Chapter **1**

INTRODUCING BIOLOGICAL INVASIONS AND THE IPBES THEMATIC ASSESSMENT OF INVASIVE ALIEN SPECIES AND THEIR CONTROL[1]

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Chapter 1

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Table of Contents

LIST OF FIGURES

Chapter 1

LIST OF TABLES

LIST OF TEXTBOXES

LIST OF SUPPLEMENTARY MATERIALS

Chapter **1**

INTRODUCING BIOLOGICAL INVASIONS AND THE IPBES THEMATIC ASSESSMENT OF INVASIVE ALIEN SPECIES AND THEIR CONTROL

1.1 INTRODUCTION: THE IPBES THEMATIC ASSESSMENT OF INVASIVE ALIEN SPECIES AND THEIR CONTROL

Invasive alien species **(Figure 1.1)**, through the process of biological invasion, are widely recognized as a major threat to nature and nature's contributions to people, with important implications for good quality of life (IPBES, 2018e, 2018f, 2018g, 2018h, 2019; **Glossary**). Biological invasions are a consequence of human activities and invasive alien species are acknowledged as one of the major drivers of local species extinctions within terrestrial and inland water ecosystems (Bellard *et al.*, 2016; IPBES, 2019a; **Chapters 3** and **4**); they have dramatically altered habitats within terrestrial, marine, and freshwater ecosystems around the world (Cacabelos *et al.*, 2020; Liu *et al.*, 2020; **Chapter 4**; **Glossary**). Invasive alien species, alongside other drivers of change in nature, are considered to be one characteristic of a new epoch – the Anthropocene (Capinha *et al.*, 2015; Crutzen & Stoermer, 2000). While the problems associated with invasive alien species have increased over the past century (**Chapters 2** and **4**), considerable progress has been made toward understanding (**Chapters 2**, **3** and **4**) and developing strategies and actions to manage them (**Figure 1.2**; **Chapter 5**). The thematic assessment report on invasive alien species and their control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES; hereafter termed the IPBES invasive alien species assessment) provides a timely synthesis of this complex but fascinating multidisciplinary field of research to underpin potential options for policy- and decision-making (**Chapter 6**).

Throughout the IPBES invasive alien species assessment, the term biological invasion is used to describe a process involving the transport of a native species outside of its natural range, intentionally or unintentionally, by human activities to new regions where it may become established and spread (Richardson *et al.*, 2010). The term invasive alien species refers to particular species within the context of the process of biological invasion; namely those that negatively impact (**Glossary**) nature and also, in some cases, nature's contributions to people, and good quality of life.

The rapidly growing threat that invasive alien species pose to nature, nature's contributions to people, and good quality of life remains underestimated and, in some cases, overlooked by policy and decision makers (IPBES, 2018a, 2019). However, concerns over the adverse impacts of invasive alien species have driven multiple efforts to establish regional and international initiatives (**Figure 1.2**; Clout & De Poorter, 2005) and policy goals **(Box 1.1)**. A pioneering initiative was the Scientific Committee on Problems of the Environment (SCOPE), which engaged scientists to document biological invasions and invasive alien species from a global perspective in 1982 (J. A. Drake *et al.*, 1989; Mooney *et al.*, 2005).

The overarching aim of the IPBES invasive alien species assessment is to critically evaluate available evidence on the severity of the threat of invasive alien species to inform potential options for decision-making. The need for sustained social-ecological (Kull *et al.*, 2018), interdisciplinary (Vaz *et al.*, 2017) and transdisciplinary approaches (Kapitza *et al.*, 2019), which are sensitive to differing knowledge systems, value perceptions and cultural attributes, is acknowledged throughout this assessment and will be critical in addressing the recently adopted goals of the Kunming-Montreal Global Biodiversity Framework (CBD, 2022).

While previous regional, global and thematic IPBES assessments have considered biological invasions and invasive alien species, an in-depth and quantitative and qualitative global analysis of them has not been conducted. Therefore, the IPBES invasive alien species assessment not only extends the findings of the previous IPBES assessments, including the IPBES Global Assessment Report on Biodiversity and Ecosystem Services (IPBES, 2019), but addresses important gaps in information. Ultimately, through the synthesis and harmonization of information at a global scale, the IPBES invasive alien species assessment examines the magnitude of the threat of invasive alien species to nature, nature's contributions to people, and good quality of life **(Box 1.2)**.

The term biological invasion describes the process involving the intentional or unintentional transport or movement of a species outside its natural range by human activities and its introduction to new regions, where it may become established and spread.[1]

Native species (synonym indigenous species) are taxa that have originated in a given area (their natural range) without human involvement, or that have arrived there without intentional or unintentional intervention of humans, from an area in which they are native. This definition excludes products of hybridization involving alien taxa since "human involvement", in this case, includes the introduction of an alien parent.[2] Some native species can spread or undergo rapid population increase and have harmful impacts. Despite their adverse effects, such native species are not considered invasive alien species.[3]

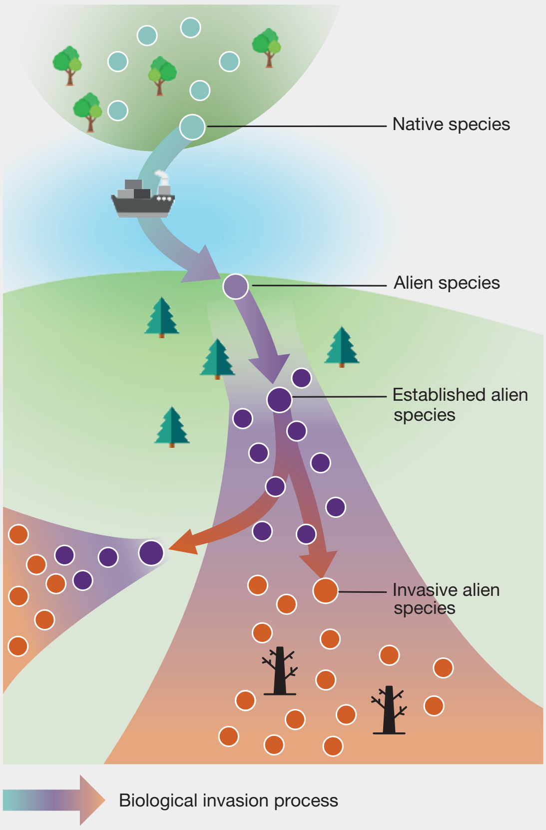
Alien species, as opposed to native species (synonyms exotic, introduced, non-indigenous, non-native), are those whose presence in a region is attributable to human actions, intentional or unintentional, that enable them to overcome biogeographical barriers.[1] Native species that expand their natural range without intentional or unintentional human involvement, for example in response to other anthropogenic drivers such as changes in land use and climate change, are not considered to be alien species.[4, 5] However, a species that spreads to new regions without direct human involvement from a region where it is alien is considered to be alien in the new region.[2]

Established (synonym naturalized) **alien species** produce self-sustaining and viable populations for a given period of time during which climatic extremes typical for the invaded region are experienced, without direct intervention by humans, or despite human intervention.[6, 2, 7]

"**Invasive alien species** are animals, plants or other organisms introduced directly or indirectly by people into places out of their natural range of distribution, where they have become established and dispersed, and generating a negative impact on local ecosystems and species".[8] Invasive alien species are a subset of established alien species that have negative impacts.

Impacts are changes to nature, nature's contributions to people and/or good quality of life.[9] Impacts can be observed or unobserved. Generally, negative impacts become more apparent and problematic when invasive alien species are well established, widespread and present for a long time. Along with their adverse effects, some invasive alien species may have positive impacts providing benefits to some people.

Drivers are factors that directly or indirectly facilitate biological invasions.



1. Richardson *et al.* (2010);
2. Pyšek *et al.* (2004);
3. Wallingford *et al.* (2020);
4. Essl *et al.* (2019);
5. Essl *et al.* (2016);
6. Blackburn, Pyšek *et al.* (2011);
7. Rojas-Sandoval & Acevedo-Rodríguez (2015);
8. IPBES (2018e);
9. Ricciardi *et al.* (2013).

Figure 1 1 **Definitions of important terms used to describe the status of a species from native to invasive alien through the process of biological invasion.**

The definition of native species provides the context for the term natural range. Stages of the biological invasion process (transport, introduction, establishment and spread) are defined in **section 1.3**.

Box 1 1 International policy targets for biological invasions.

The setting of global policy goals and targets is often considered an effective and transparent way to motivate governments and other actors (Kanie & Biermann, 2017). In recent decades, the need for prevention and management (**Glossary**) of biological invasions has been widely recognized by the Conference of the Parties to the Convention on Biological Diversity (CBD), which adopted the Strategic Framework for Biodiversity 2011-2020 in 2010, including the Aichi Biodiversity Targets (United Nations, 1992) which adopted the Strategic Framework for Biodiversity 2011-2020 in 2010, including the Aichi Biodiversity Targets, and the United Nations General Assembly, which adopted the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) in 2015. More specifically, two international commitments were made:

> "By 2020, 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 Biodiversity Target 9, Strategic Plan for Biodiversity 2011-2020 (CBD, 2010; **Glossary**).

> "By 2020, introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species." Target 15.8, SDG15 (United Nations, 2020a).

These targets were mostly directed towards biodiversity and conservation. However, while the wording of these targets does not address good quality of life directly, they are framed within a broader policy context aimed at conserving biodiversity and ensuring its sustainable use by human communities, the equitable sharing of benefits from genetic resources (CBD, 2020), and the broader goal of achieving a better and more sustainable future for all (United Nations, 2020b). As such the 2020 targets recognized the current and future threats posed by invasive alien species to humanity.

None of the 20 Aichi Biodiversity Targets were achieved at the global level (Secretariat of the CBD, 2020). The Kunming-Montreal Global Biodiversity Framework was adopted in 2022 and includes a target on invasive alien species, Target 6:

> "Eliminate, minimize, reduce and or mitigate the impacts of invasive alien species on biodiversity and ecosystem services by identifying and managing pathways of the introduction of alien species, preventing the introduction and establishment of priority invasive alien species, reducing the rates of introduction and establishment of other known or potential invasive alien species by at least 50 per cent, by 2030, eradicating or controlling invasive alien species especially in priority sites, such as islands." Kunming-Montreal Global Biodiversity Framework (CBD, 2022).

Box 1 2 Overarching questions on biological invasions.

The IPBES invasive alien species assessment addresses 11 overarching questions (IPBES, 2018a).

a. What progress has been made in tackling the Aichi Biodiversity Targets of relevance to invasive alien species globally?

b. What global-level policy initiatives would assist in invasive alien species prevention and management?

c. What are the obstacles to the uptake of invasive alien species prevention and management measures?

d. What methods are available for prioritizing invasive alien species threats?

e. How can networks assist in the prevention and management of invasive alien species? What role can regional partnerships play?

f. Are there perverse policy drivers that unintentionally create risks in relation to invasive alien species?

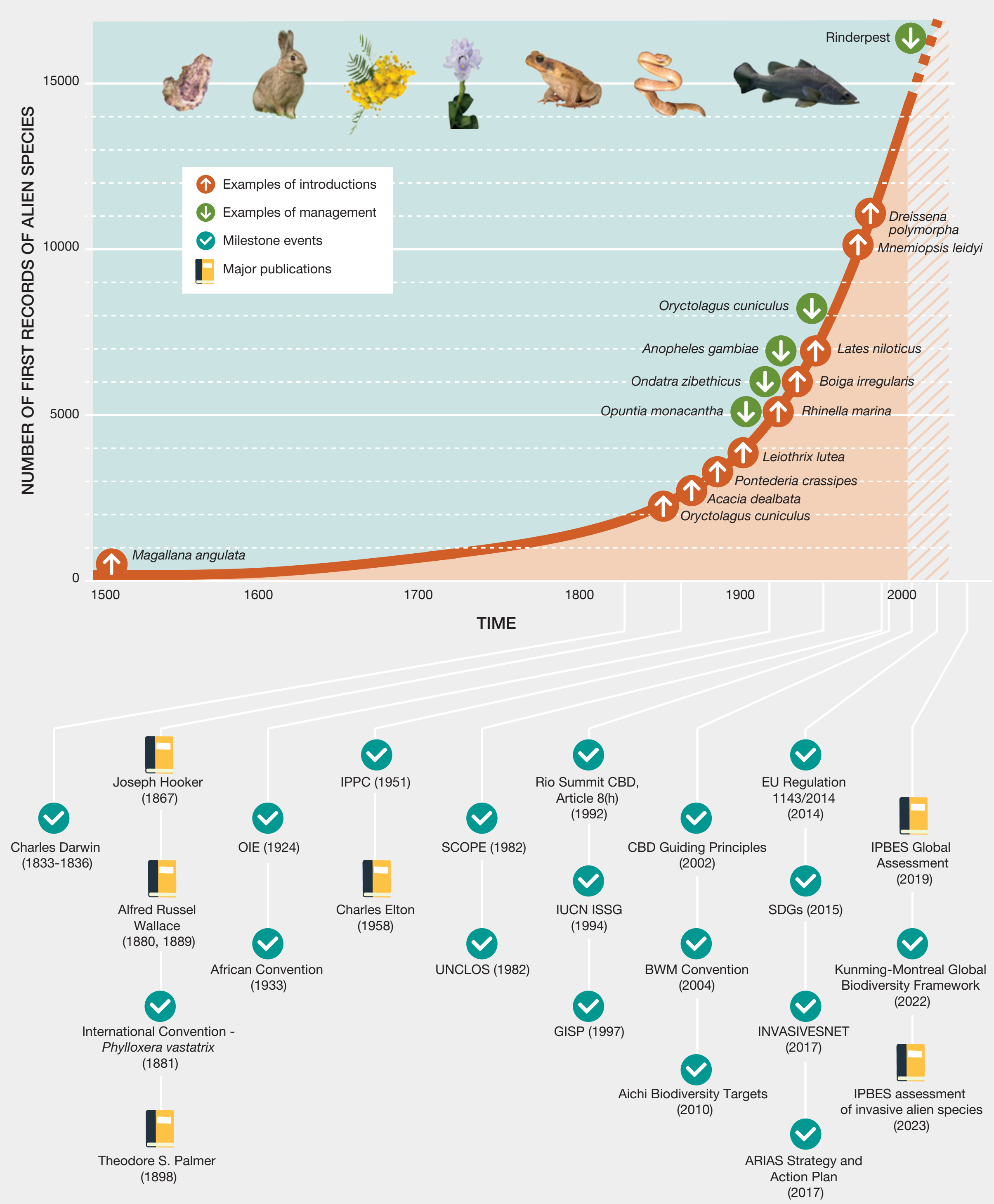
g. How can decision makers decide which issues to tackle first given limited resources?

h. Would there be value in developing a database of effective legislation, monitoring and response systems for invasive alien species, and of those countries and other stakeholders in need of capacity-building?

i. What are the impacts, risks and benefits of invasive alien species for biodiversity and ecosystem services, sustainable development and human well-being?

j. How might policy sectors, businesses, non-governmental organizations and other stakeholders benefit from better prevention and management of invasive alien species?

k. How does one prevent and manage invasive alien species that cause harm to biodiversity but contribute to economic activities?



↑	*Magallana angulata* (Portuguese oyster) was introduced in Europe in the 1500s
↑	*Oryctolagus cuniculus* (rabbit) was first recorded in Australia in 1859
↑	*Acacia dealbata* (acacia bernier) was first recorded in Sri Lanka in 1870
↑	*Pontederia crassipes* (water hyacinth) was first recorded in North America in 1884
↑	*Leiothrix lutea* (red-billed leiothrix) was first introduced in Europe in the late 1800s
↑	*Rhinella marina* (cane toad) was first recorded in Australia in 1935

- *Boiga irregularis* (brown tree snake) was first recorded in Guam in the late 1940s or early 1950s
- *Lates niloticus* (Nile perch) was first recorded in Lake Victoria in 1954
- *Dreissena polymorpha* (zebra mussel) was first recorded in North American Great Lakes in 1986
- *Mnemiopsis leidyi* (sea walnut) was first recorded in the Black Sea in 1982
- Control of *Opuntia monacantha* (common prickly pear) in South Africa (1913) and Australia (1914)
- Eradication of *Ondatra zibethicus* (muskrat) in the United Kingdom in 1939
- *Anopheles gambiae* (African malaria mosquito) was successfully managed in Brazil in the 1930s and early 1940s
- Control of *Oryctolagus cuniculus* (rabbits) in Australia in 1955
- Rinderpest is first wild animal disease to be eliminated globally in 2011
- Charles Darwin observed two European plants invading the pampas, Patagonia (1833-1836)
- International Convention on Measures to be taken against *Phylloxera vastatrix* (1881)
- Creation of the Office International des Epizooties (OIE) in 1924
- African Convention on the Conservation of Nature and Natural Resources: Article 7(5) (1933)
- Adoption of the International Plant Protection Convention (IPPC) in 1951
- Launch of the Scientific Committee on Problems of the Environment (SCOPE) programme on the Ecology of Biological Invasions in 1982
- Adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982
- Opening for signature of the Convention on Biological Diversity (CBD), including Article 8(h) on alien species, in 1992
- Creation of the International Union for Conservation of Nature (IUCN) Invasive Species Specialist Group (ISSG) in 1994
- Launch of the Global Invasive Species Programme (GISP) in 1997
- Adoption of the CBD Guiding Principles annexed to decision VI/23 on alien species, in 2002
- Adoption of the Ballast Water Management Convention (BWM) in 2004
- Adoption of the Strategic Plan for Biodiversity 2011-2020 (including the Aichi Biodiversity Targets) in 2010
- Adoption of the European Union Regulation 1143/2014 on Invasive Alien Species in 2014
- Adoption of the 2030 Agenda for Sustainable Development, including the 17 Sustainable Development Goals (SDGs) in 2015
- Creation of the International Association for Open Knowledge on Invasive Alien Species (INVASIVESNET) in 2017
- Adoption of the Arctic Invasive Alien Species (ARIAS) Strategy and Action Plan in 2017
- Creation of the Global Register of Introduced and Invasive Species (GRIIS) in 2017
- Adoption of the Kunming-Montreal Global biodiversity framework in 2022
- Joseph Hooker – devastation of native plants on islands by introduced plants, goats, and rabbits (1867)
- Alfred Russel Wallace – adverse impacts of introduced plants and animals on continents and islands (1880, 1889)
- Theodore S. Palmer – adverse impacts of introduced birds and mammals including myna in Hawaii (1898)
- Charles Elton – synthesis of evidence across diverse themes to provide first overview of the global scale and escalating adverse impacts of biological invasions (1958)
- IPBES Global Assessment Report on Biodiversity and Ecosystem Services (2019)
- IPBES Thematic assessment of invasive alien species and their control (2023)

Figure 1 2 **Timeline of key strategic events and advances in the understanding of biological invasions.**

There has been considerable progress not only in understanding the process of biological invasions and invasive alien species but also in developing strategies and actions to manage them. The timeline shows milestone events relevant to biological invasions (), major publications on biological invasions (), examples of invasive alien species' first record (), and examples of successful management (), with the central line graph illustrating the global escalation in first records of alien species. Data management report available at: https://doi.org/10.5281/zenodo.7560099

1.2 ASSESSMENT STRUCTURE

The first assessment of biological invasions and invasive alien species that is global in scope, the IPBES invasive alien species assessment, is interdisciplinary, spanning environmental and social science as well as the humanities, and comprises six chapters written by experts from all regions of the world.

There are many links and several overarching cross-cutting and key issues across the six chapters **(Figure 1.3)**, but all the chapters can be read as standalone documents presenting syntheses of existing knowledge and highlighting gaps and priorities.

The assessment is composed of six chapters:

- **Chapter 1** introduces the concept of invasive alien species; the risks posed to marine, terrestrial and freshwater ecosystems; the IPBES conceptual framework; the cross-cutting themes (good quality of life, Indigenous and local knowledge, and scenarios and models), and common themes;
- **Chapter 2** assesses past, current and future trends in the spread, pathways, evolutionary change and distribution of invasive alien species;
- **Chapter 3** presents the direct and indirect drivers responsible for the introduction, spread, abundance and dynamics of invasive alien species;
- **Chapter 4** assesses the impacts of invasive alien species on nature and nature's contributions to people and good quality of life;
- **Chapter 5** evaluates the effectiveness of past and current programmes and tools for the global, national and local prevention and management of biological

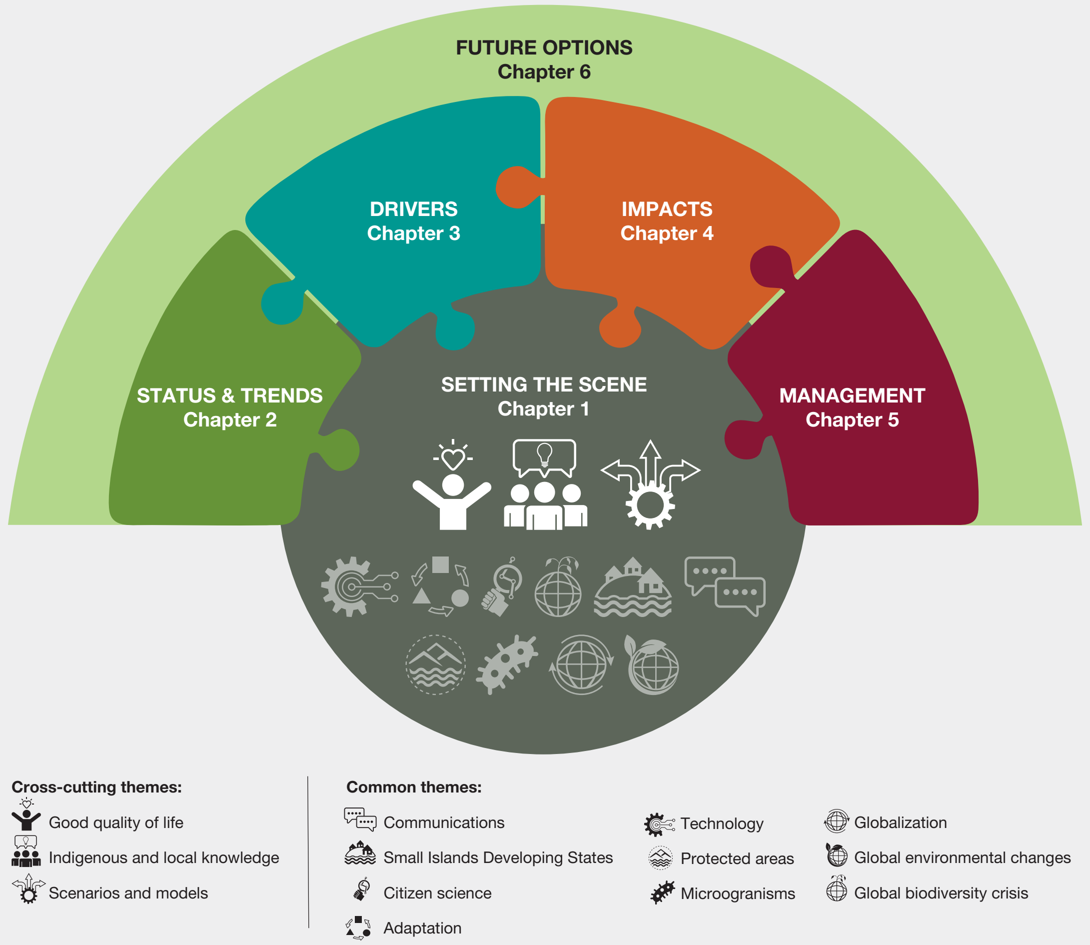


Figure 1 3 **Structure of the IPBES thematic assessment of invasive alien species and their control.**

invasions and invasive alien species and their impacts; and

- **Chapter 6** introduces future options for the prevention and management of biological invasions and invasive alien species and provides an analysis of possible policies and support tools for policy and decision makers.

Three cross-cutting themes – 1) Indigenous and local knowledge systems (**Glossary**), 2) good quality of life including human health, and 3) scenarios and modelling of trends (**Glossary**) and development of robust projections, are featured prominently throughout the IPBES invasive alien species assessment **(Figure 1.3)**. Several key issues, with relevance to two or more of the chapters, emerged during the assessment including globalization, adaptation, environmental change, the global biodiversity crisis, the role of technology, the role of communication, citizen (or community) science, the specific context of Small Island Developing States (SIDS), the role of protected areas (terrestrial, coastal, and marine) and of microorganisms. In many chapters these topics will appear as case studies. As this IPBES assessment will demonstrate, addressing invasive alien species, which are affecting many facets of the socioecological systems in which people live, can have far-reaching benefits for biodiversity and human health, and will shape the ability of future generations to live healthy, sustainable lives.

1.3 INVASIVE ALIEN SPECIES: WHAT THEY ARE AND WHY THEY MATTER

1.3.1 What are invasive alien species?

The term "alien" (synonyms: non-native, exotic, introduced, non-indigenous, allochthonous) species refers to species whose presence in a region is attributable to human actions, intentional or unintentional, that enable them to overcome biogeographical barriers (Essl *et al.*, 2018; Richardson *et al.*, 2010; Rojas-Sandoval & Acevedo-Rodríguez, 2015). It is widely acknowledged that some alien species (i.e., invasive alien species) can become established, spread (dispersed) and cause dramatic biotic and abiotic changes in the ecosystem to which they are introduced, resulting in the reduction in abundance or even extinction of native species, and/or major shifts in ecosystem functioning, and/or major adverse health, economic, social, or cultural impacts on human communities. Invasive alien species are defined in the scoping report for this assessment as "animals, plants or other organisms introduced directly or indirectly by people into places out of their natural range of distribution, where they have become established and dispersed, and generating an impact on local ecosystems and species" (IPBES, 2018e; **Figure 1.1** and **Glossary**). Although much of the focus of this assessment is on the negative impacts of invasive alien species, benefits are also discussed.

Invasive alien species can be introduced unintentionally or intentionally, and as these terms are more commonly used than directly or indirectly, they have been adopted throughout this assessment. Domestic or managed alien animals and plants are not considered to be invasive alien species while they remain in captivity or are managed by humans, but such species that establish feral or wild populations outside of captivity or cultivation would be termed invasive alien species. Furthermore, it is important to note that feral populations of domestic or managed animals (e.g., goats and fish) can have considerable adverse impacts prior to establishing sustained populations in the wild. Native species that expand their natural range without human involvement, for example in response to other anthropogenic drivers including land- and sea-use and climate change, are not considered to be alien species even though some of these range expansions result in dramatic ecosystem-level changes (**Figure 1.1**; Cannone *et al.*, 2022).

Invasive alien species are generally considered problematic because they cause environmental harm and also, in some cases, affect good quality of life. This standpoint is consistent with Article 8(h) of the CBD, which calls on the parties to "prevent the introduction of or control or eradicate those alien species that threaten ecosystems, habitats or species" **(Box 1.1)**. The term "invasive alien species" was adopted by the CBD Guiding Principles for the Prevention, Introduction and Mitigation of Impacts of Alien Species that Threaten Ecosystems, Habitats or Species (CBD, 2002; **Chapter 6**, **Table 6.3**) to define species whose introduction and spread threaten biological diversity. However, perceptions of invasive alien species may vary amongst stakeholders and Indigenous Peoples and local communities (**section 1.5.2**; see also **Chapter 5**, **section 5.6.1.2**) and it is therefore important to view invasive alien species not in isolation but within the context of the socioecological systems they are affecting (**section 1.5.2**).

It can take time for the negative impacts of some alien species to become apparent and so a precautionary approach (**Glossary**) is often adopted when categorizing an alien species as an invasive alien species (Coutts *et al.*, 2018). Generally authors do not consider the inclusion of impact within the definition of biological invasions, and instead their definition is based exclusively on ecological and biogeographical criteria (Blackburn, Pyšek, *et al.*, 2011; Occhipinti-Ambrogi & Galil, 2004; Pyšek *et al.*, 2004; Rojas-Sandoval & Acevedo-Rodríguez, 2015);

many of the datasets collated for alien species follow this approach (Pyšek *et al.*, 2017; 2020). The definition of invasive alien species, supported by the International Union for Conservation of Nature (IUCN), the CBD and the World Trade Organization (WTO), often used in policy discussions, explicitly assumes that invasive alien species cause adverse impacts on nature and also to the economy and good quality of life, including human health (IUCN, 2000). This IPBES invasive alien species assessment follows the definition of invasive alien species outlined within the scoping report (IPBES, 2018a) which includes the concept of impact on local ecosystems and species. Key terms within this definition are provided in **Figure 1.1**.

1.3.2 How many invasive alien species are there?

Patterns in the numbers of established alien species have been documented for all IPBES regions (**Chapter 2**, **section 2.4**; and specifically Bailey *et al.*, 2020; Genovesi *et al.*, 2009; Lambdon *et al.*, 2008; Turbelin *et al.*, 2017) and most taxonomic groups (**Chapter 2**, **section 2.3**; in particular Dawson *et al.*, 2017; Dyer *et al.*, 2017; van Kleunen *et al.*, 2015). However, as mentioned above, these datasets rarely distinguish those alien species which are invasive (Richardson *et al.*, 2010), and, as such, in this section the term alien species is used. Island and coastal mainland regions have higher alien species richness (i.e., total number of species) than mainland regions (Dawson *et al.*, 2017; **Figure 1.4**). Alien species richness is dependent on the number of different species introduced to a given location, often referred to as colonization pressure (Blackburn *et al.*, 2020; Lockwood *et al.*, 2009; **Glossary**).

Not all alien species transported beyond their natural ranges establish sustaining populations (Cassey *et al.*, 2018; Richardson *et al.*, 2010). Propagule pressure (**Glossary**) is a measure of introduction intensity comprising both the number of individuals introduced per introduction event (propagule size) and the frequency of introduction events (Cassey *et al.*, 2018; Colautti *et al.*, 2006; Lockwood *et al.*, 2005). Given suitable environmental conditions, the total number of individuals of a particular alien species that are introduced has been shown to be positively correlated with the establishment success of alien populations (Colautti *et al.*, 2006; Lockwood *et al.*, 2009). The more individuals released, the greater probability that the population will have sufficient genetic variation to adapt to local conditions and establish self-sustaining populations (Blackburn *et al.*, 2009).

Social and economic factors, including gross domestic product per capita and population density (**Chapter 3**, **sections 3.2.2** and **3.2.3**), are important in determining alien species richness globally (Dawson *et al.*, 2017). High trade and transport connectivity amongst regions which have similar environmental conditions can also be important in predicting the risk of invasive alien species (**Glossary**; Capinha *et al.*, 2014; Cope *et al.*, 2019; Early & Sax, 2014; Fitzpatrick *et al.*, 2007; Li *et al.*, 2014; Parravicini *et al.*, 2015) and describing global patterns of alien species richness (**Chapters 2** and **3**).

1.3.3 Drivers of change in nature affecting invasive alien species

Direct and indirect drivers of change refer to all external factors that affect nature and consequently nature's

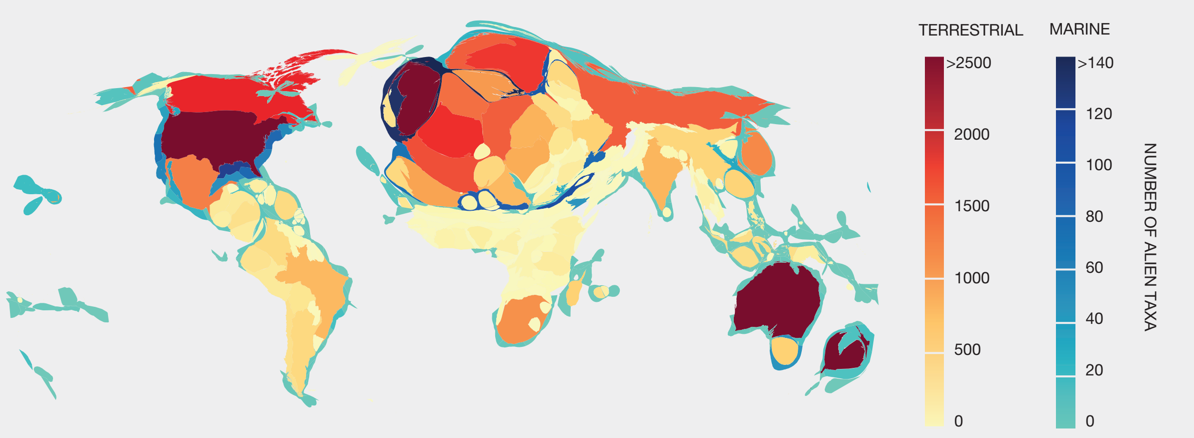


Figure 1 4 **Number of documented alien taxa in terrestrial (including freshwater) and marine environments.**

The size of regions is scaled proportionately by the number of documented alien taxa. Gaps for global alien species records are documented in **Chapter 2**. Data source: Seebens (2021).

contributions to people and good quality of life (Brondizio *et al.*, 2019). Direct drivers may be both human (anthropogenic) and non-human factors. Direct drivers affect nature directly in physical ways and include land or sea-use change, direct exploitation of natural resources, climate change, pollution, and invasive alien species. Indirect drivers are human actions that act on and alter direct drivers and other indirect drivers. Indirect drivers do not physically affect nature or nature's contributions to people, but they are the underlying cause of direct anthropogenic drivers. Indirect drivers include the role of institutions and governance (**Glossary**) systems, economic policies, and demographic, technological, and cultural influences.

The categories of indirect and direct drivers used throughout the IPBES invasive alien species assessment are based on the IPBES conceptual framework (Díaz *et al.*, 2015) with modifications specifically relevant to biological invasions and invasive alien species outlined in **Chapter 3**, **section 3.1.2**. The importance of interactions between invasive alien species and other drivers of change is acknowledged across the IPBES assessments (IPBES, 2018d, 2018e, 2018f, 2018g, 2019), and MacDougall & Turkington (2005) note that some invasive alien species may be considered passengers of global change because they only persist in an ecosystem through continued human disturbance. However, it is also important to recognize that alien species are themselves a component of biodiversity; they may be affected by other direct and indirect drivers while also interacting with native biodiversity and other alien species (**Chapter 3**, **section 3.3.5**).

Drivers may act alone or interact with each other to varying degrees, leading to additive or multiplicative effects (**Chapter 3**; Díaz *et al.*, 2018; Newbold *et al.*, 2015; Sala *et al.*, 2000) in which it is difficult to determine the relative importance of one driver over another (**Boxes 1.3** and **1.4**). For example, land-use changes are widely recognized as playing a role in promoting invasive alien species (IPBES, 2018c; Mooney & Hobbs, 2000). However, the role of indirect and direct drivers, and the complex interplay amongst them, will vary through the stages of the biological invasion process (**section 1.4**; **Glossary**). This complexity is rarely addressed within studies on invasive alien species but is increasingly recognized as an important consideration in understanding biological invasions and deriving solutions to mitigate or manage invasive alien species. It is important to recognize that drivers of change in nature such as land- and sea-use change, climate change and invasive alien species act at different temporal and spatial scales (**Chapter 3**; also **Figure 1.9** in **section 1.5**; Bonebrake *et al.*, 2019).

1.3.4 What are impacts in the context of invasive alien species?

For the purposes of this assessment, an impact is defined as a measurable change to nature, nature's contributions to people, and/or good quality of life (**Figure 1.1**; Ricciardi *et al.*, 2013; **Chapter 4**, **section 4.1.2**). It is useful to discriminate between measurable changes in physical or social parameters and value-laden decisions on whether such changes are beneficial or detrimental to humans or native species (Vimercati *et al.*, 2020). Invasive alien species can cause changes in physical, chemical, and/or biological properties, which can result in an increase or decrease in a parameter or an index. Such change may be considered as a harmful impact with respect to nature if whole ecosystems and communities are affected, or if other species are negatively (e.g., reduction in their performance and/or population size, or extinction) or positively (e.g., increase in their performance and/or population size, or establishment of new populations) affected. Impacts can also be considered as harmful (negative) or beneficial (positive) for humans if people suffer or gain from changes in nature's contributions to people or constituents of good quality of life

Box 1 3 **Interactions between invasive alien species and climate change as drivers of biodiversity loss.**

The IPBES-IPCC Co-Sponsored Workshop Report on Biodiversity and Climate Change (Pörtner *et al.*, 2021) recognized that climate change and biodiversity loss are interconnected and share common drivers through human activities. Although the outcomes of interactions between climate change and invasive alien species on community level processes is poorly understood (Robinson *et al.*, 2020), disproportionate changes in community composition across trophic levels are predicted to decrease species diversity and stability (Zarnetske *et al.*, 2012). As an example, climate change is anticipated to affect top predators more strongly than lower trophic levels, leading to an increase in herbivores and a decrease in plants (Zarnetske *et al.*, 2012). It is evident that the ongoing unprecedented changes in climate will alter the interactions between native and alien species (**section 1.6.8**). Interactions amongst drivers of change in nature, including climate change and invasive alien species but also other drivers, can generate complex feedback loops (Sinclair *et al.*, 2020; **Glossary**) with pronounced and unpredictable outcomes on evolutionary and ecosystem level processes (Pörtner *et al.*, 2021; **Chapter 3**, **section 3.5**).

Box 1 4 **Climate change, fire, and invasive alien plants.**

Many regions are experiencing unprecedented fire regimes because of human-driven ignition, coupled with intense droughts and record high temperatures associated with human-induced climate change (Bowman *et al.*, 2020; Kelly *et al.*, 2020). Undoubtedly, the increase in frequency and intensity of fires is threatening ecosystems and good quality of life in almost all parts of the world (Bowman *et al.*, 2011; **Figure 1.5**). Invasive alien species can worsen the situation by adding fire-prone fuel, which can increase not only the fuel quantity but also its flammability and its spatial continuity (Brooks *et al.*, 2004; Gaertner *et al.*, 2014). Studies have found that in several biomes, including tropical, temperate and Mediterranean regions, invasive alien plants may benefit from fires but can also act as promoters of more intense and frequent fire regimes, potentially causing more carbon release into the atmosphere (Nuñez *et al.*, 2021). In the Cerrado forest of Brazil, for example, *Melinis minutiflora* (molasses grass) and *Urochloa brizantha* (palisade grass) introduced in the 1800s are more prone to fire and although fire is a natural disturbance of this ecosystem, invasive alien grasses increase the frequency and intensity of fires (Damasceno & Fidelis, 2020). In Mediterranean climates and other semi-arid and arid ecosystems, some land-use practices, such as overgrazing, have resulted in significant increases in invasive alien European grasses such as *Bromus tectorum* (downy brome) that increase fuel load, continuity, and flammability. These conditions create a positive feedback loop between severe fires and the invasion of *Bromus tectorum* that results in multiple negative changes of natural grasslands and shrub steppe ecosystems and services (e.g., Western North America; see Pyke *et al.*, 2016). In areas with Mediterranean and temperate climates, especially in the southern hemisphere, shrubs and trees native to fire-prone ecosystems may cause extreme changes in fire regimes. In southern Africa and southern South America, Australian species of *Acacia* have shown to spread rapidly after fires and their biomass can fuel more intense fires (Le Maitre *et al.*, 2011). Similar positive feedback loops between invasive alien species and fires have been observed for *Pinus* across several ecosystems in the southern hemisphere (Cóbar-Carranza *et al.*, 2014; Franzese & Raffaele, 2017; Taylor *et al.*, 2017). Fire-prone invasive alien plants are likely to continue to spread under the more extreme climate scenarios and with the anticipated increase in conditions favourable to fire (Hurteau *et al.*, 2014). Consequently, these invasive alien plants are predicted to play a role in promoting more intense fire regimes with potential impacts on carbon cycling and further potential synergies with climate change.

Figure 1 5 **Invasive alien plants increase fire intensity and spread.**

A volunteer in Chile is trying to control a wildfire in an area invaded by *Genista monspessulana* (Montpellier or French broom). Photo credit: Guillermo Salgado Sánchez – CC BY 4.0.

(**Chapter 4**, **sections 4.1.3**, **4.4** and **4.5**; García-Llorente *et al.*, 2008; Pyšek & Richardson, 2010; F. Williams *et al.*, 2010). It is important to acknowledge that the outcomes of assessments of the benefits or positive impacts of invasive alien species should not be used to balance or offset the harmful or negative impacts, which may be irreversible including ecosystem transformation (Lockwood *et al.*, 2023; **Chapter 4**). Invasive alien species can have direct or indirect adverse impacts in their new environment even if their populations are not established or conversely can have negligible impacts even when established and widespread (**Glossary**; Jeschke *et al.*, 2013). While most literature on invasive alien species refers to the detrimental effects on ecological processes in terrestrial, freshwater and marine environments, new evidence is revealing the devastating effects on social (Bacher *et al.*, 2018; Gallardo *et al.*, 2019) and economic aspects (Diagne *et al.*, 2020). There is consensus among the scientific community that impacts of invasive alien species cannot be understood independently of other drivers of change in nature and that ecological, social, and economic aspects are also closely intertwined (Pyšek, Hulme, *et al.*, 2020; Shackleton, Shackleton, *et al.*, 2019).

Previous IPBES assessments have concluded that increased biotic homogenization (**Glossary**), or loss of biotic uniqueness, of biological communities is a major negative impact of invasive alien species which can result in the introduction and establishment of further alien species (IPBES, 2018d, 2018e, 2018f, 2018g, 2019). Local community assemblages are becoming more similar to each other on average, and this biotic homogenization (Finderup Nielsen *et al.*, 2019; McKinney & Lockwood, 1999; Yang *et al.*, 2021) has also been referred to as the "anthropogenic blender" (Olden, 2006). A recent review highlighted a consistent trend of decreasing taxonomic and phylogenetic diversity globally, providing strong evidence of widespread biotic homogenization (D. Li *et al.*, 2020). The consequences of biotic homogenization for ecosystem processes and nature's contributions to people can be substantial, but are often context specific, are hard to predict, and remain understudied. Ongoing environmental transformation is reducing the ability of ecosystems to withstand disturbance, including the arrival of invasive alien species, and so leading to decline in the resilience (**Glossary**) of natural systems (Dasgupta, 2021).

The introduction of one invasive alien species can facilitate invasion by another (**Chapter 3**, **section 3.3.5**; Simberloff & Von Holle, 1999). In some cases, this has led to an increasing rate of establishment and consequently communities of interacting invasive alien species are becoming increasingly common (Jackson, 2015; Simberloff & Von Holle, 1999). This facilitation is more likely to occur when a high number of species are introduced to an area (e.g., islands) or for alien species that are already known to interact with one another (e.g., species that co-occur within the native range or previously invaded ranges), such as pests and parasites. Indeed, parasites and pathogens are frequently introduced into new communities alongside invasive alien species and are implicated in altering the outcome of biological invasions by changing the strength of interactions between alien and native species (Dunn & Hatcher, 2015; **Box 1.14** in **section 1.6.7.2**). Co-occurring and interacting invasive alien species may amplify and exacerbate negative impacts. Indeed, biotic facilitation (**Glossary**), the synergistic interactions amongst different alien species within an invaded ecosystem, can lead to extreme adverse effects on ecosystem functions, which have been termed "invasional meltdown" (Simberloff, 2006; Simberloff & Von Holle, 1999; **Glossary**). However, in some cases interactions amongst invasive alien species can mitigate the adverse effects, for example when a predator is introduced and reduces the population of the prey of the invasive alien species (**Chapter 3**, **section 3.3.5**; Braga *et al.*, 2018; Facon *et al.*, 2006; Jackson, 2015).

The effects of an invasive alien species on an invaded biotic community will increase as the density of the invading organisms increases (Shea & Chesson, 2002). Effects on and responses of the resident species will in turn determine whether the community provides opportunities for invasive alien species (Parker *et al.*, 1999). However, while it is recognized that the outcome of biological invasions can be partially explained by the traits of alien species (invasiveness, i.e., the intrinsic biological characteristics of the species that result in the ability to invade a particular ecosystem) and characteristics of the recipient community (invasibility, i.e., susceptibility of an ecosystem to be invaded by one or multiple species), high levels of uncertainty (Leung *et al.*, 2012) are often a feature of predictions on the dynamics of invasive alien species (Facon *et al.*, 2006; Hui & Richardson, 2019). It is critical to integrate characteristics of the invading species alongside characteristics of the recipient habitats to account for the context within which the biological invasion is occurring (Foxcroft *et al.*, 2011).

Invasive alien species may reduce the phylogenetic distance among species within a community and, although in some cases they may increase the phylogenetic diversity within local sites, they can reduce phylogenetic diversity between sites (D. Li *et al.*, 2020). Ecosystem function is influenced by phylogenetic diversity (Cadotte *et al.*, 2012); ecosystems comprising community assemblages with higher phylogenetic diversity are considered to be more resilient to disturbance because they have the evolutionary potential to adapt to changing environmental conditions (D. Li *et al.*, 2020). The diversity and relative abundances (evenness) of species may strongly affect ecosystem function for community assemblages comprising combinations of functionally different species with low niche overlap (Cadotte *et al.*, 2012). While it is difficult to

Box 1 5 Role of invasive alien species within novel or emerging ecosystems.

Changes in the composition of communities as a consequence of invasive alien species will lead the emergence of new species combinations. Ecosystems containing these new species combinations are termed "novel ecosystems" or "emerging ecosystems" (Hobbs *et al.*, 2006). A broad range of examples document the emergence of novel ecosystems specifically in the context of biological invasions leading to new species combinations (Haram *et al.*, 2021; Lindenmayer *et al.*, 2008; Lugo, 2004; Mascaro *et al.*, 2008; Wilkinson, 2004). The adverse consequences of these changes include hybridization (e.g., between *Sporobolus maritimus* (small cordgrass) and *Sporobolus alterniflorus* (smooth cordgrass) leading to the emergence of the invasive alien *Sporobolus anglicus* (common cordgrass)), species declines (e.g., brown tree snake decimation of the forest bird species in Guam; Rodda & Savidge, 2007), or ecosystem-level change (e.g., changes in nutrient cycles, fire cycles or hydrology; Ehrenfeld, 2010; Ramakrishnan & Vitousek, 1989; Simberloff, 2011; Vilà *et al.*, 2011; Vitousek, 1986). However, novel ecosystems have shown to be beneficial in some contexts (Munishi & Ngondya, 2022) including, for example, by restoring ecosystem processes (Ewel & Putz, 2004; Lugo, 2004; C. E. Williams, 1997) or by providing nature-based solutions to mitigate environmental change (Munishi & Ngondya, 2022) although it is recognized that more evidence is needed for the latter (Turner *et al.*, 2022). Furthermore, context-specific adaptive governance (**Glossary**; **Chapter 6**, **Table 6.6**) coupled with pathway management (**Glossary**; **Chapter 5**, **section 5.4.3.1**) and understanding of drivers (**Chapter 3**) and more broadly the biology of alien species, including their interactions with native species, is considered critical to success of nature-based solutions for managing biological invasions (Munishi & Ngondya, 2022).

The formation of novel ecosystems that include invasive alien species has led to discussions about the implications of resulting compositional and ecological changes (e.g., Hobbs *et al.*, 2014; Murcia *et al.*, 2014). Perceptions (**section 1.5.2**) depend on many factors including concerns over environmental and societal impacts but also differing cultural values toward "nativeness" and "exoticism" and how such beliefs develop over time (Higgs, 2003). The range of perceptions may also be based on how effective the actions are likely to be in reversing the changes caused by invasive alien species. On one side of the spectrum, reversal of the novel state generated by alien species is viewed as a useful, morally necessary, and achievable goal (Hallett *et al.*, 2013; Hobbs *et al.*, 2006). On the other side of the same spectrum, the transition to a novel system due to alien species impacts is viewed as irreversible when a system has crossed an ecosystem restoration (**Glossary**) threshold (Hallett *et al.*, 2013; Hobbs *et al.*, 2006). The latter is the case for most marine biological invasions, where post-establishment management actions are mostly unsuccessful and invasive alien species can alter ecosystem functions and ultimately transform the entire landscape (E. Sala *et al.*, 2011). As an example, the snail *Littorina littorea* (common periwinkle), first recorded in the mid-1800s in the north-west Atlantic subsequently spread throughout the Atlantic coast of North America, altering the diversity, abundance and distribution of many benthic species on rocky and soft shores (Carlton, 1992).

Irreversible impacts are also likely to occur in scenarios where invasive alien species remain undetected for long periods of time. These historical biological invasions hamper our ability to recognize pre-existing native landscapes and ecosystems causing what is called "ecological mirages" (Bortolus *et al.*, 2015). The historical introduction of *Sporobolus alterniflorus* to the east coast of South America during the 1800s modified the pre-existing and extensive bare mudflats into vegetated salt marsh areas, leading to shifts in bird, fish and invertebrate biodiversity, with concomitant trophic cascades, but these changes were long overlooked (Bortolus *et al.*, 2015).

Acknowledging the uncertainty of outcomes of novel ecosystems and the potential for invasional meltdown (**Chapter 3**, **sections 3.1.3.2** and **3.3.5**), it is desirable to adopt a cautious and context-specific approach when considering the impacts of alien species and of the novel ecosystems they generate (Hobbs *et al.*, 2006), including the potential role of novel ecosystems as nature-based solutions to mitigating other drivers of change in nature (Seddon *et al.*, 2021). This uncertainty also highlights the value of pragmatism when recommending management strategies, and the benefits of engaging all stakeholders with available evidence to consider desirability, cost, and resource availability (**Chapters 5** and **6**; Hallett *et al.*, 2013; Miller & Bestelmeyer, 2016). There are many ways in which alien species interact with one another and with native species (Hui *et al.*, 2021). Novel mutualistic interactions (pollination, seed dispersal and plant-microbial symbioses) amongst alien species have been shown to facilitate other invasive alien species(Traveset & Richardson, 2014) leading to cascading effects that alter ecosystem functioning **(Box 1.11)**. Less attention has been given to interactions between alien and native species which lead to benefits, or indeed reductions in the magnitude of adverse impacts of interacting alien species (Liu *et al.*, 2018; Ross *et al.*, 2004), but it is acknowledged that beneficial interactions are also important in determining the outcomes of biological invasions on communities and consequently ecosystem function (Braga *et al.*, 2018; Halpern *et al.*, 2007; Viana *et al.*, 2019). The outcomes of species interactions are highly context-dependent (Lord *et al.*, 2017) and other drivers of change in nature will alter the population dynamics of alien and native species with consequences for eco-evolutionary and community-level processes which can be difficult to predict (Facon *et al.*, 2006; Robinson *et al.*, 2020).

quantify niche overlap and functional differences among multiple species, phylogenetic diversity can be used as a proxy of similarities and differences amongst species (Cavender-Bares *et al.*, 2009). Species-specific traits or human-mediated processes have been shown to be more important sources of variation in establishment and spread of invasive alien species than phylogenetic diversity (**Chapter 3**; Diez *et al.*, 2008). However, it is important to include multiple facets of biodiversity when assessing impacts, and phylogenetic diversity can be used as metric for predicting multifunctionality of ecosystems (Lishawa *et al.*, 2019). Innovative approaches integrating species distributions, traits, phylogenies, and interaction networks incorporating feedback loops will contribute to better understanding of biodiversity change (Pollock *et al.*, 2020) including predicting the outcomes of biological invasions (Hui & Richardson, 2019).

Since invasive alien species interact with resident species in evolving ecosystems **(Box 1.5)**, elucidating the complex adaptive networks these invasive alien and resident species form is critical to underpin understanding of the dynamics of invasive alien species and management of biological invasions. Network ecology embraces the multitude of biotic interactions within a framework of feedback loops which affect species persistence and coexistence (Borrett *et al.*, 2014; Hui *et al.*, 2016) and ultimately the functioning of ecosystems (Harvey *et al.*, 2017). Emerging insights in understanding the influence of human decisions, perceptions and management efforts within the context of ecological networks will improve forecasts on the response of networks to invasive alien species (Kueffer, 2017).

Ecological impacts of invasive alien species include adverse effects on biodiversity and also on nature's contributions to people (**Chapter 4**, **sections 4.3** and **4.4**). Invasive alien species can lead to extreme disruptions in the good quality of life of local communities (**Chapter 4**, **section 4.5**) either by indirect impacts on human health (e.g., introduced mosquitoes and disease; see **Box 1.14** in **section 1.6.7.2**), reduction of food security (e.g., invasive alien species as weeds in crop systems) or through degradation of habitats on which people depend (e.g., fire regime shifts caused by some invasive alien plants that are particularly flammable). As with any ecosystem change, there are cases where invasive alien species may provide opportunities for people to adapt and take advantage of the new conditions the species can provide. Production of firewood, new food sources and strengthening of aesthetic and cultural values have been recognized as beneficial outcomes of biological invasions (Shackleton, Shackleton, *et al.*, 2019). However, the overall impact on nature's contributions to people and good quality of life is hard to assess, as these species may have also disrupted the traditional and cultural ways of living of many Indigenous Peoples and local communities (**Chapter 4**, **section 4.6**).

1.4 BIOLOGICAL INVASION PROCESS

Over the past thirty years, different approaches to describe biological invasions have been developed (Colautti & MacIsaac, 2004; Leung *et al.*, 2012; Rejmanek & Richardson, 1996; Rojas-Sandoval & Acevedo-Rodríguez, 2015; Williamson, 1996; Williamson & Fitter, 1996). The unified framework for biological invasions **(Figure 1.6)** emerged from the integration of key features from across these commonly used frameworks and represents a single conceptual model that can be applied to all human-mediated biological invasions (Blackburn, Pyšek, *et al.*, 2011). This framework is used throughout the IPBES invasive alien species assessment.

The unified framework divides the biological invasion process into a series of stages (transport, introduction, establishment, and spread), recognizing the need for a species to overcome the barriers (geography, captivity or cultivation, survival, reproduction, dispersal, and environmental) that obstruct transition between each stage. Different factors may be advantageous in allowing species to pass through each stage **(Figure 1.6)**. The two barriers, survival and reproduction, recognize that the establishment stage is a population process, and establishment of a viable population requires self-sustaining populations encompassing multiple generations. **Chapter 4** provides a synthesis of the environmental, economic and social impacts which can occur throughout the biological invasion process. Evolutionary processes and mechanisms, including evolutionary history, founder effects, and hybridization, are also relevant (Dlugosch *et al.*, 2015; Estoup *et al.*, 2016; Facon *et al.*, 2006; Hufbauer *et al.*, 2012; Zenni *et al.*, 2017) and considered further within **Chapter 2**, **Box 2.3**.

1.4.1 Transport

Transport is the first stage in the biological invasion process (Williamson, 1996). Species have native geographic distributions with limits imposed by natural constraints, both biotic and abiotic. Human activities, such as shipping for trade, agricultural practices, and ornamental planting, can result in the movement of species beyond the barrier(s) that define these natural limits (**Chapter 3**). Humans can deliberately or inadvertently break down the natural barrier(s) which otherwise define these natural limits in the global distribution of species. This barrier is termed "geography" (Rojas-Sandoval & Acevedo-Rodríguez, 2015) in the unified framework as it is typically a physical feature (e.g., a mountain range or ocean) or a climatic barrier through which a species cannot normally disperse. However, the barrier may also be biogeographical, if distributional limits are imposed by biotic factors such as the presence

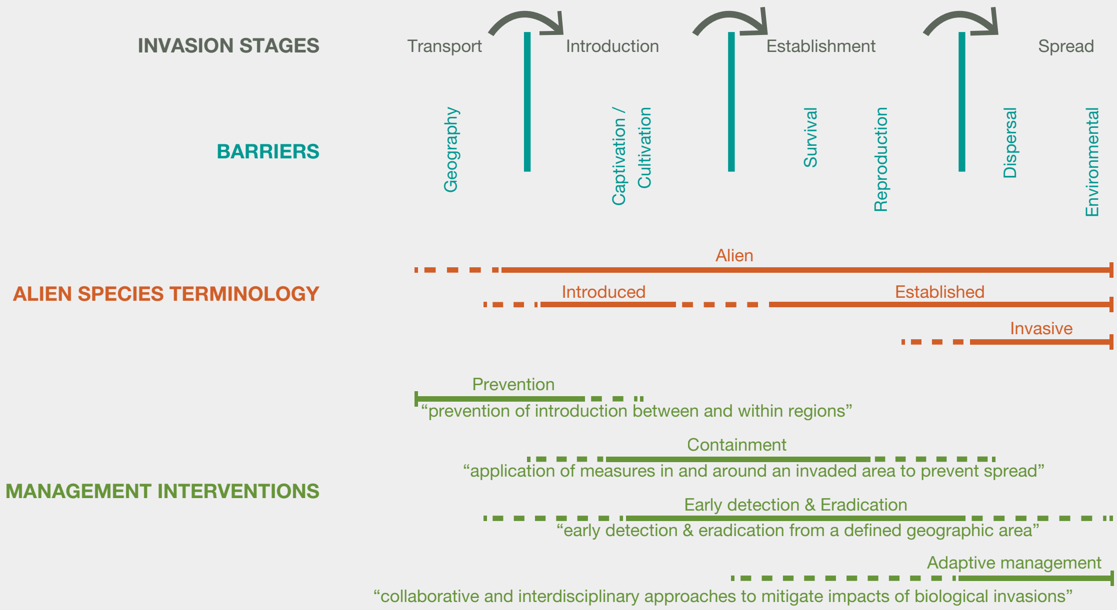


Figure 1 6 **The biological invasion process.**

Alien species terminology adopted throughout the assessment. The status of the species is reflected in the change in terminology and depends on the stage within the biological invasion process. Each stage is separated from the next by a barrier which a species must overcome in order to pass to the next stage. Alien species at different stages are associated with different management interventions. Solid horizontal lines represent the core application of the terminology, or management interventions and broken lines indicate extended application of the terminology in some contexts and where suitable management interventions may have some relevance. Adapted from Blackburn, Pyšek, *et al.* (2011), https://doi.org/10.1016/j.tree.2011.03.023, under Copyright 2011 Elsevier Ltd.

Box 1 6 Pathways of introduction of invasive alien species.

Pathways describe the many ways in which an alien species can be intentionally or unintentionally introduced through human activities from one geographical location to another (Hulme *et al.*, 2008; Pyšek *et al.*, 2011). Recognizing the importance of linking pathways to management or legislative options, a pathway scheme was developed by Hulme *et al.* (2008) that coupled policy options with the broad mechanisms by which alien species could be introduced to a region. The Conference of the Parties to the CBD subsequently adopted (and refined) the pathway scheme proposed by Hulme and colleagues (Hulme, 2014; Hulme *et al.*, 2008) to give a unified system for categorizing alien species pathways (CBD, 2014). The CBD Pathway Scheme distinguishes intentional and unintentional introductions, the six broad mechanisms of introduction (categories) and a number of corresponding subcategories. Furthermore, Saul *et al.* (2017) have published guidance for interpretation of the categories in introduction pathways, including for the six broad mechanisms of introduction:

Release in nature: intentional introduction of alien species for the purpose of human use in the natural environment;

Escape: unintentional movement of alien species from confinement (e.g., in zoos; aquaria; botanic gardens; agriculture; horticulture; aquaculture and mariculture facilities; scientific research or breeding programmes; or from keeping as pets) into the natural environment;

Transport-contaminant: unintentional movement of alien species as contaminants of a commodity that is intentionally transferred through international trade, development assistance, or emergency relief;

Transport-stowaway: unintentional movement of alien species attached to transporting vessels and associated equipment and media;

Corridor: unintentional movement of alien species into a new region following the construction of transport infrastructures in whose absence spread would not have been possible;

Unaided: secondary natural dispersal (**section 1.4.4**) of alien species that have been introduced by means of any of the foregoing pathways.

of competitors, predators, parasites and pathogens, or the absence of mutualists. Barriers to dispersal promote diversification by driving important evolutionary processes (e.g., speciation) and as such environmental conditions that prevent organisms from dispersing have far-reaching consequences for the organization of life on earth (Caplat *et al.*, 2016). The ways in which alien species are intentionally or unintentionally introduced through human activities from one geographical location to another are termed "pathways" (Hulme *et al.*, 2008; Pyšek *et al.*, 2011). An alien species may arrive within a new region through the importation of a commodity, arrival of a transport vector (physical means or agent, such as ship, train, aircraft, or other vehicle), which an alien species moves in or on (IUCN, 2017), and/or natural spread from a previously invaded region (Hulme *et al.*, 2008). These three mechanisms of arrival can be subdivided into six major pathways **(Box 1.6)**. It is evident that the pathways through which alien species are transported and introduced to new regions are changing over time (Essl *et al.*, 2015; Hulme *et al.*, 2008) and it is apparent that some of the most problematic invasive alien species arrive through multiple pathways (Essl *et al.*, 2015; Saul *et al.*, 2017) and repeated introductions (J. R. U. Wilson *et al.*, 2009). The movement of alien species may be facilitated by a broad range of human factors, or drivers of change, especially those related to the economy, human demography, and land-use (**Chapter 3**).

1.4.2 Introduction

A species may be moved to a location beyond its natural distributional limits but will only go on to invade an area if it is introduced beyond captivity and cultivation from that location (Williamson, 1996). To become introduced, individuals of that species must overcome the (sometimes literal) barriers imposed by captivity or cultivation (Rojas-Sandoval & Acevedo-Rodríguez, 2015). A deliberate (intentional introduction) act may be with the aim of establishing an alien species, for example if the species can be considered economically (e.g., game species) or environmentally (e.g., biological control agents, **Glossary**) or culturally (e.g., landscape gardening; van Kleunen *et al.*, 2018) beneficial. Over time, a wider understanding of the harm that invasive alien species can cause (Pyšek, Hulme, *et al.*, 2020) led to the conclusion that most introductions are not deliberate, but are unintentional. Important anthropogenic factors, or drivers, that may facilitate the introduction of invasive alien species include escape from captivity (e.g., pet animal escapes, seed spread from botanical gardens, larvae or adults that escape from aquaculture facilities) or escape by stowaways (e.g., organisms in ballast water), although some can result from intentional liberation of individuals into a novel environment (e.g., ceremonial release of animals) (Dyer *et al.*, 2017; Magellan, 2019; Pyšek, Hulme, *et al.*, 2020; Simberloff *et al.*, 2013; **Chapter 3**).

1.4.3 Establishment

Introduced species will fail to become invasive if they are unable to produce a self-sustaining and viable population in the new location, a process that is termed "establishment" (Williamson, 1996). This stage in the biological invasion process requires that introduced individuals both survive and reproduce in the new environment, and hence that barriers to survival and reproduction are overcome (Pyšek, Bacher, *et al.*, 2020; Rojas-Sandoval & Acevedo-Rodríguez, 2015). Therefore, as mentioned in **section 1.3.2**, biological invasions are a function of propagule pressure, colonization pressure, abiotic characteristics of the invaded ecosystem and biotic characteristics of the recipient community and invading species (Catford *et al.*, 2009; Lockwood *et al.*, 2009) including ecological and evolutionary change (Facon *et al.*, 2006).

The number of individuals introduced into a new environment has been the most consistently described and widespread correlate of establishment success of alien species (Blackburn, Prowse, *et al.*, 2011; Lockwood *et al.*, 2005). Indeed, propagule pressure is considered the most reliable predictor of biological invasion success (Colautti *et al.*, 2006). As already described, the term propagule pressure incorporates both the number of individuals released in one introduction event and the number of such events (Lockwood *et al.*, 2005). Small introduced populations, with a few notable exceptions (Briski *et al.*, 2018; Roman & Darling, 2007), are likely to fail to establish because of constraints of demography, genetics or environmental variation, even if the location is suitable for their survival and reproduction (as is also the case for small populations of threatened native species) (Cassey *et al.*, 2018; Duncan *et al.*, 2014; Lockwood *et al.*, 2005).

The outcome of a specific introduction and establishment is dependent on resource availability, interactions with other species including natural enemies (predators and parasites), and the abiotic environmental conditions (Catford *et al.*, 2009; Roy & Lawson Handley, 2012; Shea & Chesson, 2002). These factors all vary in time and space and can be modified by human influences or drivers of change in nature (**Chapter 3**) and natural disturbances (Catford *et al.*, 2012). The relative importance of these factors varies between species. As an alien species increases in population density, it will influence the invaded locality through interactions with other species within the community. The process of biological invasion is dynamic and specific outcomes of interactions vary over time and with context including the responses of humans to the invasive alien species, which can range from adaptation to management including eradication and ecosystem restoration **(Box 1.7)**.

The concept of invasibility, the susceptibility of a community to become invaded by one or several species, has been described as an intrinsic community and ecosystem attribute, but this view has been challenged because the lack of available information on species that have failed to establish makes it difficult to infer whether some species are more invasive or some habitats more invasible than others (Colautti *et al.*, 2006; Zenni & Nuñez, 2013). Furthermore, invasiveness of an alien species and the invasibility of the recipient ecological network are interlinked (Hui *et al.*, 2021); establishment success is a function of the interaction between traits or invasiveness of the species (e.g., behaviour, physiology, life history) and invasibility of the environment (e.g., climate, habitat) (Abramides *et al.*, 2011),

Box 1 7 Ecosystem restoration enhancing resilience to invasive alien species.

Ecosystem restoration is defined as any intentional activity that initiates or accelerates the recovery of an ecosystem from a degraded state (IPBES,[3] e.g., **Figure 1.7**) – i.e., assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed – and is often used to reinstate ecosystems that have been altered by invasive alien species. An exciting extra role for ecosystem restoration is to prevent the establishment and spread of invasive alien species in the first place. Indeed, there is increasing interest in using restoration to enhance ecosystem resilience to perturbations as environmental change accelerates.

Invasive alien species are recognized as one of five major drivers of change in nature, with adverse impacts on nature and also, in some cases, nature's contributions to people and good quality of life (**Chapter 4**). As such, management of biological invasions is critical to achieving ecosystem restoration (**Chapter 5**, **section 5.5.7**). However, there is also considerable evidence of invasive alien species as "passengers" of change (S. D. Wilson & Pinno, 2013). Restoring ecosystems to prevent the establishment and spread of invasive alien species is most obviously beneficial under the so-called "Passenger Model", under which invasive alien species are facilitated by anthropogenic environmental change – such as disturbance or eutrophication (**Chapter 3**, **sections 3.3.1** and **3.3.3**). In this case invasive alien species are "passengers" that benefit from the altered environment rather than themselves driving change (MacDougall & Turkington, 2005).

Invasive alien species are frequently a problem during ecosystem restoration, and much research focuses on how to control them. By contrast, studies of the ability of restored ecosystems to prevent the establishment and spread of invasive alien species are few, and most assess resistance during the early stages of ecosystem restoration. For example, Foster *et al.* (2015) found that following experimental additions of invasive alien species, including the highly invasive alien legume *Lespedeza cuneata* (sericea lespedeza), restored American prairie strongly limited invasive alien species compared to unrestored prairie. In general, a high native diversity might be expected to increase resistance to invasive alien species (Byun *et al.*, 2018). However, there is a lack of evidence about the ability of ecosystem restoration to limit biological invasions over the long-term and at large scales.

2021 marked the start of the United Nations-sponsored Decade on Ecosystem Restoration, acknowledging that ecosystem restoration could become central in efforts to resist and effectively prevent biological invasions. Ecosystem restoration has many other benefits, including the enhancement of ecosystem functions and benefits to people, the provision of habitat for native species, and resilience to ongoing environmental change.

3. IPBES glossary: https://ipbes.net/glossary

Figure 1 7 Restoring calcareous grassland in southern England.

Left: flower rich calcareous grassland following ecosystem restoration. Right: *Ochlodes venata faunus* (large skipper) after ecosystem restoration. Photo credit: Maico Weites – CC BY 4.0.

but crucially also depends on human actions (Duncan *et al.*, 2003; Redding *et al.*, 2019) and on many different and interacting drivers of change in nature (**Chapter 3**, **section 3.5**).

1.4.4 Spread

The next stage in the biological invasion process is known as spread, whereby individuals from an established population disperse across the new environment (Williamson, 1996), increasing the size of the geographic distribution of the alien species. An alien species can spread in various ways, such as through natural dispersal or transport alongside human activities (**section 1.4.1**). Spread requires the alien species to overcome a barrier imposed by limits to dispersal (e.g., the distance between suitable habitat patches), and a barrier imposed by environmental suitability (Rojas-Sandoval & Acevedo-Rodríguez, 2015), which will tend to increase with distance from its location of establishment (Lomolino *et al.*, 2010). Spread of an alien species is a sequence of population establishments, and so environmental suitability can be viewed as presenting barriers to survival and reproduction that must be overcome in each newly colonized location. Human factors, especially those related to disturbance and the creation of corridors, may act as drivers facilitating the spread of alien species within and beyond their non-native range (**Chapter 3**, **sections 3.3.1**, **3.4.2**). It is important to note that there are often time lags, sometimes of decades or more, between introduction, establishment, and spread (Essl *et al.*, 2011; Kowarik, 1995; Seebens *et al.*, 2017).

Introduced populations of alien species can also be a source of new introductions; this is referred to as secondary spread (Bertelsmeier & Keller, 2018). Patterns of spread of alien species have been widely documented (Ascunce *et al.*, 2011; Chapman *et al.*, 2020; Keller *et al.*, 2012; Lombaert *et al.*, 2010) and the mechanisms underpinning secondary spread have been the subject of many studies and some debate (Bertelsmeier & Keller, 2018). A single introduced population can be the source of many secondary introductions and so an alien species may spread rapidly even in the absence of further direct introductions from the native range. This has led to the hypothesis that adaptations for increased invasiveness could have occurred in introduced populations compared to native populations. The term “bridgehead population” or “bridgehead effect” has been used in reference to alien species establishing a stronghold or base population prior to further incursions to other environmentally suitable regions (Lombaert *et al.*, 2010). However, evidence for adaptive evolution within bridgehead populations of introduced alien species is lacking (Bertelsmeier & Keller, 2018) but evolution can play a role in the survival and establishment of introduced species through local adaptation to the novel conditions in the invaded range (Facon *et al.*, 2006; Hufbauer *et al.*, 2012). Introduced populations can reach higher densities than those in the native range, for example because of increased resource availability in the invaded range (Catford *et al.*, 2009). The resulting high abundance, alongside other factors including ongoing introductions from the native range, increases the probability of the alien species moving to new regions with human activities, including trade networks (Banks *et al.*, 2015), providing the necessary connectivity to facilitate the secondary spread (Chapman *et al.*, 2020).

1.4.5 The management-invasion continuum

The invasion curve (**Figure 1.8**; **Glossary**) diagrammatically presents the four stages of biological invasion over time. The curve can be contextually interpreted as number of alien species, area occupied or levels of impact over space and time. It was first developed for policymakers in Australia (Victorian Government, 2010), and is now widely used across government agencies in the United States, Canada, New Zealand and Japan and by some international organizations including the IUCN. As already stated, invasive alien species often have a lag-phase during establishment (Essl *et al.*, 2011; Kowarik, 1995; Seebens *et al.*, 2017). This is followed by a dispersal phase of variable duration during which there is often logarithmic growth, up until the point at which the invasive alien species occupies a large area and so is in the widespread phase when the biophysical or socioecological negative impacts are high and affect a large proportion of the landscape/seascape (**Chapter 4**). The invasion curve highlights the importance of preventative measures (**Figure 1.8**; **Chapter 5**, **section 5.5.2**) before an invasive alien species arrives, and retaining the ability to manage an invasive alien species in the early stages of invasion after arrival. It supports understanding and decision-making of management options along the management-invasion continuum (**Chapter 5**, **sections 5.2** and **5.3**). While the invasion curve is employed widely to understand the process of biological invasions, this assessment will also utilize the IPBES conceptual framework, which is described in **section 1.6.1**.

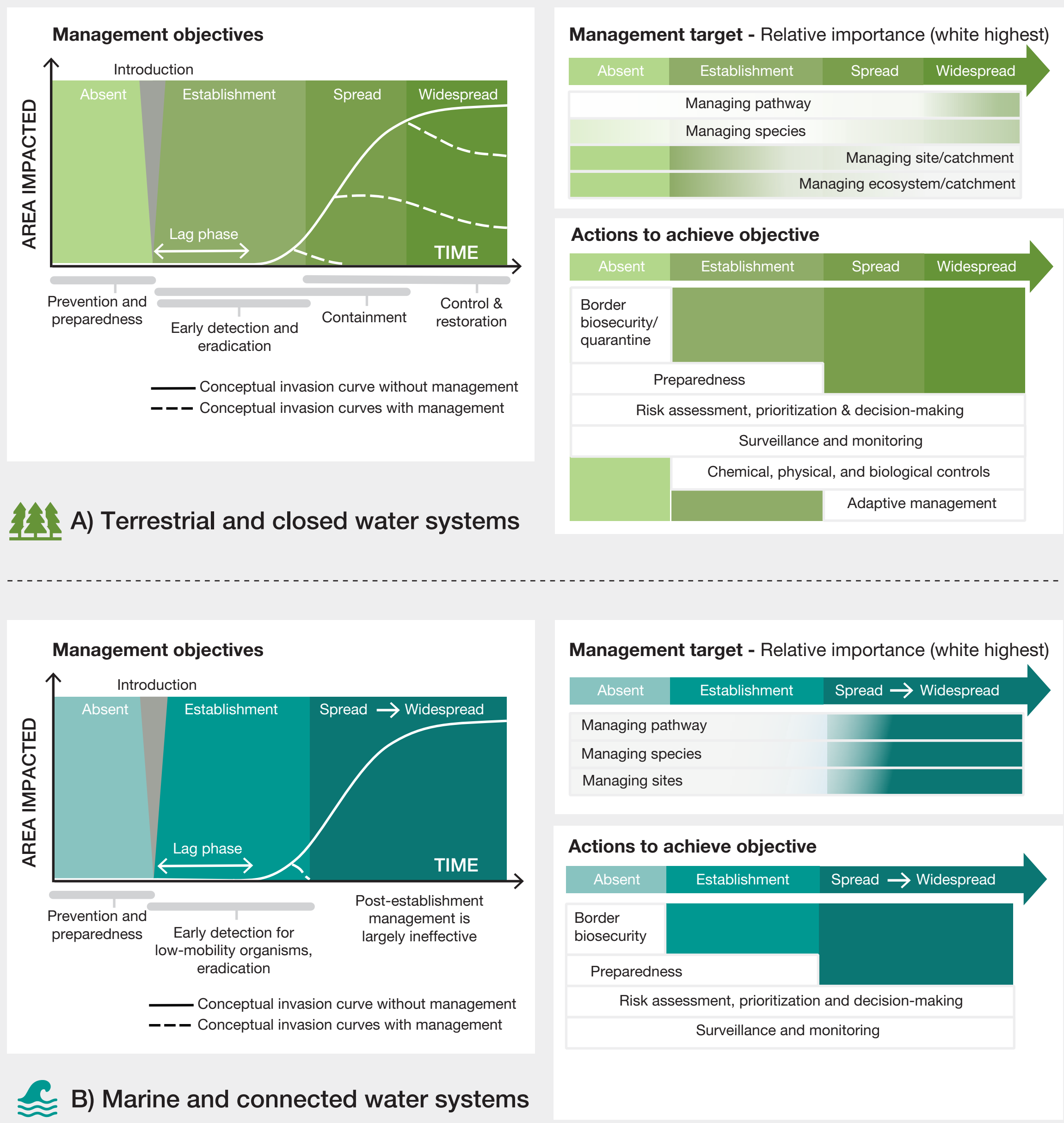


Figure 1 8 **Conceptual diagram of management-invasion continuum (see also Chapter 5, Figure 5.1).**

The generalized invasion curve without management and the expected changes in the invasion curve with appropriate management actions in **A)** terrestrial and closed water systems (including coastal systems and salt marshes) and in **B)** marine and connected water systems. White boxes indicate the optimal management objectives at each stage of the biological invasion process. Colour gradient of managing pathway, species, site and ecosystem boxes show how the relative focus generally changes as biological invasions progress. White boxes indicate typical management actions necessary to achieve each management objective. Post-establishment management actions are not shown under panel B since these are generally not achievable in these systems. In a management context, the first detection (introduction point), the lag phase (see **Glossary**) and the exponential spread phases are important points to design an early detection and rapid response management plan. This figure is conceptual, and the curves do not represent actual population dynamics of invasive alien species.

1.5 SOCIOECOLOGICAL CONTEXT

Increasing attention has been given to understanding the context dependency of biological invasions (Pyšek, Bacher, *et al.*, 2020; Sapsford *et al.*, 2020). Thus, the outcome of each biological invasion not only depends on the propagule pressure and traits of the species invading, but on the recipient ecosystem and its defining parameters within a specific time span and a specific spatial scale (Pauchard & Shea, 2006; **section 1.3.2**; **Figure 1.9**). This context dependency goes beyond ecological parameters as it is at least partly determined by human culture, incorporating behaviour, government policies and regulations, and other social components, including social differentiation and, at times, violent conflict (**Figure 1.9**; Howard, 2019; Kelsch *et al.*, 2020).

Modelling and predicting the spread and potential impacts of invasive alien species on biodiversity and human health and well-being are widely seen as critical to better curtail the harm they can cause to ecosystems and human communities (**Chapter 4**, **section 4.7.1**, and **Chapter 5**, **section 5.6.3.2**). Although there have been considerable advances in this regard, increasingly, scientists are recognizing the inherent difficulties of forecasting these processes in complex socioecological systems (Lenzner *et al.*, 2019). There are several reasons why this remains the case, despite progress in both the natural and social sciences in the study of biological invasions.

Invasive alien species respond to multiple natural and anthropogenic drivers (**Chapter 3**), which can also have synergistic effects on the outcomes of biological invasions. Pörtner *et al.* (2021) highlight the importance of recognizing the complex and multiple connections between climate and other drivers of change in nature. For example, positive feedback loops between plant invasions and more intense and frequent fires **(Box 1.4)** associated with climate change can completely shift fire regimes (Brooks *et al.*, 2004). The sphere of social interactions and human behaviour increases

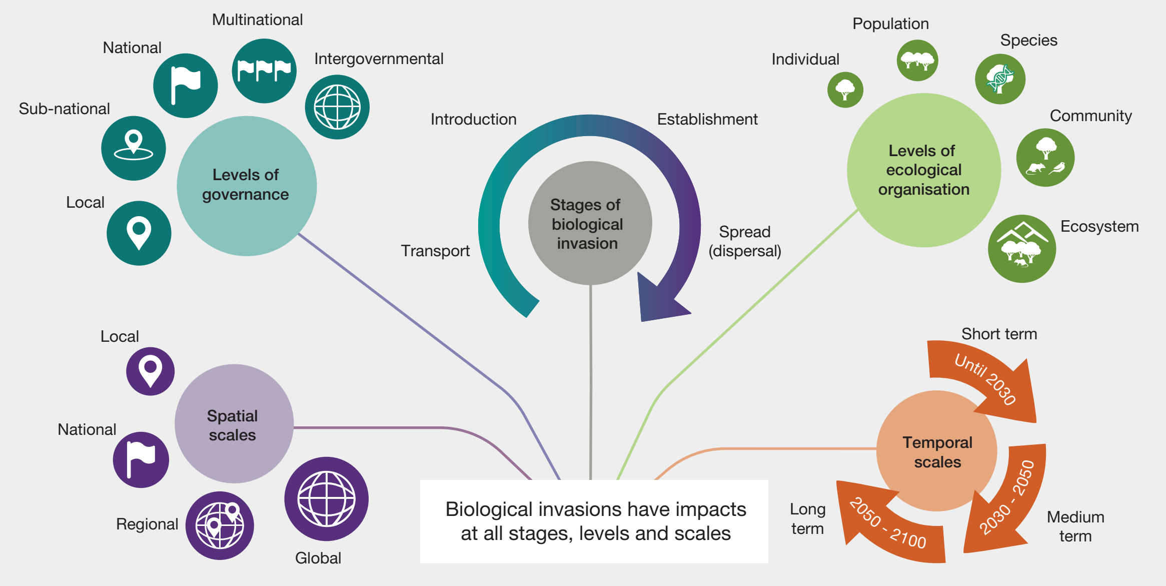


Figure 1.9 **Context dependency in biological invasions across multiple spatial and temporal scales, and governance and ecological levels.**

Underlying processes span various spatial (bottom-left: local to global) and temporal scales (bottom-right: short to long-term). Impacts of invasive alien species on nature, nature's contributions to people and good quality of life also vary across temporal and spatial scales and may differentially affect each level of ecological organization (top-right: from individuals to ecosystems). For some invasive alien species, the impacts are immediate and continue into the long-term (e.g., fast-spreading pathogens such as Zika virus, or fast-spreading predators such as lionfish) while for others there may be a considerable time lags, spanning decades in some cases, before the impacts are apparent (e.g., many invasive alien trees, see Kowarik, 1995). Some invasive alien species have local impacts (e.g., *Carassius auratus* (goldfish) released into small ponds by pet owners) while others impact globally (e.g., *Batrachochytrium dendrobatidis* (chytrid fungus)); and while many invasive alien species have impacts at the individual, population, or community level, others adversely impact entire ecosystems (e.g., eucalyptus and pine trees transforming native grasslands into shrub or wood land). Finally, different levels of governance (top-left: from local to inter-government) affect how biological invasions progress and are managed (e.g., local governance of invasive alien species may differ from national or international policies).

the complexity of mitigation efforts, which can be very difficult to communicate to policy- and decision-makers, to a wide variety of stakeholders, and to Indigenous Peoples and local communities. The effects of human caused fires (i.e., ignition) associated with a particular cultural behaviour have the potential to accelerate fire regime changes, and complicate management decisions alongside the outcomes from biotic and abiotic modelling. As another example, many aquatic invasive alien species are spread through recreational boating and if people who engage in this activity are unaware of the need to practice hull cleaning, and of the damage that invasive alien species can inflict on other recreational pastimes, they will be unlikely to take part in mitigation efforts.

Human responses to the threats posed by invasive alien species, including the introduction of alien species to achieve biological control and the use of chemicals or other agents in eradication programmes, can also affect the possibility of future biological invasions and the range of management responses and policy choices (**Chapters 5** and **6**). If people have begun to adapt to the presence of invasive alien species in a way that benefits them, then efforts to eradicate these species may not be seen as acceptable by some stakeholders (Howard, 2019), and there may also be resistance, on ethical grounds, to management methods that involve lethal responses.

Understanding the process of biological invasions within the context of varying spatial and temporal scales is important but can be challenging, because mechanisms underpinning the patterns are influenced by scale and the peculiarities of the phenomena being studied (Pauchard & Shea, 2006; Sapsford *et al.*, 2020). While patterns of biological invasions have now been documented at multiple spatial and temporal scales (**Chapter 2**), most studies have explored the mechanisms behind biological invasions only at small spatial scales because of the difficulties in experimental design and replicability. Furthermore, most mechanistic studies only look at short periods of time (i.e., a few years). Thus, there is still a critical gap in understanding the process of biological invasion over a range of scales. Simple scaling up is of limited value because processes and mechanisms vary at different scales and changes over time are rarely linear (Kowarik, 1995; Levin, 1992). However, in the last two decades and because of the accumulation of extensive observational datasets and the development of new analytical tools (Sagarin & Pauchard, 2012), macroecological studies are filling some of these gaps. It is now possible to consider invasive alien species on large temporal and spatial scales and therefore link patterns to processes and reveal underpinning mechanisms more robustly than was previously possible (e.g., Seebens *et al.*, 2015, 2021; **Chapter 2**). Indeed, the first estimates of future alien species projections, based on long-term alien species trends, are now available (Seebens *et al.*, 2021), indicating that past trends of invasive alien species will continue to accelerate for many taxonomic groups and regions. Multiscale solutions can help to address the threats posed to the natural world by multiple drivers of change in nature (Bonebrake *et al.*, 2019).

1.5.1 Characterizing stakeholders and biological invasion stages

Invasive alien species can variously affect, and be affected by, different categories of stakeholders across the stages of the biological invasion process **(Figure 1.10)**. A stakeholder refers both to those people who have the capacity to affect (influence) or are affected by (have interests in) biological invasion processes, outcomes, and policies. The IPBES invasive alien species assessment identifies three groups of stakeholders in relation to stages of the biological invasion process. They include “influencing stakeholders”, who influence biological invasion processes, management or policies; “affected stakeholders”, who are affected by biological invasions as “winners” or “losers”; and “contributing stakeholders” **(Figure 1.10)**, who contribute directly or indirectly to biological invasions without necessarily being influential or affected (Dandy *et al.*, 2017). Such groups are not mutually exclusive – both individuals and organizations can belong to several of these categories **(Figure 1.10)**.

Within the “influencing” and “affected” stakeholder groups, Dandy *et al.* (2017) identify several categories of stakeholders, described in **Table 1.1**.

1.5.2 Perceptions and values

Social and cultural dimensions of biological invasions encompass people’s awareness, perceptions, values, attitudes, and interests **(Table 1.2)**. The study of these dimensions helps to better understand social conflicts, engagement and action or inaction throughout the biological invasion process described in **section 1.4**, and particularly in the context of the management of biological invasions and control of invasive alien species (Estévez *et al.*, 2015; Kueffer & Kull, 2017; Novoa *et al.*, 2017; Shackleton, Richardson, *et al.*, 2019). Some key literature from the environmental humanities has been critical in drawing attention to the entanglement of the ecological context and cultural values in biological invasions (Frawley & McCalman, 2014; Head, 2017; Tassin & Kull, 2015) and in showing that management of biological invasions depends on human decision making and behavioural change for success (Head *et al.*, 2005; McNeely, 2001).

Research activity on the social and cultural dimensions of biological invasions is slowly accelerating but is still in

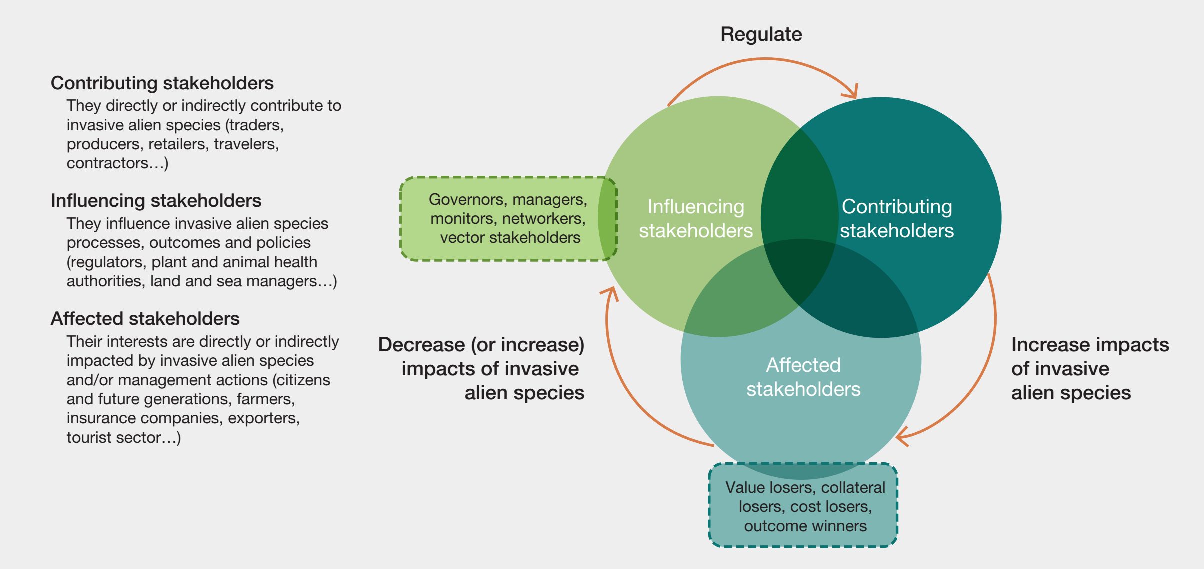


Figure 1 10 **Involvement of different stakeholder groups in the context of biological invasions.**

Table 1 1 **Groups and categories of stakeholders considered in the IPBES invasive alien species assessment.**

For a full description of the Stakeholder categories, please consult **Supplementary material 1.1.**

Stakeholder group	Stakeholder category	Description
Influencing stakeholders	Vector-stakeholders	Individuals or organizations whose activities, intentionally or unintentionally transport, introduce and/or spread invasive alien species
	Governors	Individuals or organizations who set formal and informal rules or establish norms that guide and drive management of biological invasions and adaptation, including prevention across all stages of the biological invasion process
	Monitors	Individuals or organizations who predict, identify, detect, conduct surveillance of and share information on invasive alien species across all stages of the biological invasion process
	Managers	Individuals or organizations who undertake "on-the-ground" responses to biological invasions across all stages of the biological invasion process
	Networkers	Individuals or organizations who disseminate information and key messages between actors relevant to biological invasions management, connecting other stakeholders with differing perspectives and operating at different scales
Affected stakeholders	Value losers	Individuals or organizations for whom nature's contributions to people and good quality of life are reduced by invasive alien species or by management responses across all stages of the biological invasion process
	Cost losers	Individuals or organizations who bear the direct economic costs of responding to invasive alien species, such as paying for labour and materials required for eradication or containment, or for information dissemination across all stages of the biological invasion process. These direct costs can be incurred in addition to the loss of existing value (i.e., cost losers may often also be value losers)
	Collateral losers	Individuals or organizations who lose value indirectly as a consequence of the adverse impacts of invasive alien species or their management across all stages of the biological invasion process
	Outcome winners	Individuals or organizations for whom nature's contributions to people and good quality of life are increased by invasive alien species or by their management responses across all stages of the biological invasion process. In some cases, invasive alien species provide additional nature's contributions to people, in other cases, these stakeholders are able to turn harm into benefit
Contributing stakeholders	Individuals or organizations who directly or indirectly contribute to biological invasions	

Table 1 2 **Primary and underlying factors that shape people's perceptions of invasive alien species.**

Updated from Shackleton, Richardson, *et al.* (2019).

Primary factors driving perceptions of invasive alien species	Example sub-categories
Individual(s)	Demographic characteristics (gender, education, job, etc.) Experience of species and effects Knowledge systems Sense of place Social relationships and group membership Individual values and beliefs Livelihood strategies
Species	Introduction and species status (invasion status) Residence time Species traits Taxonomic/functional group Species charisma
Effects/Impacts (potential and realized) (beneficial and detrimental)	Economic Ecological Social, religious, and cultural Food security
Socio-cultural contexts	Land tenure system Management history Public and media discourse Socio-economic development Social and cultural institutions and value systems Relationship to the land Social memory Language used Livelihoods
Landscape context	Availability of alternative resources (e.g., from native species) Ecosystem type Land use and cover Landscape beauty/scenery or attractiveness Management history Ecosystem services
Institutional, governance and policy context	Historical processes Institutional frameworks International agreements Legislation, regulation, and enforcement Policy and governance strategy Scientific knowledge and understanding Power and responsibility

its infancy (Kapitza *et al.*, 2019; Vaz *et al.*, 2017). There have been important contributions to the understanding of biological invasions from the humanities **(Box 1.8)** and social sciences. However, a review of studies on biological invasions published between 1950 and 2014 revealed that contributions from the social sciences were limited to less than five per cent and that up to the 1990s interdisciplinary collaborations were largely confined to interactions between ecological and environmental sciences (Vaz *et al.*, 2017).

Kapitza *et al.* (2019) conducted a systematic review of studies on social perceptions of invasive alien species published before 2016. While the scope of this study was limited to the perception of invasive alien species themselves (thus excluding studies on perceptions of control or management of invasive alien species) it does reveal some important insights. First, most studies investigated perceptions of the general public (79 per cent), followed by decision-makers' (35 per cent) and scientists' (23 per cent) perspectives. Second, these studies reported a frequent use of quantitative methods using questionnaires, while only 14 per cent of the studies used qualitative methods such as interviews. Arguably, this indirectly led to a bias towards measuring perceived detrimental impacts of invasive alien species as these were more commonly included as items in questionnaires than the benefits of invasive alien species. Third, there were large biases in taxonomy (more than half of the studies (58 per cent) focused on plants), ecosystems (the majority of the studies (78 per cent) focused on terrestrial ecosystems), and geographical region (more than half of the studies were conducted in either North America (32 per cent) or Europe (28 per cent). This systematic review demonstrates the difficulty of ascertaining a clear picture of social perceptions

Box 1 8 **Contributions to understanding of biological invasions from historical studies.**

Since the emergence of the field of invasion biology in the 1980s, ecologists have increasingly recognized that the study of biological invasions involves significant ethical and cultural considerations that fall outside the purview of the biological sciences (Frawley & McCalman, 2014; Simberloff & Rejmanek, 2011). Historians have contributed to this research in three key ways: 1) by identifying the historical drivers of species migration; 2) by describing the emergence of narratives of biological invasion in scientific discourse and the impacts of invasive alien species control programmes; and 3) by deconstructing the language of prevalent biological invasions frameworks. They have shown that although species have always migrated across ecosystems, species movement accelerated from the eighteenth century onwards due to the mobilization of global agriculture, the extraction of biological matter for "exotic" horticulture, and land-use change (K. Thomas, 1984; Robbins, 2002; Ritvo, 2014; Bewell, 2017). Historians have described this advent of species movement "the Columbian exchange" (Crosby, 1972) and "ecological imperialism" (Crosby, 1986); few would disagree that the spread of commercial trade has been and continues to be the main driver facilitating species' introductions, including those now driven by climate change.

Legislation permitting the widespread control of certain plants and animals, unintentionally imported to colonial plantations, that had negative impacts on crops date back to the late eighteenth century. However, it wasn't until the late nineteenth century that some alien species were described as invasive. Historians have pointed to Charles Darwin, T.H. Huxley, his grandson Julian Huxley, and Charles Elton as key figures in the articulation of invasive alien species as a subject of scientific interest. This emergent narrative of biological invasion has been associated with xenophobia, successive wars, the start of the collapse of European empires, and early science fiction that addressed themes of alien invasion and scientific attempts to control it (Alt, 2010; Hovanec, 2018; Chang, 2019).

Historians and geographers have argued that neither "invasive" nor "native" are stable characteristics but are rather narratives of behaviours and interactions between species in ever-changing bio-cultural environments (Cronon, 1992; Smout, 2003; Frawley & McCalman, 2014). Such narratives often change over time (Hobbs *et al.*, 2006; Pawson & Christensen, 2014; Rangan & Kull, 2009; Ritvo, 2014). Some argue that "invasive" implies the previous existence of a static biota free from alien species when no such past exists (Rotherham & Lambert, 2013; Ritvo, 2014). Others have analysed the theory of "shifting baselines" — the way that each generation, without considering historical factors, bases science and policy decision-making around their own ecological circumstances (Dizard, 2010; Pauly, 1995; Vera, 2010).

Several critical studies have addressed the power of narratives about biological invasions in driving responses to changing environments such as eradication programmes (Smout, 2003; Trigger, 2008), and suggest that such stark binaries obscure the dynamism of changing environments (Head & Muir, 2004; Beinart & Wotshela, 2003; C. D. Thomas, 2017; Shah, 2020), including biodiversity gains and cultural losses. Failures to consider the diversity of rights-holders and stakeholders when addressing anthropogenic drivers of species loss in the past have enabled the continuation of colonial science in conservation decision-making (Grove, 1996; Griffiths & Robin, 1997; Caluya, 2014). Some historians urge that there is a need to emphasize the role of class and race in order to avoid deepening global inequalities (Nixon, 2011; Moore, 2016; Caluya, 2014). Researchers across the humanities are nevertheless in agreement that to solve the current and future interconnected problems of the global environmental crisis, we need to understand the complex interactions of ecologies, cultures, and societies of the past.

of biological invasions, despite their importance to the IPBES invasive alien species assessment.

An important aspect of perception is public awareness of invasive alien species. Public awareness is notoriously difficult to measure, but it is fundamental if preventive regimes (see **Glossary**) are to be adopted within communities. Schelhas *et al.* (2021) conducted an extensive review of public awareness and derived four important conclusions:

1. Knowledge of public awareness of invasive alien species is still quite limited and comes from either case study research or census studies. Case studies found that people are often generally aware of the existence of invasive alien species, but have limited knowledge about specific species, their impacts on biodiversity or the role of people in their introduction (e.g., García-Llorente *et al.*, 2008; Lindemann-Matthies, 2016; Verbrugge *et al.*, 2013, 2014). Findings from a survey on attitudes of citizens towards biodiversity show that, across Europe, introduced plants and animals are perceived as a lower threat to biodiversity compared to air and water pollution, human-made disasters, intensive farming, deforestation and over-fishing, climate change and conversion of natural areas to other uses (European Commission, 2013, 2015, 2019). However, in highly impacted locations, such as Hawai'i (Kalnicky, 2012) and in countries with a long history in plant and animal invasions, such as New Zealand (Hulme, 2020b), public interest and knowledge are often greater, as is support for management.
2. Invasive alien species are often viewed differently by the public than by scientists or policy makers. A mail

survey in the United States showed that members of the public ranked invasive alien species as 19 out of 24 ecological risk items, while professional risk assessors ranked them as ninth (Slimak & Dietz, 2006). A species' perceived harmfulness and human responsibility for its spread were the most important animating factors, while non-nativeness did not necessarily raise concerns (Qvenild *et al.*, 2014; Selge *et al.*, 2011). However, species' charisma (characteristics that positively affect the perceptions, attitudes, and behaviours of people towards them) can also have implications on public perceptions and consequently management interventions (Jarić *et al.*, 2020). Time also plays a role in shaping public perceptions, as people may be unaware of the origin of introduced species as they are regarded as normal or desirable in their natural surroundings (Genovart *et al.*, 2013) – this is sometimes also referred to as shifting baseline syndrome (Clavero, 2014).

3. It is suggested that the terminology employed to call attention to invasive alien species and their control should be chosen carefully (Clergeau & Nuñez, 2006; Janovsky & Larson, 2019; Larson, 2005; Verbrugge *et al.*, 2016). The use of metaphors or derogative language is common in both scientific and popular writing about biological invasions, but little is known about the effects on public values or opinions. How the issue-area is framed by officials, scientists, politicians, and other leaders will have an impact on subsequent policy development; biological invasions can be seen primarily as threats to biodiversity, national security, human health, trade, or even cultural homogeneity (Stoett, 2010).

4. Indigenous voices and values are under-represented in scholarly discourse about invasive alien species (e.g., Bhattacharyya & Larson, 2014). The IPBES invasive alien species assessment has attempted to be inclusive, but see Schelhas *et al.* (2021) for an elaborative view on the importance of considering Indigenous and local knowledge, unique cultural dimensions and engaging Indigenous Peoples and local communities in the management of biological invasions and the control of invasive alien species, using two examples from the United States to show how invasive alien species can either culturally impoverish or enrich Indigenous Peoples and local communities (see also Pfeiffer & Voeks, 2008). The social justice concerns related to Indigenous Peoples and local communities as they manage biological invasions should not be overlooked (Head & Atchison, 2015).

Perceptions of invasive alien species and support for management are thus influenced by a wide range of values (**Table 1.2**; **Boxes 1.9** and **1.10**; see also Carter *et al.*, (2021) who extend this overview with ethical considerations for including social perspectives in research planning and decision-making). Research in the past five years has become more diverse in terms of theoretical and methodological approaches, for example by analysing how socio-historical processes interact with biological invasions (Archibald *et al.*, 2020), developing "sense of place" as a concept to explain how place attachment can promote or impede action against invasive alien species, or reframing biological invasions as socioecological phenomena to enhance cross-fertilization across ecological sciences and social sciences (Gawith *et al.*, 2020; Vaz *et al.*, 2017). Encouragingly, collaborative knowledge platforms are being developed (e.g., Bennett & van Sittert, 2019; Udo *et al.*, 2019), but further efforts for realizing collaboration between natural and social sciences are much needed for a more holistic understanding of perceptions of invasive alien species and critical for developing adequate control and policy responses.

Box 1 9 Human values and the invasive alien carp in North America.

A group of invasive alien carps (cyprinid fishes) were brought from Eastern Asia to Arkansas, United States of America in the 1960s to serve as biological control agents in aquaculture ponds (Besek, 2019). Many escaped soon after their importation and have since been migrating up the Mississippi River watershed, adversely impacting both social and ecological systems along the way. Since the early 2000s, many stakeholders with an interest in the North American Great Lakes have been advocating for the construction of a hydrologic barrier to stop invasive alien carp from entering and impacting their fisheries. This proposed barrier, however, would drastically impact regional shipping and transportation, setting up a substantial political battle regarding how to best manage invasive alien carp spread. This contentious social context has significantly impacted the work of scientists trying to assess invasive alien carp migration, tying their work to local politics and human values in numerous ways. For instance, most scientists have refused to offer unqualified predictions about the future migration of invasive alien carp because the ecological processes involved are so complex, and many political actors have seized on this indeterminacy to publicly question science methodologies and laboratory techniques used to study invasive alien species. Some scientists have been requested to explain and defend their work in federal courtrooms. This heated political climate has in some ways given extra attention to detection techniques, improving their precision, but has also led many scientists to avoid working on invasive alien carp altogether.

Box 1 10 **Conceptual perspectives from the social sciences.**

Social science and humanities research on biological invasions has grown steadily since the 1990s (Vaz *et al.*, 2017). Some of this work addresses perceptions, attitudes, and behaviours with a perspective towards enabling management and control of invaders (Rotherham & Lambert, 2013; Shackleton, Richardson, *et al.*, 2019). Arguably, when social science is integrated with biological invasion science, it has followed an "ABC" framework, focusing primarily on attitudes, behaviour, and choice (Shove, 2010). Some researchers are leaning towards more explicitly "critical" approaches to biological invasion science (Head, 2017; Kull, 2018). By "critical", social scientists refer to approaches that question underlying processes and conceptual foundations, seeing knowledge as political and transformative.

Several factors inform a critical social science perspective. It is challenging to consider landscapes being invaded without looking at how they have been co-produced by humans in myriad ways (for instance, clearance, soil degradation and introductions), and in many cases the invasive alien species themselves (for instance, genetic selection for species that have been introduced). This focus shifts attention from dangerous invaders to human complicity in biological invasions (Kueffer, 2017). Second, the study of invasive alien species has a specific trajectory and social context that shapes the knowledge produced on biological invasions (Archibald *et al.*, 2020). The social-political context of the institutions that undertake biological invasion-related research and seek to manage biological invasions and control invasive alien species (state weed agencies, land managers), is relevant, as this determines the voices and knowledge systems that are heard. The IPBES conceptual framework is attentive to the need to examine a variety of knowledge systems (Díaz *et al.*, 2015). A third necessity is to investigate how knowledge about invasive alien species is used and implemented, and what the consequences are for people and landscapes (Kull, 2018). The establishment of lists of high risk invasive alien species, for quarantine systems, or for community weed-pulling days; sending rangers out to spray herbicides on invasive alien plants or lay poison traps for invasive alien animals; establishing major public works policies like South Africa's "Working for Water" programme – each of these actions has knock-on effects, creates winners and losers, and creates ripples in the system that are not entirely predictable nor agreed to by all parties (Atchison & Head, 2013; Bach *et al.*, 2019; Fall, 2013; Gallardo *et al.*, 2019; Head *et al.*, 2015).

1.5.3 Ethics and invasive alien species

The management of invasive alien species, in particular sentient animals, raises multiple ethical debates with regards to animal welfare and rights, and this is considered an under-addressed animal welfare issue in conservation (Carter *et al.*, 2021; Doherty & Russell, 2019; Hampton & Hyndman, 2019; **Chapter 5**, **section 5.6.2.1**).

There are philosophical differences between proponents of animal rights, who focus on the individual animal, and those who focus on conservation at a species or ecosystem level, with the former having an increasing influence on public opinion and legislation. The extension of legal rights to animals and nature imposes moral and legal limits on acceptable human uses of the environment, and if the legal personality (**Glossary**) of both ecosystems and individual animals is acknowledged, the interests of individual animals may conflict with interests of individual species, as can be the case with native and invasive alien species (Futhazar, 2020). Arguably, the rights of native species to exist need to be respected (hence the importance of prevention and adapting the precautionary principle) but once an invasive alien species is established, the picture is more complicated.

Deciding whether and how to control invasive alien species involves analysing risks, and considering international consensus principles for ethical wildlife control which are informed by social and cultural values in addition to scientific, technical, and practical information. As discussed above, there is a diverse range of perceptions of invasive alien species, both positive and negative (Shackleton, Richardson, *et al.*, 2019). Moral dilemmas posed by controlling invasive alien species can involve subjective judgements about the perceived ecological value of protected species *versus* the lack of importance of invasive alien species (Mankad *et al.*, 2019) or indeed the charisma of one species compared to another (Jarić *et al.*, 2020).

Different invasive alien species management methods can raise different ethical debates. Genome editing can pose ethical questions because of concerns about the risks and unknown consequences of releasing genetically modified plants or animals into the wild (**Chapter 5**, **section 5.4.4.2**) (Bertolino, 2020). Gene suppression-drives may pose risks to global populations of invasive alien species and so are being considered with caution (Thresher, 2020). There are several reports outlining the risks and opportunities of these technologies (**Chapter 5**, **section 5.4.4.2**; Invasive Species Advisory Committee (ISAC), 2017; Redford *et al.*, 2019). Biological control can pose potential social and environmental risks, but often brings benefits (Müller-Schärer *et al.*, 2020; Thomas & Willis, 1998), and evokes a normative debate (Mankad *et al.*, 2019). It is relevant to consider social values and emotional and cultural associations, in addition to stakeholder preferences, humaneness and effectiveness, when managing invasive alien species (Mankad *et al.*, 2019).

Lethal management methods can be particularly controversial and a framework for assessing the success and sustainability of a particular management decision that takes into account ecology, economic and ethics has been proposed (Warburton & Anderson, 2018). Prevention is often the "preferred option for managers and desirable and philosophically acceptable to animal rights advocates" (Perry & Perry, 2008). Furthermore, proponents of compassionate conservation state that humans should do no harm and consider that individual animals matter.

Given the range of values and management options, there are unique conceptual and governance challenges associated with invasive alien species (Stoett, 2007). The language used to describe invasive alien species has sometimes been labelled as nativist (Gbedomon *et al.*, 2020), and is predominantly negative. Inglis (2020) states that; "the invasive discourse is couched in language which immediately prejudices people against the animals. This leads to the killing of these animals being viewed as both morally acceptable and indeed necessary." Nevertheless, Shackelford *et al.* (2013) suggest finding middle-ground in the native/non-native debate that recognizes the merits of both sides when assessing management options. Furthermore, there is no globally accepted definition of animal welfare and interpretation of the concept of animal welfare evolves with advances in our understanding of animals (Dawkins, 2017; Harrop, 2013; Mellor *et al.*, 2020; White, 2013).

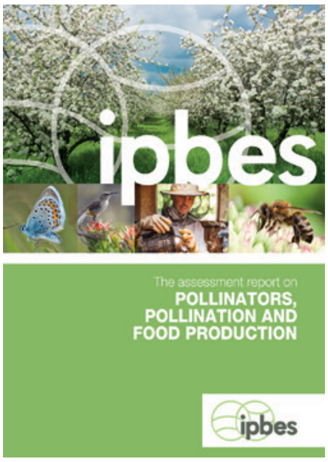
An eighteenth Sustainable Development Goal on animal health, welfare and rights has been suggested to ameliorate trade-offs between animal welfare and sustainability, with the management of invasive alien species noted as an example (Visseren-Hamakers, 2020). Accordingly, as discussed in **Chapter 6**, balancing values across multiple and interrelated stakeholder groups is an important consideration within invasive alien species management (Carter *et al.*, 2021).

1.6 CONCEPTUAL BASIS FOR THE INVASIVE ALIEN SPECIES ASSESSMENT

IPBES assessments aim to identify policy-relevant findings for decision-making in government, the private sector and civil society by synthesizing and critically evaluating peer-reviewed scientific literature, grey literature, and other available knowledge, such as Indigenous and local knowledge. Assessments do not generate new data, but seek to create new understanding through summary, sorting and synthesis using different methods to manage complexity.

The IPBES invasive alien species assessment builds upon several IPBES assessments, which include

Box 1 11 **Biological invasions and pollination processes.**



The IPBES Assessment Report on Pollinators, Pollination and Food Production (IPBES, 2016b) considered the outcomes of biological invasions on pollinator populations, diversity, network structure and pollination processes and confirmed that ecological and evolutionary contexts are important. Although predicting the consequences of the arrival of an invasive alien species within a pollinator network is difficult, because of the ecological complexity inherent with multiple interacting species, it is apparent that the trophic position (plant/herbivore/pollinator/predator) and degree of specialization of an invasive alien species can be informative. Invasive alien species can alter the function, structure and stability of plant-pollinator networks with adverse impacts on specific native pollinator species and, sometimes, reductions in overall pollinator abundance or diversity (Vilà *et al.*, 2009). In native pollination networks dominated by generalist plants and pollinators, invasive alien plant species are often readily integrated. Consequently, networks including alien plants are characterized by increased plant and pollinator richness and high values of nestedness (Stouffer *et al.*, 2014). As an example, alien species (plants and pollinators) comprised 56 percent of the total number of interactions within pollination networks on the Galápagos Islands. Alien insects within these pollination networks linked mostly to generalist plant species resulting in increased nestedness and network stability (Traveset *et al.*, 2015). Such changes to the community structure increase network cohesiveness but disrupt native ecological interactions (Traveset *et al.*, 2015). The impacts of invasive alien species on pollinators and pollination are likely to be further exacerbated when coupled with other threats including wildlife diseases, climate or land-use change (González-Varo *et al.*, 2013; Schweiger *et al.*, 2010; Sunny *et al.*, 2015; Vanbergen & Initiative, 2013).

thematic assessments of Pollinators, Pollination and Food Production (IPBES, 2016b; **Box 1.11**), Land Degradation and Restoration (IPBES, 2018c); Sustainable Use of Wild Species (IPBES, 2022c); Methodological Assessments of Scenarios and Models of Biodiversity and Ecosystem Services (IPBES, 2016c), and of the Diverse Values and Valuation of Nature (IPBES, 2022a); four regional assessments of Biodiversity and Ecosystem Services (IPBES, 2018d, 2018e, 2018f, 2018g); and the Global Assessment of Biodiversity and Ecosystem Services (IPBES, 2019).

1.6.1 The IPBES conceptual framework and its use in the invasive alien species assessment

The IPBES conceptual framework[4] aims to facilitate interdisciplinary collaboration and science-policy dialogues (Díaz *et al.*, 2015). It explicitly considers diverse disciplines, different stakeholders and Indigenous Peoples and local communities (**section 1.5.2**), and several knowledge systems (natural sciences, social sciences and humanities, Indigenous, local and practitioners' knowledge).

4. A full description of the IPBES conceptual framework, and associated definitions, is available in **Supplementary material 1.2**.

The IPBES conceptual framework includes six interlinked elements constituting a socioecological system that operates at various scales in time and space: nature; nature's contributions to people; anthropogenic assets; institutions and governance systems and other indirect drivers of change; direct drivers of change; and good quality of life.

The IPBES invasive alien species assessment falls within the IPBES conceptual framework, and uses it to understand how the major threat posed by invasive alien species can be reduced while those that are considered important components of nature and nature's contributions to people can be maintained in order to improve good quality of life. The assessment recognizes the importance of integrating this knowledge in the broader context of global change. By superimposing the specificities of the assessment over the IPBES conceptual framework, **Figure 1.11** shows the interactions between invasive alien species and the other elements of the IPBES conceptual framework. All these relationships are dynamic, changing over time, and different scenarios (i.e., trajectories for each component) are likely to lead to different outcomes. Socioecological contexts, including public awareness and stakeholder engagement levels, can also change according to the spatial scale under consideration (i.e., local, regional, global), thus affecting how invasive alien species are perceived and managed.

Box 1 12 Nature's contributions to people.

Nature's contributions to people are an integral part of the IPBES conceptual framework **(Figure 1.11)** and represent all the contributions, both positive and negative, of living nature (i.e., diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life for people (Díaz *et al.*, 2018). Beneficial contributions from nature include such things as food provision, water purification, flood control, and artistic inspiration, whereas detrimental contributions include transmission of disease, particularly those affecting animal, plant, and human health **(Box 1.14)**, and other ways in which harm to people or their assets or community stability/resilience may occur as a consequence of invasive alien species. Many of nature's contributions to people may be perceived as beneficial or detrimental depending on the cultural, temporal, or spatial context (Díaz *et al.*, 2018; **sections 1.5.2**, **1.5.3**; **Chapter 4**, **section 4.1.3**). The concept of nature's contributions to people addresses the need to recognize the cultural and spiritual impacts of biodiversity, in ways that are not restricted to a discrete cultural ecosystem services category, but instead encompass diverse world views of human-nature relations (Mace, 2014).

The IPBES invasive alien species assessment adopts the 18 categories identified by IPBES for reporting nature's contributions to people (Díaz *et al.*, 2018). These 18 categories of nature's contributions to people are organized into three partially overlapping groups, according to the type of contribution they make to people's quality of life **(Figure 1.12)**:

Material nature's contributions to people: substances, objects, or other material elements from nature that directly sustain people's physical existence and material assets. They are typically physically consumed in the process of being experienced.

Non-material nature's contributions to people: nature's effects on subjective or psychological aspects underpinning people's quality of life, both individually and collectively.

Nature's regulating contributions to people: functional and structural aspects of organisms and ecosystems that modify the environmental conditions experienced by people, and/or sustain and/or regulate the generation of material and non-material contributions.

Box 1 12

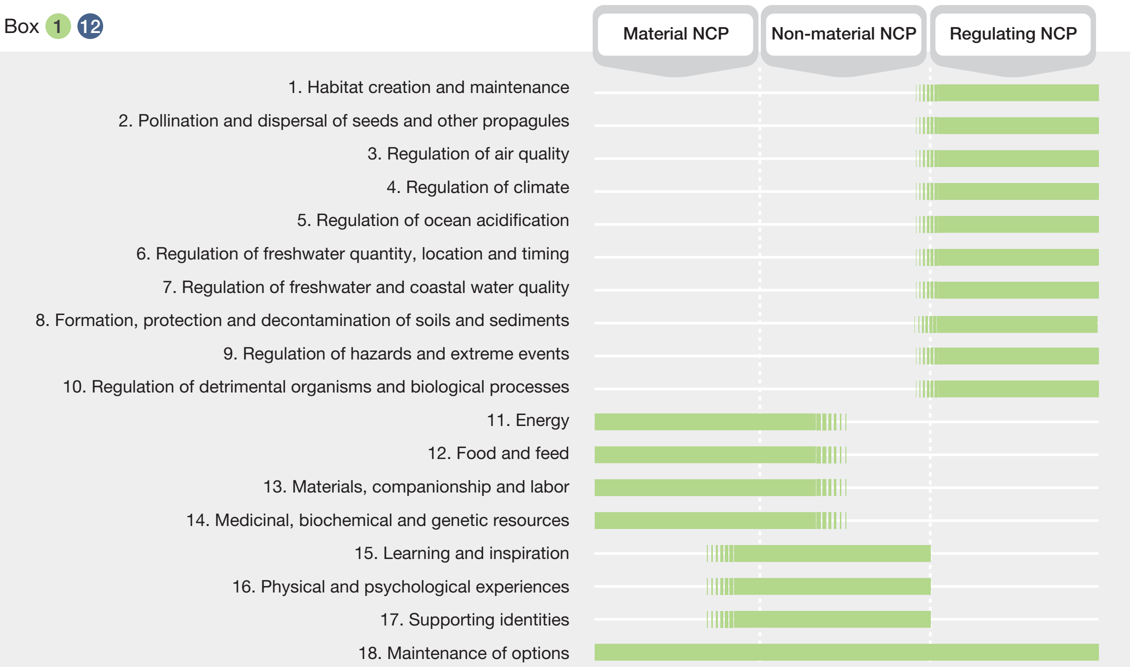
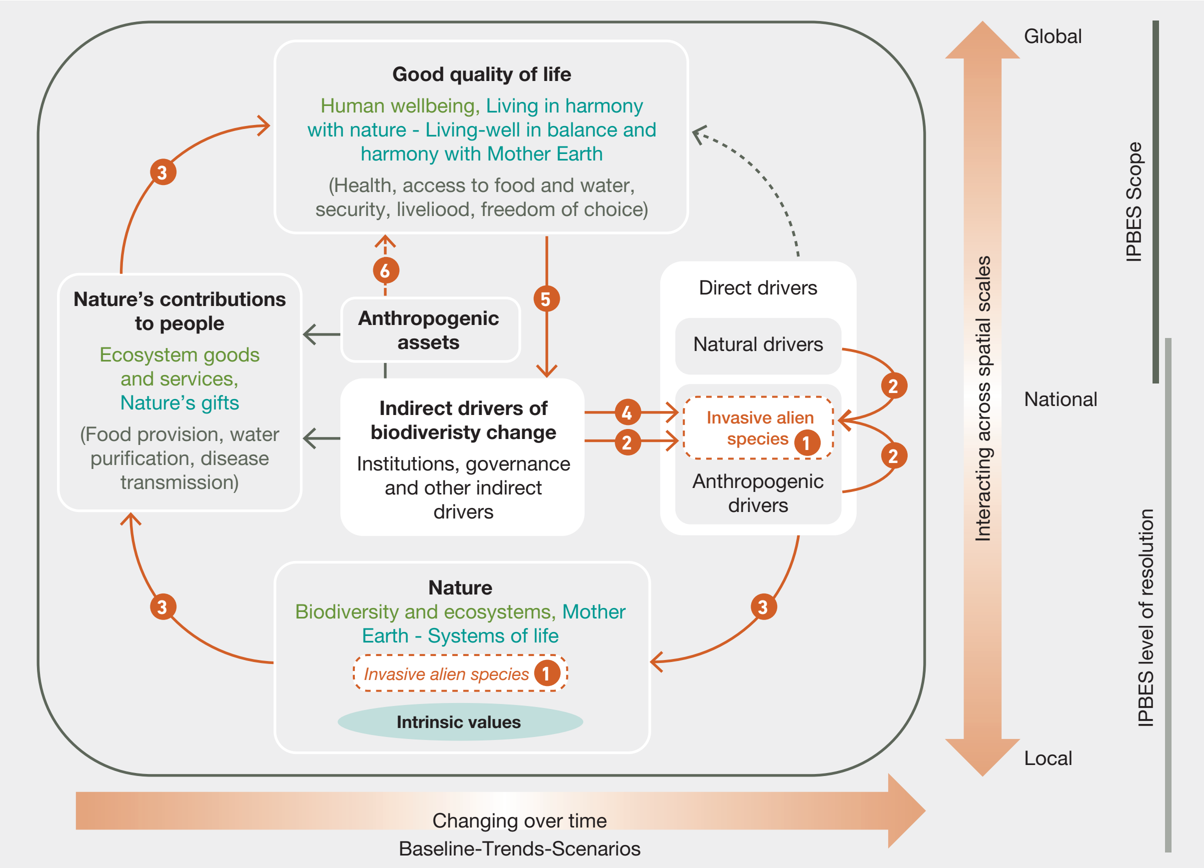


Figure 1 12 **Categories of nature's contributions to people (NCP).**

From Brondizio *et al.* (2019), https://doi.org/10.5281/zenodo.3831852, under license CC BY 4.0. These categories are used in this assessment of invasive alien species.



1 **Status and trends of invasive alien species:** invasive alien species are one of five major direct drivers of change, and at the same time are part of nature. This assessment captures both aspects, with their dynamics being addressed in **Chapter 2**.

2 **Synergies and interactions of invasive alien species with other drivers of change in nature:** the transport, introduction, establishment and spread of invasive alien species are facilitated, modified and amplified through interactions and synergies with other direct and indirect drivers of change in nature (e.g., climate change, economic drivers) as well as by natural hazards and biodiversity loss (addressed in **Chapter 3**).

3 **Impacts of invasive alien species on nature, nature's contributions to people and good quality of life:** invasive alien species impact nature in diverse ways, and often in ways that interact with other drivers of change in non-linear ways (synergistic, antagonistic) (addressed in **Chapter 4**). Changes to nature, including in ecosystem functions, underpin changes to nature's contributions to people (see **Box 1.12**), which can affect society in detrimental or, in some cases, beneficial ways (addressed in **Chapter 4**). The effects of invasive alien species on people and good quality of life (**section 1.6.7.2**) can be direct or through other components of the ecosystems (e.g., human health may be affected by parasites and contagious emergent diseases) (addressed in **Chapter 4**).

4 **Responses to biological invasions:** institutions, governance and other societal indirect drivers of change in nature can respond to biological invasions through direct management measures, including prevention and adaptation, restoration and policies (addressed in **Chapters 5** and **6**).

5 **Influence of people on responses to invasive alien species:** biological invasions' management and policies are driven by how people perceive and act in response to the threat of invasive alien species (addressed in **Chapters 1**, **5** and **6**).

6 **Adaptation to invasive alien species:** society can also adapt to invasive alien species and thus mitigate their adverse impacts on good quality of life; for example, invasive alien species can become new sources of food security (addressed in **Chapters 5** and **6**).

Figure 1 11 **The IPBES conceptual framework adapted to the IPBES invasive alien species assessment.**

Interactions amongst the components of the IPBES conceptual framework that are relevant to biological invasions are indicated in numbered arrows (boxes, arrows and numbers), with detailed descriptions provided in the lower panel of the figure. Unnumbered arrows represent the relationships between different components of the IPBES conceptual framework as defined in Díaz *et al.* (2015), that are not studied in this assessment. Adapted from Díaz *et al.* (2015), https://doi.org/10.1016/j.cosust.2014.11.002, under license CC BY-NC-SA 3.0.

1.6.2 Literature review

The IPBES invasive alien species assessment's findings emerge from systematic and transparent evaluations of available evidence to date[5] combined with experts' inputs, taking into account different worldviews and knowledge systems. Existing evidence encompasses published scientific and grey literature, including Indigenous and local knowledge, government publications, policy documents and briefs, technical reports and datasets, etc. This assessment also builds on previous IPBES assessments and other relevant global assessments such as the Global Biodiversity Outlook series, the United Nations Environment Programme (UNEP) Global Environment Outlook series, and the Millennium Ecosystem Assessment.

Authors were guided by the IPBES Data Management Policy (IPBES, 2020a), and the flexible protocol for systematic review that was first developed by the Global Assessment of Biodiversity and Ecosystem Services (Brondizio *et al.*, 2019; Collaboration for Environmental Evidence, 2013), which is critical to achieve scientific credibility and transparency of the assessment, following the FAIR (findable, accessible, interoperable, and reusable) data principles.

Authors sought to represent the most relevant and highest quality evidence, with the highest level of synthesis available as a priority; and provided supplemental material if necessary to fully cover and evaluate the topic, or to include the most up-to-date information. Methodologies and workflows for literature reviews usually include two practical steps: 1) concurrent database searches of different kinds of literature (e.g., peer reviewed and "grey" published literature, unpublished but openly available reports and databases) to minimize potential biases and 2) personal knowledge and experience of authors regarding key seminal resources or publications not appearing as an output from first step (if available).

Data and information have been compiled from many sources and domains spanning scales from local to global **(Figure 1.13)**. Throughout the chapters, following

5. The cut-off date for the inclusion of published sources was 15 December 2021, which corresponds to the start of the second external review (second draft of the chapters and first draft of the summary for policymakers). In line with IPBES procedures, additional citations were included passed this date when prompted by a comment made during the second external review (accessible at https://ipbes.net/ias) and when seen as relevant by experts.

extensive synthesis of available evidence, gaps in existing knowledge were revealed and documented with an overarching synthesis of gaps, and options for addressing them, provided within **Chapter 6**. The IPBES Regional Assessments of Biodiversity and Ecosystem Services all recognize gaps in data and information which are particularly pronounced in some regions and for many taxa (IPBES, 2018g, 2018f, 2018d, 2018e, 2018c). However, the growth in availability of datasets globally is encouraging (**Chapter 2**, **section 2.1.4**), although there remain lags in collating and sharing information on invasive alien species and consequently gaps in datasets across all regions.

The analysis of Indigenous Peoples and local communities' issues and knowledge also benefited from an "online call for contributions", which collected 30 references that were reviewed and selected to inform specific sections of the assessment. Three Indigenous and local knowledge dialogue workshops were also held throughout the timeframe of the assessment, which led to suggested literature and government reports being reviewed (**section 1.6.7.1**).

Authors documented their sources as well as their methodologies and workflows for literature reviews in data management reports, which are linked as footnotes, where appropriate. Across all chapters, references are cited within the text and the full reference is provided at the end of each chapter. The executive summaries of the chapters and the background text of the summary for policymakers include statements with traceability enclosed in curly brackets linking the statements to their underlying chapter subsections.

These systematic literature reviews, combined with expert-based critical opinions, are intended to enable the IPBES invasive alien species assessment to generate key findings and policy-relevant messages to support decision-makers in better understanding and tackling the complex issue of biological invasions and invasive alien species (**section 1.6.3**).

1.6.3 IPBES confidence framework

Confidence levels assist authors in the process of assessing and communicating the degree of uncertainty, or confidence, related to key findings. The evidence includes publications, data, theory, models and information **(Figure 1.14)** from multiple disciplines and knowledge

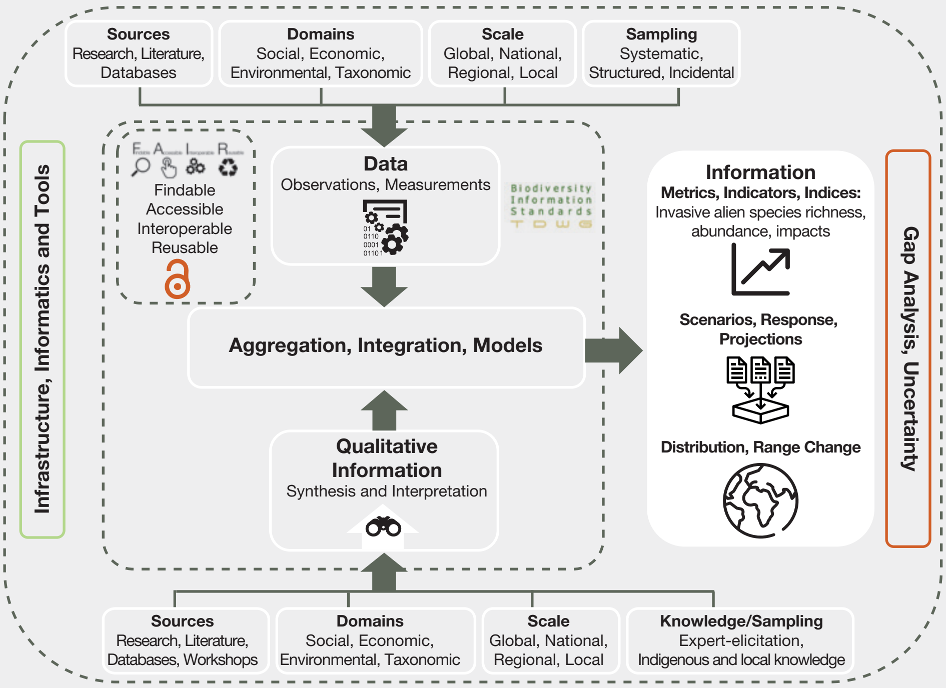


Figure 1 13 **Connections amongst types of evidence.**

Data and knowledge (**Chapter 2**) from many sources and domains spanning various scales and sampling techniques are combined to establish information in the form of metrics, indicators and indices which contributes knowledge on drivers (**Chapter 3**) and impacts (**Chapter 4**), ultimately informing management (**Chapter 5**) and future options (**Chapter 6**).

Figure 1 14 **The four-box model for the qualitative communication of confidence.**

Confidence increases towards the top-right corner as suggested by the increasing strength of shading. The four-box confidence framework developed for IPBES assessments is based on the quantity and quality of evidence assessed (x-axis) in combination with the level of agreement of experts using their judgment (y-axis). From IPBES (2016a), https://doi.org/10.5281/zenodo.2616458, under license CC BY 4.0.

systems. These confidence terms inform and communicate to decision-makers the degree of confidence that the assessment author teams associate to the key findings throughout the assessment and, importantly, highlight where further investigation is required to inform robust evidence-based decision making. Further details of the approach are documented in the IPBES Guide to the Production of Assessments (IPBES, 2018b).

The summary terms to describe the evidence are:

- **Well established:** There is a comprehensive meta-analysis or other syntheses/multiple independent studies that agree.
- **Established but incomplete:** There is general agreement although only a limited number of studies exist; there is no comprehensive synthesis, and/or the studies that exist address the question imprecisely.
- **Unresolved:** Multiple independent studies exist but their conclusions do not agree.
- **Inconclusive:** There is limited evidence and a recognition of major knowledge gaps.

1.6.4 IPBES regions and sub-regions

The IPBES invasive alien species assessment is global and encompasses alien species in terrestrial, freshwater and marine ecosystems across regions. It adopts the IPBES categorization of regions and sub-regions (**Figure 1.15**; IPBES technical support unit on knowledge and data, 2021) to structure its analysis (**Chapters 2, 3, 4, 5** and **6**). The IPBES technical support unit on knowledge and data (2021) also produced the dataset describing the IPBES regions and sub-regions and their corresponding countries or areas, in line with decision IPBES-3/1.

1.6.5 IPBES units of analysis

Each region and sub-region **(Figure 1.15)** are divided into multiple spatial units (biomes and ecosystems), spreading across borders. The invasive alien species assessment therefore adopts the 17 IPBES units of analysis (**Table 1.3**, see **Chapters 2, 3, 4, 5** and **6**) also used in previous IPBES assessments and defined by the IPBES Global Assessment (IPBES, 2019)[6] to support its analysis.

6. Definitions of the IPBES units of analysis available in **Supplementary material 1.3**

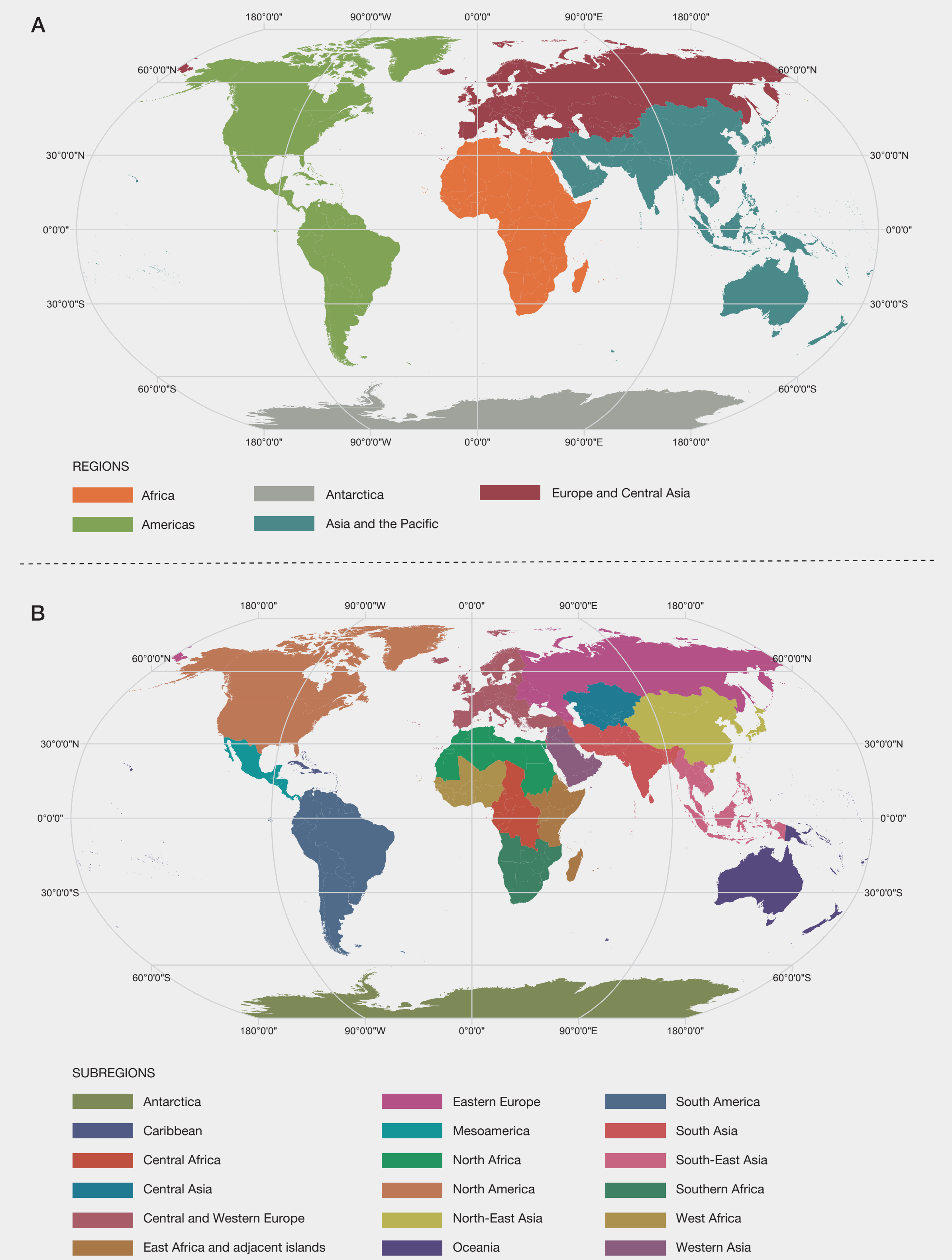


Figure 1 15 **IPBES regions (top) and sub-regions (bottom).**

Source: IPBES technical support unit on knowledge and data (2021), https://doi.org/10.5281/zenodo.5719431, under license CC BY 4.0.

Figure 1 16 **Photo montage of invasive alien species across regions and biomes.**

From top to bottom, left to right: *Pinus mugo* (mountain pine); *Passer domesticus* (house sparrow); *Rattus rattus* (black rat); *Vulpes vulpes* (red fox); *Vachellia nilotica* (gum arabic tree); *Aedes albopictus* (Asian tiger mosquito); *Undaria pinnatifida* (Asian kelp); *Lissachatina fulica* (giant African land snail); *Pontederia crassipes* (water hyacinth); *Solenopsis invicta* (red imported fire ant); *Procambarus clarkii* (red swamp crayfish); *Carcinus maenas* (European shore crab); *Caulerpa taxifolia* (killer algae); *Pterois miles* (lionfish); *Mustela vison* (American mink).

Table 1 3 **Examples of invasive alien species for each IPBES unit of analysis.**

The examples do not necessarily include the most widespread or harmful invasive alien species, but examples to provide representation of the diversity of species in each unit of analysis.

Unit	Biomes	Examples[7,8]- see Figure 1.16 for illustrations
1. Tropical and subtropical dry and humid forests	Terrestrial	*Cenchrus setaceus* (fountain grass) *Lissachatina fulica* (giant African land snail) *Cenchrus ciliaris* (buffel grass) *Homalodisca vitripennis* (glassy winged sharpshooter)
2. Temperate and boreal forests and woodlands	Terrestrial	*Lupinus polyphyllus* (garden lupin) *Lumbricus terrestris* (lob worm) *Pueraria montana* (kudzu) *Solenopsis invicta* (red imported fire ant)
3. Mediterranean forests, woodlands and scrub	Terrestrial	*Acacia longifolia* (golden wattle) *Pheidole megacephala* (big-headed ant) *Centaurea solstitialis* (yellow starthistle) *Aedes albopictus* (Asian tiger mosquito)
4. Tundra and high mountain habitats	Terrestrial	*Pinus mugo* (mountain pine) *Poa annua* (annual meadowgrass)
5. Tropical and subtropical savannas and grasslands	Terrestrial	*Prosopis glandulosa* (honey mesquite) *Felis catus* (cat) *Andropogon gayanus* (tambuki grass) *Bubalus bubalis* (Asian water buffalo)
6. Temperate grasslands	Terrestrial	*Pinus radiata* (radiata pine) *Pinus patula* (Mexican weeping pine) *Rattus rattus* (black rat) *Rattus norvegicus* (brown rat)
7. Deserts and xeric shrublands	Terrestrial	*Bromus tectorum* (downy brome) *Canis lupus dingo* (dingo) *Vachellia nilotica* (gum arabic tree) *Sus scrofa* (feral pig)
8. Wetlands – peatlands, mires, bogs	Freshwater	*Reynoutria japonica* (Japanese knotweed) *Mimosa pigra* (giant sensitive plant) *Procambarus clarkii* (red swamp crayfish) *Pomacea canaliculata* (golden apple snail)
9. Urban/Semi-urban	Human (anthrome)	*Parthenium hysterophorus* (parthenium weed) *Linepithema humile* (Argentine ant) *Lonicera tatarica* (Tatarian honeysuckle) *Aedes albopictus* (Asian tiger mosquito) *Passer domesticus* (house sparrow) *Sturnus vulgaris* (common starling) *Columba livia* (pigeons)

Table 1 3

Unit	Biomes	Examples[7,8]- see Figure 1.16 for illustrations
10. Cultivated areas (incl. cropping, intensive livestock farming, etc.)	Human (anthrome)	*Artemisia vulgaris* (mugwort) *Mustela vison* (American mink) *Acacia longifolia* (golden wattle) *Nosema bombi* (microsporidian parasite)
11. Cryosphere	Terrestrial, freshwater and marine	
12. Aquaculture areas	Human (anthrome)	*Undaria pinnatifida* (Asian kelp) *Magallana gigas* (Pacific oyster) *Carassius gibelio* (Prussian carp) *Pacifastacus leniusculus* (American signal crayfish)
13. Inland surface waters and water bodies/freshwater	Freshwater	*Potamogeton crispus* (curlyleaf pondweed) *Dreissena polymorpha* (zebra mussel) *Gambusia affinis* (western mosquitofish) *Myxobolus cerebralis* (whirling disease agent) *Phragmites australis* (common reed) *Pontederia crassipes* (water hyacinth)
14. Shelf ecosystems (neritic and intertidal/littoral zone)	Marine	*Sargassum muticum* (wire weed) *Carcinus maenas* (European shore crab) *Hemigrapsus sanguineus* (Asian shore crab) *Mytilus galloprovincialis* (Mediterranean mussel)
15. Open ocean pelagic systems (euphotic zone)	Marine	*Pterois volitans* (red lionfish) and *Pterois miles* (lionfish)
16. Deep sea	Marine	
17. Coastal areas intensively and multiply used by human	Marine	*Batillaria attramentaria* (Japanese false cerith) *Caulerpa racemosa* (green algae) *Caulerpa taxifolia* (killer algae) *Carcinus maenas* (European shore crab)

7. For more examples, see **Supplementary material 1.4**
8. Note that scientific names follow the taxonomy used in the original papers. Examples were chosen based on a systematic literature review. Data management report available at: https://doi.org/10.5281/zenodo.5518254

1.6.6 Nomenclature and taxonomy

The IPBES invasive alien species assessment generally follows the Global Biodiversity Information Facility (GBIF) Backbone taxonomy (GBIF, 2021), with a few exceptions for marine species, where authors have followed the World Register of Marine Species (WoRMS, 2022).

For increased accessibility where available, English common names, following the Centre for Agriculture and Bioscience International (CABI) Invasive Species Compendium (CABI, 2022) as the main reference source, are indicated alongside scientific names throughout the report.

The assessment acknowledges the diversity of common names across the globe, as well as their cultural importance (**section 1.6.7.1**). Common names are therefore sometimes included in the local language if pertinent to a specific case study, where such names are available and appropriate.

1.6.7 Cross-cutting themes

A number of cross-cutting themes have been acknowledged as important to IPBES assessments. In this assessment, three major cross-cutting themes are developed across chapters. 1) Indigenous Peoples and local communities are recognized as possessing detailed knowledge on biodiversity and ecosystems, and accordingly, IPBES is committed to promoting an enhanced recognition of and to working with Indigenous and local knowledge systems (Annex 1 of decision IPBES-7/1). 2) Good quality of life is included within the context of the IPBES conceptual framework and within the ongoing IPBES values assessment (IPBES, 2022a). 3) The Methodological Assessment of Scenarios and Models of Biodiversity and Ecosystem services (IPBES, 2016c) led to the commitment to continuing advanced work on scenarios and models of biodiversity and ecosystem functions. For each of the three cross-cutting themes, liaison groups were formed with representation of at least one expert from each of the chapters.

1.6.7.1 Indigenous and local knowledge

Engaging with Indigenous Peoples and local communities

Indigenous Peoples and local communities is a term used internationally by representatives, organizations, and conventions to refer to individuals and communities who either self-identify as Indigenous or as members of distinct local communities that maintain an inter-generational historical connection to place and nature through livelihoods, cultural identity, languages, worldviews, institutions, and ecological knowledge (IPBES, 2019). Indigenous Peoples and local communities are, typically, ethnic groups who are descended from and identify with the original inhabitants of a given region, in contrast to groups that have settled, occupied or colonized the area more recently (IPBES, 2019). At least a quarter of the global land area is traditionally owned, managed, used, or occupied by Indigenous Peoples, representing about 38 million km^2 (Garnett *et al.*, 2018). In addition, a diverse array of local communities, including farmers, fishers, herders, hunters, ranchers, and forest users, manage substantial areas under various property and access regimes (IPBES, 2019). Accordingly, Indigenous Peoples and local communities are stewards to an impressive diversity of nature's contributions to people (Brauman *et al.*, 2020; see **Chapter 2**, **Box 2.6**). However, these lands and waters may be increasingly impacted by invasive alien species (**Chapter 2**, **Box 2.6**; **Chapter 4**, **section 4.6**).

As a result of their close relationship with nature, and dynamic Indigenous and local knowledge systems, many Indigenous Peoples and local communities have developed new understandings and knowledge of biological invasions and invasive alien species (Howard, 2019; Jevon & Shackleton, 2015). They are observers to the introduction and spread of invasive alien species and their impacts on humans and biodiversity, often in environments where scientific monitoring (**Glossary**) and research are sparse or challenging. Many Indigenous Peoples and local communities have a good understanding of the often complex and interacting roles of drivers facilitating the introduction, establishment and spread of invasive alien species on their lands (**Chapter 3**, **Box 3.15**), and also employ their knowledge of the environment to develop responses or management strategies (**Chapter 5**) and are key, active participants in management and decision-making (**Chapter 6**, **section 6.4**; Fischer, 2007; Gratani *et al.*, 2011; Jagoret *et al.*, 2012). Indigenous Peoples and local communities are also in a position to judge trade-offs between beneficial and harmful impacts of invasive alien species both in terms of livelihoods and the environment, as they have to live with them or manage them in their lands and waters (S. J. Hall, 2009; Kannan *et al.*, 2016; Koichi *et al.*, 2012). For example, local authorities in Queensland, Australia, consulted with Girringun Aboriginal rangers and residents to better understand the extent of myrtle rust impacts on native plant species, and to design responses that align to the risk level posed, so as not to undermine local livelihoods (see also Grice *et al.*, 2012; Head & Atchison, 2015). Many Indigenous Peoples and local communities are therefore concerned that their knowledge, needs and views are not properly considered in both research and management of biological invasions (IPBES, 2020b, 2020b).

Working with Indigenous and local knowledge in the assessment

There is a clear need to work with Indigenous Peoples and local communities on assessments and activities related to biological invasions and invasive alien species. However, Indigenous and local knowledge is still often under-represented in research on biological invasion science, which represents a great loss to overall understanding and capacity to manage biological invasions and control invasive alien species. The IPBES invasive alien species assessment therefore aims to work with Indigenous and local knowledge, and to build its conclusions on the best available science and Indigenous and local knowledge. It recognizes that there are numerous barriers to effectively working with Indigenous and local knowledge in a global-scale assessment, including language, data and information flow, accessibility of information, representation of diverse groups within Indigenous communities, and differing understandings and conceptualizations of risk (e.g., Maclean *et al.*, 2021; Michán, 2011; Muller *et al.*, 2009). To overcome these issues as far as possible, the assessment follows the IPBES approach to recognizing and working with Indigenous and local knowledge (Decision IPBES-5/1, annex II), with the support of the IPBES task force and technical support unit on Indigenous and local knowledge. This work included convening three dedicated workshops[9] on Indigenous and local knowledge that brought together Indigenous Peoples and local communities and assessment authors (IPBES, 2020b, 2020b, 2022b), and the consideration of literature beyond the scientific journals

9. The first dialogue workshop took place in Montreal, Canada on 15-16 November 2019; the second dialogue workshop was held online from 21 September to 1 October 2020; and the third dialogue workshop was held online on 1-3 February 2022.

and major invasive alien species databases[10], including materials received through an online call for contributions for the assessment. Assessment authors also carried out an extensive cross-chapter review of literature on Indigenous and local knowledge. Consideration of free, prior and informed consent was key to this work.

The diversity of Indigenous Peoples and local communities' perspectives on invasive alien species

Indigenous Peoples and local communities' perspectives on invasive alien species often differ from scientific perspectives. Indigenous Peoples and local communities perceive invasive alien species in terms of both the particular ecological context and the cultural world views and traditions of their communities (Ellen, 2020). Science also brings its own set of value judgements relating to invasive alien species. This can lead to differences in understanding, responses, and management practices relating to biological invasions. Perspectives on any given invasive alien species will also vary within and between communities, as different community members may experience different impacts depending on gender, age, livelihood and a multitude of other factors (IPBES, 2022b). The great diversity of Indigenous Peoples and local communities' conceptions across species, places, cultures, livelihood systems and time periods, and consequential actions and responses to invasive alien species and the management of biological invasions, makes generalization almost impossible (IPBES, 2020b). Understanding these differing perceptions is therefore a key task for the assessment, and recognition of diverse perspectives is important if effective collaboration between scientists, policymakers, and Indigenous Peoples and local communities is to occur **(Box 1.13)**.

Many Indigenous Peoples and local communities emphasize the inter-relatedness of humans, the land, water, and other species (Barbour & Schlesinger, 2012), which can lead to acceptance of new species. For example, the Anishnaabe of the Great Lakes Region of North America explain the arrival of new plants or animals as a natural process of migration and must then determine why they have come and what their relationship with these migrants might be (Reo & Ogden, 2018). Thus, while some Anishnaabe support invasive alien species eradication, others argue: "…we're supposed to respect all of nature. To me having respect for nature is respecting the fact that it knows how to balance itself and stop trying to introduce different things to fix this and fix that…Respect nature and it will balance. I mean everything has its cycles, leave it alone for gosh sakes. Let it do its thing and quit playing God." (Reo & Ogden, 2018, quoting Kathy LeBlanc, a cultural leader and elder from the Bay Mills Indian Community).

In other cases, established invasive alien species have become a valued part of the socioecological system and are reflected in cosmology. Xeni Gwet'in and Tsilhqot'in of British Columbia now link their identity with *Equus caballus* (horses), describing them as relatives, individuals, or neighbours with family groups. As one elder put it, "The wild horses are like us. They've got routes they go to. They have plans… The mares are sort of the leaders, like in our culture the women have power. They are really respected and strong. So, the stud would protect the mares, but the mare would decide where to go, when to go. And it's quite interesting, in our culture it's the same" (Bhattacharyya & Slocombe, 2017).

Also, in some cases, the introduction of some invasive alien species occurred so long ago that these species can be perceived as native and now "belong to country" (Bach & Larson, 2017). Meanwhile, in many cases,[11] invasive alien species are perceived by Indigenous Peoples and local communities as "negative", often referred to as "weeds" or "pests", and "new" in contrast to "native species" often due to negative impacts on food systems, medicines, and livelihoods of Indigenous Peoples and local communities (IPBES, 2019b; **Chapter 4**, **section 4.6**). A further key issue can be that Indigenous Peoples and local communities' cosmologies or cultural world views may not have a place for these new species: invasive alien species may often be seen as a cultural and spiritual threat, as well as an ecological issue (Grenz, 2020; IPBES, 2020b, 2022b; Trauernicht *et al.*, 2013). For example, among the Māori of New Zealand, Peltzer *et al.* (2019) report that introduced predators have significantly challenged the key cultural concept of "whakapapa", which portrays the genealogical connections between the natural world, including humans, and the cosmological domain. Similarly, among some Australian Aboriginal groups, invasive alien species are a threat because they have no dreaming – no origins accounted for in the ancestral creation of the landscape – and thus no law or responsibilities assigned to families to care for and respect them (Crowley, 2014; Salmón, 2000). Some Indigenous Peoples and local communities explain dramatic and especially negative changes in the landscape, such as an invasive alien species, as a failure of humans to uphold their responsibilities: For example, the Soliga describe the establishment and spread of the invasive alien plant *Lantana camara* (lantana) in Southern India as the punishment of the Hindu Lord Shani for unknown moral infringements by the local communities (Puri, 2015; Thornton *et al.*, 2019).

10. Data management report available at: https://doi.org/10.5281/zenodo.5760266

11. Data management report available at: https://doi.org/10.5281/zenodo.5760266

Box 1 13 Indigenous and local knowledge of invasive alien species in names, stories, and songs.

Indigenous and local knowledge of invasive alien species may be embedded in stories, poetry, and songs. A poem from Ethiopia illustrates local understandings of the adverse impacts of invading *Prosopis juliflora* (mesquite, or woyane harar trees) on fodder resources and cattle grazing practices, and their interactions with other drivers of change in nature:

"Cattle from upland, cattle from lowland
Goats from here, sheep from there
Are you [my camels] ever going to have the trees
That you once had all for yourselves?
In the summer, the floods
In the winter the locusts
In the upland the Christians
On the lowland the sorghum fields
In awash the woyane trees
Where should I take you my heart [my she camel]?"
(Balehegn, 2016)

Indigenous and local knowledge of biological invasions may also be embedded in specific names, which may also reveal much about how an invasive alien species is perceived. Most invasive alien species are given new names by Indigenous Peoples and local communities, which may indicate origin or foreignness as well as inclusion in a similar generic category, and can have political undertones. For example, the Kawaiwete of Brazil label the incoming, and more aggressive, hybrid African-European honey bee as a "honey wasp", in contrast to the benign local "honey bee" (Athayde *et al.*, 2016). In Kenya, the introduction of the invasive alien tree *Prosopis juliflora* is locally dubbed woyane harar after the Tigrinean People's Liberation Front (TPLF), which introduced the tree for land reclamation, fodder, and wood fuel (Berhanu & Tesfaye, 2006; Rettberg, 2010; Tessema, 2012). *Chromolaena odorata* (Siam weed) is known as rumput golkar or golkar grass in Timor after the ruling government party of Indonesia, as it overshadows competitive plants (McWilliam, 2000). Similarly, Congress grass refers to the poisonous *Parthenium hysterophorus* (parthenium weed) across India, said to have been inadvertently gifted to the nation in wheat that was imported for famine relief by Nehru's Congress Party in the mid-1950s (OpIndia, 2021). Invasive alien salmonids in the fresh waters of Argentinian Patagonia are known to the Mapuche as cosa de winka ("white man stuff"), associated with the arrival of settlers who introduced these environmentally damaging species for sport fishing; they are now considered as ill omens that disturb native fish populations and the sacred status of the waters and their inhabitants (Aigo & Ladio, 2016). More positively, *Prosopis juliflora* is welcomed by many in Jordan, despite acknowledging its negative impacts, as a source of vegetation cover, fodder, firewood, and charcoal, and is known as Al salam ("the peace"; Al-Assaf *et al.*, 2020).

As noted above, diversity in perception may also occur within communities. In Chitwan National Park, Nepal, Tharu household socioeconomic characteristics influence the perceived value of invasive alien *Mikania micrantha* (bitter vine). Those families that were more dependent on forest products incurred more of both the costs and the benefits associated with *Mikania micrantha* than less forest dependent families (Murphy *et al.*, 2013; Rai & Scarborough, 2015). *Sus scrofa* (feral pig) in Northern Australia is similarly either vilified for its negative impacts on vegetation, soils, other wild foods, cultural heritage sites, and because it increases the spread of invasive alien *Lantana camara* (lantana), or highly valued as an important food source for those with lower socioeconomic status (Koichi *et al.*, 2012). Likewise, there are diverging perspectives on *Bubalus bubalis* (Asian water buffalo) and *Equus caballus* (horses) in Northern Australia, with many worried about damage to sacred sites and wild foods, while others benefit from them directly or want financial returns from animals when they are controlled (Ens *et al.*, 2016; **Chapter 4**, **Box 4.14**). Underemployed or low income Māori have benefited from invasive alien species, such as products from possums and pacific rats, while other Māori see them as both ecological and cultural threats (Peltzer *et al.*, 2019). Similarly, Hawaiian cattle (Fischer, 2007), and *Camelus dromedarius* (camels) and *Bubalus bubalis* in Australia (Vaarzon-Morel, 2010; Weston *et al.*, 2012) have been viewed in mixed fashion. Overall, the different perceptions within and between communities, caused by gender, age, knowledge status, livelihoods, and spirituality, result in a diversity of viewpoints on management and policy options for biological invasions (**Chapters 5** and **6**).

1.6.7.2 Good quality of life

Invasive alien species not only affect biodiversity and the ecological processes underpinning nature's contributions to people, but they also directly or indirectly affect good quality of life (or human well-being). Good quality of life is the achievement of a fulfilled human life, a notion which varies strongly across different societies and groups within societies. It is a context-dependent state of individuals and human groups, comprising access to food, water, energy and livelihood security; health, good social relationships; equity, security, cultural identity; and freedom of choice and action **(Table 1.4)**. Much of this provision is a result of nature's contributions to people **(Figure 1.12**; **Box 1.12)**, but its fair distribution and progressive attainment relies principally on governance arrangements and social capital/ infrastructure. Good quality of life and health encompass not just physical health, but psychological health, including the satisfaction created by cultural expression and stability, spiritual fulfilment, and reliable access to the resources necessary to thrive as a human being. Though people generally introduce alien species deliberately in order to improve their incomes, food security, or tangible material assets, invasive alien species can threaten good quality of life in various ways at both the individual and community level **(Box 1.9)**; but it can also be argued that efforts to manage invasive alien species can be seen in some cases as detrimental to good quality of life, especially if they involve the cessation of access to natural resources for some groups in society, or inappropriate use of hazardous chemicals. There are also clear cases where communities have adapted to invasive alien species (**Chapter 6**, **section 6.2.2.5**), sometimes because they lacked other options (IPBES, 2022a) and where this has enhanced local good quality of life. Although the preponderance of evidence suggests that invasive alien species are mainly viewed as threats and challenges to human communities, at least one recent study indicates that adaptation is a more dominant response than eradication efforts (Howard, 2019).

It follows that management techniques and policy development will likely benefit from taking into careful consideration the trade-offs among different constituents of good quality of life. For example, people might be willing to accept reductions in their resources, safety, health or lifestyle choices for what they consider a greater cause, such as community survival or national pride. Furthermore, communities will not necessarily be united in how they feel about the values of invasive alien species and associated detrimental or beneficial impacts (Kelsch *et al.*, 2020; Shackleton, Larson, *et al.*, 2019). Many citizens may feel quite neutral or are apathetic about the issue.

There is also the question of scale. While it is obvious that good quality of life encompasses individuals and small communities, it can also refer to national or even supranational identities, stability, survival and resilience. For example, framing invasive alien species as a local problem as opposed to a national security issue will have an impact on policy response options and levels of related resource allocation (Stoett, 2010). Ultimately, considering good quality of life across scales and linking levels of governance will improve the management of biological invasions (**Chapter 6**, **section 6.3.1.1**). **Table 1.4** below presents some examples of constituents of good quality of life which have been considered in the present assessment.

Another prominent element affecting good quality of life is the differentiation in status and access to resources related

Table 1 4 **Constituents of good quality of life and examples of their subcategories.**

The overarching premise for all constituents is the freedom of choice and action, that is, the opportunity to be able to achieve what a person values doing and being. Adapted from Bacher *et al.* (2018); Millennium Ecosystem Assessment (2005).

Constituents of human well-being	Examples
Safety – human security	Personal safety Gender equality Secure resource access Security from disasters Resilient communities
Material and non-material assets	Adequate livelihoods Sufficient nutritious food Shelter Access to goods Recreation
Health	Physical health Feeling well/psychological health Access to clean air and water Absence of infectious disease
Social, spiritual and cultural relations	Social, spiritual and cultural practice Social infrastructure and governance Environmental, social justice and equity Mutual respect Friendship Identity and autonomy
Freedom of choice and action	Control over events and actions

to gender. There is limited research on the interplay between gender relations and invasive alien species, but it is clear that women can be impacted differently in cases where they are expected to engage in many of the forms of labour that are most directly affected by invasive alien species, such as health care, firewood gathering, and the acquisition and use of water for cleaning, sanitation, or family consumption (Fish *et al.*, 2010; Shrestha, 2021). Women are often tasked with the difficult (and often futile) job of weeding by hand, which can take up valuable time better spent on other quality-of-life-related tasks and expose them to dangerous pesticides and herbicides (Terefe *et al.*, 2020). The sharp thorns of the invasive alien *Prosopis juliflora* (mesquite) shrub (native to Mexico, introduced in Ethiopia in 1999) harm the hands of women collecting fuel wood (Terefe *et al.*, 2020). It has also been suggested that personal safety can be compromised with the advent of invasive alien plants; for example, local reports of sexual assault under cover of dense stands of invasive alien *Acacia* spp. invasions have been made (Shackleton, Shackleton, *et al.*, 2019; de Neergaard *et al.*, 2005). More international research on the role of gender in invasive alien species identification, management, and monitoring is needed for a more nuanced perspective to emerge.

The succession of emerging zoonotic diseases in the early twenty-first century has led to the development of several holistic and interdisciplinary approaches to safeguard health. Current concepts such as Planetary Health, EcoHealth, and One Health (**Glossary**) stress the importance of understanding the links between human, animal, and environmental health, though with a strong emphasis on safeguarding the health of vertebrates (Lerner & Berg, 2017). The World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), and the World Organisation for Animal Health (WOAH, founded as OIE) provide international standards for human health, plant health, and animal health, respectively. Working together with the UNEP through a One Health High-Level Expert Panel (OHHLEP), they have jointly defined One Health as "an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems. This approach recognizes that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent. It mobilizes multiple sectors, disciplines and communities at varying levels of society to work together to foster well-being and tackle threats

Box 1 14 The role of invasive alien species in zoonotic disease transmission.

The relationship between invasive alien species and human health, particularly pathogenic microbes, and emerging infectious diseases (Pyšek, Hulme, *et al.*, 2020) is especially relevant in a decade which began with a global coronavirus disease (COVID-19) pandemic that killed close to 20 million people (The Economist, 2022), ravaged the world economy, and exacerbated inequality and poverty (Ritchie *et al.*, 2020). Invasive alien species can have serious implications for human health (Lazzaro *et al.*, 2018; Pyšek & Richardson, 2010): alien species can act as a vector of pathogens (e.g., *Aedes albopictus* (Asian tiger mosquito) for dengue fever; Brady & Hay, 2020; Hulme, 2014); produce allergenic pollen (*Ambrosia artemisiifolia* (common ragweed); Richter *et al.*, 2013); and be poisonous (e.g., *Rhinella marina* (cane toad); Bacher *et al.*, 2018) or venomous (e.g., sea jellies; Kideys & Gücü, 1995). Indeed, the COVID-19 pandemic has demonstrated the catastrophic consequences of ongoing environmental transformation, wildlife exploitation, and the movement of organisms in a globalized world (IPBES, 2020c; Nuñez *et al.*, 2020).

Parasites (including pathogenic bacteria, fungi and viruses) can be introduced into an invaded range alongside an invasive alien species (Bojko *et al.*, 2021; Dasgupta, 2021; Daszak *et al.*, 2000; Evans, 2003; Roy *et al.*, 2017). Additionally both introduced and endemic parasites can change the strength of interactions between species and ultimately affect the outcome of a biological invasion (Amsellem *et al.*, 2017; Dunn & Hatcher, 2015). Pathogens causing emerging infectious diseases (WHO, 2014), which spread into new host populations or species, are rarely treated as invasive alien species, but it is widely recognized that the introduction of novel organisms (those without evolutionary analogues in the recipient environment) have the potential to be incredibly disruptive (Nuñez *et al.*, 2020; Saul & Jeschke, 2015; Vilà *et al.*, 2021).

The role of invasive alien species in the transmission dynamics of emerging zoonotic diseases is often overlooked (Nuñez *et al.*, 2020; Vilà *et al.*, 2021) despite the interlinkages between human health and biodiversity loss having now been explored in great detail by the scientific community (Estrada-Peña *et al.*, 2014; Jones *et al.*, 2008; UNEP *et al.*, 2015; Wolfe *et al.*, 2007). Integrated approaches that take into account the landscapes and seascapes in which socio-ecological systems, including their human dimensions, are embedded, could be part of an effective collective response to the threats posed by invasive alien species and related pathogenic diseases. Invasive alien species are part of these broader systems, and the harm to human health which results from their spread and from emerging infectious diseases share many characteristics **(Figure 1.17)**. Pathogenic microbes which cause human epidemics and pandemics are highly successful invasive alien species, transmitted by human behaviour. Integrated interdisciplinary approaches will contribute to increased understanding of the interplay amongst factors driving disease transmission whether in humans, other animals or plants (Vilà *et al.*, 2021).

to health and ecosystems, while addressing the collective need for clean water, energy and air, safe and nutritious food, taking action on climate change, and contributing to sustainable development" (UNEP, 2021). There have been previous efforts to integrate biological invasions within the One Health approach (Conn, 2014; Hulme, 2020a; F. A. B. Meyerson *et al.*, 2009; L. A. Meyerson *et al.*, 2002; L. A. Meyerson & Reaser, 2002, 2003). However, despite the critical role invasive alien species can play as reservoirs and vectors of zoonotic diseases (**Box 1.14**; Hulme, 2014; Roy *et al.*, 2017, 2023), Planetary Health, EcoHealth, and One Health approaches have yet to systematically integrate the threat and impacts of biological invasions into their analyses (IPBES, 2020c; Chinchio *et al.*, 2020; Bertelsmeier & Ollier, 2020; Nuñez *et al.*, 2020; Vilà *et al.*, 2021). The acceptance of the One Health approach as appropriate by many governments and international organizations might change this, however. A more biosecurity-focused approach has also been suggested: "One Biosecurity" would integrate the One Health framework with the practical necessities associated with the provision of biosecurity, including the prevention of all invasive alien species (Hulme, 2020b; **Glossary**). One Biosecurity could be informed through a streamlined approach to the prediction of emerging biosecurity risks (whether pathogens, pests, or weeds), a global network of surveillance (**Glossary**) and information sharing, and coordinated international responses to incursions of invasive alien species. Such an approach could be underpinned by a regulatory framework that parallels the International Health Regulations of the WHO (Hulme, 2021) (**Chapter 6**, **section 6.7.2.2**).

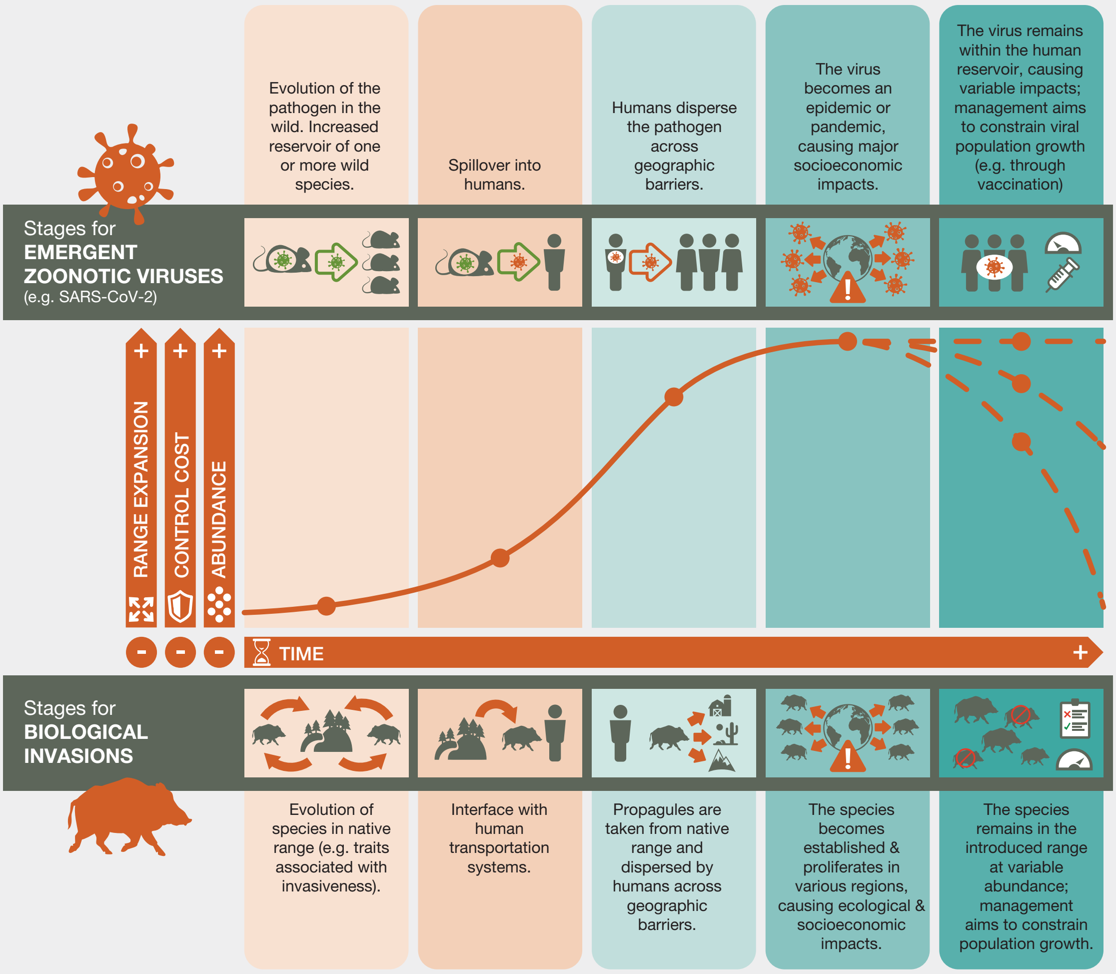


Figure 1 17 **Comparison of the stages of a zoonotic viral epidemic and those of a biological invasion.**

Source: Nuñez *et al.* (2020), https://doi.org/10.1016/j.tree.2020.05.004, under license CC BY 4.0.

1.6.7.3 Scenarios and modelling

Understanding the drivers and patterns of invasive alien species dynamics is crucial for designing and implementing appropriate management and monitoring strategies (Brundu & Richardson, 2016). There is a growing need to reconstruct the routes of introduction of invasive alien species (Estoup & Guillemaud, 2010; Gautier *et al.*, 2022) to predict biological invasions and effectively support different types of intervention, from early detection to management of established invasive alien species (S. A. Hall *et al.*, 2021; Van Wilgen *et al.*, 2011). Indeed, the importance of model- and scenario-based prevention and early detection has been highlighted in several policies including the European Union Regulation 1143/2014 on invasive alien species (European Union, 2014). Modelling approaches have been used to define coarse climatic envelopes for invasive alien species (Brundu & Richardson, 2016; Pino *et al.*, 2005), and reconstructing routes of biological invasions (Gautier *et al.*, 2022). Fine-scale species distribution modelling and prediction requires information on local environmental and habitat factors (Vicente *et al.*, 2011), as well as linking correlative models to demographic variables or demography-based population models (Kueffer *et al.*, 2013; Vicente *et al.*, 2019). The prevention, early detection and management of biological invasions will consequently benefit from increased knowledge, more informative predictions, and accurate and plausible future scenarios (Chornesky *et al.*, 2005; Genovesi & Monaco, 2013; Roura-Pascual *et al.*, 2021).

For invasive alien species, scenarios and models have been applied to inform understanding of how spatial-temporal patterns emerge (**Chapter 2**, **section 2.6.5**; **Chapter 4**, **section 4.7.1**), of which processes are underlying these patterns, and of how ecological, economic, and societal drivers relate to the emergence of the observed patterns (**Chapter 3**, **Box 3.14**). Scenarios and models differ in their approach to investigate historic, current, and future patterns of alien species richness, abundance and distributions. While models aim to predict alien species patterns based on how environmental, economic or social variables relate to species occurrence or abundance, scenarios are based on alternative possible future states of those variables resulting in projections of potential future patterns of biological invasions (IPBES, 2016c; Lenzner *et al.*, 2019; Roura-Pascual *et al.*, 2021). In the section below, scenarios and models are briefly contrasted in terms of how patterns and dynamics are analysed, the methods used, their different uses, and the advantages and disadvantages of each approach. A systematic review was undertaken to assess the current use of scenarios and models within the context of biological invasions.[12]

12. Data management report available at https://doi.org/10.5281/zenodo.5706520

Models

Models can be defined as "qualitative or quantitative representations of key components of a system and of relationships between these components".[13] There are four broad groups of model types (main model types) identified (IPBES, 2016c):

i. Expert-based models include any type of qualitative expert opinion (where experts are defined as a single person or group of people that hold specific knowledge of a process, species or system of interest). Experts may include scientists and other academics, relevant stakeholders and Indigenous Peoples and local communities (**section 1.6.7.1**).

ii. Correlative models (also called statistical models) use empirical data to estimate parameter values for processes that are implicit rather than explicit.

iii. Process-based models (also mechanistic models) explicitly integrate processes or mechanisms based on established scientific understanding.

iv. Hybrid models combine correlative and process-based modelling approaches.

Most papers identified through the systematic review used correlative models (57 per cent of 781 observations), followed by process-based models (33 per cent), hybrid models (8 per cent) and expert-based systems (1 per cent).

There are also interdisciplinary models and integrated assessment models (IPBES glossary[12]) that are used to describe the complex relationships between environmental, social and economic drivers (e.g., Havlík *et al.*, 2014) by integrating trans-disciplinary knowledge to capture large-scale dynamics, interactions and feedbacks of a specific system (Harfoot *et al.*, 2014). Integrated assessment models assess "wicked problems" which are highly complex, socioecological problems including many variables and actors (Termeer *et al.*, 2019). Currently, biological invasions are not included in existing global integrated assessment models, but such an integration would be highly beneficial (Lenzner *et al.*, 2019).

Further details, including opportunities and limitations, of these modelling approaches are provided in the data management report.

Scenarios

Scenarios are "representations of possible futures for one or more components of a system, particularly for drivers of change in nature and nature's benefits, including

13. IPBES glossary: https://ipbes.net/glossary

alternative policy or management options”.[14] Different types of scenarios can be identified and are applicable in specific contexts:

i. (Exploratory scenarios (also called “explorative scenarios” or “descriptive scenarios”) examine a range of plausible futures, based on pre-defined drivers and their assumed future trajectories starting from the present conditions.

ii. Target-seeking scenarios (also called “goal-seeking scenarios” or “normative scenarios”) have a clear objective or set of objectives for a point in time in the future (i.e., a specific target) and aim to describe plausible pathways to achieving this outcome. The procedure of developing such scenarios is called backcasting.

iii. Policy-screening scenarios aim to evaluate alternative policy or management options. They either follow a similar logic to target-seeking scenarios where a future policy goal is determined, or they can be developed through policy screenings (also called “ex-ante scenarios”). See the IPBES glossary and the methodological assessment report on scenarios and models of biodiversity and ecosystem services (IPBES, 2016c) for more detail.

Most of the papers identified through the systematic review focused on exploratory scenarios (87 per cent of papers), followed by policy-screening (7 per cent) and target-seeking scenarios (6 per cent). In most papers, scenarios were quantitative (82 per cent) as opposed to qualitative (9 per cent) or both quantitative and qualitative scenarios (8 per cent).

Overall, scenarios aim to provide a holistic view on global trends and processes and how they might shape the world’s future under different assumptions. For many drivers of change in nature (e.g., climate; IPCC, 2014) and socioeconomic domains (e.g., demography, land-use; Hurtt *et al.*, 2011), such scenarios have already been developed. However, biological invasion scenarios have not been available until recently (Corrales *et al.*, 2018; Dehnen-Schmutz *et al.*, 2018; Ricciardi *et al.*, 2017). The need for scenarios for short (2030), mid (2030-2050), and long-term (2050-2100) trends in alien species richness and distribution at various scales to inform targets has been recognized (Bellard *et al.*, 2013; Roura-Pascual *et al.*, 2021). Increasing data availability and increased understanding of (historic) trends, distribution and impacts of invasive alien species globally and locally makes the development of scenarios for biological invasions feasible (Lenzner *et al.*, 2019). Recently, the first alternative futures for biological invasions were published (Roura-Pascual *et al.*, 2021). Roura-Pascual and colleagues developed 16 different qualitative scenarios storylines, which can be grouped into four archetypes based on their description of potential futures. The scenarios develop potential future trajectories of the world until 2050 with a special focus on drivers relevant for biological invasions (Essl *et al.*, 2020) and projected changes in alien species richness.

14. IPBES glossary: https://ipbes.net/glossary

Moreover, recently IPBES has developed a framework for the creation of independent multiscale biodiversity scenarios for constructing pathways towards desirable futures for nature – the Nature Futures Framework (IPBES, 2022d). A distinguishing feature of the Nature Futures Framework, beyond classical environmental scenario frameworks, is the consideration of a plurality of perspectives and values towards nature within the scenarios, facilitating the assessment of different views on nature and ensuring the integration of these views through participatory approaches. While the Nature Futures Framework has not yet been applied in the context of biological invasions, it has considerable potential for exploring the role of invasive alien species in future biodiversity change across scales and contexts.

Scenarios and models in invasive alien species research

The scenarios and models’ liaison group undertook a systematic review[15] including an initial set of 30,299 research papers of which 778 research papers were found to consider both the use of models and scenarios to evaluate the patterns and trends of invasive alien species. The search was restricted to indexed publications in English, ensuring a structured, systematic approach to the use of the terms “invasive alien species”, “modelling” and “scenarios”. A summary of the outcomes is provided here with further information available in the data management report.14 In some cases, a single paper focused on multiple categories (e.g., a model applied to both the United Kingdom and Portugal), and these are categorized as separate observations. The information is summarized as either a percentage of papers or of observations.

Patterns and trends

The Americas was the IPBES region with the highest proportion of observations across all papers, with 33 per cent of all observations (total number of observations: 1,153), followed by Europe and Central Asia (26 per cent), Asia and the Pacific (24 per cent), Africa (13 per cent) and finally Antarctica (2 per cent). In 3 per cent of the papers, the IPBES region was not stated. Most papers focused on only

15. Data management report, including full output of the review, available at https://doi.org/10.5281/zenodo.5706520

one IPBES region (78 per cent of a total of 778 papers) and one country (70 per cent).

Most of the papers (63 per cent of all papers) were focused on only one invasive alien species with most focusing on invasive alien plants (including bryophytes; 40 per cent of observations from a total of 858 observations), followed by invertebrates (30 per cent), fishes (8 per cent), mammals (7 per cent), amphibians, birds and reptiles (3 per cent); and finally, fungi (2 per cent) or other invasive alien species taxa such as algae, bacteria, virus or protozoan (2 per cent). Furthermore, the majority of papers focused on only one particular IPBES unit of analysis (96 per cent of 778 papers), with the terrestrial environment dominating the literature extracted from the review with 75 per cent of observations (from a total of 813), followed by the freshwater (15 per cent) and the marine (8 per cent) environments. The impacts of invasive alien species were addressed in only 22 per cent of papers with most of these papers focusing on negative impacts (18 per cent of all papers). Invasive alien species pathways were considered in only 10 per cent of papers. Only 23 per cent of papers (n=182) considered invasive alien species management, and most papers focused on one (54 per cent) or two management strategies in combination (37 per cent).

The cross-cutting themes identified for the IPBES invasive alien species assessment were poorly represented in the papers with only 1 per cent considering Indigenous and local knowledge, 3 per cent considering good quality of life and 6 per cent including nature's contributions to people.

Further descriptive summaries and results from the review, including multidimensional scaling, illustrating the clustering of model and scenario features from across the papers, are available in the data management report.[16] Further specific detailed information from the review is included within the relevant chapters.

1.6.8 Key issues in the discussion of biological invasions

Throughout this assessment several key issues, some extant and some emerging, have been identified as critical to the discussion of biological invasions. The key issues identified within this assessment include the advent of **globalization**, the **impact of global environmental change** (and, in particular, the global biodiversity crisis), the **use of adaptation strategies**, the **role played by technology**, the **challenges for islands and protected areas**, and the **role micro-organisms play** in the broader understanding of invasive alien species.

16. Data management report available at https://doi.org/10.5281/zenodo.5706520

The most obvious issue is that of **globalization**, which has acted as an important overarching driver facilitating the unprecedented spread of invasive alien species that humans face today. There is a strong historical link between colonization by European powers and biological invasions, and the rise of global transport and trade has been a primary driver responsible not only for the transport and introduction of invasive alien species but also for the advent of biotic homogenization, which lowers resilience and increases vulnerability to further invasive alien species. Globalization is a catalyst exacerbating the problems of a human-dominated biosphere that has led to the Anthropocene, a world with biophysical systems profoundly shaped by human activity. The increasing levels of invasive alien species on a global scale are stark evidence of this era. At the same time, international instruments developed to prevent the spread of invasive alien species rely heavily on international organizations that are at least partially reflective of the process of globalization.

Another central key issue is the present and future **impact of global environmental change**, and the underlying direct and indirect anthropogenic drivers of change, not only on the spread and introduction success of invasive alien species but also on options for management (**Chapters 3** and **5**). Climate change and land and sea use, but also pollution (chemical, plastics, debris, etc.), ocean acidification, and other systems-level direct drivers of change in nature are currently shaping the Anthropocene, and driving, in particular, the loss of biodiversity (IPBES, 2019). Invasive alien species have long been identified as one of the primary drivers of this global biodiversity crisis, and they interact with other drivers of global environmental change to exacerbate it (**Chapters 3** and **4**).

The overarching issue of **human community adaptation** is noticeable as well: While invasive alien species can cause both harm and benefits, some human communities (at various scales, from rural areas to Indigenous Peoples and local communities to cities to regions) have in fact adapted to the presence of invasive alien species, and it is informative to see how, why, and in what forms this adaptation took place over time. This key issue, which is even more pertinent in the current era where climate change is forcing unprecedented adaptation and evolving survival strategies, is discussed more explicitly in **Chapter 6**, **section 6.2.2.5**. In some cases, the response to invasive alien species does not adequately deal with the threats they pose, and adaptation may be the only or the preferred policy response. It is important to note that prevention is an effective approach to managing invasive alien species and the costs of responding to biological invasions far outweigh the costs of prevention (Diagne *et al.*, 2021). However, in some cases, invasive alien species have become part of socio-ecological systems and are here to stay.

The evolving **role played by technology** is another key issue. The development of the steam engine enabled faster trans-ocean voyages involving ballast water usage, thus acting as a driver that accelerated pathways for

Box 1 15 **The role of citizen (or community) science in monitoring invasive alien species.**

Citizen science (also known as community science, participatory monitoring, community-based environmental monitoring, crowd science, crowd-sourced science, civic science, or volunteer monitoring) is a term that describes the diverse range of approaches in which scientific research is conducted, in whole or in part, by volunteers with varying levels of expertise (Gura, 2013; Pocock *et al.*, 2014, 2018). Citizen science is defined by the European Commission Green Paper as "general public engagement in scientific research activities where citizens actively contribute to science either with their intellectual effort, or surrounding knowledge, or their tools and resources" (Consortium, 2013; Follett & Strezov, 2015).

People contribute to biodiversity and ecosystem research through citizen science in diverse ways including providing data, raising new research questions, and communicating and disseminating findings. Citizen science can be broadly considered as contributory or collaborative (co-created). Within contributory citizen science, participants are primarily involved in data collection while through collaborative citizen science, participants are involved in various stages of the scientific process including identifying the scope and research questions through to interpreting and using the results. Citizen science not only results in scientific advances but is also known to increase public understanding of science by improving the scientific capacity of participants through skills acquisition and learning (MacPhail & Colla, 2020; Steven *et al.*, 2019).

There are many diverse approaches to surveillance and monitoring of invasive alien species. Citizen science is seen as particularly relevant for environmental monitoring and has a long history in many countries with some initiatives in Northern Europe and North America having been ongoing for more than a century (Allen, 1976; Miller-Rushing *et al.*, 2012; Pocock *et al.*, 2015). Many of the large-scale and long-term global biodiversity datasets have relied on contributions from volunteers. Indeed, citizen science is often used to engage people in scientific projects that may be impractical for individuals or small groups to conduct alone because of the need to gather or analyse "big data" (Willett *et al.*, 2013).

Volunteers have made substantial contributions to understanding biological invasions (Roy *et al.*, 2015) from documenting the arrival, establishment, and spread of alien species through to predicting potential new arrivals through horizon scanning (Roy *et al.*, 2020) and so contributing to early-warning. The breadth of expertise provided by taxonomic experts from volunteer biological recording communities is essential for horizon scanning. Prioritization of invasive alien species through horizon scanning can be used to inform mass participation approaches involving the public (or where relevant special interest groups such as anglers) in monitoring and surveillance underpinning early-warning.

The advent of mobile computing technologies in smartphones and tablets and the corresponding proliferation of mobile applications (apps) have greatly expanded the potential of citizen science for contributing to research on invasive alien species (Adriaens *et al.*, 2015). As mobile phones become increasingly ubiquitous (users now exceed 2.8 billion people worldwide; Alavi & Buttlar, 2019), citizen science is undergoing an unprecedented shift in the scale and quantity of available data (Silvertown, 2009; Teacher *et al.*, 2013). Popular biodiversity reporting apps like eBird (Sullivan *et al.*, 2014) and iNaturalist (Unger *et al.*, 2021) have user communities in the hundreds of thousands, generating enormous quantities of data for research (e.g., over 1 million records in iNaturalist in the first seven years; Pimm *et al.*, 2014). Invasive alien species reporting apps, which enable users to submit geotagged observations of invasive alien species, are an excellent new source of spatiotemporally explicit occurrence data for invasive alien species management and research, and seen as a major pathway to implementing surveillance and monitoring at national and global scales (Martinez *et al.*, 2020). The number of invasive alien species reporting apps available is steadily increasing, ranging from regional apps to those focused on particular taxa including aquatic organisms, insects, and plants (e.g., Goëau *et al.*, 2013; Laforest & Bargeron, 2011; Scanlon *et al.*, 2014; Wallace *et al.*, 2020).

Many mobile devices now include a variety of onboard sensors and instrumentation like barometers, gyroscopes, accelerometers, microphones, cameras and ambient light sensors, and the capability of storing data from these sensors and uploading it to online databases (Lane *et al.*, 2010). Onboard sensors are increasingly used to facilitate and even automate citizen science participation *via* invasive alien species apps, for example in bioacoustics surveys for invasive alien amphibians (Platenberg *et al.*, 2020). Artificial intelligence and machine learning, especially in image recognition, are further enhancing mobile app contributions to citizen science, by allowing for the automated identification of organisms in user-submitted images (Terry *et al.*, 2020). The steady improvement and increasing availability of online invasive alien species occurrence databases and their integration with mobile technology is another major and ongoing advance underpinning citizen science (Martinez *et al.*, 2020; Reaser *et al.*, 2020; Seebens *et al.*, 2020).

Science-society-policy interactions are developed through open and collaborative approaches amongst participants involved in citizen science (Powell & Colin, 2009; Gardiner & Roy, 2022). Collaborative research outcomes, resulting from open, networked and transdisciplinary citizen science approaches, can ultimately contribute to democratic decision-making.

the transport of invasive alien species (sailing ships also needed ballast but used soil, which itself carried invasive alien species but at slower delivery times) (**Chapter 3**, **section 3.2.3**). Modern technology (including genetics/genomics, informatics, and drone surveillance) is facilitating the transport of alien species around the globe *via* e-trade (**Chapter 3**, **sections 3.2.3** and **3.2.4**), but are also being used in new and inventive ways to discover, track, and manage invasive alien species and their impacts (**Chapter 5**). New online tools and technologies, particularly new data streams and data integration methods, will increase capacity to deliver a global monitoring and decision-support system for managing biological invasions (Martinez *et al.*, 2020; McGeoch & Jetz, 2019). Relatedly, communication strategies in the internet age have emerged as fundamental as people share new information about identifying and dealing with invasive alien species. Citizen science (**Glossary**), including approaches that encompass visual identification technologies and other innovations, has become a popular and valuable approach to underpin research and policy on biological invasions and invasive alien species (**Box 1.15**; Encarnação *et al.*, 2021; Roy *et al.*, 2015).

Insular environments, from oceanic islands and deep sea hydrothermal vents to freshwater systems and fragmented habitats, have provided insights into the relationships between geographic patterns and biological processes (D. R. Drake *et al.*, 2002). Such insular systems feature prominently in this assessment. Islands, especially SIDS, are considered particularly vulnerable to invasive alien species because of the difficulty of prevention where globalization, including mass tourism, has become deeply integrated into island economies. Invasive alien species on islands have been shown to have some of the most detrimental impacts compared to continental ecosystems, including the extinction of many endemic species (e.g., Bellard *et al.*, 2016; Pyšek, Blackburn, *et al.*, 2017). Indeed, invasive alien species are ranked as the leading cause of biodiversity loss on islands (Bellard *et al.*, 2016; Russell *et al.*, 2017). However, there are many examples whereby management of invasive alien species, including approaches to prevent arrival and eradication of specific taxa, has proven successful on islands (**Chapter 5**; Courchamp *et al.*, 2003; Russell *et al.*, 2017).

While most invasive alien species tend to thrive in anthropogenically disturbed ecosystems, some species are able to reach even the most remote and well conserved areas, including those formally declared as **protected areas** (Liu *et al.*, 2020; **Chapter 4**, **section 4.3.1.2**). Indeed, it is clear that the establishment of protected areas, in both terrestrial and marine environments, does not preclude the unintentional introduction and spread of invasive alien species, such as those associated with illegal wildlife trade and other activities such as fishing and recreation without high biosecurity standards. Indeed, there are concerns that biological invasions are insufficiently considered when devising management plans for marine protected areas in particular (Galil, 2017; Giakoumi *et al.*, 2016). Furthermore, historic or current intentional introductions such as through afforestation projects associated with climate change mitigation efforts can pose a threat to protected areas worldwide (Richardson, 1998), and ecosystem restoration projects also face similar concerns.

Another important key issue within biological invasions is the consideration of **microorganisms**, from virus to protozoa, including the links between invasive alien species and plant, animal, and human diseases including zoonotic diseases such as COVID-19, H1N1 flu (swine flu) and viral haemorrhagic fever (Ebola; **Box 1.14**). Such microorganisms have profound implications for good quality of life (Amsellem *et al.*, 2017) and biosecurity (Hulme, 2020a), and create space for further discussions of ecosystem-based and One Health approaches.

These key issues are relevant to natural science, social science, the humanities and policy developments, and will likely shape the evolution of our understanding of the biological invasion process in the years to come.

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