impacts, alongside more tangible economic costs (e.g., 50). The CBD has called for these schemes to be further developed to help reach Target 6 of the GBF, specifically by facilitating the global prioritization of IAS based on their impacts (112). Ongoing research is exploring the context dependence of impacts [how they vary by ecosystem, species interactions, and human values (113)], their temporal dynamics [how they change over time (114, 115)], and options for recognizing positive impacts when assessing overall risks (49).

Impacts can be characterized by their type (what has changed), magnitude (how large the change is), and their direction (positive or negative). We follow the Global Impacts Dataset of Invasive Alien Species (GIDIAS) (116) in distinguishing three broad categories of impacts: on nature, on ecosystem services and disservices (ESD), and on people.

Global Impacts Dataset of Invasive Alien Species (GIDIAS): a dataset on the positive, negative, and neutral impacts of 3,353 invasive alien species

Assessing negative or positive impacts in structured frameworks requires careful consideration, as interpreting the direction of impact as positive or negative involves value-laden assumptions (117) and requires the identification of the entity (e.g., people, native species) that benefits or experiences harm. In GIDIAS, impacts on nature refer to changes in biotic and abiotic ecosystem properties. They are considered positive when native species benefit from ecosystem changes due to IAS and negative when native species are harmed. However, some impacts on nature (e.g., changes in abiotic ecosystem properties) cannot be assigned a clear direction when their effects on native species are unknown (47, 49, 111). IAS may increase ecosystem services or reduce disservices (positive) or vice versa (negative). Impacts on people are assessed by considering changes in constituents of human well-being, such as material or immaterial assets, safety, health, social relations, and freedom of choice. Impacts are positive when people benefit from IAS and negative when they are negatively affected. IAS can also cause multiple types of impacts at the same location that may need to be assessed using different metrics and indicators, even if they are caused by the same invasion event. However, whether using globally accepted frameworks or tailored local studies, amalgamating to an overall impact of IAS can be controversial as values attached to different impacts might differ among people and sectors (118). This can result in perceived trade-off or conflict caused by alien species with purported benefits and detriments. Assessing the breadth of impacts, as introduced below, in equitable ways is one key emerging challenge for impact frameworks and invasion science.

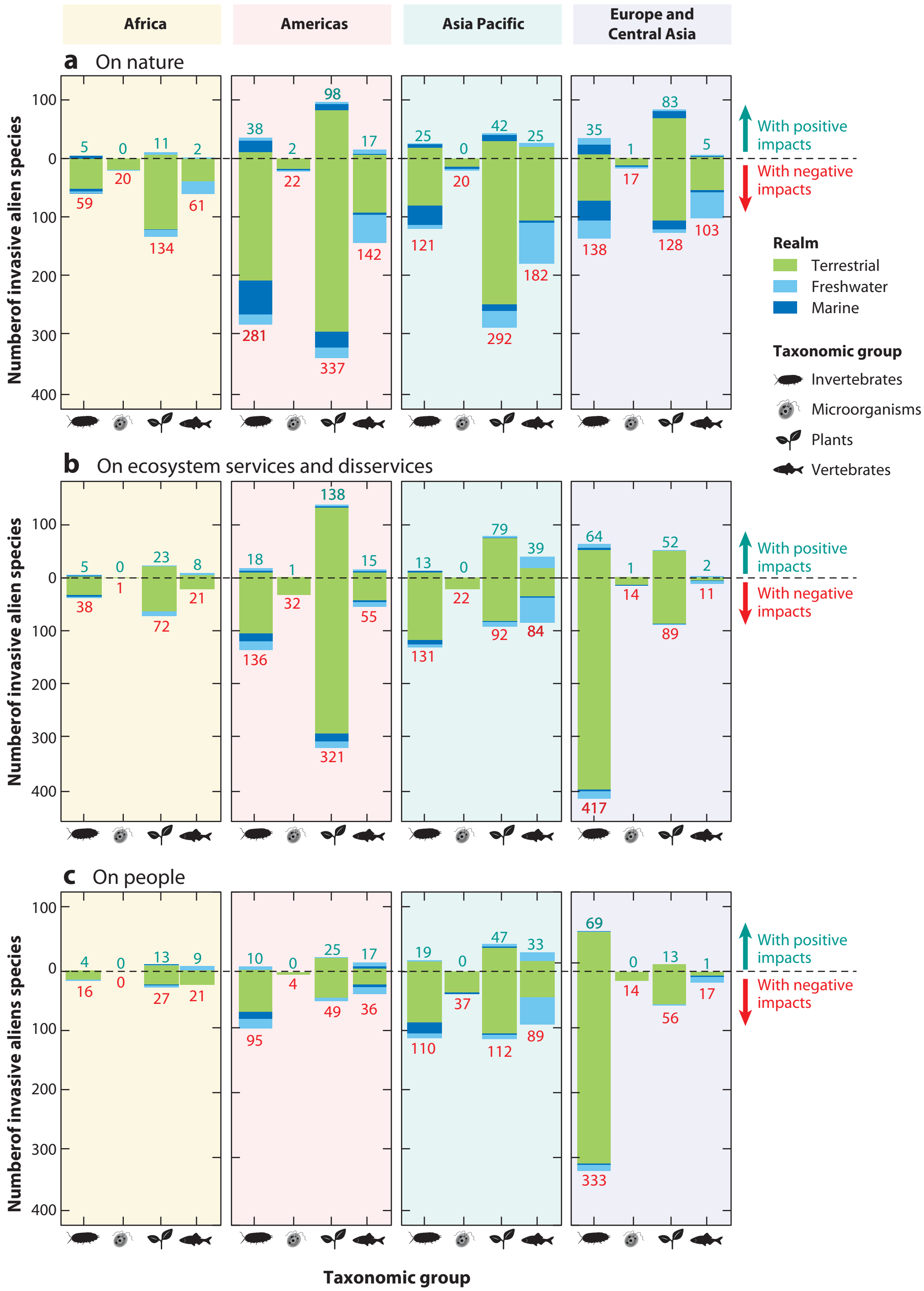
4.2. Global Patterns of Impacts of Invasive Alien Species

Looking at macroecological patterns of invasive species impact has only become possible in recent decades; such patterns have revealed the scale of the issue and existing knowledge gaps. GIDIAS has documented impact for approximately 10% of known alien species, the proportion varying by taxonomic group (e.g., 5% for plants, 20% for invertebrates), with impacts documented across all taxonomic groups, geographic regions, and habitat types except the deep sea and cryosphere.

IAS causing negative impacts on nature, ESD, and people are far more frequently reported than those causing positive impacts—by a factor of approximately four. This pattern holds across all regions; freshwater, marine, and terrestrial realms; and taxonomic groups (**Figure 4**). This strongly suggests that the dominance of negative impacts is a genuine pattern and not an artifact of bias in data collection (see also 119). Most impacts of IAS have been reported from the Americas, Europe, and Central Asia (**Figure 4**), possibly reflecting higher research effort than in Africa, Asia, and the Pacific. Microorganisms are the least-studied group.

4.3. Impacts on Nature

In terrestrial ecosystems, most documented impacts on nature are associated with invasive alien plants, predominantly those invading forests, grasslands, and human-dominated habitats. In contrast, fewer impacts are reported from highly stressful environments such as cold (e.g., tundra, alpine zones), arid (e.g., deserts), or waterlogged habitats (e.g., peatlands). In freshwater systems, approximately 80% of recorded impacts stem from inland surface waters and standing water bodies, with fewer reports from aquaculture systems. In the marine realm, nearly all impacts are documented in shelf ecosystems—shallow seafloor areas extending from the shoreline to the shelf break, typically less than 200 m deep. Impacts from the open ocean and deep sea remain virtually



(Caption for **Figure 4** appears on following page)

Figure 4 (*Figure appears on preceding page*)

Numbers of invasive alien species with documented positive and negative impacts globally, by impact type [(*a*) on nature, (*b*) on ecosystem services and disservices, and (*c*) on people], region, realm (terrestrial, freshwater, marine), and invasive alien species taxon (invertebrates, microorganisms, plants, vertebrates). Impacts on nature refer to changes in biotic and abiotic ecosystem properties. They are considered positive when native species benefit from ecosystem changes due to invasive alien species and negative when native species are harmed. Invasive alien species may increase ecosystem services or reduce disservices (positive impacts) or vice versa (negative impacts). Impacts on people are assessed by considering changes in human well-being. Impacts are positive when people benefit from invasive alien species and negative when they are negatively affected. Note that invasive alien species can also cause multiple types of impacts and in multiple locations; thus, the same species might be counted more than once. Invasive alien species causing impacts for which a direction could not be assigned (e.g. changes in abiotic ecosystem parameters such as soil water content or pH) and invasive alien species for which no impacts could be found are not included. Positive and negative impacts are visualized by columns in the upper and lower direction, respectively. The numbers at the end of each bar indicate the total number of alien species recorded with positive impacts (*upward*), and negative impacts (*downward*). Across all impact types, regions, realms, and taxonomic groups, invasive alien species with negative impacts are recorded more frequently than those with positive impacts, strongly suggesting that the dominance of negative impacts is a genuine pattern and not an artifact of bias in data collection (see also Reference 119). Most invasive alien species have been reported from the Americas and Europe and Central Asia, possibly reflecting higher research effort than in Africa and Asia and the Pacific, Microorganisms are the least-studied group. Data from GIDIAS (116).

undocumented. More than half of the studies on nature impacts of IAS document changes to abiotic ecosystem properties that cannot be assigned a direction (113).

The IAS most frequently associated with negative impacts on native species include a range of vertebrates such as rats (*Rattus* spp.), domestic cat (*Felis catus*), cane toad (*Rhinella marina*), and fish species like lionfish (*Pterois* spp.) and common carp (*Cyprinus carpio*). Several ant species are also prominent contributors to negative impacts. In contrast, positive impacts on native species are most often attributed to invasive plants and invertebrates, typically through the provision of habitat or trophic resources. Importantly, negative impacts tend to occur within the same taxonomic group (e.g., invasive plants harming native plants), whereas positive impacts often cross taxonomic boundaries. For instance, invasive plants frequently benefit native invertebrates, whereas invasive invertebrates and vertebrates tend to benefit native species within their own taxonomic group. Data from global introductions of large mammalian herbivores indicate that native species at higher trophic levels are disproportionately affected by IAS, both positively and negatively (119).

IAS can impact nature through various mechanisms directly (e.g., competition, predation, or hybridization) or indirectly (e.g., transmission of diseases, abiotic changes to ecosystems, or interactions with other species) (47, 49, 111). Negative impacts span the full spectrum of mechanisms and magnitudes, from subtle reductions in individual performance to complete local extinctions of native populations (113).

Some IAS have caused global extinctions, particularly when native species had restricted ranges with clear geographic boundaries (e.g., islands, mountain ranges, or isolated lakes). IAS are considered the sole cause of 16% of all species extinctions documented by the IUCN Red List (120) and are a significant contributing factor in nearly 60% of known extinctions. For example, the predatory rosy wolf snail (*Euglandina rosea*), introduced to Pacific islands to control the giant African snail (*Lissachatina fulica*), has been implicated in several global extinctions of island-endemic snails (121). Approximately 6% of IAS with documented impacts have caused local extinctions of native populations, with such events recorded across all ecological realms. In terrestrial and freshwater systems, vertebrates (>50%) and invertebrates (>25%) are the primary drivers of local extinctions. In marine systems, invasive plants (including algae, 35%) and invertebrates (48%) are most frequently responsible.

Islands are disproportionately affected by IAS. Most global extinctions due to IAS have occurred on islands, and local extinctions are nearly twice as likely on islands compared to mainland regions (20% versus 9% of all directional impacts). Interestingly, areas designated for nature conservation experience impacts from IAS at similar levels as nonprotected areas, suggesting that protection measures have not effectively shielded ecosystems from impacts of biological invasions (113).

4.4. Impacts on Ecosystem Services and Disservices

Most information on the impacts of IAS on ESD comes from terrestrial ecosystems, primarily involving invasive plants. More than half of these impacts occur in cultivated areas and in temperate and boreal forests. Insects are a major group causing negative impacts, particularly in Europe and Central Asia. In aquatic systems, 70% of reported impacts occur in inland surface waters and standing water bodies. Fewer than 4% of known IAS cause impacts in marine ecosystems (most of these in shelf ecosystems). This low representation of marine IAS may reflect a knowledge gap rather than a true absence of impact on ESD in seas and oceans.

The proportion of reports with negative impacts on islands (76%) is similar to that on mainland locations, except that islands have more than double the number of reports of IAS providing food and feed as well as pollination and dispersal services for mainland locations (113). Only 5% of the impacts on ecosystem services have been documented in protected areas. There are no observations of the impact of IAS on the psychological, learning, or inspirational changes that IAS may cause to people in protected areas.

The most studied IAS causing negative impacts on ecosystem services occur in freshwater ecosystems. For example, water hyacinth (*Pontederia crassipes*) alters water quality and regulation and obstructs navigation. These changes reduce fishing opportunities, limiting food availability for local communities that rely on rivers and lakes for subsistence (122). Water hyacinth also negatively affects recreational fishing, diminishing both physical and psychological experiences. Many invertebrates such as the zebra mussel (*Dreissena polymorpha*), along with various mollusks, gastropods, and crustaceans, modify water regulation and habitat maintenance. They can also serve as reservoirs for pathogens, both native and introduced, that threaten native species (123).

Many IAS exert varied positive and negative ESD impacts depending on context and the socioeconomic perspective, for example, tilapia (124), mesquite (*Neltuma* spp.) (125), and various invasive crayfish and crabs (126). However, even when positive effects are documented, these rarely fully mitigate or compensate for the negative impacts (82).

IAS affect all categories of ESD. The most significant ESD impacts of IAS are those that affect habitat creation and maintenance; food and feed supply; and the provision of materials, companionship, and labor (116). In these and many other categories of impact, IAS can have both negative and positive impacts. Alien species that were intentionally introduced for particular reasons usually continue to provide ecosystem services even after they establish beyond sites of cultivation/captivity and cause negative impacts (113). For example, alien fish, crustaceans, and mollusks were introduced to aquatic ecosystems (especially in Asia) as food sources (**Figure 4**), but some have subsequently caused major ecological harm. Similarly, alien trees planted for timber production continue to provide ecosystem services to people.

4.5. Impacts on People

Impacts of IAS on people are mostly reported from populated areas and places where human communities have the strongest dependence on natural systems or primary production (127, 128). Such impacts are predominantly reported in terrestrial systems (**Figure 4**), especially from cultivated lands, tropical and subtropical forests, and semiurban/urban areas, followed by freshwater systems (113). However, impacts on people are also reported from less populated habitats, such as deserts

(129). In the marine realm, impacts are mainly reported from island communities, especially in Asia and the Pacific (130) (**Figure 4**).

Invasive alien invertebrates and microbes are responsible for a disproportionately high number of negative impacts on people, and there are few reported benefits (**Figure 4**). Prominent impacts include fire ants, giant African land snail, marine jellyfish, and the dengue virus transmitted by invasive mosquitoes (113). Humans have rarely found beneficial uses for invasive microbes, and adaptation to invertebrates is uncommon (with the notable exception of edible aquatic invertebrates like the Asian clam *Corbicula fluminea*). Distinct groups of IAS have almost exclusively negative impacts (116). These include pathogenic IAS that cause disease or injury; agricultural pests that threaten food production, livelihoods, and material assets (e.g., fall armyworm *Spodoptera frugiperda*, cassava mealybug *Phenacoccus manihoti*), and forest pests and pathogens (e.g., emerald ash borer *Agrilus planipennis*, oomycetes *Phytophthora* spp.) that cause dieback of native trees, leading to the loss of amenity, climate regulation, cultural value, and economic resources (131, 132). Impacts from invasive plants and vertebrates tend to be more complex, varying with social-cultural-economic contexts and through time (113, 127). For example, mesquite (*Neltuma juliflora*) has caused significant harm to some communities, while others have adapted and derived benefits from this species (133). At a global scale and across all major taxonomic groups, IAS consistently cause more negative than positive impacts on people (**Figure 4**), resulting in a net decline in human well-being.

While some IAS do provide benefits, these are often contextual and contested. In some cases benefits arise under conditions of limited agency, disempowered decision-making, or lack of alternatives, and they are accompanied by significant long-term costs (82, 113, 134). Benefits derived from IAS are usually material (i.e., food, fuel, medicine), although they may also have cultural dimensions (e.g., pigs are central in many Pacific Island cultures) (135). For IAS with the most reported positive impacts on people (116), two of these so-called positive species have negative impacts on natural systems in more localized areas (Eucheuma seaweed *Eucheuma denticulatum*, feral pigeon *Columba livia*), while others are major ecosystem-transforming invasive plants (e.g., black locust *Robinia pseudoacacia*, water hyacinth) or invasive vertebrates with widespread negative impacts on ecosystems (common carp *Cyprinus carpio*, wild horse *Equus ferus*).

Change to material and immaterial assets is the most reported way IAS affect people (60% of cases), but research into the breadth of impacts of IAS on human well-being has expanded in recent years (128). Studies show how human health, safety, relationships (including social, spiritual, and cultural), and freedom of choice or action can all be affected by IAS (116). To achieve more equitable and comprehensive assessments of IAS impacts on people, it is essential to better understand the magnitude of impacts to all constituents of well-being (48). This includes addressing the current research bias toward monetary and asset-based impacts, which may overlook more nuanced or intangible dimensions of harm and benefit.

5. MANAGEMENT AND GOVERNANCE

5.1. A Developing Practice

Efforts to concertedly manage biological invasions started in the late nineteenth century (2). The scale of some early efforts was impressive. In the early twentieth century, thousands of kilometers of rabbit-proof fences were established in Australia (though these were ultimately ineffective). Also in Australia, the Commonwealth Prickly Pear Board was established to address invasions by alien cacti (*Opuntia* spp.). Over the period 1920 to 1939, the board spent well over 1 billion USD (adjusted to 2025 values) (136). This program, focused on classical

Eradication: the extirpation of an entire population of an alien species from a site to which the likelihood of reintroduction is negligible

Integrated governance: a strategic approach that connects systems, sectors, and levels of organization to promote holistic management, better decision-making, and improved service delivery

biological control, was, unlike the initial work on rabbits (*Oryctolagus cuniculus*), very successful. While science has developed markedly since then, many of the broad lessons around the need for coordinated action and the value of prevention remain essentially the same. What has improved is the development of best practices to evaluate the likely consequences of interventions (137) and systems to incorporate views and perceptions into risk-based evaluations of interventions.

While the scale and magnitude of invasions often seem overwhelming and sometimes in practice we may need to accept changes and embrace novel ecosystems (138), in many cases, something either can be done or could have been done in advance. There are many examples of successful management efforts around the world; among them are cases that have targeted different pathways of introduction and spread (e.g., limiting introductions via ballast water to the North American Great Lakes) (139, 140), tackled individual IAS and groups of taxa (e.g., classical biological control of plants) (141), and dealt with IAS in different sites (particularly the eradication of invasive vertebrates on islands) (142) and across different socioecological settings [e.g., integrative restoration on tropical islands (143) and addressing wild boar in protected areas in Argentina (144)]. Evidence is accumulating to show that policies and regulations can be effective (139, 145, 146). Progress in invasion science is helping us to prepare in advance, generate usable predictions, and develop management techniques and approaches that will help reduce invasions in many systems to levels where their impacts are manageable or preventable (147).

5.2. A Coordination Problem: The Need for Integrated Governance

The successful management of biological invasions can have significant positive returns on investment, ranking among the most effective conservation interventions (148). However, management is often costly, and those who benefit from intentional introductions or pathways that introduce alien taxa are often different from those who suffer the worst impacts of invasions. Benefits and costs also often vary in time and space (149). This often creates complex conflicts of interest (150, 151). It is thus essential to allocate appropriate funding for objective and equitable decision-making processes and employ regulatory and control mechanisms for what are ultimately societal issues.

Some rules of thumb are emerging on what to do and when, as are lessons on the transferability of insights from successful interventions in one region to other regions (e.g., 152) or among different invasion contexts [e.g., insights from dealing with invasive forestry trees can be applied for reducing the risk in using alien plants for biofuels (153)]. However, invasion events are often context specific (154), and adaptive management is usually crucial (155). While best-practice guidelines can be and have been developed, interventions need to be monitored and improved and outcomes tracked. Management can be complicated, but if approached appropriately, e.g., by managing pathways rather than targeting each species separately, solutions can be found (156). Given the need for adaptability, managing biological invasions is thus often essentially a problem of coordination. Analyses of successful interventions also highlight the importance of having an inspirational and committed leader (157); the challenge is to empower those who are motivated, noting that top-down interventions are not always effective, sustainable, or embraced by those tasked with dealing with invasions or those experiencing impacts. Appropriate structures, leadership, and support are needed to facilitate interventions. This concept has been termed integrated governance (158). An example of how this is evaluated at a national level for South Africa is provided by Wilson et al. (159). The One Biosecurity concept shows how integrated governance can assist with the management of biological invasions pre- and postborder (57).

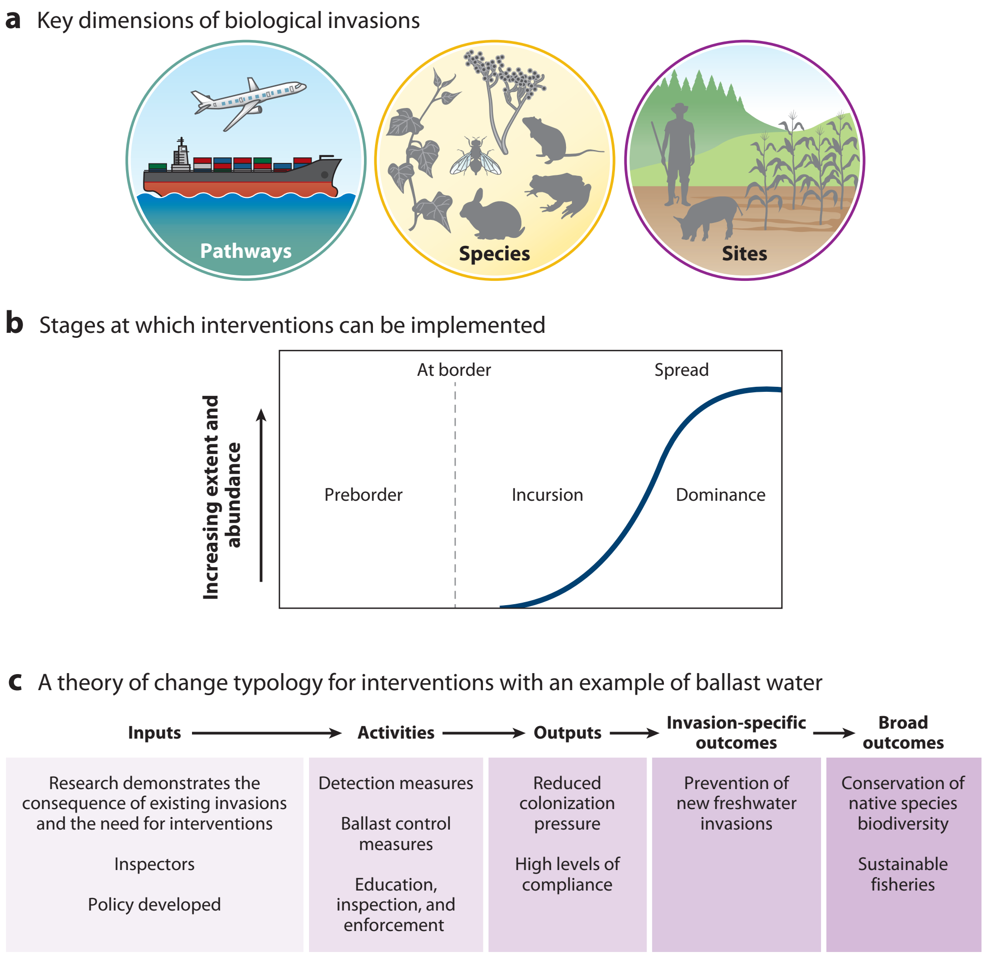


Figure 5

Three proposed building blocks for developing management plans for biological invasions. (*a*) It is important to explicitly and separately consider activities addressing pathways of introduction and spread, alien species, and sites that are or could be invaded. (*b*) It is important to consider activities at different stages of the unified framework. (*c*) It is important to identify outcomes (either broadly or invasion specific) and from there consider what outputs are needed to reach the outcomes, which activities would result in the outcomes, and what inputs are needed for the activities (i.e., follow a theory of change–type approach).

5.3. The Need for a Clear Management Framework

Another emerging insight is that planning effective management requires clarity regarding the intended outputs and outcomes, as well as the development of carefully structured plans (**Figure 5**). Although various frameworks developed in invasion science have advanced our general understanding (34, 35), overarching conceptual frameworks have arguably had little impact on how biological invasions are managed. The invasion curve (simplified in **Figure 5*b***) is an excellent communication tool for demonstrating the relative cost of interventions at different stages (e.g., 160). Important guiding documents exist for various activities [e.g., a tool kit has been developed to assist countries in meeting Target 6 of the GBF (161)] and to guide specific choices [e.g., how to track progress toward eradication (162) or where to manage first (163)]. However, the resulting frameworks have arguably provided few useful insights, especially for marine systems, which are poorly represented. For example, although plotting management actions onto the unified framework of biological invasions and specifying goals for particular invasion stages (e.g., 164) produces appealing graphics, there are too many exceptions for this approach to be useful in practice, emphasizing that the management context matters. Containment can be crucial even if an invasive taxon is widespread, for example, preventing the spread of *Phytophthora* from nurseries (165). Although eradication has been achieved for some widespread taxa [e.g., smallpox (166)], in other cases attempting to eradicate even limited incursions can be viewed as too costly and unlikely to succeed [particularly in marine settings (167)].

Here we outline three broad aspects of effective management plans (**Figure 5**).

First, the management approach should explicitly and specifically consider pathways, species, and sites. Explicitly considering pathway action plans, species-specific management efforts, and site-specific actions is a crucial framing for effective management planning (168; see also the invasion syndrome concept in 169). Since prevention is usually the most cost-effective strategy, managing pathways is key to reducing species introductions and the impacts that follow in all contexts. Nonetheless, plans and strategies often need to be hierarchical. For example, an action plan to address a horticultural pathway must also focus on specific sites (e.g., historical plant collections and large nurseries) and species groups (e.g., the cactus trade), as the context matters (e.g., influencing which stakeholders to involve and how).

Second, the invasion stage to be targeted should be explicitly considered. The management focus will often differ depending on the invasion stage targeted. Issues of detection are particularly important in the case of new incursions. When faced with the task of prioritizing management efforts to address an ongoing invasion, it is essential to consider which organisms to manage first, bearing in mind the variation in how different organisms contribute to the spread, as well as the different budget constraints (170). For widespread invasions, it is crucial to focus on protecting those assets that are deemed the most valuable (171), and more recently priority assets have included the sociocultural [e.g., culturally important sites (172)], in addition to the economic or environmental, as our understanding of the impacts of biological invasions has expanded.

Third, be explicit and specific about inputs, activities, outputs, and outcomes. In line with the theory of change (173), it is important to specify the desired outcomes from the outset. Once the desired outcomes have been set, outputs required to achieve them can be identified, as can the activities needed to deliver these outputs. This makes it much easier to determine the inputs needed for interventions required to achieve the essential outputs (**Figure 5**). Clearly specifying and separating the different elements helps to ensure that the intervention matches the problem and the proposed solution.

It is thus crucial to ensure that management is clear about the goals and the approach to be taken if integrated governance is to succeed. Importantly, if outcomes are not monitored, management cannot be adaptive. This approach must also be extended beyond solely bioecological considerations to incorporate socioecological factors. For example, broad desired outcomes of interventions can be societal engagement and reconnection with nature (174). Invasion-specific outcomes potentially include a community of practice for effectively addressing biological invasions (175). Achieving these outcomes requires awareness and appreciation of the issues by both those affected and those tasked with managing invasions. Activities can involve, for example, consultation exercises, volunteering programs (176), and citizen engagement in control attempts [e.g., fishing competitions in the Caribbean targeting the lionfish *Pterois* spp. (177) or physical removal of wattles (*Acacia* spp.) from sand dunes (178)]. Thinking about such issues in advance, and drawing on interdisciplinary expertise, is crucial to ensure that any conflicts of interest are managed proactively (179).

5.4. Barriers and Gaps

Regardless of the quality of the planning, diverse barriers delay or prevent the implementation of management actions across regions and biomes. Jurisdictional boundaries, inadequacy of regulations, lack of expertise, poor stakeholder engagement, and uncertainty on where to allocate limited resources are typical challenges faced by managers of biological invasions (147, 180). These are all related to coordination. We echo the sentiment of the IPBES Report that biological invasions are, unlike many other global change issues, often tractable and solvable (19). We are, nonetheless, faced with a legacy of invasions [i.e., an invasion debt (181)]. While many invasions can be effectively managed, in other cases (particularly with microorganisms, and in edaphic, marine, and connected aquatic systems) we may have to live with altered ecosystems. But, to reiterate the point, if appropriate action is taken at the right time, biological invasions can be prevented, invasions can be reversed and systems restored, or impacts can be substantially reduced.

Common reasons for inaction include gaps in knowledge about species and their interactions and impacts under different scenarios, as well as a lack of monitoring of species abundance and distribution over time and space, not only of the invader but of the resident species in response. While this is true for some regions (e.g., central Asia or tropical Asia), some ecosystems (e.g., marine), and some groups [e.g., microbes (40)], in other cases the inaction is often related to a lack of communication, consensus, and compromise among countries, sectors, and jurisdictions. Moreover, while different methodologies and technologies exist, they are not necessarily available to all regions and ecosystems. Even when they are, a lack of international cooperation and interjurisdictional coordination stalls most of the decisions or ensures that action cannot be sustained over time. This is of considerable concern as, in general, the economic cost of inaction is high (182), and inaction is inimical to prevention. Implementing an active preborder strategy can significantly reduce species introductions and their impacts. Inaction should be viewed as an active decision that often has predictable, and in some cases irreversible, consequences; a lack of knowledge is therefore no excuse for inaction (19).

Language, viewed as an idiom, can also often be a barrier that impedes or delays interventions locally, regionally, and globally. Most of the evidence in invasion science is produced in English, but managers and policy makers from many countries speak different languages and often lack access to the latest findings and experiences. The solution is knowledge and language brokers, which brings another set of incentives, gaps, and considerations (such as values, transparency, and epistemic justice) that play key roles in the process (183). Language, viewed as terminology, also causes confusion. We do not wish to enforce verbal hygiene (184), and terms should be used that are appropriate provided they are clearly defined (185). Whichever terms are used, it is important to separate concepts in strategies and action plans in a way that will reduce overlap (**Figure 5**). A recurrent issue in the management of biological invasions (as with many disciplines addressing global change) has been the use of similar terms to mean different things. For example, the word eradicate literally means to pull up from the roots (ex + radis), that is, mechanical control—a specific management activity. In general parlance, the term to eradicate is synonymous with control, that is, to reduce abundance—an output. In invasion management, the term is often used in a specific context, that is, eradication is defined as the goal of removing all individuals and propagules from a defined site where the likelihood of reinvasion is negligible (186)—this is an outcome that, if achieved, means control is no longer needed at a site, allowing investments to be reallocated.

6. CONCLUSIONS

Nearly 40,000 alien species have been introduced outside of their native ranges (either intentionally or accidentally) and have established populations (40). Technological innovations, improved protocols for detection and identification, expert collaborations, digitalization, harmonization, and public access to global databases over the last few decades have greatly improved our ability to track trends in biological invasions. Nevertheless, many taxa and regions are clearly undersampled. Despite the potentially confounding effect of different levels of research intensity, it seems safe to conclude that the highest numbers of alien species are found in wealthy countries of the Global North, largely because of their long histories of introducing alien species through trade relationships that began during the colonial era. Importantly, most of the long-term trends of alien species show no sign of saturation (**Figure 2**).

Since the main drivers of biological invasions, such as economy, land- and sea-use change, and climate change, are all intensifying and predicted to strengthen further, there are no indications that introduction rates and propagule pressure will decline. Without effective mitigation, many more species will be moved around the world. Managing species introductions without causing major disruption of trade is the key challenge. Examining the different roles of direct and indirect drivers on the transport, introduction, establishment, and spread of alien species provides a clear indication of where interventions might be most effective. Indirect drivers generally play a greater role in the transport and introduction of alien species, whereas direct drivers are more important mediators of establishment and spread. The challenge is that many of these drivers interact and the outcomes of such interactions remain poorly studied (70). There is, however, increasing recognition that many interactions between drivers will be synergistic, such that the combined effects of multiple drivers will be greater than the sum of their individual effects (187). It is, therefore, of concern that of all the indirect drivers, science and technology are often perceived to play limited roles in biological invasions (**Figure 3**). Scientific evidence should play a stronger part in shaping the values of society and the direction of policy if we are to have sustainable solutions to direct drivers such as land- and sea-use change, climate change, and natural resource exploitation (188). Scientific advances through the development of improved surveillance and control technologies have the potential to mitigate the transport, introduction, establishment, and spread of alien species (189).

Substantial progress is being made in understanding the multifaceted impacts of IAS. Impacts—whether positive, negative, or involving trade-offs across ecological and societal domains—are now increasingly considered in policy and management. This broadened perspective has facilitated the development of some sustainable management interventions. Research into the multiplicity of impacts may further extend our management options. For instance, the concept of multifunctional landscapes promotes strategies that mitigate negative impacts while retaining certain benefits. Protected areas, set-asides, or reserves—even at local scales such as through fenced areas (190)—can safeguard ecological and cultural assets from IAS, while still allowing local communities to harvest IAS for economic gain. Voluntary codes of conduct are gaining traction as a mechanism for reducing impacts, for example, for alien trees used in agroforestry, forestry, and ornamental horticulture (191, 192). While the macroecological patterns of IAS alert us to the major global challenge, increased awareness of impacts at local to regional scales still plays a key role in understanding the problem and mobilizing management action.

Despite this increased awareness, many issues affect our ability to manage biological invasions. Crucial interactions with other global change drivers create challenges [e.g., attempts to mitigate climate change have led to the widespread planting of potentially invasive trees (193)]. While new technologies offer the potential to radically improve what is possible (e.g., gene drives), they come with risks (147). There is an increasing recognition of the potential for futures thinking to guide strategic interventions and planning (194, 195). Ultimately, however, the major limiting factor is often the same—the efficacy of interventions can be dramatically improved through integrated governance. We argue that we need to be ambitious (in terrestrial systems); realistic (in marine systems); and persistent, adaptable, and collaborative (everywhere).

SUMMARY POINTS

1. Invasion science has evolved over the last three decades into a formally defined interdisciplinary endeavor that is converging around widely accepted concepts and frameworks for addressing biological invasions as a driver of global environmental change.
2. The historical context, including our sociopolitical history and human movements, has influenced the expansion of alien species; in response, policies, programs, and research agendas have simultaneously influenced the development of invasion science.
3. The introduction of alien species increased massively following the discovery of shipping routes in the late fifteenth century, and it surged after World War II. Nearly 40,000 alien species are established globally, with hotspots located primarily in developed countries with long histories of trade. For most taxa, long-term trends show no sign of saturation and are expected to continue rising in the future.
4. Indirect drivers, particularly economic development and human movements, are the dominant forces behind the transport and introduction of alien species. Direct drivers like land-use change, natural resource exploitation, and pollution are more prominent in facilitating the establishment and spread of alien species.
5. Invasive alien species (IAS) are a key driver of global biodiversity loss and severely harm people's well-being. Impacts of IAS are now recognized as a multidimensional issue encompassing environmental, economic, health, and cultural effects. Significant advances in impact quantification have led to the implementation of standardized frameworks like Environmental Impact Classification of Alien Taxa (EICAT) and Socio-Economic Impact Classification for Alien Taxa (SEICAT), which categorize impacts by magnitude, and the creation of a Global Impacts Dataset of Invasive Alien Species (GIDIAS), facilitating objective risk assessment for policy-making. Globally, negative impacts on nature, on ecosystem services, and on people are reported far more frequently than positive ones, and islands are disproportionately affected.
6. Successful management of biological invasions requires integrated governance; clear planning that considers pathways, species, and sites; and explicit goal-setting with measurable outcomes. Local context matters for understanding the capacity and coordination of people and techniques. Despite huge challenges, biological invasions are often tractable; with persistence, adaptability, collaboration, and leveraging of scientific and technological innovation, invasions can be halted, future invasions can be prevented, and many impacts can be reduced to manageable levels.

FUTURE ISSUES

1. The incompleteness, and in many cases lack, of inventories of alien species and their impacts in some parts of the world is hindering comprehensive assessments and the prioritization of interventions to mitigate the threat of IAS at all spatial scales. This is

particularly problematic in less-developed countries, in aquatic systems, and for taxa other than vertebrates and vascular plants. Protocols for compiling accurate and accessible inventories need to be consistently applied globally.

2. Interactions between multiple drivers (both direct and indirect) that shape biological invasions remain poorly studied. Since many of these interactions appear to be synergistic, an improved understanding is crucial to guide focused interventions that avoid unintended consequences whereby an action taken for one driver of change exacerbates another.
3. Closing knowledge gaps is essential for identifying the key determinants and context dependencies of IAS impacts and for clarifying how they vary in time and space. Such insights are crucial for improving our ability to predict the consequences of emerging invasive species, particularly those without a known invasion history. It is important to improve the flow of empirical data on IAS impacts into structured global frameworks [e.g., EICAT, SEICAT, GIDIAS], especially in areas where knowledge gaps persist—such as for cascading impacts; through interactions with other drivers of change; and in underrepresented regions, taxa and ecosystems. These frameworks must be continuously refined and strengthened to support evidence-based decision-making.
4. There is a need to develop integrated strategies, guidelines, and decision-support tools that explicitly consider the multifaceted nature of IAS impacts—both positive and negative—to support more nuanced and context-sensitive management decisions.
5. More effective management of biological invasions demands sustained resourcing, integrated governance, and dedicated coordination. Clear, outcome-based planning is required to explicitly address pathways, species, and sites, while leveraging scientific and technological innovations. Embracing the opportunities from global initiatives such as One Health to coordinate action on IAS, as proposed by the implementation of One Biosecurity, should be a key priority in upscaling the future governance of biological invasions.
6. Raising societal and stakeholder awareness of the rapidly growing problems associated with IAS and their diverse impacts is critical to build broader support for effective management at global and local scales.

DISCLOSURE STATEMENT

H.E.R. is cochair of the IPBES *Thematic Assessment Report on Invasive Alien Species and Their Control*. The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

D.M.R. led the completion of the manuscript; he and P.P. oversaw overall organization and conceptualization. All authors contributed to the development of the article. Primary authorship for the different sections is as follows: D.M.R. and P.P. wrote Section 1; H.S. and L.A.M. wrote Section 2; P.E.H. wrote Section 3; S.B., E.R.-C., and M.V. wrote Section 4; and J.R.U.W. and E.S. wrote Section 5. H.E.R. provided substantial input to all sections. All authors reviewed and contributed insights to all sections.

ACKNOWLEDGMENTS

All the authors were involved in the *Thematic Assessment Report on Invasive Alien Species and Their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES). We thank all contributors to the IPBES report; many of their contributions and insights are reflected in this review. S.B. acknowledges funding from the Swiss National Science Foundation SNSF (grant IC00I0-231475). P.P. was supported by grant 26-21350S (Czech Science Foundation) and long-term research development project RVO 67985939 (Czech Academy of Sciences). H.E.R. was supported by the Natural Environment Research Council as part of the UK Centre for Ecology & Hydrology National and Public Good Program delivering National Capability (grant NE/R016062/1). H.S. acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) (grant 521529463). E.S. was supported by CONICET PIP 11220210100507CO. M.V. acknowledges funding from MCIN/AEI/10.13039/501100011033/FEDER, UE (grant RADIOPOPO PID2021-122690OB-I00). J.R.U.W. thanks the South African Department of Forestry, Fisheries and the Environment (DFFE) for funding noting that this publication does not necessarily represent the views or opinions of DFFE or its employees. We thank Zuzana Sixtová for technical assistance.

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