Chapter 1[1]: Introducing biological invasions and the IPBES thematic assessment of invasive alien species and their control

Supplementary materials

[1] This is the final text version of the supplementary material of Chapter 1 of the IPBES Thematic Assessment Report on Invasive Alien Species and their Control (https://doi.org/10.5281/zenodo.7430682)

Supplementary material 1.1. Categorization of stakeholders

This description of all categories of (1) influencing stakeholder and (2) affected stakeholder groups complements **section 1.5.1**.

Influencing stakeholder group

Vector-stakeholders are stakeholders whose activities physically move an invasive alien species along an invasion pathway, intentionally or not, including, for example, logistics actors involved in the import-export of commodities, workers, and resource owners or users (e.g., livestock owners, fishers, recreationists) moving equipment or other material. A wide range of supply chains involving numerous stakeholders gradually aggregate towards a smaller number of logistics actors. Vector-stakeholders may be implicated in ongoing introduction-spread-introduction cycles, but they have no direct stake in later invasion stages.

Governors are stakeholders who set formal and informal rules or establish norms that guide and drive the behaviour and practices of others. Formal rules may flow from trade agreements or legislation, while informal rules may take the form of organizational guidance, industry best practice codes, standard operating procedures, or even marketing arrangements; but someone makes pivotal decisions about which actions are taken or not, thus defining the priorities intrinsic to biosecurity and invasive alien species management including surveillance regimes, inspection, phytosanitary practices, and resource allocation. Pre-pathway governors undertake a wide range of relevant policy-making and standard-development that set the context of invasions. As invasive alien species move towards and cross jurisdictional boundaries, local scale governors implement specific protocols and rules aimed at limiting the opportunities for invasive alien species movement and establishment. Further rules, guidance, and norms are involved as containment (see **Glossary**) and mitigation actions are undertaken, such as movement controls, outbreak management protocol development (often in concert with 'monitors'), and legal notification. When human adaptation is required (see **Chapter 6**, **section 6.2.3.5**), governors may generate rules that enable affected stakeholders to 'learn to live' with new species, managing impacts and adopting less vulnerable practices.

Monitors are stakeholders with the knowledge and skills necessary to predict, identify, and detect invasive alien species, and who organize surveillance, undertake tests to identify invasive alien species, deliver research, conduct surveillance, or share information. Pre-pathway, monitors may engage in knowledge generation and sharing, horizon-scanning, and risk analysis; later, monitors may design protocols, sanitation procedures, and data production protocols. Once invasive alien species are established, monitors are integral to targeted surveillance, diagnostics, and outbreak planning, and may engage in adaptive research and testing of management solutions. Finally, when humans must adapt to invasive alien species, monitors often have the capabilities to support the creation of resilient environments and effective mitigation measures.

Managers possess the skills, competencies, and technology required to undertake 'on-the-ground' responses to invasive alien species – including treatment of infested or infected material and all types of cultural, mechanical, manual, chemical, and biological control. **Chapter 5**, **sections 5.4.3** and **5.4.4** give an overview of several current and future technologies. Managers might come from public bodies, non-governmental organizations, and the private sector, and many are resource managers such as farmers and fishers. Manager behaviours and actions shift from preparedness (e.g., enabling biosecurity, see **Glossary**, through technology transfer) to sanitation and quarantine actions early in a pathway, through to invasive management (e.g., mitigation, eradication, and restoration). If long-term establishment of an invasive alien species occurs, some managers may be involved in ongoing mitigation of impacts, while other Managers could take action to establish and maintain socio-ecosystems that are resilient to invasive alien species.

Networkers are those stakeholders with the capacity to disseminate information and key messages between actors relevant to invasive alien species management. They can also play important bridging or 'Network Administrative' roles, connecting other stakeholders with differing perspectives and operating at different scales. Trade bodies and associations often occupy this position, as do government or non-governmental agencies; as invasions progress, there is considerable variation in relation to the nature of the information required, its scale of delivery, and its intended audience, a shift from preparatory behaviours at broad scales, such as engagement in risk analysis, creating or convening networks for consensus building, design of interventions, surveillance and coordination, to rapid dissemination of alerts at the point of potential introduction, and then to information sharing and facilitating collaboration where containment, eradication, or mitigation of an invasion is needed.

Affected stakeholder group

Many stakeholders may or may not have a functional role to play in biological invasions governance and management, but their interests are nevertheless directly or indirectly affected, as they experience either losses or gains from invasive alien species or from management actions.

Value losers are stakeholders for whom nature's contributions to people and good quality of life are reduced by invasive alien species or by management responses to invasive alien species. This category may consist of a very wide range of stakeholders, as invasive alien species may negatively affect the monetary or nature's-contributions-to-people value of natural resources, the cultural qualities of landscapes, and the biodiversity value of ecosystems.

Cost losers are those 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. These direct costs can be incurred in addition to the loss of existing value (i.e., cost losers may often also be value losers). Cost losers commonly consists of landowners, residents, and public bodies that are legally responsible for the management of invasive alien species affecting their resources.

Collateral losers are those who lose value indirectly as a consequence of invasive alien species impacts or, importantly, their management. This can include, for example, reputational damage to contractors or public bodies resulting from poor invasive alien species policy or management, perceived or actual losses of nature's contributions to people or good quality of life due to non-target effects of management (such as from pesticide use), or reduced attractiveness (e.g., for tourism or recreation) of specific environments affected by invasive alien species. There are value losses prior to introduction, including biosecurity implementation costs (e.g., treatment of raw materials or transport media), and opportunity losses through exclusion of actors from import-export within known invasive source regions. At later stages, when invasive alien species have begun to impact on new environments or when management is implemented, new value losers and losses emerge, as can also occur as the need to live with an invasive alien species becomes clear (e.g., the need to invest in more resilient livelihoods, economic activities or biosecurity measures).

Outcome winners are those for whom invasive alien species, or their management, produce benefits. Some species are introduced because they provide nature's contributions to people for specific stakeholder groups, while other stakeholder groups are able to turn harm into benefit, for example by using invasive alien species for bioenergy. While invasive alien species management creates cost losers, managers may benefit by obtaining income from control work, manufacturing materials and equipment used in control, or selling chemicals and pesticides. Monitors may benefit through contracts to investigate invasive alien species and their impacts. 'Winner' stakes may be created by pre-pathway research, innovation and development processes, but are most obvious at later stages of invasion when the impacts and potential outcomes of invasion emerge.

Contributors are similar to outcome winners, but with generally fewer direct connections to and knowledge of invasive alien species. These are individuals and groups engaged in activities that are beneficial to them (particularly economic behaviours) that are implicated in invasions – particularly behaviours that drive supply chains and pathways. Contributory activities are broad and most obviously include trade and consumption. Perhaps the clearest examples are stakeholders engaged in the trade of commodities such as live plants or animals, but also those engaged in tourism. This stakeholder category perhaps does the most to highlight the importance of the widespread behaviours and values that are intrinsic to invasive alien species issues. Contributory behaviours occur primarily in the earliest stages of invasion – especially in value creation activities (demand creation and marketing) and consumer choice.

Supplementary material 1.2. IPBES conceptual framework

This description of the IPBES conceptual framework is extracted from Díaz et al. (2015) and complements **section 1.6.1**.

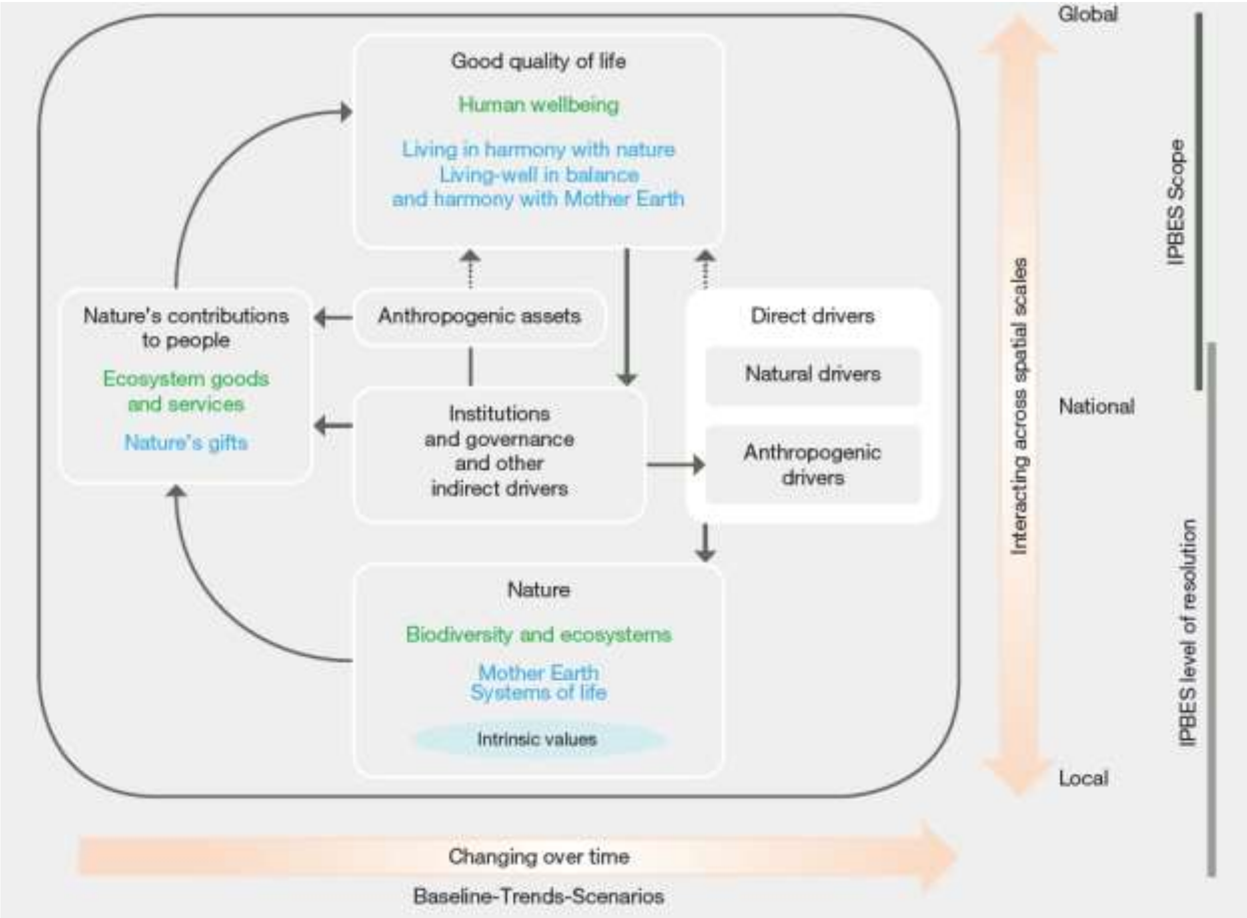

Figure SM.1.1. The IPBES conceptual framework. Source: Díaz et al. (2015), https://doi.org/10.1016/j.cosust.2014.11.002, under license CC BY-NC-SA 3.0.

The IPBES conceptual framework is a highly simplified model of the complex interactions between the natural world and human societies. The model identifies the main elements (boxes within the main panel outlined in grey), together with their interactions (arrows in the main panel), that are most relevant to the Platform's goal. "Nature", "nature's contributions to people", and "good quality of life" (indicated as black headlines and defined in each corresponding box) are inclusive categories that were identified as meaningful and relevant to all stakeholders involved in IPBES during a participatory process, including various disciplines of the natural and social sciences and the humanities, and other knowledge systems, such as those of Indigenous Peoples and local communities. Text in green denotes scientific concepts, and text in blue denotes concepts originating in other knowledge systems. The solid arrows in the main panel denote influence between elements, and dotted arrows denote links that are acknowledged as important, but that are not the main focus of the Platform. The thick coloured arrows below and to the right of the central panel indicate the scales of time and space, respectively. This conceptual framework was accepted by the Plenary in decision IPBES-2/4, and the Plenary took note of an update presented in IPBES/5/INF/24 and in decision IPBES-5/1. Further details and examples of the concepts defined in the box can be found in the **Glossary** and in **Chapter 1**.

Nature, in the context of the Platform, refers to the natural world, with an emphasis on biodiversity. Within the context of science, it includes categories such as biodiversity, ecosystems, ecosystem functioning, evolution, the biosphere, humankind's shared evolutionary heritage, and biocultural diversity. Within the context of other knowledge systems, it includes categories such as Mother Earth and systems of life. Other components of nature, such as deep aquifers, mineral and fossil reserves, and wind, solar, geothermal and wave power, are not the focus of the Platform. Nature contributes to societies through the provision of contributions to people.

Anthropogenic assets refers to built-up infrastructure, health facilities, knowledge (including indigenous and local knowledge systems and technical or scientific knowledge, as well as formal and non-formal education), technology (both physical objects and procedures), and financial assets, among others. Anthropogenic assets have been highlighted to emphasize that a good life is achieved by a co-production of benefits between nature and societies.

Nature's contributions to people refers to all the contributions that humanity obtains from nature. Ecosystem goods and services, considered separately or in bundles, are included in this category. Within other knowledge systems, nature's gifts and similar concepts refer to the benefits of nature from which people derive good quality of life. Aspects of nature that can be negative to people (detriments), such as pests, pathogens or predators, are also included in this broad category.

Nature's regulating contributions to people refers to 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. For example, these contributions include water purification, climate regulation and the regulation of soil erosion.

Nature's material contributions to people refers to substances, objects or other material elements from nature that sustain people's physical existence and the infrastructure (i.e., the basic physical and organizational structures and facilities, such as buildings, roads, power supplies) needed for the operation of a society or enterprise. They are typically physically consumed in the process of being experienced, such as when plants or animals are transformed into food, energy, or materials for shelter or ornamental purposes.

Nature's non-material contributions to people refers to nature's contribution to people's subjective or psychological quality of life, individually and collectively. The entities that provide these intangible contributions can be physically consumed in the process (e.g., animals in recreational or ritual fishing or hunting) or not (e.g., individual trees or ecosystems as sources of inspiration).

Drivers of change refers to all those external factors that affect nature, anthropogenic assets, nature's contributions to people and good quality of life. They include institutions and governance systems and other indirect drivers, and direct drivers (both natural and anthropogenic).

Institutions and governance systems and other indirect drivers are the ways in which societies organize themselves and the resulting influences on other components. They are the underlying causes of environmental change that are exogenous to the ecosystem in question. Because of their central role, influencing all aspects of human relationships with nature, they are key levers for decision-making. “Institutions” encompasses all formal and informal interactions among stakeholders and the social structures that determine how decisions are taken and implemented, how power is exercised, and how responsibilities are distributed. To varying degrees, institutions determine the access to and control, allocation and distribution of the components of nature and of anthropogenic assets and their contributions to people. Examples of institutions are systems of property and access rights to land (e.g., public, common-pool or private), legislative arrangements, treaties, informal social norms and rules, including those emerging from indigenous and local knowledge systems, and international regimes such as agreements against stratospheric ozone depletion or for the protection of endangered species of wild fauna and flora. Economic policies, including macroeconomic, fiscal, monetary or agricultural policies, play a significant role in influencing people’s decisions and behaviour and the way in which they relate to nature in the pursuit of benefits. However, many of the drivers of human behaviour and preferences, which reflect different perspectives on a good quality of life, work largely outside the market system.

Direct drivers, both natural and anthropogenic, affect nature directly. “Natural drivers” are those that are not the result of human activities and are beyond human control. These include earthquakes, volcanic eruptions and tsunamis, extreme weather or ocean-related events such as prolonged drought or cold periods, tropical cyclones and floods, the El Niño/La Niña Southern Oscillation and extreme tidal events. The direct anthropogenic drivers are those that are the result of human decisions, namely, of institutions and governance systems and other indirect drivers. Anthropogenic drivers include habitat conversion, e.g., degradation of land and aquatic habitats, deforestation and afforestation, exploitation of wild populations, climate change, pollution of soil, water and air and species introductions. Some of these drivers, such as pollution, can have negative impacts on nature; others, as in the case of habitat restoration, or the introduction of a natural enemy to combat invasive species, can have positive effects.

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, and also health, good social relationships and equity, security, cultural identity, and freedom of choice and action. From virtually all standpoints, a good quality of life is multidimensional, having material as well as immaterial and spiritual components. What a good quality of life entails, however, is highly dependent on place, time and culture, with different societies espousing different views of their relationships with nature and placing different levels of importance on collective versus individual rights, the material versus the spiritual domain, intrinsic versus instrumental values, and the present time versus the past or the future. The concept of human well-being used in many western societies and its variants, together with those of living in harmony with nature and living well in balance and harmony with Mother Earth, are examples of different perspectives on a good quality of life.

Reference

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J. R., Arico, S., Báldi, A., Bartuska, A., Baste, I. A., Bilgin, A., Brondizio, E., Chan, K. M., Figueroa, V. E., Duraiappah, A., Fischer, M., Hill, R., … Zlatanova, D. (2015). The IPBES Conceptual Framework—Connecting nature and people. *Current Opinion in Environmental Sustainability*, *14*, 1–16. https://doi.org/10.1016/j.cosust.2014.11.002

Supplementary material 1.3. IPBES units of analysis

Table SM.1.1. IPBES units of analysis: complement to **section 1.6.5**.
Source: IPBES (2019)

Unit (Terrestrial)	**Definition**
1. Tropical and subtropical dry and humid forests	Includes humid and dry broadleaf forests centred between the tropics and subtropical latitudes, and tropical and subtropical coniferous forests. Humid forests are characterized by low variability in annual temperature and high levels of rainfall (>2,000 mm annually); forest composition is dominated by evergreen and semi- evergreen tree species. Dry forests occur in climates that are mostly warm year-round, with annual rainfall ranging from 200 to 1,500 mm. There is a well-defined dry season which can last several months and vary with geographic location. Semi-deciduous and deciduous trees predominate in these forests. Tropical and subtropical coniferous forests are found predominantly in North and Central America. They experience low levels of precipitation and moderate variability in temperature. They are characterized by diverse species of conifers, whose needles are adapted to deal with the variable climatic conditions.
2. Temperate and boreal forests and woodlands	Boreal and temperate forest biomes experience a continental climate, with growing seasons of <130 days and >140 days, respectively. Both can be of coniferous (spruce, fir, larch, or pine) and/or deciduous (broad-leafed, angiosperm) trees. At high latitude montane forests and in the north, these forest biomes border on the tundra. Both forest types are disturbance-driven, mostly from fires, wind, and insect infestations. In the boreal where fire return intervals vary widely (<50 years to >500 years), these result in a large-scale mosaic. Temperate deciduous forests are divided into sub-classes depending on the relative amount of annual rainfall. Temperate rain forests are characterized by mild winters, with abundant precipitation, mostly as rain. They are seldom subject to catastrophic wildfires, therefore often attain the climax stage of old-growth forests. In northern temperate rain forest, coniferous trees are dominant, whereas in the southern hemisphere deciduous species are also common or dominant.
3. Mediterranean forests, woodlands and scrub	Mediterranean forests, woodlands, and scrub are fire-prone ecosystems with typically dry (and generally hot) summer and rainy (and generally mild) spring and winter. They occur across 22 countries in five continents: southern Europe and northern Africa (Mediterranean Basin), South Africa (Western Cape), Northwestern America (e.g., California chaparral), Southern America (Chilean matorral), and Southern Australia. Vegetation types include coniferous or (mostly evergreen) broadleaf forests and woodlands, savannahs and grasslands, scrublands and mosaic landscapes, resulting from a strong interaction between heterogeneous environmental conditions and a long-lasting influence of human activities and wildfires. Mediterranean ecosystems

	support an extremely high diversity of unique animal and plant species, most of them adapted to the stressful conditions of long, hot, and dry summer.
4. Tundra and high mountain habitats	Tundra is an ecological community of mosses, lichens, herbs, and dwarf shrubs living under extreme conditions of cool summers and very cold winters. In the treeless plains of Arctic Europe, Asia, and North America, arctic tundra is underlain by a permanently frozen subsoil hundreds of meters deep (permafrost) which is absent under the mountain tundra found at high altitudes of the world's mountains. Mountain tundra is found at altitudes above the treeline and may include extensive grasslands. Shrubs are characteristic plants of tundra but these become smaller and are even absent at high latitudes and high altitudes. Plant production is relatively high in arctic tundra because permafrost restricts drainage and thus keeps surface layers moist. Migratory animals such as caribou/reindeer, fish, and millions of geese and other birdlife take advantage of summer plant growth and few predators to reproduce and grow in the arctic tundra. *Similarities with Notes in relation to other units:* this unit is distinguished from the cryosphere as being characterized by vegetation cover.
5. Tropical and subtropical savannas and grasslands	This unit comprises large expanses of land in tropical and subtropical latitudes characterized by a discontinuous tree canopy in a continuous grass layer, although tree cover is highly variable, ranging from few scattered trees to fairly dense woodlands. Annual rainfall ranges between 350-1,500 mm, concentrated in the warm season. However, there may be great variability in soil moisture throughout the year. Herbivory by large- and medium- sized mammals that have evolved to take advantage of the ample forage, as well as periodic fires are distinctive features of these habitats. *Notes in relation to other units:* subtropical shrublands are included in unit 7 (Deserts and Xeric shrublands). Some parts of these two units may overlap, as it is common for some areas of the subtropical savannas to be described as xerophytic shrublands.
6. Temperate grasslands	Temperate grasslands occur where seasonal climates and soils favour the dominance of perennial grasses and related life forms. They are distributed mainly in the middle latitudes with differing names across continents. Steppes, prairies, pampas, and veld areas, but also including (semi-) natural (ancient or primary) grasslands and forest-steppes, wood-pastures, temperate savannas, and open shrublands in the regions of Temperate and Boreal broadleaved, mixed, and coniferous forests; Mediterranean regions; and of mountains below the timberline.

	Notes in relation to other units: this unit excludes tundra and grasslands above the timberline (unit 4). Many temperate grasslands have been transformed into agricultural grasslands, which are included in unit 10 (cultivated areas).
7. Deserts and xeric shrublands	This unit comprises large expanses of land in tropical and subtropical latitudes characterized by sparse often discontinuous vegetation and large portions of bare soil. Deserts and xeric habitats are characterized by severe shortage of water. Two sub-units can be distinguished: deserts with annual rainfall below 200 mm and steppe or shrublands with annual rainfall that ranges between 200 and 350 mm, concentrated in the cool season. Both steppe and deserts can have a dense herbaceous/grassy vegetation after the rains for a relatively short period of the year. Deserts may be hot or cold, mainly dependent on altitude. High mountain deserts can be found in the rain shadows of the Himalayas and Andes regions. Herbivory by large- and medium-sized mammals that have evolved to accommodate to these dry and sparse vegetation conditions is a distinctive feature of these habitats. *Notes in relation to other units:* this unit excludes Antarctica (unit 12, cryosphere), though it meets some of the criteria of a cold desert.
8. Wetlands – peatlands, mires, bogs	Wetlands are permanent or temporary, freshwater, brackish, and marine areas not deeper than 6 m (bogs, swamps, marshes, estuaries, deltas, peatlands, potholes, vernal pools, fens, and other types, depending on geography, soil, and plant life). Wetlands are areas where water covers the soil, or is present either at or near the surface of the soil all year or for varying periods of time during the year. Water saturation by groundwater, precipitation, surface waters, and ocean tides largely determines how frequently or continually the soil is inundated and develops and the types of plant and animal communities living in and on the soil. These are neither aquatic nor terrestrial systems, but transitional ones. Includes natural and constructed permanent forest-covered inland marshes and wet meadows (dominated by herbaceous plants), swamps (dominated by shrubs), wooded swamps (dominated by trees), seasonal freshwater wetlands (playa lakes, vernal pools, potholes, marshes), seawater and freshwater tidal swamps and marshes, estuaries, areas linked to estuaries or beyond the upper edges of tidal salt marshes where the influence of salt water ends, and unforested mires such as bogs, fens, and other peatlands.
9. Urban/Semi-urban	Although urban and semi urban areas are a tiny fraction of the world's surface, they are the nexus of human activity with >50% of the population and 70 - 90% of economic activity. The functional urban area (FUA) is defined as a city plus its commuting zone by the European Union and the Organisation for Economic Co-operation and Development (OECD). This was formerly known as larger urban zone (LUZ). Urban and semi-urban areas are places dominated by the built environment, including all non-vegetative and human-constructed elements, of a given landscape unit. In general, global urban area lacks a consistent, unambiguous definition. There are approaches from different perspectives that draw on a combination

	of satellite imagery, census information, and other maps. In this assessment the unit is mapped from European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover dataset (value=190).
10. Cultivated areas (incl. cropping, intensive livestock farming etc.)	Cultivated systems can be defined as areas in which at least 30% of the landscape is in croplands, shifting cultivation, or confined livestock production in any particular year. These can include farms, orchards, rangeland, and other agricultural concerns. The defining characteristic is the level of alteration. Very heavily managed agro-ecosystems involve the planting of non-native crop species or rearing of livestock, the introduction of non-native plants often to the detriment of native species, irrigation to augment water, and boosting of production by nutrient addition through fertilizers. There are also less heavily managed agro-ecosystems, often based on local rainfall and few nutrient inputs, which do allow native wildlife species to thrive alongside those species introduced for commercial purposes, and shifting cultivation systems. Rangelands grade into natural grasslands depending on intensity of use/alteration, and may include a mix of densely populated areas with areas used for pasture. *Notes in relation to other units:* fishery production areas and commercial forests are not included in this Unit. Fisheries occur in the ocean units (14, 15, and 16) as well as in aquaculture areas (unit 12). Commercial forests cannot be discriminated on a global scale from natural forests (units 1 and 2), so cannot reliably be mapped separately, even though by their characteristics would fit in this unit.
11. Cryosphere	The cryosphere consists of regions where the temperature is so low that water exists primarily in a frozen state most of the time, that is, the polar regions, glaciers, and alpine regions. It also includes non-ice-covered areas where temperatures are below freezing. It contains many highly unique habitats / ecosystems such as sea ice, ice shelves, the extreme cold and dry regions of Antarctica including the Antarctic dry valleys and the sub- glacial/ice sheet lakes (e.g., Lake Vostok). Organisms inhabiting sea ice overlap in terms of species occurrences considerably with Shelf ecosystems and Open ocean pelagic systems. *Notes in relation to other units:* Permafrost (permanently frozen subsoils) are included in the tundra and high mountain unit (4). The cryosphere (unit 11) includes sea ice and ice shelves, but the sea below or adjacent to them falls into unit 15 or 16 (according to the position of the compensation depth).
12. Aquaculture areas	Aquaculture is the farming of aquatic organisms and involves direct intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Aquatic organisms which are harvested by an individual or corporate body which has owned them throughout their rearing period contribute to aquaculture, while those exploitable as a common property resource are the harvest of fisheries. Aquaculture areas are thus any area of land, freshwater, or marine water that is used in the production of cultured aquatic organisms.

	Notes in relation to other units: in some other schemes, freshwater aquaculture is included in cropland (unit 10), but the coverage of terrestrial, freshwater, and marine for the Global Assessment makes it more consistent to group in this unit.
13. Inland surface waters and water bodies/freshwater	Inland waters are permanent above-ground freshwater, deeper than 6 m water bodies (e.g., lakes, rivers, reservoir/ponds, reservoirs, water courses) including their littoral zones, supporting a natural community of both plants and animals. Littoral zones include those parts of banks or shores that are sufficiently frequently inundated to prevent the formation of closed terrestrial vegetation. *Notes in relation to other units:* inlets, estuaries and temporary seasonal, or intermittent rivers, lakes, and flooded areas are NOT included in this definition of inland waters (see units 8 (wetlands/peatlands/bogs) and 14 (shelf, marine ecosystems)).
14. Shelf ecosystems (neritic and intertidal/littoral zone)	In-shore pelagic and benthic systems extending from the coastline to the 200 m depth contour, entirely within the photic zone where Net Primary Production is positive. At the coast the unit includes the intertidal/littoral zone to the Mean High Tide Water Line including estuaries and inlets. The boundary with open ocean systems at the 200 m contour is a gradient rather than a discrete transition. In Antarctica, the 500 m depth contour is a more natural boundary for this unit. The unit contains many highly productive and biodiverse pelagic and benthic habitats intensively used by people for multiple services, including food, shelter, and transport, such as coral reefs, seagrass meadows, and mangroves. *Notes in relation to other units:* inshore polar regions with permanent ice are placed in the cryosphere (unit 11), floating above, or beside, this unit; freshwater coastal rivers/lakes and wetlands (units 8 and 13) may form a boundary with estuaries in this unit; shelf systems intensively/multiply used by man are separated from this unit into unit 17.
15. Open ocean pelagic systems (euphotic zone)	This unit covers the open ocean beyond the 200 m depth contour on the seabed (500 m in Antarctica), and from the surface to 200 m deep. The 200 m limit is known as the maximum for the compensation depth, where sunlight is reduced to 1% of surface levels. Above this, phytoplankton growth is sustained depending on nutrient supply and surface water stratification. In this so-called euphotic zone Net Primary Production is positive, supporting almost the entire marine food web. Open ocean pelagic systems include highly productive and oligotrophic (low productivity) waters, as well as sea-ice-covered polar seas. *Notes in relation to other units:* the boundary between this unit and shelf ecosystems (unit 14) is a gradient rather than a discrete transition. Units 15 and 16 are vertically layered throughout their range, and are linked by biogeochemical pelagic-benthic coupling and vertical migration of organisms. The boundary between them is of significant ecological but low physiological

	relevance since species are specifically adapted to pressure (http://www.marinespecies.org/deepsea/). The cryosphere (unit 11) includes sea ice and ice shelves, which may extend over this unit. The sea ice is habitat of a variety of marine organisms ranging from microorganisms to birds and mammals.
16. Deep sea	The permanently dark off-shore open ocean beyond and deeper than the 200 m depth contour on the seabed (beyond 500 m in Antarctica). The unit is entirely below the compensation depth, where no light-dependent Net Primary Production occurs. The deep sea includes the dark pelagic zones and the upper 1 m of the sea- floor sediment. It comprises a variety of different habitats such as continental slopes, vents, and seamounts. *Notes in relation to other units:* partially overlaps with shelf ecosystems (unit 14) because most boundaries between marine ecosystems are gradients rather than discrete transitions. Units 15 and 16 are vertically layered throughout their range, and are linked by biogeochemical pelagic-benthic coupling and vertical migration of organisms. The boundary between them is of significant ecological but low physiological relevance since species are specifically adapted to pressure (http://www.marinespecies.org/deepsea/).
17. Coastal areas intensively and multiply used by human	Coastal zones are the land-sea interface and defined as "a strip of land and sea of varying width depending on the nature of the environment, human uses and management needs". Currently, 2.5 billion people live within 100 km of the coast, placing a disproportionate stress on coastal and marine ecosystems. Intense multiple uses result in physical and biological restructuring mainly through (i) urban expansion and increased human population density, (ii) the fishing and aquaculture industry, (iii) maritime transport and associated infrastructure, and (iv) tourism and associated accommodation and facilities. These developments are associated with protection infrastructure (breakwaters, groynes, sea walls, etc.) as a reaction to the dynamic nature of the shoreline. *Notes in relation to other units*: heavily-altered and multiply-used areas that are focused on biological function for aquaculture are included in unit 12, Aquaculture areas. There may be some difficulty in separating this unit from unit 9, Urban/semi-urban, as many of the structures defined here will be contiguous with it. Operationally, this unit will be mapped as a linear feature of the coastline, based on the adjacency of units 9 (urban/semi-urban areas), 10 (cultivated areas) and 12 (aquaculture), and a human coastal proximity index. It lies at the boundary between terrestrial units and unit 14, shelf ecosystems.

Reference

IPBES. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. https://doi.org/10.5281/ZENODO.3831673

Supplementary material 1.4. Illustrative examples of invasive alien species across IPBES units of analysis

Table SM.1.2. Illustrative examples of invasive alien species within terrestrial, freshwater, brackish, and marine environments spanning all the IPBES units of analysis around the world. Examples given were chosen to represent an animal and a plant with ecological or socio-economic impact selected from the most cited papers.[2] See IPBES units of analysis in **supplementary material 1.3**.

Notes: No examples of impact were found for Cryosphere and Deep Sea. Mechanism of impact was described based on Environmental Impact Classification for Alien Taxa (EICAT) and Socio-Economic Impact Classification for Alien Taxa (SEICAT) categories (**Chapter 4, Box 4.2**).

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
Terrestrial	Tropical and subtropical dry and humid forests	*Cenchrus setaceus* (fountain grass)	Asia and the Pacific (Sub-region: Oceania)	Chemical impact on ecosystem (nutrient cycling): changes in the sequestration of carbon in aboveground biomass	(Litton et al., 2006)
		Lissachatina fulica (giant African land snail)	Americas (Sub-region: South America)	Competition: competes with native molluscs for space and food Negative impacts on economic sectors (agriculture sector): a pest in ornamental gardens, vegetable gardens, and small-scale agriculture Negative impact on human health: an intermediate host of *Angiostrongylus*	(IPBES, 2020a, 2020b; Thiengo et al., 2007)

[2] Data management report available at: https://doi.org/10.5281/zenodo.5518254

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				cantonensis (rat lungworm), a nematode that can cause meningoencephalitis in people, and it may be a potential host of *Angiostrongylus costaricensis*, a zoonosis which causes abdominal angiostrongylosis. Negative impact on Indigenous Peoples and local communities: Snails consume plants and cause a considerable threat to agriculture. Farmers may have to abandon their farms if the snails have consumed all of their crops. They have the potential to be harmful to human health in Antigua.	
		Cenchrus ciliaris (buffel grass)	Americas (Sub-region: Mesoamerica)	Negative impacts on economic sectors (animal production): have lower net primary productivity Negative impact on Indigenous Peoples	(Franklin et al., 2006)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				and local communities: limit Aboriginal people's access to country in Kimberley region, blocking access to important cultural ceremonial sites, hunting sites, recreation sites. Disrupts cultural burning regimes by changing the fuel load and negatively affecting people's ability to collect bush foods.	
		Homalodisca vitripennis (glassy winged sharpshooter)	Americas (Sub-regions: North and South America)	Negative impacts on economic sectors (agriculture sector): important pests in commercial agriculture, as they transmit the bacterial plant pathogen *Xylella fastidiosa* (Pierce's disease of grapevines). *Xylella fastidiosa* induces diseases of grapevines, citrus, coffee, almond, alfalfa, stone fruits, landscape ornamentals, and native hardwoods	(Redak et al., 2004)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				for which there is no cure.	
	Temperate and boreal forests and woodlands	Several (13) plant species (e.g., *Reynoutria sachalinensis* (giant knotweed), *Heracleum mantegazzianum* (giant hogweed), *Lupinus polyphyllus* (garden lupin))	Europe and Central Asia (Sub-region: Central and Western Europe)	Competition: competes with native species for space. Physical impact on ecosystem: change in light regime for native species because of the cover and height of invading species	(Hejda et al., 2009)
		Lumbricus terrestris (lob worm), *Bimastos rubidus* (European barkworm), *Octolasion tyrtaeum* (woodland white worm)	Americas (Sub-region: North America)	Physical impact on ecosystem: mixing of soil layers Chemical impact on ecosystem (nutrient cycling): a net loss of C from the soil, affects on N cycling Structural impact on ecosystem: alteration of the soil foodweb, soil structure, humus forms, plant communities, and soil biota, e.g., microarthropods (mites, collembolans), enchytraeids	(Bohlen et al., 2004)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				(potworms), or nematodes	
		Pueraria montana (kudzu)	Americas (Sub-region: North America)	Physical impact on ecosystem: change in light regime for native species Negative impact on well-being and sustainable development: loss of recreational activities, aesthetic attraction, touristic value	(Forseth & Innis, 2004)
		Solenopsis invicta (red imported fire ant)	Americas and Asia and the Pacific (Sub-regions: North America and Oceania)	Negative impacts on economic sectors (agriculture sector): damage crops Negative impact on human health: bites people Negative impact on human infrastructure: infests electrical equipment. Negative impact on Indigenous Peoples and local communities: frequently bites and inflicts severe pain, necessitating	(IPBES, 2020a; Morrison et al., 2004)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				hospitalization on occasion. People's lifestyles have been impacted as a result of this in Australia.	
	Mediterranean forests, woodlands and scrub	*Acacia longifolia* (golden wattle)	Europe and Central Asia (Sub-region: Central and Western Europe)	Chemical impact on ecosystem (nutrient and water cycling): accumulates higher litter densities with greater N contents and lower C/N ratios than the native areas, which corresponds to lower C/N ratio and to higher potential rates of nitrification in the invaded soils; alters the soil properties with increased levels of organic C, total N and exchangeable cations resulting in higher microbial biomass, basal respiration, and b-glucosaminidase activity	(Marchante et al., 2008)
		Pheidole megacephala (big-headed ant)	Americas; Europe and Central Asia; Asia and Pacific	Predation: predator to native species such as ants, other insect species, snails, spiders, and centipedes	(Wetterer, 2012)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
			(Sub-region: North America; Central and Western Europe; Oceania)	Indirect impact: predation on insects cause the reduction in population and extinction of insectivorous birds Negative impacts on economic sectors (agriculture sector): household and agricultural pest	
		Centaurea solstitialis (yellow starthistle)	Americas (Sub-region: North America)	Chemical impact on ecosystem: has caused losses of soil moisture reserves Negative impact on well-being and sustainable development (hindering local and regional sustainable development with respect to water security): the value of the lost water may range from 16 to 75 million dollars per year in the Sacramento River watershed alone	(Gerlach, 2004)
		Aedes albopictus (Asian tiger mosquito)	Europe and Central Asia (Sub-region: Central and	Negative impact on human health: injuries, transmission of diseases as an	(Abramides et al., 2011)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
			Western Europe)	important vector of several arboviruses, such as dengue, chikungunya virus, yellow fever, and several other types of encephalitis	
	Tundra and High Mountain habitats	*Pinus mugo* (mountain pine)	Europe and Central Asia (Sub-region: Central and Western Europe)	<u>Competition:</u> competes with grassland for space, nutrient, and light	(Dullinger et al., 2003)
		Poa annua (annual meadowgrass)	Antarctica	<u>Competition:</u> competes with the native vascular plants, exerting a negative impact on their physiology and biomass	(Bajwa et al., 2019; Chwedorzewska et al., 2015; Maharjan et al., 2019)
	Tropical and subtropical savannas and grasslands	*Prosopis glandulosa* (honey mesquite)	Americas (Sub-region: North America)	<u>Competition:</u> competes with native grass for space and nutrients	(Brown & Archer, 1999)
		Felis catus (cat)	Asia and Pacific (Sub-	<u>Predation:</u> declines in mammal	(IPBES, 2019; Woinarsk

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
			region: Oceania)	populations in Australia	i et al., 2015)
		Andropogon gayanus (tambuki grass)	Asia and Pacific (Sub-region: Oceania)	Negative impact on well-being and sustainable development (Restrictions concerning aesthetic values and natural heritage): invasion threat is posed by a number of high-biomass non-native grasses; due to impacts on fire regimes in the World Heritage site (Kakadu National Park) Negative impact on Indigenous Peoples and local communities: limits Aboriginal peoples' access to country in Kimberley region, blocking access to important cultural ceremonial sites, hunting sites, recreation sites. Disrupts cultural burning regimes, by changing the fuel load, and negatively affecting peoples'	(Bach et al., 2019; Setterfield et al., 2013)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				ability to collect bush foods.	
		Bubalus bubalis (Asian water buffalo)	Asia and Pacific (Sub-region: Oceania)	Negative impact on well-being and sustainable development (Restrictions concerning aesthetic values and natural heritage): buffalo graze and browse in a region of significant biological and cultural importance, adversely affecting ecosystem functioning by trampling and soil compaction, and overgrazing native species Negative impact on Indigenous Peoples and local communities: dig up the billabongs, change the appearance and damage important cultural sites of Ngukurr aboriginals, in Arnhem land.	(Ens et al., 2016; Petty et al., 2007)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
	Temperate Grasslands	Several plant species (e.g., *Pinus radiata* (radiata pine), *Pinus patula* (Mexican weeping pine))	Southern hemisphere countries	Structural impact on ecosystem: by causing shifts in life-form dominance, reduced structural diversity, increased biomass, disruption of prevailing vegetation dynamics, and changing nutrient cycling patterns	(Richardson, 1998)
		Rattus rattus (black rat), *Rattus norvegicus* (brown rat)	Asia and Pacific (Sub-region: Oceania)	Indirect impact: predators, by affecting the movement of their key prey, indirectly influence the structure and function of above- and below-ground communities (number of seabirds, especially petrels and shearwaters decrease) Negative impact on Indigenous Peoples and local communities: have devastating effects on native biota that can be important for food, cultural heritage practices	(Fukami et al., 2006; Peltzer et al., 2019)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				and expressions, and tribal identity to the Māori community, New Zealand	
		Several species (e.g., *Bromus tectorum* (downy brome), *Euphorbia esula* (leafy spurge))	Americas (Sub-region: North America)	Competition: competes with native grass for water and nutrients Negative impacts on animal production: by lowering yield and quality of forage, interfering with grazing, poisoning animals, increasing costs of managing and producing livestock, and reducing land value	(DiTomaso, 2000)
		Several microorganisms, terrestrial plants, terrestrial invertebrates, amphibians and reptiles, and mammals	Asia and Pacific (Sub-region: North-East Asia)	Various negative impacts on economic sectors: direct economic losses to agriculture, forestry, stockbreeding, environment, and public facilities Negative impact on human health	(Xu et al., 2006)
		Bromus tectorum	Americas (Sub-	Chemical impact on ecosystem (nutrient	(Evans et al., 2001)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		(downy brome)	region: North America)	and water cycling): impact N availability by changing litter quantity and quality, rates of N_2-fixation, or rates of N loss	
		Canis lupus dingo (dingo)	Asia and Pacific (Sub-region: Oceania)	Predation: impacts on livestock production through predation on stock and its role as an ecosystem engineer	(Letnic et al., 2012)
	Deserts and xeric shrublands	*Vachellia nilotica* (gum arabic tree)	Asia and Pacific (Sub-region: Oceania)	Structural impact on ecosystem: increases soil erosion, impedes stock access to water, and increases water loss through transpiration Negative impacts on economic sectors: reduces pasture production, increases mustering times and costs	(Kriticos et al., 2003)
		Sus scrofa (feral pig)	Americas (Sub-region: South America)	Physical impact on ecosystem (e.g., disturbance): has strong negative effects on the superficial soil	(Caruso et al., 2018)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				layers due to its rooting behaviour Negative impacts on economic sectors: (an agricultural lands) cause economic impacts in the region	
	Wetlands – peatlands, mires, bogs	Several species (e.g., *Reynoutria japonica* (Japanese knotweed), *Sporobolus anglicus* (common cordgrass), *Mimosa pigra* (giant sensitive plant))	Global	Structural impact on ecosystem: they can alter soil nutrient regimes. They can also inhibit the natural regime of flood pulsing or flammable woody plants and litter can increase fire frequency and intensity. Negative impact on Indigenous Peoples and local communities: In Senegal, the *Mimosa pigra* has an impact on water flows, navigation, and agriculture. Mimosas take over areas and alter ecosystems, causing damage to property, plants, and animals. Mimosa also reduces wildlife's grazing range.	(IPBES, 2020a, 2020b; Zedler & Kercher, 2004)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				When the plant is touched, it shrinks and folds its leaves in order to expose its thorns, which are poisonous. It also has an impact on people because it limits livestock's access to water. It also makes fishing difficult. It also reduces agriculture, which can cause to hunger in Zambian communities. In Canada, invasive plants are displacing native wetland species, including medicinal plants, and altering ecosystem functions in wetlands, aquatic and, terrestrial habitats.	
		Procambarus clarkii (red swamp crayfish)	Europe and Central Asia (Sub-region: Central and Western Europe)	Predation: predates on aquatic stages of amphibians and can cause their populations to decline Competition: affects amphibian communities through loss of suitable breeding sites and loss of	(Ficetola et al., 2011)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				fitness if breeding occurs in invaded sites	
		Phragmites australis (common reed)	Americas (Sub-region: North America)	Structural impact on ecosystem: decreases in plant biodiversity, declines in habitat quality for fish and wildlife Negative impact on human infrastructure: causes difficulties for drainage water removal, irrigation water supply, and recreational or commercial fishing access Negative impact on Indigenous Peoples and local communities: make it difficult to gather food and medicine from wetlands, and it can change the habitat. There are significant impacts on culture and traditions of the Mohawk community of Kahnawà in Montreal, Canada.	(Hazelton et al., 2014; Reo et al., 2017)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		12 apple snails e.g., *Pomacea canaliculata* (golden apple snail)	Asia	<u>Predation:</u> alters benthic community structure <u>Herbivory:</u> altered macrophyte community structure in natural and managed wetlands through selective herbivory <u>Negative impacts on economic sectors:</u> they have become major pests of aquatic crops, including rice <u>Negative impact on Indigenous Peoples and local communities:</u> Farmers report that native snail populations were reduced. *Pomacea canaliculata* also damages many other cultivated and non-cultivated plants in Ifugao Rice Terraces, Philippines. Snails consume the young leaves and stems of newly transplanted rice seedlings,	(Horgan et al., 2014; Joshi et al. 2001; IPBES, 2020)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				necessitating their replanting. While farmers raised their seed investments, rice yields dropped by more than half. In the ricelands, approximately six species of edible snails, mudfish, and one edible weed have vanished in Tabuk Cordillera Region, Philippines.	
	Urban/Semi-urban	*Parthenium hysterophorus* (parthenium weed)	Asia and Pacific (Sub-region: South Asia)	Negative impact on human health: causes skin allergy, rhinitis, and irritation to eyes of the residents in the vicinity Negative impact on Indigenous Peoples and local communities: in the Gangetic plain (Tarai region in the south) of central Nepal, *Parthenium hysterophorus* is considered as harmful, with no fodder value	(Kohli et al., 2006; Shrestha et al., 2019)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		Passer domesticus (house sparrow), *Sturnus vulgaris* (common starling), *Columba livia* (pigeons)	Americas (Sub-region: North America)	Competition with native species for food and nests	(Shochat et al., 2010)
		Linepithema humile (Argentine ant)	Americas (Sub-region: North America)	Indirect impact: reduces the number of native ants, and thereby availability of food resources for *Phrynosoma coronatum* (Coast Horned Lizard).	(Suarez & Case, 2002)
		Lonicera maackii (Amur honeysuckle), *Lonicera tatarica* (Tatarian honeysuckle)	Americas (Sub-region: North America)	Negative impacts on economic sectors (on forestry sector): reduced forest cover	(Borgmann & Rodewald, 2005)
		Aedes albopictus (Asian tiger mosquito)	Americas (Sub-region: North America)	Negative impact on human health: transmits the endemic eastern equine encephalitis, is a significant vector of re-emerging	(Rochlin et al., 2013)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				arthropod-borne viruses such as chikungunya, dengue, and West Nile	
	Cultivated areas (incl. cropping, intensive livestock farming etc.)	Several species (e.g., *Artemisia vulgaris* (mugwort), *Centaurea diffusa* (diffuse knapweed))	Americas; Asia and Pacific; Europe (Sub-region: North America; Oceania)	Chemical impact on ecosystem: inhibitory effects on whole plant growth of both herbaceous and woody species through their allelopathic activity	(Weston & Duke, 2003)
		Mustela vison (American mink)	Europe and Central Asia	Predation: have a significant effect on ground-nesting birds, rodents, and amphibians Competition: competes with European mink and the Eurasian polecat for prey Negative impacts on economic sectors (indirect impact through predation): trout and salmon farms and hatcheries, rabbit and sheep farms	(Bonesi & Palazon, 2007)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		Numerous Australian *Acacia* species (e.g., *Acacia longifolia* (golden wattle), *Acacia salicina* (cooba))	Global	Structural impact on ecosystem: reduces water resources by increasing evapotranspiration, impacting the hydrological and carbon cycles; Decreases species diversity, as its dense coverage lowers the soil temperature and light penetration	(Richardson et al., 2011)
		Nosema bombi (microsporidian parasite)	Americas (Sub-region: North America)	Negative impacts on economic sectors (on agriculture sector): threat to native bumble bee populations	(Meeus et al., 2011)
Aquatic (marine and freshwater)	Cryosphere				
	Aquaculture areas	*Undaria pinnatifida* (Asian kelp), *Eucheuma* and *Kappaphycus* species	26 countries in the Pacific, east Africa and the Caribbean, the Mediterranean	Structural impact on ecosystem: causes changes to the composition of native macroalgal communities	(Schaffelke et al., 2007)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		Magallana gigas (Pacific oyster), *Magallana ariakensis*, *Magallana angulata* (Portuguese oyster), *Crassostrea virginica* (eastern oyster), *Ostrea edulis* (European oyster), *Saccostrea glomerata* (Sydney rock oyster)	Worldwide to 73 countries	<u>Structural impact on ecosystem</u>: decrease of biodiversity, change of population and food-web dynamics and nutrient cycling, habitat degradation, disease, poor water quality, and detrimental species interactions	(Ruesink et al., 2005)
		43 taxa of macroalgae (e.g, *Sargassum muticum* (wire weed), *Undaria pinnatifida* (Asian kelp))	Europe and Central Asia (Sub-region: Central and Western Europe) Asia and Pacific (Sub-region: Oceania)	<u>Negative impacts on economic sectors: algae</u> proliferate in oyster aquaculture facilities (pillars, ropes, and oysters) and thus reduce available light, water circulation, and nutrient supplies to the detriment of oyster growth and a loss of revenue <u>Negative impact on Indigenous Peoples and local</u>	(IPBES, 2020b; Verlaque, 2001)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				communities: *Sargassum muticum* is a growing problem in Fiji, yet there is almost no literature on its impacts.	
		Several animals (e.g., *Carassius gibelio* (Prussian carp), *Pacifastacus leniusculus* (American signal crayfish), *Procambarus clarkii* (red swamp crayfish))	Europe and Central Asia Americas (Sub-region: South America)	Structural impact on ecosystem: outcompeting native species and altering habitat structure (i.e., crayfish plague dissemination, bioaccumulation of pollutants (storage and magnification of toxic substances in tissues), community dominance, competition, predation on native species, and habitat modifications), Food web alteration: generally causing changes in the energetic budget of the invaded ecosystem (e.g., by removing key-stone species, primary producers, etc.) Hybridization: salmonids (e.g., *Salvelinus fontinalis* (brook trout)) often	(Aigo & Ladio, 2016; Savini et al., 2010)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				cause genetic impairment of native stocks by hybridization Transmission of disease: cyprinids (e.g., herbivorous carps) are vectors of diseases and parasites Negative impact on Indigenous Peoples and local communities: Salmonids displace the native fish almost completely in the Mapuche communities of Puel, in the Neuquén province of Argentina. Socio-cultural change that goes hand in hand with the arrival of the white man.	
	Inland surface waters and water bodies/freshwater	Various alien species of plants and animals (e.g., *Potamogeton crispus* (curlyleaf pondweed), *Cyclotella cryptica* (diatom),	Americas (Sub-region: North America)	Competition: competes with native species for space, food, light Predation: predate on native species Structural impact on ecosystem: impacts on the structure of	(Mills et al., 1993)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		Dreissena polymorpha (zebra mussel), *Dreissena rostriformis bugensis* (quagga mussel), *Gambusia affinis* (western mosquitofish))		freshwater ecosystems as a result of its filter-feeding activities. Negative impacts on economic sectors: in losses to commercial Great Lakes fisheries	
		Various alien species (e.g., *Aphanomyces astaci* (crayfish plague), *Myxobolus cerebralis* (whirling disease agent), *Lythrum salicaria* (purple loosestrife), *Myriophyllum spicatum* (spiked watermilfoil), *Phragmites australis* (common reed))	Americas (Sub-region: North America)	Competition: competes with native species for food and space Predation: predates native benthic species Disease transmission: parasitic infection for aquatic species Structural impact on ecosystem: molluscs that are primary consumers and disrupt the food web from its base, fishes that disrupt the food web from its apex or centre, decapods that act as powerful omnivores, aquatic plants that have	(Strayer, 2010)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				strong engineering effects and affect the quality and quantity of primary production, and diseases, which probably have been underestimated as an ecological force; habitat alteration	
		Pontederia crassipes (water hyacinth)	Americas (Sub-region: North America)	Chemical impact on ecosystem: decreases dissolved oxygen, nitrogen, phosphorous. Structural impact on ecosystem: decreases phytoplankton production, changes diversity of aquatic invertebrates, increases habitat heterogeneity and structural complexity Negative impacts on economic sectors: greatly affects fishery through changes in fish community composition, or changes in catchability of harvested species; fish catch rates have	(Villamagna & Murphy, 2010)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				decreased because water hyacinth mats block the access to fishing grounds, delay access to markets and increase costs (effort and materials) of fishing Negative impact on well-being and sustainable development: direct impacts are to boating access, navigability and recreation; and to pipe systems for agriculture, industry and municipal water supply, access to fishing grounds and fish catchability	
		Dreissena polymorpha (zebra mussel)	Americas (Sub-region: North America)	Structural impact on ecosystem: transformed freshwater food webs and biogeochemistry (caused planktonic food webs to wither and littoral food webs to flourish), reduce dissolved oxygen in the water column	(Strayer, 2009)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
				Negative impact on human infrastructure: alters power plants and municipal drinking-water plants through fouling of pipes Negative impact on well-being and sustainable development: collapses of sport fisheries	
	Shelf ecosystems (neritic and intertidal/littoral zone)	*Sargassum muticum* (wire weed)	Europe and Central Asia (Sub-region: Central and Western Europe)	Structural impact on ecosystem: habitat forming species, change community structure and species composition	(Buschbaum et al., 2006)
		Carcinus maenas (European shore crab), *Hemigrapsus sanguineus* (Asian shore crab)	Americas (Sub-region: North America)	Competition: competes for food resources with native grapsid crabs	(Jensen et al., 2002)
		Mytilus galloprovincialis (Mediterranean mussel)	South African coast	Structural impact on ecosystem: competitive displacement of indigenous species and a dramatic	(Robinson et al., 2005)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact[*]	Reference
				increase in intertidal mussel biomass	
	Open ocean pelagic systems (euphotic zone)	*Pterois volitans* (red lionfish) and *Pterois miles* (lionfish)	Atlantic coral reefs	<u>Predation:</u> on a wide variety of marine fauna including juvenile mesopredators; overconsumption of small native reef fishes	(Hixon, 2011)
	Deep-Sea				
	Coastal areas intensively used for multiple purposes by humans	Several species (e.g., bryozoan *Membranipora membranacea*, *Carcinus maenas* (European shore crab), *Batillaria attramentaria*	Americas (Sub-region: North America)	<u>Predation:</u> predates on native species (mussels) <u>Competition:</u> competes with native species for food resources, space	(Grosholz, 2002)

Ecosystem	Unit of Analysis	Example taxa	IPBES Region where species is alien	Examples of impact*	Reference
		(Japanese false cerith))			
		Perna perna (brown mussel), *Teredo bartschi* (shipworm pecies) and *Teredo furcifera* (Deep-cleft shipworm)	Americas (Sub-region: North America)	Negative impact on human infrastructure: fouling problems on natural and man-made structures; damage to untreated wooden structures	(Kennish, 2002)
		Several species (e.g., *Sargassum muticum* (wire weed), *Caulerpa racemosa* (green algae), *Caulerpa taxifolia* (killer algae))	Mediterranean	Negative impacts on economic sectors (Negative impacts on animal production including fisheries and aquaculture): possess toxic metabolites	(Boudouresque & Verlaque, 2002)
		Carcinus maenas (European shore crab)	Asia and Pacific (Sub-region: Oceania)	Negative impacts on economic sectors: decreases juvenile abundance of *Katelysia scalarina* (sand cockle)	(Walton et al., 2002)

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Chapter 5[1]: Management; Challenges, Opportunities and Lessons learned

Supplementary materials

[1] This is the final text version of the supplementary material of Chapter 5 of the IPBES Thematic Assessment Report on Invasive Alien Species and their Control (https://doi.org/10.5281/zenodo.7430682)

Supplementary material 5.1. Characterization of invasive alien species management by Indigenous Peoples and local communities

Supplement to **sections 5.2.1, 5.3.1.2** and **5.6.1.1**

Results of characterization of invasive alien species management by Indigenous Peoples and local communities based on 76 case studies (**Table SM.5.1**). Focus of management, ecosystems where management was conducted, managed taxa and motives for management were shown with the frequency of mention, frequency of percentages and percentage of cases reporting in parentheses. The case studies used for the characterization are a subset of studies on invasive alien species and Indigenous Peoples and local communities.[2]

Table SM.5.1. Characterization of invasive alien species management by Indigenous Peoples and local communities based on 76 case studies.

	Freq.	Freq. %	% Cases reporting
Management focus (n of cases = 76)	80	100.0	
Species	59	73.8	77.6
Pathway	2	2.5	2.6
Site	5	6.3	6.6
Ecosystem	4	5.0	5.3
Species X Site	10	12.5	13.2
Ecosystems where management was conducted (n of cases = 76)	76	100.0	
Terrestrial	64	84.2	84.2
Freshwater	10	13.2	13.2
Marine	2	2.6	2.6
Managed taxa (n of cases = 76)	120	100.0	
Animals (mammals, birds, reptiles, amphibians)	17	14.2	22.4
Fish (including crustacean)	13	10.8	17.1
Invertebrates	1	0.8	1.3
Insects	17	14.2	22.4
Plants	68	56.7	89.5
Fungi	2	1.7	2.6
Pathogen	2	1.7	2.6
Motives for management (n of cases = 71)	115	100.0	
Nature conservation	17	14.8	23.9
Improvement or protection of good quality of life			
Protect crop production	32	27.8	45.1
Protect livestock production	8	7.0	11.3

[2] Data management report available at: https://doi.org/10.5281/zenodo.5760266

Protect fishery production	1	0.9	1.4
Cultural or spiritual reasons	15	13.0	21.1
Protect resource use	17	14.8	23.9
Protect human health	4	3.5	5.6
Protect access or mobility	3	2.6	4.2
Protect Infrastructure	2	1.7	2.8
Obtain financial return (through getting jobs, business opportunities)	12	10.4	16.9
No active motives			
Following legislative requirements	4	3.5	5.6

Supplementary material 5.2. Pathway surveillance tools and technologies

Supplement to **section 5.4.2.1**

Sensor networks and smart traps - Recent growth in personal mobile computing has led to improvements in size and energy efficiency of electronic sensor devices, enabling their deployment on small-sized animals. Dubbed "One Giant Leap for Wildlife Tracking", lightweight telemetric tags have been deployed on hummingbirds, pigeons, toucans, and flying foxes. Miniature inertial measurement units, microphones, or weather sensors can be used to classify animal activities. Urination/defecation can be detected which can then be used to provide cues as to the shedding of a virus or seed dispersal, informing spatial predictive disease models. While most satellite trackers are still quite bulky, with a minimal weight of about 5g, smaller radio-frequency identification devices that weigh from 0.2g to 1g have been used to track insects such as bees, beetles, and dragonflies. Until recently, wireless sensor networks were limited to Wi-Fi or Bluetooth connectivity, restricting the range in which data could be collected (usually between 100 m and 1km). Examples of long-range systems have been developed in the context of Internet of Things (IoT) applications. Inexpensive off-the-shelf systems promise connectivity of 10 km, meaning that only a few base-station nodes would be required to collect data from most properties. An ongoing development includes battery life and robust casings are major considerations. Real time data processing algorithms to autonomously inform decision-making are generally developed for bespoke applications and are increasingly including machine learning and Artificial Intelligence. Lack of investment in digital information and communication technology (ICT, see glossary) connectivity infrastructure in remote and rural areas where properties or natural assets are generally large is a constraint, however, soon to be launched networks of low orbital communication satellites may bring broad band connectively to the entire globe.

Environmental Deoxyribonucleic Acid (eDNA) can be used to identify fish fry imported for the pet trade, or to monitor invasive aquatic species in rivers, ports or ballast water. The development of eDNA-based approaches for environmental and ecosystem applications has accelerated in recent years, and there have been a number of applications reported for the analysis of pests or invasive alien species, mostly for aquatic species due to the ease of sample acquisition and processing, including assessment of bivalve infestation with *Dreissena polymorpha* (zebra mussel; Peñarrubia et al., 2016), the invasive *Orconectes rusticus* (rusty crayfish; Dougherty et al., 2016), and invasive mosquitoes (Schneider et al., 2016). eDNA can be coupled to unmanned platforms and to automate analyses. Samples can be obtained from the broader environment, or from places such as run-off water, animal paths or the filtrate of air sacks. The only material constraint to the use of eDNA analysis may be the development of the required Polymerase Chain Reaction (PCR) for targeted sequencing or high-throughput DNA sequencing (HTS). There can also be complexity in respect of standardizing the sampling strategy, such that the sensitivity and specificity of eDNA analysis can be compared benchmarked with existing methods. This could limit the sensitivity of detection, although an increasing number of optimized sampling methodologies are being published (for example, Furlan et al., 2016). Metabarcodes are the next step to condense many geographically or temporally separated samples analysed for the same content adding power to an eDNA approach (Yamamoto et al., 2017).

Sentinel surveillance and monitoring - Sentinel alien plants (mainly trees) are similarly used for detecting invasive alien insects, nematodes and plant diseases. Sentinel plants used for surveillance assume that a risk of an invasive alien species has been identified and possible entry and dispersal pathways determined, and host ranges are well known. Sentinel plants are used either exotic in key locations (e.g., ports of entry) in the country that has identified the risk of invasion or native plants used and planted overseas to see what novel exotic alien pests and diseases are attracted to them (reviewed by Mansfield et al., 2019). Roques et al. (2015) described how sentinel European trees were planted in China during 2007-2011 as early warning of the invasive potential and likely impacts of Asian invertebrates that could colonize European trees should they arrive in Europe. Of more than 100 insect species, mostly defoliators, observed on five genera of tree hosts, at least six species were capable of larval development. This approach is being developed globally into an international plant sentinel network focused on linking botanic gardens and arboreta, National Plant Protection Organizations.[3] In a different example, *Merops ornatus* (Australian bee eater) was used to monitor the presence of alien honeybees (for example, *Apis cerana* (Asian honeybee)) by the analysis of scats at roost sites (Bellis & Profke, 2003). Sentinel beehives of *Apis mellifera* (European honeybee) are also strategically placed in ports and other points of entry in Australia for early detection of varroa mites. Wild caught honey bees have also been used to carry out surveillance of plant pathogens both known and not previously recorded (Roberts et al., 2018). It has also been suggested that managed honeybee colonies equipped with pollen traps could be used as a surveillance method for invasive plant species, given this is already an approach for understanding the source plants for honey bee pollen collection (Roberts et al., 2018).

Acronyms

DNA	Deoxyribonucleic Acid
HTS	high-throughput sequencing
PCR	Polymerase Chain Reaction

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Supplementary material 5.3. Species-based surveillance, detection and diagnostics tools and technologies

Supplement to **section 5.4.2.2**

Earth observation – remote sensing detection - Key advantages of remote surveillance over on-ground visual inspections include the larger coverage, the ability to use a range of spatial scales, repeatability and transferability of the procedure, the increased penetration of inaccessible areas, and the generally lower cost compared to the field teams (Jurdak et al., 2015). Some options for customizing the process to a particular application include the development of targeted application-specific sensors and sensing workflow, the development of specific and powerful algorithms based on, for instance, object recognition using machine learning or artificial intelligence for sampling specific targets and contexts, and data analytics to enable rapid (in some cases, real-time) generation of usable information. The data security and privacy issues still need to be resolved for many sensor network systems. Remote sensing can target specific invasive alien species directly using a specific optical signature or can detect their presence indirectly through methods such as suitable habitats or change in a landscape parameter over time (for example, where a weed is spreading, or a pest is feeding on vegetation). Invasive alien plants can be detected from their novel structure or phenology compared to native vegetation (Huang & Asner, 2009), or fast growth rate (rate of vegetation change over multi-date assessment; Diao & Wang, 2016). Less distinct species might be detected only at particular phenological stage(s) when they differ enough from their surrounding (Huang & Asner, 2009; Müllerová et al., 2017; Somodi et al., 2012). The detection and mapping of cryptic or low-density invasive alien species in complex landscapes may be difficult – in particular, when large areas need to be assessed. As fast-growing species, invasive alien species (especially herbs) can also be detected using a series of canopy height models throughout the season, generated either from light detection and ranging or photogrammetry (Structure from Motion algorithm; (Westoby et al., 2012), being especially true for herb species that show seasonal cycle (Martin et al., 2018).

Volatile detection technologies **-** The use of volatile detection technologies to detect a range of invasive alien species targets represent as genuine commercial opportunities, and could change the economics, practice and success of port-of-entry invasive alien species, surveillance and pest or disease control and eradication. The principle technical constraints are the identification of a unique volatile signature for each intended target, the ability to develop sensors that are sensitive enough to detect the volatiles at levels required and the ability of the device to discriminate the volatiles in real-world samples. Miniaturized and portable Gas chromatography mass spectrometry equipment is now available and has been tested for a range of applications including water quality testing (Wirth et al., 2012) and the detection of trace materials in forensic applications (Visotin & Lennard, 2016). These could be evaluated for their performance as biosecurity threat detectors. Portable technologies such as electronic noses have been trialled for insect detection in agricultural products with limited success (Wu et al., 2013). Various electronic noses or array-based sensor technologies have been developed for non-invasive diagnosis of disease (reviewed in Adiguzel & Kulah, 2015; Queralto et al., 2014; *Table SM.5.2)*, and these might also be trailed for invasive alien species targets. These technologies are designed to be analogous to biological olfactory systems, where an array of sensors sample an odorant space and pattern-recognition processes identify and classify the odours. Many different types of sensors have been developed for this purpose, including quartz crystal microbalance sensors, metal-oxide sensors, conducting polymer sensors, colorimetric sensors and fluorescence sensors (Adiguzel & Kulah, 2015; Queralto et al., 2014). These differ in their sensitivity, selectivity, response time and their limitations, which are tightly associated with the nature of the sensing mechanism. The limits of detection of the different sensing technologies range from parts per million (ppm) to parts per billion (ppb) (Adiguzel & Kulah, 2015). Each of these limitations needs to be considered when choosing a technology for a given use case.

Table SM.5.2. Advantages and disadvantages of mass spectrometry techniques and selected array-based sensors

Source: Queralto et al. (2014)

Technology	Advantages	Disadvantages
Mass spectrometry-based techniques	Ability to detect cancer-specific Volatile organic compounds; highly standardized techniques; compatible with pre-concentration technique, such as solid phase micro extraction (SPME) and needle trap micro extraction methods to further improve the sensitivity	Expensive; require a skilled operator; long analysis time
Array-based sensors	Cheap, portable, fast, and potential to detect Volatile organic compounds at low concentrations	Cannot identify cancer-specific Volatile organic compounds. Sensor training and standardization are required. Breath Volatile organic compound fingerprints depend on sensor type.
1. Quartz crystal microbalance (QCM)	High precision and sensitivity, diverse range of sensor coatings available	Poor signal-to-noise ratio, sensitivity to humidity and temperature, complex circuitry
2. Au/Pt nanoparticles	Fast response to a diverse set of analytes	Sensitive to humidity
3. Carbon nanotube (CNT)-based sensor	Fast response time, reversible	Sensitive to humidity, less response to saturated hydrocarbons
4. Conducting polymer	Sensitive to various Volatile organic compounds; fast response time	Sensitive to humidity and temperature, poor sensor life Composite
5. Colorimetric sensor	High sensitivity and selectivity high dimensionality; limited humidity effect	Sensor is non-reversible (disposable); for array hydrocarbons, pre-oxidation is required for high sensitivity

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Supplementary material 5.4. Future technologies

Supplement to **section 5.4.2.3**

Table SM.5.3. Summary of surveillance and diagnostic technologies for invasive alien species management

Biosensors and nanotechnology sensors	Combine a biological component with a physicochemical detector ("bioreceptor") to identify chemical substances and thus aid in monitoring many aspects of plant, animal and human health. Biosensors could play a significant future role in the prevention, detection and management of emergency animal disease outbreaks (Neethirajan et al., 2017), with likely comparative benefits for outbreaks of invasive alien species. Nanomaterials can improve the mechanical, electrochemical, optical and magnetic properties of biosensors, leading toward single-molecule biosensors within high-throughput biosensor arrays, one of the challenges of this technology (Mehrotra, 2016). Other challenges include the development of means by which to enhance the signal-to-noise ratio, and ways to enhance transduction and amplification of the signal. These technologies are in their infancy for invasive alien species applications, so it is hard to understand future constraints. They may be related to policy and regulatory issues and animal ethics issues.
CRISPR diagnostics	Microbial CRISPR and CRISPR-associated (CRISPR-Cas) adaptive immune systems contain programmable endonucleases that can be leveraged for CRISPR-based diagnostics. CRISPR diagnostics is likely to be quickly adopted for the rapid and accurate identification of infectious diseases of plants and animals. Gootenberg et al. (2017) found that specific high-sensitivity enzymatic reporter unlocking (SHERLOCK), an in vitro nucleic acid detection platform, was also able to detect Zika virus in clinical isolates (serum, urine or saliva). Further laboratory and clinical work are required to evaluate the performance of CRISPR-based diagnostics in a range of settings – including multiplex point-of-care, which may prove to be its most powerful application.
Multiplexed diagnostic real-time handheld tools	Multiplexed point-of-care testing describes the simultaneous on-site detection of different analytes from a single specimen (Dincer et al., 2017). This approach has recently gained increasing importance for clinical diagnostics, with emerging applications in resource-limited settings such as found in remote locations. Plant and animal disease diagnostics can be undertaken in real time in field settings including a capacity to test for a range of diseases at the same time. Ideally, the system should be able to analyse different types of compounds simultaneously – for example, RNAs, metabolites, proteins, exosomes and cells – and should provide accurate results in all cases. Handheld portal devices have now come in the market that can be used for aspects of this approach (e.g., MinION for portable real-time device for DNA and RNA sequencing).

Disease mRNA biomarkers	A biomarker is a signal released as a component of an organism's response to a particular pathogenic agent or pathogenic process, and thus indicative of the presence of that pathogen or process. Complex biomarkers have now been identified for the sensitive detection of diseases or processes at a stage when they may otherwise have been difficult to identify. Biomarkers are naturally linked to biosensors. Biosensors use a bioreceptor to identify the biomarker, and a transducer to transmit the signal to a receiver that can then interpret and display the outcome. Biosensors based on biomarkers could be deployed alone, or in complex sensor networks. They could also be deployed on unmanned ground-based, aerial or underwater vehicles. Examples by Cowled et al. (2017) and Barkema et al. (2018) show application in animal diseases. Potentially, the approach could also be applied to the rapid detection of some key plant diseases, as miRNA responses are known to occur for viral infections (Zhou & Luo, 2013), bacterial infections (Fahlgren et al., 2007), fungal infection (Campo et al., 2013) and nematode parasitism (Li et al., 2012). Collectively, these advancements are likely to mean that biomarkers become increasingly prominent as tools for invasive alien species applications.

Acronyms

CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DNA	Deoxyribonucleic Acid
RNA	Ribonucleic Acid

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Supplementary material 5.5. Pathway management – prevention options

Supplement to **section 5.4.3.1**

To eliminate hull biofouling and niche areas fouling, different tools and technologies have been developed in line with following the International Maritime Organization Guidelines on biofouling (The Marine Environment Protection Committee, 2011). Vessel in-water cleaning or treatment is recognized as an important and practical tool to maintain a vessel free of biofouling. Hull grooming (Tribou & Swain, 2015) involves a variety of tools and techniques as manual (soft brushes, scrapers and pads) or mechanical (water jets, rotating brushes with divers or remotely operated vehicles (ROV)). Usually, these techniques do not capture the chemical contaminants associated with the cleaning as well as the organisms (adults, larvae or viable propagules, (Scianni & Georgiades, 2019). Other more complex system includes in-water cleaning tools where the organisms removed are captured and treated (with filtration, heat, biocides, or UV light). Technology is developing fast and in a recent work, Tamburri et al. (Tamburri et al., 2020) evaluated in-water cleaning and capture systems in vessels with different environmental conditions and biofouling levels obtaining good results, according to environmental standards for water quality and biofouling level (*section 5.5*). Depending on the type of biofouling, vessel, available logistic at the place are the tools and technologies that can be effectively applied to reduce the amount of organisms attached (Castro et al., 2020). Soft brushes, water jets or other similar tools are only effective when there is a slime layer, when the macrofouling is well developed, more aggressive tools and techniques are needed. Other more complex methods include the encapsulation or enclosure of the entire structure, usually affordable for recreational vessels and floating docks. If the encapsulation is made only with water, organisms are killed because of the level of anoxia (Keanly & Robinson, 2020), but this method can be accompanied by the use of biocides such as chlorine and acetic acid (Morrisey & Woods, 2015; Roche et al., 2015). Niche areas, such as dry-docking support strips, bow thrusters, rudders, propeller shafts, anodes, and internal pipework, concentrates the highest quantity of biofouling organisms and are usually difficult to clean and maintain. Specially the access and inspection to the internal pipework of recreational vessels is difficult, and the exposure to heat (i.e., thermal stress) is viewed as the most acceptable treatment because it affects biofouling organisms quickly and without environmental contamination (Growcott et al., 2017). For example, for small vessels, Cahill et al. (2019) designed and tested a portable seawater heating for dockside use (with a recirculation system).

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Supplementary material 5.6. Species-led management technologies

Supplement to **section 5.4.3.2**

Fertility control for invasive alien vertebrates - Fertility control technology can be most effectively applied in limiting the growth of low density/small populations for which conventional control methods are impractical, or to slow the recovery of a population following conventional control. Such approaches can also reduce disease transmission (Ramsey, 2007). One labour intensive approach to fertility control is trap-neuter-release programme. This approach requires capture of all or most animals and at this point euthanasia would be a cheaper option, but in cases of strong public opposition trap-neuter-release programme is a more feasible option (Scapin et al., 2019). Depending on the extent to which social structure controls breeding, perverse outcomes may occur (Caughley et al., 1992). For ungulates, more than 50 per cent of fertile females will need to be maintained infertile to achieve a meaningful reduction in the population size, even when fertility rates are low (Hobbs et al., 2000), but fertility reduction rates may be slow (Raiho et al., 2015). Understanding the population demographics alongside modelling of the individual and population-level responses to any chemical or vaccine fertility control approach is important for future management (Cowan et al., 2020) as compensatory demographic processes can reduce fertility control effectiveness. Simulated field trials of female sterilization of European rabbits suggest that high levels of sterility (80 per cent) are needed to achieve population suppression with compensatory survival of sterilized females and recruits (Twigg et al., 2000). Brushtail possum populations subject to female sterility experienced higher immigration rates of dispersing juveniles, mitigating the impact of sterility, demonstrating the need for large scale application of the method (Ramsey, 2005).

The principles of hormonal and immune contraception have been researched for decades. Synthetic hormone implants have been tested and shown to temporarily reduce fertility in species such as macropods and brushtail possums (Massei & Cowan, 2014; Wilson & Coulson, 2016). Gonadotropin releasing hormone has been a key target for wildlife fertility control, using agonists or antagonists of the hormone to disrupt fertility (Herbert & Trigg, 2005). Most fertility control approaches for wildlife have been investigating the concept of immuno-contraception, a process where an immune response to key reproductive proteins or hormones is elicited in the animal and subsequently interferes with reproductive processes. A suite of targets has been investigated for immune contraception approaches, the two most common ones include the zona pellucida protein and the Gonadotropin releasing hormone. Gonadotropin releasing hormone conjugated to an immune adjuvant is available as a commercial contraception vaccine (GonaCon), inducing an immune response in the animal that interferes with the downstream release of hormones affecting ovulation and sperm production (Massei & Cowan, 2014). Gonadotropin Releasing *Hormone (GnRH;* GonaCon™ - 0.032% GnRH) is registered in the United States to control feral horses, donkeys and deer. The zona pellucida protein is formed by a group of glycoproteins that surround the egg cell and play a key role in sperm recognition and binding.

A long-term Australian research programme (1991-2005) also investigated the possibility to deliver subunit zona pellucida protein via genetically modified virus vectors into target species in a self-disseminating vaccine, in a process termed virally vectored immune-contraception (Hardy et al., 2006; McLeod et al., 2008). Preparations made from pig ovaries (available in large quantities from abattoirs) have been shown to be effective in several ungulates, monkeys, seals, bears and marsupials, but not rodents, cats, dogs or wild pigs (Massei & Cowan, 2014). Proof-of-concept that a virally delivered zona pellucida protein3 subunit resulted in long-term infertility was shown in house mice and rabbits (Redwood et al., 2008; van Leeuwen & Kerr, 2008), but has so far not been successful in foxes or cats

(Munks, 2012; Strive et al., 2007). The research programme was disbanded in 2005, due to a combination of perceived public perception risks surrounding the use of genetically modified viruses in wildlife, and a lack of demonstrated transmissibility for the most advanced of the model systems.

A critical component determining the applicability of fertility control is the availability of a suitable delivery mechanism. If problems associated with remote one-off delivery and/or the development of methods for self-dissemination can be overcome, then landscape scale control applications and a broader range of target species may be feasible. Effective means of oral delivery of fertility control agents, or even self-disseminating agents have been extensively researched but are not yet available. Other approaches include the use of the chemical 4-Vinylcyclohexene diepoxide, which acts by depleting the pool of primary follicles in rats, resulting in long term fertility (Dyer et al., 2013). Current research is investigating a palatable formula that will allow effective oral delivery. Chemical products or injectable vaccines will generally be required to have regulatory assessment and approval. A philanthropically funded organization termed Alliance for the Contraception of Cats and Dogs supports research aiming at the development of one-shot non-surgical treatment for these two target species.[4]

Sterile insect technique and other relevant invasive alien invertebrate augmentative approaches - Genetic modification has been available to sterile insect technique for at least 18 years (Alphey, 2002) and produced working products even if these have failed to pass regulatory hurdles. Genetic sexing techniques (or female lethal constructs) are difficult and expensive to develop, but are currently available for use in some control programmes (for example, medfly; Alphey, 2002). The regulatory processes and public concerns however have impeded field trials and releases. Oxitec, the private company developing technologies in this field, found this when it tried to release OX513A *Aedes aegypti* (yellow fever mosquito) in Florida Keys in 2012 (Center for Veterinary Medicine et al., 2016). Improved genetic approaches are under development using RNA interference (Pomcio et al. in review) and clustered regularly interspaced short palindromic repeats (CRISPR)/Cas gene-editing technology to produce non-genetically modified male sterile or female lethal genetic lines (Choo et al., 2018) could also open Sterile insect technique to many more invertebrate pest types and change the economics, practice and success. Current approaches are focussing on gene silencing where possible as regulatory approvals can be easier.

Automation and artificial intelligence are also being used to overcome shortcomings of traditional Sterile insect technique. Computers are better than humans at picture classification tasks (Wu et al., 2015) so this has been applied to solve sex sorting for Sterile insect technique. Verily's Debug project has made its visual sex sorting of adult *Aedes aegypti* (yellow fever mosquito) part of an automated rearing process that has been used with *Wolbachia*-infected *Aedes aegypti* to provide the sterility aspect (Crawford et al., 2020). BigSis[5] has developed a proprietary end-to-end automated insect rearing process that incorporates computer vision for sex sorting and a proprietary method for protecting insects from the deleterious effects of sterilization with ionizing radiation. This has led to products that have successfully avoided or minimized regulatory hurdles by creating a process that works with native wild type strains. For example, BigSis Sterile insect technique products have been cleared by regulators in England in less than a year without permit.

Viral biological control of invasive alien vertebrates - Viral biological control agents are highly taxon-specific to the target species, and risk assessment are needed to assess as far as possible any likelihood of future adaptation to any closely related species, following release. To a large extent, the stability of a

[4] http://www.acc-d.org/

[5] www.bigsis.tech

virus in respect of its target is a characteristic of the viral family to which it belongs. Some viruses (for example, influenza virus) are known to switch species while others (for example, herpes viruses) are generally considered to be highly species-specific.

Viral biological control is ideally suited to the landscape-scale control for terrestrial vertebrate pests and whole-of-river control of invasive freshwater aquatic species. Viral biological control may provide for the long-term sustainable suppression of pest populations and impacts in each of these situations. If part of an integrated pest management strategy (and likely a dominant part), modelling has indicated that Viral biological control can contribute to the eradication of a pest species. In this context, Viral biological control may be particularly effective when combined with fertility control or genetic-control methods.

In Australia, cyprinid herpesvirus 3 (Cy-HV3, carp virus) has undergone extensive efficacy and host-specificity testing and is considered (on the basis of these criteria) to be a suitable viral biological control agent for European carp from this perspective (McColl et al., 2014, 2017). An assessment of the feasibility of using the carp virus as a biological control agent for carp in Australia is underway including extensive published research on public acceptability, risk assessment (including indirect effects – such as its impact on food webs and complex native predator/prey relationships) and disease epidemiology modelling in a natural landscape context (FRDC, 2021). Similarly, a highly-virulent tilapia lake virus (TiLV) against invasive tilapia fish has recently been described which may also be highly specific (Bacharach et al., 2016). The potential use of this virus as a biological control tool in Australia is currently at the scoping stage. The time required to identify, evaluate and obtain approvals for a potential viral biological control agent, including strong public and political support is generally in the order of five to 15 years. As for classical biological control, efficiencies may be gained from the adoption of an agent that has been deployed successfully in another country. The evaluation of potential viral biological control agents generally requires the use of a biological containment level 3/4 facility.

Ribonucleic Acid interference (RNAi) is a generic approach to altering gene expression, using highly specific gene-silencing constructs the efficacy and versatility of which has been demonstrated across a wide range of plants, invertebrates and vertebrates. Although some generic principles will apply, most applications will be specific to particular hosts (whether plants, invertebrates or vertebrates) and to the cells within these hosts that the RNAi is seeking to target. RNAi, where effective, has potentially very broad applications against highly specific species and upregulated gene targets. RNAi constructs need to be designed to eliminate any effects on potential non-target species. One of the key advantages of RNAi is that cellular changes are not inherited across a generation, so host is not itself genetically modified. The challenge is delivery of the RNAi molecules to the relevant target cells in a broad population. Delivery to the mucosal epithelial cells of chickens, for example, is very different to delivery to gonads of prawns or to wild flying insects. Where this difficulty can be overcome, the approach has enormous potential to the agricultural, horticultural and livestock industries, as well as to conservation management and public health. RNAi also provides a highly specific means by which to augment the resistance of plants, animals and people to key diseases. RNAi could reduce the use of conventional chemicals, and has the potential to be used to assist in production of sterile flies within a sterile insect technique programme (*section 5.4.3.2*). RNAi may also have application for altering the expression of highly- conserved genes across related species, although this is yet to be explored. The lead time for the development of a new product would depend largely on whether an effective delivery mechanism has been identified. If it has, then five to 10 years might be required to bring the application from basic research through to a registerable product. If a delivery system has not been identified, then the lead time will be very difficult to estimate. Once one RNAi application domain has been registered, then the process is likely to be simpler and faster for future applications.

Genetic control approaches – Genetic-control approaches have either not moved beyond the proof-of-concept stage (for example, viral vectored immunocontraception and daughterless carp), or remain at a development phase. Early work conducted in Australia showed that sex biasing in fish populations was possible (Thresher et al., 2014). Naturally occurring Trojan y-chromosome system has been worked on extensively in the United States of America (Wang et al., 2014), although no practical control attempts have been made despite being a non-genetically modified based approach. The T-Sry mouse system is also at the developmental stage in the United States, resourced and supported through an international Genetic Biocontrol of Invasive Rodents consortium. Other naturally occurring sex biasing genetic mechanisms occur in many different types of organisms (Wedell et al., 2019). All of these approaches have developed a vast body of knowledge about fertility targets and the reproductive biology of the target species, upon which modern gene-technology approaches can be built. Work on synthetic gene-drive system has only been possible in the last ten years with the discovery of CRISPR (and some related precision technologies such as transcription activator-like effector nuclease) which allow gene deletions or precise editing of a few nucleotides in single genes (Cong et al., 2013; Mali et al., 2013). The most commonly recognized synthetic approach is the "homing gene-drive" system, but it is only one synthetic approach and has only been successfully developed in mosquitos and not yet in vertebrates as the approach is not easily translatable. A working homing gene-drives can theoretically force deleterious gene constructs (for example, sex biasing gene) into a wild population following the release of only a few modified individuals (Esvelt et al., 2014). The gene-drive cassette includes the CRISPR/Cas9 gene scissors which guide RNA to the point of incision in the genome and the deleterious gene "payload" to be inserted. The CRISPR/Cas9 cassette can copy itself between precise identical locations on maternal and paternal chromosomes. Following a successful sexual reproductive event with either a mother or father carrier, all offspring will carry the gene-drive on both copies of the targeted chromosome. All of their descendants will also carry and pass on the gene-drive to all offspring. In theory, therefore, a single individual released carrying a gene-drive cassette can eventually transfer the cassette to all individuals in a descendent population after a series of generations. All synthetic approaches require genetic modification of the target organism and allows broadening of the types of deleterious genes that could be included as part of the gene-drive cassette beyond sex-biasing mechanisms. These could include increased individual susceptibility to an otherwise benign pathogen or chemical applied as an additional control measure, or other changes to other desired species-specific genetic targets. The details of the approaches becoming available are changing fast (for example, Dhole et al., 2018; Prowse et al., 2017), so it will be important to stay up to date regarding developments for genetic mechanisms for suppressing established invasive alien species globally (e.g., Legros et al., 2021). The initial research and development and implementation costs for genetic control are likely to be high and, for non-gene-drive based systems, are likely to continue until long-term control has been achieved (or not).

In almost all cases synthetically modified target organisms with invasive alien species control in mind will be classed as genetically modified organisms and will be subject to genetically modified regulatory approval. Many international forums therefore bring together scientists (genetic, technical and risk analysis), ethicists and regulators to discuss how gene-drive research could and should be conducted. Large sectors of the public are very concerned about the use of genetically modified technologies for pest, weed and disease control, particularly in a commercial context. Perceived versus scientifically assessed levels of risk, cultural values, the degree to which the situation has wide public support and the degree to which permission for the use of this technology remains in the public control are all relevant issues for public acceptability in the short and long-term. A substantial body work is appearing addressing this (Delborne et al., 2018; George et al., 2019; Jones et al., 2019; Kokotovich et al., 2020). The challenges of understanding pubic acceptability of genetic control approaches have been exemplified by the case of introducing the genetically modified *Castanea dentata* (American chestnut) to counter devastating *Cryphonectria parasitica* (blight of chestnut; Barnhill-Dilling et al., 2019) and the cases for release of genetically modified mosquitos to protect the communities in Africa and the Americas from malaria (Cisnetto & Barlow, 2020) and Zika virus (Adalja et al., 2016) respectively (Resnik, 2018, 2019). The cases, and their successful use will probably define further applications of these technologies globally. It is likely that public acceptability will vary from case-to-case. For example, the acceptability of a genetic-control approach for mice may differ when applied either: (a) to mitigate a threat to the biodiversity on an island; or (b) to mitigate a threat to grain production and storage (Carter et al., 2022). It will be important to place the communication of risks in the context of alternative methods. Importantly, the technology has been accepted as a research and development focus by some but not all conservation non-governmental organizations.

The regulatory framework for this technology exists in some countries, and the processes and permits required are generally understood. In the instance where genetic control is based on standard genetic modification technology, this would parallel processes for the registration and release of genetically modified crops. Where a genetic technology involves simple gene-editing and no additional Deoxyribonucleic Acid (DNA) from other species, there are lower levels of regulation in some parts of the world (e.g., Japan, Australia and United States). There is concerted international debate to ensure that gene-drive research, development and deployment are conducted with appropriate social, ethical and legal oversight. Use of CRISPR/Cas 9 is also subject to patents and the patent holders are being very cautious about use in most contexts. There is freedom-to-operate in terms of the basic research, but the development phase will require licences for commercial or general deployment.

Acronyms

CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DNA	Deoxyribonucleic Acid
GnRH	Gonadotropin Releasing Hormone
RNA	Ribonucleic Acid
RNAi	Ribonucleic Acid Interference

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Supplementary material 5.7. Ecosystem restoration

Supplement to **section 5.4.3.3b**

Ecosystem Restoration: Indigenous peoples may not use more western terms of “management” and “restoration” when working to change the impacts of invasive alien species in their country, landscapes and culturally and spiritually important places. Where Indigenous Peoples care for their traditional lands impacted by invasive alien species, they do not use scientific terminologies. Examples include a) traditional fire management practices used to manage invasive alien plants by the Yellomundee Aboriginal Bushcare employing Yellomundee Firesticks in New South Wales, Australia and b) traditional approaches to reducing the impacts of invasive alien invertebrates in tea-plantations surrounded by sacred groves, social forestry, gardens, parks and small rivers in North Bengal. The Bunuba Aboriginal rangers of the Fitzroy River in Western Australia look after country in accordance with their culture and customs, using a place-based approach across the broader landscape by identifying the values of those places and then managing the vegetation at those sites by developing specific invasive alien plant management plans based on site cultural significance to ensure a holistic approach to maintaining a healthy country. This highly successful place-based approach is a type of site or ecosystem-based approach in partnership with the Western Australian Government Department of Biodiversity Conservation and Attractions (DBCA) and Monash University (Ens et al., 2015).

Research through the Kimberley Land Council considered the governance context of weed management by Aboriginal ranger groups in the Kimberley, northwest Australia. The Kimberley is the traditional homelands of diverse Aboriginal peoples from about 27 different language groups. The research focuses on the changing context of native title which has led to about 93.5 per cent of the Kimberley being recognized, with the majority of the weeds work undertaken by indigenous ranger groups from the community. Bardi Jawi Ranger Kevin George emphasized the role of traditional authority in weeds management. Traditional authority is an important part of the way decisions are made between Aboriginal people, their organizations, and their “law bosses” or elders. For Kevin, weed management projects by governments or non-government organizations need to respect traditional authority, as well as local knowledge and priorities. Weed management is not just a technical, scientific, economic or ecological issue. Weed management is about how relationships between people, their lands and waters – their country – are respected (Ens et al., 2015; **Box SM.5.1**).

Box SM.5.1. Wunambal Gaambera Healthy Country Planning, Kimberley Northwestern Australia.

The Wunambal Gaambera Aboriginal people have native title over Wunambal Gaambera Country, which covers about 2.5 million hectares of land and wundaagu (sea), in the north Kimberley region of northern Australia (Wunambal Gaambera Aboriginal Corporation, 2010). This Country has been home to the Wunambal and Gaambera people for thousands of years. The Wunambal Gaambera people, as their ancestors did, call this land “our Uunguu” (our living home). In the Lalai, the Law for caring for our country was made. The ancestors passed their stories down from generation to generation from Wanjina who left their images and stories in rock art throughout Wunambal Gaambera Country.

The Wunambal Gaambera people developed a Healthy Country Plan to collectively determine the Targets and Threats to the Country. Their Healthy Country Plan grew from work that the Wunambal Gaambera traditional owners, have been doing since the late 1990s. These combined activities have helped the Wunambal Gaambera people tell others about the importance of looking after the country and to make sure their unique cultural and natural assets and values are kept healthy and passed to future generations. “Everything in our Uunguu is connected”. Through planning workshops ten key nested important Targets were identified by the Wunambal Gaambera people. The Wunambal Gaambera people collectively identified threats for each target with all targets being interconnected. The Health of each Target was identified by including land and seascape health, cultural health and biophysical health, adding to an overall health rating for each target. Each threat was ranked between low to very high based on what people knew when the plan was written. The Wunambal Gaambera people determined that they had to make sure that all sides of the threats are looked at and managed properly. One threat was called weeds and another threat was called feral animals.

The weeds and feral animal threats had an overall threat rating of High which means the threat may cause serious damage to all or part of the targets which it impacts if the current situation or rate of damage continues. If this happens it would be very expensive and difficult to make the target healthy. Some of the problems caused by weeds to the Country include clogging up the homes and places (habitats) of plants and animals “that should be in our country”, making plant and animals “that should be here” sick and, in some cases die and disappear, impeding travel and collection of food and medicine plants, hunting and fishing and making it hard for animals to move through country, causing pollution and messing up yawal (waterholes).

Some of the threats identified from feral animals were: damaging wulo (rainforest) polluting and muddying yawal (waterholes) with droppings and carcasses, spreading weeds and bringing disease that can harm plants, fish and seafoods such as our marlinju (oysters), and parasites that can cause animals like aamba (kangaroos and wallabies) to get sick, damaging rock art by rubbing against the paintings, trampling some of our food and medicine plants. The introduced cane toads impact on animals like the wijingarri (northern quoll) which are special in dreaming stories, compete with and eat small meat foods like diigu (birds), poison and kill small meat food like wobarda (water monitor) and wijingarri (northern quoll) and also disturb cultural sites.

Having established their Vision, 10 targets and threats the Wunambal Gaambera people established objectives they would like to achieve to keep the targets healthy and fix or lessen the threats. The objective relevant to invasive species was that: by 2015 we will be managing and controlling pest species on Wunambal Gaambera Country and by 2020 pest species will have a smaller impact.

The Wunambal Gaambera approach is neither referred to as management or restoration, but rather as reducing threats to key targets a critically important strategic approach to identifying the problem, impacts and then tackling the impacts of, in this case pests, weeds and feral animals and interconnections. There is often a difference in perceptions between indigenous and non- Indigenous Peoples around feral animals, by which the western scientific approach will work to eradicate a species from the country, whereas the Wunambal Gaambera will see these feral animals as having been born on country and so having connections to the land they were born on, in the same way as the people do. Wunambal Gaambera have concerns around ethics of wasting food and cannot bear to see an animal shot or culled and left to rot on country. Ownership of these animals reverts to the owner of the land on which the animal was born, with these people being the decision makers about the future of the animal, and the meat for example which may come from an animal. It is complex and needs to be factored into any decisions about how feral animals are to be treated (Wunambal Gaambera Aboriginal Corporation, 2010)

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Supplementary material 5.8. International Standards for Phytosanitary Measures

Supplement to **section 5.3.1.2**

The International Plant Protection Convention (IPPC) International Standards for Phytosanitary Measures (ISPMs) greatly assist in management strategies by providing global standards in plant health management.[6] ISPMs cover a wide range of topics, including: pest risk analysis, surveillance, phytosanitary pest status, pest reporting, regulated pest lists, pest eradication, export certification, import control, inspection and emergency measures. There are also a number of ISPMs that are specific to the international movement of regulated articles, such as: biological control agents, wood packaging material, wood, seeds, growing media in association with plants, processed products, and used vehicles, machinery and equipment. These ISPMs are relevant to Article 8(h) since the regulated articles are potential pathways for the introduction and spread of invasive alien species:

General ISPMs:

- ISPM-1 Phytosanitary principles for the protection of plants and the application of phytosanitary measures in international trade
- ISPM-5 Glossary of phytosanitary terms
    - Supplement 1: Guidelines on the interpretation and application of the concept of "official control" and "not widely distributed" (2012)
    - Supplement 2: Guidelines on the understanding of "potential economic importance" and related terms including reference to environmental considerations (2003)
    - Appendix 1: Terminology of the CBD in relation to the Glossary of phytosanitary terms (2009)
- ISPM-20 Guidelines for a phytosanitary import regulatory system

ISPMs related to pest status and pest risk analysis:

- ISPM-2 Framework for pest risk analysis
- ISPM-8 Determination of pest status in an area
- ISPM-11 Pest risk analysis for quarantine pests
- ISPM-19 Guidelines on lists of regulated pests

ISPMs related to pathways:

- ISPM-3 Guidelines for the export, shipment, import and release of biological control agents and other beneficial organisms
- ISPM-15 Regulation of wood packaging material in international trade
- ISPM-38 International movement of seeds
- ISPM-39 International movement of wood
- ISPM-40 International movement of growing media in association with plants for planting
- ISPM-41 International movement of used vehicles, machinery and equipment

ISPMs related to surveillance, eradication and pest free areas:

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[6] https://www.ippc.int/en/core-activities/standards-setting/ispms/

- ISPM-4 Requirements for the establishment of pest free areas
- ISPM-6 Surveillance
- ISPM-9 Guidelines for pest eradication programmes

Acronyms

IPPC	International Plant Protection Convention
ISPM	International Standards for Phytosanitary Measures

Supplementary material 5.9. Examples of effective surveillance strategies

Supplement to **section 5.5.2**

Some examples of specific surveillance include the Mamalu Poepoe programme which is coordinated through the Hawaii Invasive Species Council[7] targeting invasive ants, mosquitoes, coconut rhinoceros beetle and Africanized bees at airports (Kaufman & Atwood, 2019). The main objective of the programme was to provide baseline data on invasive ants at airports. The programme was useful for early detection of other invasive alien species not already present. Swarm traps were used to detect strains of Africanized bees and Biogent sentinel traps for detection of adult mosquitoes. Trials were conducted to identify the most efficient and cost-effective traps and lures that are more sensitive to detection of mosquitoes at airports. There are cooperative agricultural pest surveys[8] which conduct science-based national and state surveys targeted at specific plant pests, diseases, and weeds identified as threats to United States of America's agriculture and environment. These activities are accomplished primarily under the United States Department of Agriculture funding that is provided through cooperative agreements with state departments of agriculture, universities, and other entities. Surveys conducted through the cooperative agricultural pest surveys programme are a second line of defence against the entry of harmful plant pests and weeds, in addition to inspections of commodities at the border. These surveys enable the programme to target high-risk commodities, gather data about pests specific to a commodity, and establish baseline data on pests that were recently introduced into the United States. The objective of the cooperative agricultural pest surveys programme is to provide a survey profile of plant pests in the United States deemed to be of regulatory significance through early detection and surveillance activities.[9]

In Mexico, surveys are carried out to target invasive birds and are designed around areas of likely colonization in urban wooded parks. The repeated surveys build up a registry of invasive bird species of differing habitat and seasonal preferences across cities and provides information on their invasiveness over time (Pineda-López et al., 2013). New Zealand's marine high risk Site Surveillance is a programme of surveys targeted at early detection of invasive alien marine species in the country which reports on range extension of these species already established. The surveys are undertaken biannually at ports and harbours around New Zealand that receive relatively high amount of international shipping and are therefore considered to be most at risk. The methodology consists of risk-based stratification of the marine environment within each harbour, which is then used to prioritize allocation of sample effort based on the likely distribution of founding populations of the target species (Inglis et al., 2006). Since its inception in 2002, the programme has detected one primary target pest species (*Sabella spallanzanii* (Mediterranean fanworm) in 2008), 16 invasive alien species that were not previously known from New Zealand, and has recorded numerous range extensions for invasive alien marine species including *Sabella spallanzanii*; the tunicates, *Styela clava* (Asian tunicate) and *Eudistoma elongatum*; the decapod crustaceans, *Charybdis japonica* (lady crab) and *Metapenaeus bennettae* (bay prawn); *Arcuatula senhousia* (Asian date mussel); and the algae *Undaria pinnatifida* (Asian kelp) and *Grateloupia turuturu* (devil's tongue weed) (Seaward et al., 2015).

The National Plant Health Surveillance System managed by the Australian Government Department of Agriculture, Water & Environment is designed for early detection of Australia's top 40 unwanted and alien "National Priority plant or quarantine pests and diseases" (Australian Government, 2019).

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[7] https://dlnr.hawaii.gov/hisc/

[8] http://caps.ceris.purdue.edu/

[9] https://www.aphis.usda.gov/aphis/ourfocus/planthealth/pest-detection

Surveillance is carried out by State governments, the Australian government and plant industries with the support from the community. Targeted programmes are conducted at international entry points such as sea and airports and also provide data to support trade and market access to Australian producers (Anderson et al., 2017; Plant Health Australia, 2018). The system is supported by a nationally integrated plant biosecurity diagnostic network which focus on building diagnostic capability and capacity across Australia and New Zealand (Plant Health Australia, 2018).

Australia is one of the few countries in the world that is free of varroa mites that impact *Apis mellifera* (European honeybee) hives. This pest of bees has been kept out through a science-based and very targeted and effective surveillance programme using sentinel hives (*section 5.4*) at ports of entry where surveillance efforts are prioritized based on risk maps (*section 5.2*; Heersink et al., 2016)

Australia's National arbovirus monitoring programme monitors the distribution of economically important arboviruses of livestock (*section 5.4*). Data is gathered throughout Australia by serological monitoring of sentinel cattle herds and trapping of insect vectors. The programme design is based around the probability of arbovirus transmission and sites are monitored to ascertain areas of disease freedom and to detect new strains of virus and assess seasonal intensity in endemically infected areas (Animal Health Australia, 2019).

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Supplementary material 5.10. Examples of eradication programmes

Supplement to **section 5.5.3**

According to Island Conservation's Database of Island Invasive Species Eradications (DIISE, 2018), there have been over 1,500 eradication attempts of vertebrate alien species. As a result, 38 mammal species have been eradicated, in almost 1,100 events, with an 88 per cent success rate on 798 islands followed by 9 bird species, in 22 events, with an 82 per cent success rate on 22 islands. There is only one case of successful reptilian eradication, which took place on the Seychelles. In the case of invertebrates, 81 invasive alien species have been eradicated from 50 islands (Glen et al., 2013). Lastly, 75 invasive plant species have been eradicated from 19 islands. However, most biodiversity threatened by invasive alien species on islands occurs on islands too big for current technologies to achieve eradications, which prompted greater focus on new genetic approaches which helps to push these boundaries (Campbell et al., 2019).

One invasive alien species group that has been strongly targeted in eradication programmes are ants, which cause impacts to human wellbeing, the environment and agricultural systems. A global study principally carried out on continents including 316 eradication campaigns targeting 11 species had a success rate of 66 per cent (n=236, 75 per cent). Over 50 per cent of these campaigns remain unpublished (Wylie et al., 2016). These have been done in the Seychelles, United States of America, Galápagos islands, Australia, New Zealand and People's Republic of China. Most of the successful programmes have been done in Australia and New Zealand (Wylie et al., 2016). The cost of implementation increases with the increase in area and is higher compared to costs of mammal eradication. The total area that invasive ants have been eradicated worldwide is approximately 9,500 ha. The largest successful eradication of red imported fire ants to date, is in the greater Brisbane metropolitan area in Australia (over 100 km^2) which has already cost the country over AU$ 400 million. The programme used multiple methods as, aerial broadcast, hand broadcast, and nest drenching, and included the use of novel technologies to monitor new outbreaks. Overall, the most frequent programmes have been on *Anoplolepis gracilipes* (yellow crazy ant) while the most successful ones have been on *Pheidole megacephala* (big-headed ant). The chemical substances: fipronil, hydramethylnon, and juvenile hormone mimics are commonly used, often in combination. The methods used for delivering baits were mainly by hand (56 per cent), aerially by helicopter (36 per cent), multiple methods (5 per cent) and by drenching nests with an aqueous solution (2 per cent). The number of successful eradication programmes against ants has increased significantly in recent years due to effective surveillance which picks up new incursions quickly (McNaught et al., 2019) and effective eradication approaches being developed for allowing rapid response (Hoffmann et al., 2016), however many other ant eradication programmes are still ongoing after many years because they were not targeted early enough (Wylie et al., 2016). It is also necessary to develop better methods of removal, including more natural history and proper taxonomic identification of taxa to increase the efficacy of chemical substances and baits, to minimize or mitigate non-target risks as well as to develop better technologies to confirm eradication (Hoffmann et al., 2016).

In the case of plants, the success rate of eradications programmes is generally low (*Figure 5.23*) because of the soil seedbank and the difficulty to detect and remove them (Panetta & Timmins, 2004). Frequently, the longevity of the seed bank of some species is unknown. For this reason, it is necessary to conduct long-term surveillance to detect emerging seedlings. Eradication campaigns have been most often attempted in the agricultural sector (Pluess et al., 2012). In a review (Rejmanek & Pitcairn, 2002) concluded that infestations over 1000 ha are unlikely to be eradicated. "Knowledge of the extent of a weed incursion (the "delimitation" criterion) is considered fundamental for eradication success, as an incursion will progress from any infestations that remain undetected and thus uncontrolled" (Panetta & Lawes, 2005). Generally, weed eradication programmes require 10 years or more to achieve their objective, because even after the last plant has been removed monitoring is necessary to continue for the life of the seedbank (Panetta, 2007). The optimal time to stop monitoring and end the programme is really an economic trade-off between the cost of continued surveying and the cost of escape and damage if eradication is declared too soon (Regan et al., 2006).

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Supplementary material 5.11. Smallholder farmers and the management of *Spodoptera frugiperda* (fall armyworm)

Supplement to **section 5.5.5**

Asare-Nuamah et al. (2022) and Koffi et al. (2020) found that almost 90 per cent of their sampled farmers from Ghana used synthetic pesticides for fall armyworm control. Tambo et al. (2020) and Houngbo et al. (2020) also reported that 87 per cent and 91 per cent of sampled farmers in Rwanda and Benin, respectively, applied synthetic pesticides to control fall armyworm. The widespread use of synthetic pesticides has been attributed to the distribution of free or subsidized pesticides by several African governments in response to the fall armyworm invasion (Asare-Nuamah, 2022; Day et al., 2017; Tambo, Day, et al., 2020). Unfortunately, some of the farmers use restricted and highly toxic synthetic pesticides, and there is little or no use of personal protective equipment while spraying the pesticides, thereby posing high risks to human health (Kansiime et al., 2019; Murray et al., 2019, 2021; Rwomushana et al., 2018; Tambo, Day, et al., 2020).

Nearly 40 per cent of the papers reported evidence of farmers' control of fall armyworm using biopesticides, which are low-risk products compared to synthetic pesticides. The biopesticides are mostly neem-based products, and extracts of other plants such as tobacco, chilli and *Mucuna pruriens* (velvet bean) (Dassou et al., 2021; FAO, 2018; Kansiime et al., 2019; Kumela et al., 2019; Murray et al., 2019). Rwomushana et al. (2018) found an increase in the use of biopesticides for fall armyworm control in Ghana, due to policy effort by the government to promote their usage. The physical control methods include handpicking of fall armyworm egg masses and caterpillars, as well as the destruction of infested plants. A study by Tambo et al. (2020) has shown evidence that households with few members (who are thus more likely to be labour-constrained) and households who cultivate larger plots, have lower likelihoods of engaging in handpicking of fall armyworm due to its labour intensiveness. There are also concerns that the handpicking of fall armyworm may increase the labour burden of women and children (Harrison et al., 2019; Tambo, Day, et al., 2020; 2019; 2020). It was found that the use of cultural methods for fall armyworm management was popular in areas where extension programmes (plant clinics and information and communications technology-based extension campaigns) have been used to promote integrated pest management (Tambo et al., 2019; Tambo, Kansiime, et al., 2020; Tambo, Uzayisenga, et al., 2020).

An exception is the use of fish soup, which was identified as a traditional method of controlling fall armyworm in Malawi (Murray et al., 2019). Rwomushana et al. (2018) suggested that the use of the traditional methods was becoming popular in Zambia as the number of farmers using them for fall armyworm control doubled between 2017 and 2018. They attributed this to the lack or reduced distribution of pesticides by the Zambian government and the use of traditional non-chemical approaches to maize production by smallholder farmers in the country.

Factors constraining the management of fall armyworm

This fall armyworm information constraint is partly due to limited capacity of extension workers (Kassie et al., 2020; Murray et al., 2019; Tambo et al., 2019), who are key sources of information for many smallholders. Hence, farmers tend to be exposed to incorrect or contradictory information from different sources (Abukari et al., 2021) or do not know what to do to combat the pest (FAO, 2018), or lack an understanding of the risks associated with the indiscriminate use of pesticides against fall armyworm (Murray et al., 2019).

Effectiveness of the management practices

Most of the studies examined the effectiveness of the fall armyworm management practices based on farmers' perceptions. Pesticides were generally perceived to be effective against fall armyworm (FAO, 2018; Houngbo et al., 2020; Rwomushana et al., 2018; Tambo, Kansiime, et al., 2020). For example, Tambo et al. (2020) found that in each of their four study countries (Ghana, Uganda, Zambia and Zimbabwe), more than 90 per cent of the synthetic pesticide users reported that this method was effective against fall armyworm. In Ghana, 88 per cent of smallholder farmers who used biopesticides claimed that it was effective (Tambo, Kansiime, et al., 2020), while in Namibia, almost all commercial farmers who applied pesticides to control fall armyworm said that the method was effective (FAO, 2018). However, according to Kumela et al. (2019) 60 per cent of sampled farmers in Kenya mentioned that pesticides were not effective for the control of fall armyworm. Similarly, Koffi et al. (2020) noted that for nearly two-third of farmers synthetic pesticides were ineffective when sprayed on maize leaves, but 92 per cent of the farmers who received some training and adopted target application of pesticides were satisfied with the effectiveness of the pesticides, pointing to the importance of farmer training in the successful management of the pest.

The perceived degree of effectiveness of other fall armyworm management practices varies considerably across studies. For instance, early planting, handpicking, planting resistant varieties, crop rotation and replanting were largely perceived as extremely or somewhat successful in Namibia (FAO, 2018). Conversely, early planting and handpicking were rated as relatively ineffective against fall armyworm by farmers in Benin (Houngbo et al. 2020). The application of ash was, however, unsuccessful in both Namibia (FAO, 2018) and Benin (Houngbo et al., 2020). According to Rwomushana et al. (2018) majority of farmers in Ghana and Zambia who used physical and cultural methods such as handpicking, weeding and uprooting and burning of infested plants to control fall armyworm reported these non-effective. Similarly, Murray et al. (2021) noted that most of the cultural control methods were c ineffective against fall armyworm in Kenya. As noted by Tambo et al. (2020), farmers' perceived effectiveness of the various fall armyworm management is likely influenced by several factors, including the level of fall armyworm infestation, the timing of application of the practice, and field conditions.

Several of the studies also explored the effectiveness of the fall armyworm management practices using statistical analysis, instead of farmers' perceptions. The results generally showed that farmers who used fall armyworm management practices achieved positive outcomes in terms of reduced yield losses (FAO, 2019), increased maize yield (Bariw et al., 2020; Kassie et al., 2020; Tambo, Uzayisenga, et al., 2020), increased maize consumption (Tambo, Uzayisenga, et al., 2020), and reduced hunger (Tambo et al., 2021). Three of the studies (Bariw et al., 2020; Kassie et al., 2020; Tambo, Day, et al., 2020) further showed that greater gains were achieved when farmers used a combination of the fall armyworm management practices. For example, using survey data from Ghana and Zambia, Tambo et al. (2020) showed that spraying of pesticides alone was associated with maize yield gain of 90 per cent, while handpicking alone did not significantly enhance yield; but combining the two methods produced maize yield gains of 125 per cent. Likewise, Kassie et al. (2020) found that individual fall armyworm control measures were ineffective in preventing yield losses, but combining different control strategies, such as using chemicals and handpicking or handpicking and ash, was effective in mitigating yield loss due to fall armyworm in southern Ethiopia.

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Supplementary material 5.12. Case study: classical biological control of *Oryctolagus cuniculus* (rabbits)

Supplement to **section 5.5.5.3**

Box SM.5.2. *Oryctolagus cuniculus* (rabbits) biological control in Australia

Myxomatosis is caused by a poxvirus (family *Poxviridae*, genus *Leporipoxvirus*) and is vectored by insects. In rabbits of the genus *Sylvilagus* (cottontail rabbits) in the Americas, infection causes only localized skin tumours, but resulted in high mortality in European rabbits. The virus was released in Australia in the late 1940s which initially reduced the number of rabbits to the tune of 90-99 per cent (*Figure SM.5.1*). However, the individuals that survived developed immunity and reduced the impact of myxomatosis. In 1968 and 1993, *Spilopsyllus cuniculi* (European rabbit flea) and *Xenopsylla cunicularis* (Spanish rabbit flea) were released to enhance transmission in hot dry regions (Cooke, 2014).

In the mid-1980s, a novel disease of rabbits emerged, rabbit haemorrhagic disease, caused by a single-stranded positive-sense Ribonucleic Acid (RNA) virus (RHDV1). In 1991, RHDV1 was imported into containment in Australia for assessment and testing. Despite strict biosecurity and quarantine, within months the virus had escaped to the mainland and spread rapidly. Both the escape and the subsequent rapid spread were most likely vectored by flying insects. In 1996, RHDV1 was officially registered in Australia as a pest control agent (Cooke, 2014; Saunders et al., 2010). A vaccine for the released strain was subsequently developed and made available to the domestic and pet rabbit trade (AVA, 2011).

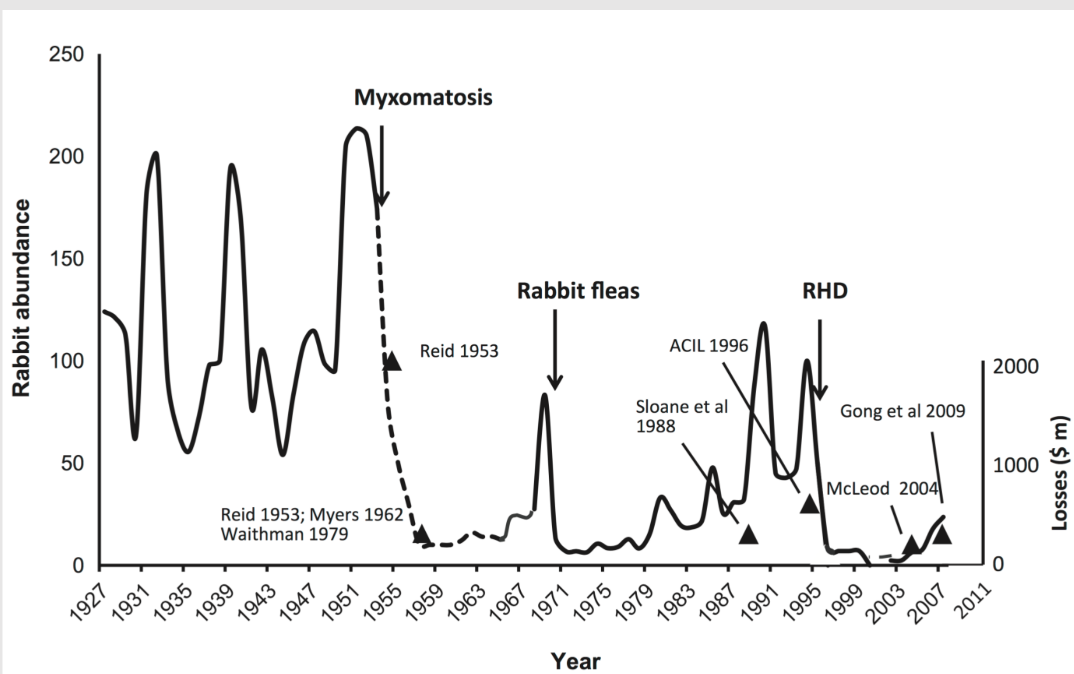

Figure SM.5.1. Diagram showing how *Oryctolagus cuniculus* (rabbits) abundance in semi-arid South Australia has varied through time in response to the release of biocontrol agents. The estimated

Australia-wide economic losses to rabbits (triangles) are also shown. Scale for losses shown on right-hand side of figure. Adapted from Saunders et al. (2010)

The original release of RHDV1 in Australia was estimated to have cost about AU$ 12 million over seven years for research, including safety aspects. The return on that investment has been estimated at AU$ 350 million annually (Saunders et al., 2010). Considering myxomatosis and RHD together, the overall value to the wool and meat industry in Australia is estimated to have cumulative economic benefits of about AU$ 70 billion in 2011 (Cooke et al., 2013). Regardless, post-RHD rabbit populations still cost the Australian wool and beef industry an estimated AU$ 200 million annually (Gong et al., 2009). Sustained RHD biological control has resulted in the recovery of three previously threatened desert mammal species such that they now qualify for a downgrading of their categorization on the International Union for Conservation of Nature (IUCN) red list (Pedler et al., 2016). In arid zones, sustained low rabbit populations has led to the significant regeneration of native vegetation (Sandell, 2002).

Acronyms

AU$	Australian dollar
RHDV	Rabbit Haemorrhagic Disease Virus
RNA	Ribonucleic Acid

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Supplementary material 5.13. Case studies – role of national and international networks and regional partnerships in management

Supplement to **section 5.6.3.1**

Local - In Hawai'i, island-based partnerships (referred to as invasive species committees, or ISCs) have operated on all six of the main, non-privately held Hawaiian Islands since 2001 (Kraus & Duffy, 2010). The invasive species committee (ISC) structure consists of an independent committee of interested parties (e.g., Federal and State agencies, private organizations, landowners, or business association) who are supposed to jointly identify and eradicate the most-threatening invasive alien species. The actual control work is led by an ISC manager, a field leader and field crew, supported by information officers, data management and sometimes also including a volunteer work force. While sustained funding sources remain as issue, the model has been successful in circumventing political interference and gaining public support (Kraus & Duffy, 2010).

National - Countries which hold overseas territories provide an example of subnational collaboration. In 2005, the International Union for Conservation of Nature (IUCN) French Committee launched an initiative on invasive alien species in the French overseas territories with the aim of improving access to information, increasing management capacity, and strengthening cooperation among the thirteen overseas territories and with their neighbouring countries (Soubeyran et al., 2015). With a budget of 140,000 € per year, two action plans were implemented between 2005 and 2011, by informal working groups consisting of a network of national and local experts and stakeholders from research institutions, non-governmental organizations and public agencies (*section 5.6.3.1*). Outcomes of the initiatives include a website[10] with a species database (630 alien taxa), a bibliographic database (490 references) and numerous documents such as protocols for control, guidelines for preventive action and regulations in force, and regional workshops to promote transnational cooperation (Soubeyran et al., 2015).

Global - **Section 5.4.1** and **Table 5.4** listed databases relevant for planning and implementation of management. In addition, some examples are provided here of international networks assisting management of invasive species at global scale namely Invasive Species Specialist Group (ISSG), The Inter-American Biodiversity Information Network (IABIN), Asia-Pacific Forest Invasive Species Network (APFISN), European Network on Invasive Alien Species (NOBANIS), Centre for Agriculture and Bioscience International (CABI) and the European Alien Species Information Network (EASIN).

Networks: The ISSG is a global network of scientific and policy experts on invasive species, organized under the auspices of the Species Survival Commission (SSC) of the IUCN. The Invasive Species Specialist Group (ISSG) was established in 1994. It currently has 196 core members from over 40 countries and a wide informal global network of over 2000 conservation practitioners and experts who contribute to its work. The ISSG promotes and facilitates the exchange of invasive species information and knowledge across the globe and ensures the linkage between knowledge, practice and policy so that decision-making is informed (Pagad et al., 2015). The two core activity areas of the ISSG are policy and technical advice, and information exchange through our online resources and tools and through networking. The ISSG used to publish a biannual newsletter "Aliens" featuring articles on

[10] www.especes-envahissantes-outremer.fr

issues related to invasive species. The ISSG manages the Global Invasive Species Database (GISD) which is an online, freely available premier resource of information on invasive species, their ecology, spread, management, and impacts. The GISD aims to increase public awareness about invasive species and to facilitate effective prevention and management activities by disseminating specialist's knowledge and experience globally to a broad audience. The IUCN and its ISSG have also recently published a global standard for the Environmental Impact Classification for Alien Taxa (EICAT; IUCN, 2020b).

IABIN for invasive species was established in 2002 as the first thematic network (I3N) (Grosse et al., 2006), formed through an agreement between countries in the Americas. The objective of I3N was to facilitate cooperation on invasive alien species information discovery, collection, management, and distribution, and provide training on the use of tools developed and freely distributed by the network. Other four networks were established, but never as developed: Species and Specimens, Pollinators, Ecosystems, and Protected Areas. The I3N was Coordinated by the National Biological Information Infrastructure (NBII) of the United States Geological Survey (USGS) and funded through a Global Environmental Facility (GEF) project. A Focal Point in the National Government was nominated for each participating country, and the Coordinating Institution was supported by a Technical Working Group (TWG). A National Lead (and sometimes a Co-Lead) was defined for each country to take charge of technical and development issues. The main focus of the network was to standardize and share information and to build capacity for the management of invasive alien species in participating countries. Practical products were devised and developed, an I3N website with information and products for download, a national database template with an online interface, a risk assessment tool, a pathways assessment tool and a list server. The database was developed in full consistency with global data management initiatives on invasive species to ensure harmonization of vocabulary and definitions. Once the database template was ready, it was implemented in Brazil and Argentina first, then provided to more than twenty countries throughout Latin America and the Caribbean. This product was delivered with a training workshop hosted by the I3N in which technical, scientific and managerial information were provided, case studies were presented by locals, and one day was devoted to training on database use. At one point, 13 countries had national databases online. Of these, only four are functional to this day. The tools developed by I3n were distributed beyond the region of initial coverage through training provided for Association of Southeast Asian Nations (ASEAN), reaching ten countries in that region, and to different Caribbean states through the CABI Caribbean GEF project. The database was initially developed in Microsoft Access software in 2004. For reasons of copyright and costs, some countries were unable to implement the database in that format. A new version was developed in open-source software based on feedback from the users for improvement and released in 2011. The old versions were replaced country by country, with some technical assistance provided for installation and use, including manuals in English, Spanish, and Portuguese.

Why didn't the databases last in most countries? Mostly, because institutions in charge lacked specific mandates on invasive species, or for lack of expertise and/or lack of people working on biological invasions. Most databases hosted by national governments were lost after elections as technical staff were replaced. A few were hosted by universities or non-governmental organizations. The four databases that have persisted are managed by non-governmental organizations and universities. In each case, there is someone in charge keen to maintain and build on the work that has been done and because the data were deposited in an open-source repository. In most cases, unfortunately, people learned from the experience but were not able to carry on without specific funding or an official mandate. The risk assessment tools were used by some governments as a base to develop customized assessments. These initiatives were linked to other global programmes and represented the beginning of governance on invasive species in most countries in Latin America. The I3N network was discontinued when the GEF project that funded its work was terminated in 2011.

APFISN has been established as a response to the immense costs and dangers posed by invasive species to the sustainable management of forests in the Asia-Pacific region. It is a cooperative alliance of 34 member countries of the Asia-Pacific Forestry Commission (APFC). The network operates under the umbrella of APFC which is a statutory body of the Food and Agriculture Organization (FAO). The APFISN focuses on inter-country cooperation that helps to detect, prevent, monitor, eradicate and/or control forest invasive species in the Asia-Pacific region (Asia-Pacific Forest Invasive Species Network, 2021).

NOBANIS was established as a network between authorities of the region. The network was initiated with funding by the Nordic Council of Ministers. One of the main goals of NOBANIS is to provide tools for implementing the precautionary approach against the unintentional dispersal of invasive alien species. It also establishes regional cooperation to aid countries in eradication, control and mitigation of these species. The establishment of NOBANIS was a response to the recommendations that came out of the Convention of Biological Diversity (CBD) 6th meeting of the Conference of Parties (COP) in 2002. The NOBANIS has a national focal point in each of the participating countries.

CABI is an international non-profit organization that hosts a large number of invasive alien species-related projects linking different countries and rural communities, especially in Asia and Africa. CABI has developed the open access Invasive Species Compendium as an open access tool to support identification of invasive alien species globally.[11]

Acronyms

APFC	Asia-Pacific Forestry Commission
APFISN	Asia-Pacific Forest Invasive Species Network
ASEAN	Association of Southeast Asian Nations
CABI	Centre for Agriculture and Bioscience International
EASIN	European Alien Species Information Network
EICAT	Environmental Impact Classification for Alien Taxa
FAO	Food and Agriculture Organization (of the United Nations)
GEF	Global Environment Facility
GISD	Global Invasive Species Database
IABIN	Inter-American Biodiversity Information Network
ISC	Invasive Species Commission
ISSG	Invasive Species Specialist Group
IUCN	International Union for Conservation of Nature

[11] https://www.cabi.org/ISC

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Chapter 6[1]: Governance and policy options for the management of biological invasions

Supplementary materials

[1] This is the final text version of the supplementary material of Chapter 6 of the IPBES Thematic Assessment Report on Invasive Alien Species and their Control (https://doi.org/10.5281/zenodo.7430682)

Supplementary material 6.1. Invasive Alien Species in the Antarctic: Policy and Governance

This supplementary material complements **Box 6.10**.

The Broader Antarctic Region and its Governance Arrangements

Policies that are relevant to biodiversity and to ecosystem services in the Antarctic region are developed, usually independently, by the Antarctic Treaty Consultative Parties (ATCPs), the Commission for the Conservation of Antarctic Living Resources (CCAMLR), and by the States responsible for the islands north of 60°S. The ATCPs are advised by the Committee for Environmental Protection (CEP), established by the Protocol on Environmental Protection to the Antarctic Treaty of 1991 (hereafter the Protocol), and by the Scientific Committee on Antarctic Research (SCAR), a committee of the International Science Council (Protocol Article 10.2).

Article 4 of Annex II to the Protocol on Environmental Protection (hereafter Article 4; ATCM, 2009) concerns the Introduction of Non-Native Species and Diseases. Article 4 prohibits the introduction of living organisms not native to the Antarctic Treaty Area onto land or ice shelves, or into water, expect in accordance with a permit. It also prohibits the introduction of non-sterile soil, live poultry, and other living birds. Article 4 also requires that Antarctic Treaty Parties should to the maximum extent practicable ensure that non-sterile soil is not accidentally imported into the region.

Permits may be issued for the importation of alien cultivated plants and their propagules for controlled use, and for species of living organisms for controlled experimental use. Prior to expiration of permits, the organisms have to be removed from the Treaty area or disposed of by incineration or an equally effective measure. Article 4 also requires that any species not native to the Antarctic Treaty area that is introduced to the area without a permit be removed, wherever feasible, unless removal poses a greater environmental impact. Article 4 also requires that all reasonable steps be taken to control the consequences of an introduction to avoid harm to fauna and flora.

The CAMLR Convention recognizes the conservation significance of the effect of the introduction of alien species (Article II.3.c), but has no further detail about them. Nonetheless, Article V acknowledges the obligations and responsibilities of the ATCPs for the protection and preservation of the environment of the Antarctic Treaty area. Contracting Parties to the CAMLR Convention must also abide by the Protocol on Environmental Protection to the Antarctic Treaty and its annexes and other measures. Antarctic Specially Protected Areas (ASPAs) can, and frequently do, include provisions to limit the introduction of alien species. Resolution 28/XXVII on Ballast Water Exchange in the Convention Area was adopted in 2008 by the CAMLR Convention Contracting Parties to limit the introduction of alien marine species.

The Agreement on the Conservation of Albatrosses and Petrels (ACAP) applies to many species in the broader Antarctic region (ACAP, 2018). Section 1.4.1 of Annex 2 specifies that Parties shall take all feasible action to prevent the introduction, deliberately or otherwise, of alien taxa of animals, plants or hybrids or disease-causing organisms that may be detrimental to populations of albatrosses and petrels. Section 1.4.2 commits Parties to take measures to the extent feasible to control and, where possible, eradicate alien taxa of animals or plants, or hybrids thereof, that are, or may be, detrimental to populations of albatrosses or petrels.

Invasive Alien Species Policy Implementation in the Antarctic

Based on the advice of the CEP, the ATCPs have a significant focus on reducing Invasive Alien Species introductions to and impacts on the area south of 60°S. Current guidance for doing so is encapsulated in the CEP Non-Native Species Manual (ATCM, 2019; hereafter the Manual).

Article 4 of Annex II to the Protocol does not consider unintentional introductions specifically (Hughes et al., 2015). Nor does have it have provisions concerning species transfers between Antarctica's very different ecoregions. The Manual, however, covers both unintentional introductions and transfers between regions, largely because of the effective translation of recent research (e.g., Hughes & Convey, 2010, 2012; J. E. Lee & Chown, 2011) to policy through the CEP. Although the pace of such translation and uptake has been criticized (Hughes & Pertierra, 2016), the rate of development of responses within the ATS has been relatively rapid, with these responses exceeding those typically expected elsewhere, as measured through a comparison with international responses to the relevant Aichi Targets of the CBD Strategic Plan for Biodiversity 2011-2020 (Chown et al., 2017). The Manual has also been supplemented by other practical guidance for those operating in the region. Perhaps the best example is the COMNAP/SCAR Non-Native Species Voluntary Checklists for Supply Chain Managers (SCAR & COMNAP, 2019), which provides practical guidance (and the evidence underlying it) to prevent the introduction of non-indigenous species to Antarctica. Other organizations, such as the Antarctic tourism industry body, the International Association of Antarctica Tour Operators (IAATO), have similar guidance for its members (IAATO, 2020). In the 2018/2019 season, more than 50 000 tourists visited Antarctic and numbers are expected to rise.

Two further complexities of invasive alien species policy implementation in the Antarctic Treaty Area are that: (i) Article 7 of Annex III, on Waste Disposal and Management, to the Protocol, precludes the use of pesticides (other than those required for scientific, medical or hygiene purposes) south of 60°S; (ii) Annex I to the Protocol requires that all activities to be undertaken in the Antarctic Treaty area require some level of impact assessment. Those expected to have less than a minor or transitory impact can proceed, those with a minor impact require an Initial Environmental Evaluation, and those with a greater than minor or transitory impacts require a Comprehensive Evaluation (Hughes et al., 2015). The legal language in the Protocol and its Annexes make many of the required assessments complicated because of the lack of clear and objective language (Hughes et al., 2015; Hughes & Pertierra, 2016).

Although the Manual makes reference to marine invasions, and in particular the Practical Guidelines on Ballast Water Exchange in the Antarctic Treaty Area (ATCM, 2006), what is made most clear is the absence of guidelines for the prevention of the introduction of marine invasive alien species and the absence of clear guidance as to the approach required if marine alien species or invasions are detected. The Manual is similarly largely silent about the continental water bodies of the Antarctic south of 60°S. By contrast, a great deal of advice is provided for terrestrial systems, including flow charts on how to respond to introductions. Notwithstanding all of the advice and agreements, Antarctic Treaty policy implementation proceeds through implementation in national law, which is highly variable between the nations which operate in the Antarctic and which are party to the Treaty and Protocol (Hughes & Pertierra, 2016). Moreover, any nation that is not a Party to the Treaty or the Protocol cannot be prevented from operating in Antarctica.

The sub-Antarctic and maritime Antarctic islands under national control differ from the areas south of 60°S precisely because these islands fall within national jurisdictions. Thus, international conventions which apply to nations apply strictly to these areas too. Thus, national plans to give effect to the requirements of these conventions must necessarily include the sub-Antarctic and maritime Antarctic islands under the control of the particular nations, and this is often done. Indeed, in many cases, proactive approaches to conservation are taken. For example, of the sub-Antarctic islands, the Crozet archipelago, the Kerguelen islands, Heard and McDonald Islands, Macquarie Island and the New Zealand sub-Antarctic islands have all been accepted onto the Word Heritage List (World Heritage Committee, 1997, 1998, 2019).

As a consequence of differences in national requirements, a variety of approaches to the prevention and control of alien and invasive alien species have been implemented. The majority of the islands have management plans or equivalent guidance which specify the approach to prevention of introductions, the responses required if introductions are detected, and requirements for eradications (**Figure SM.6.1**). For all of the islands, it is clear that the threats posed by invasive alien species are well appreciated (De Villiers et al., 2006).

The implementation of policy to prevent introductions varies considerably. For example, extensive biosecurity requirements exist and inspections are mandatory for all ships and cargo departing for or arriving in South Georgia, including private yachts, as well as for storage facilities used to ship materials to the territory (GSGSSI, 2019). By contrast, specific biosecurity procedures have not been implemented for storage facilities and cargo supplying the Crozet and Kerguelen islands, and private vessels visiting these islands are not subject to biosecurity inspection (TAAF, 2017). Similarly, fresh produce may not be taken ashore to either of the Prince Edward Islands (CIB, 2010, section 5.2.2), but this may be done under strict conditions for Heard Island (Australian Department of the Environment, 2014, section 5.4.12), and routinely for the Crozet and Kerguelen islands (Hughes et al., 2011).

Policies to eradicate or control invasive alien species, where practicable, are common to all management plans for the sub-Antarctic islands. On several of the islands, extensive eradication programmes have either been undertaken or are planned (Bester et al., 2000; Chapuis et al., 2004; Headland, 2012; Martin & Richardson, 2019; Preston et al., 2019; Springer, 2016). In several cases, however, alien species eradications are listed as low management priorities, either because these measures are currently infeasible, likely to be too costly, or because there is a lack of information about the potential consequences of invasive species removal, which has previously caused unintended issues in sub-Antarctic ecosystems (Bergstrom et al., 2009).

Policy Harmonization Across the Antarctic and Antarctic Treaty System

Because governance of the Antarctic falls within the ATS, and the application of its instruments (such as CCAMLR, the Protocol) often fall within the same government departments, harmonization of approaches across the region can be considered reasonably well advanced. However, substantial differences in implementation do exist among nations (e.g., Hughes &

Pertierra, 2016; Peter et al., 2013). Nonetheless, what should be done to limit the impacts of invasive alien species and the reasons for doing so, are uniformly articulated to the ATCPs. A clear example is provided by the CEP Non-Native Species Manual (ATCM, 2019). Considerable progress has therefore been made in addressing the requirements for reducing the introduction and spread of invasive alien species, in monitoring the situation, and in responding to new incursions and developing eradication approaches (Hughes & Convey, 2012; McGeoch et al., 2015).

Much of the policy for areas south of 60°S and for the sub-Antarctic islands and Maritime Antarctic islands north of this parallel is similar, though implementation for the sub-Antarctic is often more stringent because agreement on policy is more straightforward for a single country than for many countries within a single forum (such as the Antarctic Treaty Consultative Meetings; Leihy et al., 2020). Three primary reasons can be readily identified for the similarities in policy, and in some aspects in implementation, for regions north and south of 60°S. (1) The same individuals are involved in the research on invasive alien species and in developing policy advice and deliberating on it in the appropriate forums in both areas. (2) Science in, from and about Antarctica and the Southern Ocean, including the sub-Antarctic islands, is coordinated and facilitated by the SCAR, which has included a focus on invasive alien species for several decades (Kennicutt et al., 2019; Walton et al., 2018). (3) The science-policy interface in the Antarctic Treaty setting has been reasonably effective, especially for invasive alien species management, at least until now (Hughes et al., 2018). That situation may be changing as external and internal challenges to the ATS grow (Chown & Brooks, 2019).

Future Invasive Alien Species Policy Options for Antarctica and the sub-Antarctic Islands

The broader Antarctic region is changing rapidly as a consequence of global climate change (Le Roux & McGeoch, 2008; Lebouvier et al., 2011; Rintoul et al., 2018; Swart et al., 2018), with most analyses indicating that risks of establishment, spread and impact of alien species will increase (Aronson et al., 2015; Duffy et al., 2017; Frenot et al., 2005; McCarthy et al., 2019; McClelland et al., 2018; Pertierra et al., 2020). Human activity in the region is also growing due to growth in scientific stations and numbers of science and support personnel, and in numbers of tourists (Chown & Brooks, 2019). Thus, invasive alien species policy requirements for the future will have to focus especially on what these changes mean for introductions from elsewhere into the Antarctic region. Distinguishing introductions from range shifts will remain a major challenge (Hughes & Convey, 2012; S. Y. Lee et al., 2014). Transfers of species among these regions, as a consequence of direct or indirect human actions, are not yet the subject of adequate policy consideration (Hughes et al., 2019; Hughes & Pertierra, 2016). At the heart of the challenge lies an inadequate understanding of biodiversity variation across Antarctica and the Southern Ocean, and how species are responding to changing conditions (Chown et al., 2015; Gutt et al., 2015; Kennicutt et al., 2019).

In the face of these challenges, a focus on better biosecurity measures, for prevention, and the development of clear surveillance policy and practices to identify and characterize new establishments as they occur is essential, especially for marine systems (Aronson et al., 2015; Hughes et al., 2015; Hughes & Pertierra, 2016). Extension of protected areas with strict biosecurity policies, and recognition that protected areas are connected to their surrounding systems is essential (Shaw et al., 2014). Concerted eradication actions will also be required given recent developments. For example, as a consequence of changing climates, mice (alien) are proliferating on sub-Antarctic Marion island, decimating native invertebrates, and now switching to predation on albatross chicks and adults (Dilley et al., 2016; Jones et al., 2019; McClelland et al., 2018).

Although these requirements have variously been identified by the Antarctic Treaty Consultative Parties (ATCM, 2019) and by CCAMLR, they are not yet being given the practise-led research attention they deserve. At present the CEP has little means by which to provide financial support for such work (Liggett et al., 2017). SCAR does facilitate such work, and in the past has been responsible for great strides forward in practise-led research outcomes (Hughes et al., 2010), but relies on national science programmes to provide the majority of support.

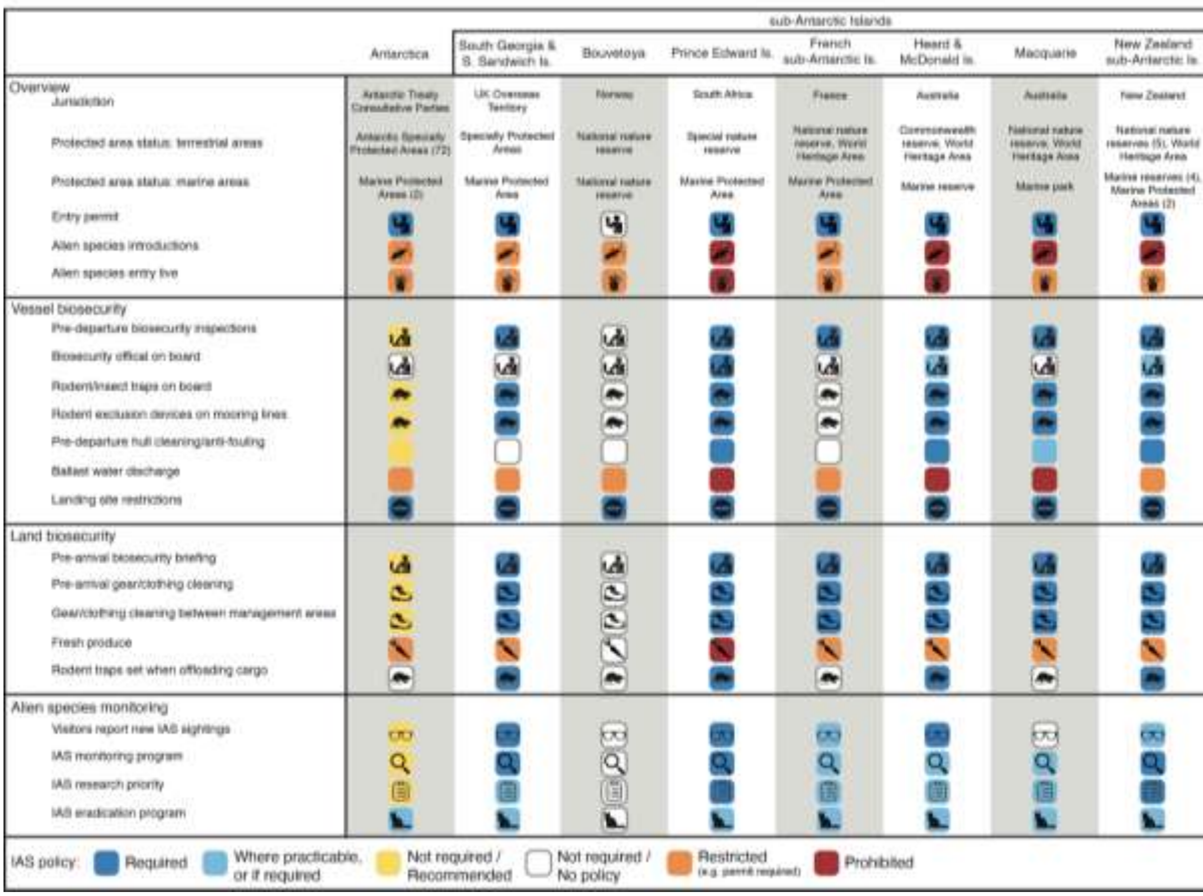

Figure SM.6.1. Biosecurity and invasive alien species (IAS) monitoring and eradication measures in place across Antarctica and the sub-Antarctic islands.

Acronyms

ATCPs	Antarctic Treaty Consultative Parties
CCAMLR	Commission for the Conservation of Antarctic Living Resources
CEP	Committee for Environmental Protection
SCAR	Scientific Committee on Antarctic Research

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Supplementary material 6.2. Table of knowledge and data gaps

This supplementary material complements **section 6.6**.

Synthesis of the most important knowledge and data gaps identified and collated through the assessment. Confidence levels in the summary for policymakers were allocated with full consideration of these gaps, which, if closed, would strengthen the understanding of biological invasions. Experts have assessed the estimated research costs, scientific challenge to close these gaps, as well as the potential gain in increasing understanding and tackling biological invasions successfully globally (from very low to very high). The listed gaps may not be relevant at local or regional scales. Data management report available at: https://doi.org/10.5281/zenodo.7840018

CATEGORY	GAP	IMPLEMENTATION CHALLENGE		POTENTIAL GAIN	
		Estimated research cost	Estimated scientific challenge	For taking management action	For better understanding biological invasions
Interoperable data for monitoring invasive alien species and effects of drivers of biodiversity change	Incomplete data and understanding of the conditions that facilitate successful integration of policy developments into management plans {6.6.1.4}	orange	orange	purple	orange
	Lack of indicators of the various dimensions of biological invasion that are policy-relevant, sensitive, reliable, relevant at national and global scales, sustained for medium-to-long-term tracking of progress and part of a responsive policy environment {6.6.3}	orange	orange	purple	purple
Gaps in how invasive alien species affect nature's contributions to people	Incomplete data on impacts on nature's contributions to people and good quality of life {4.7.2}	teal	teal	purple	purple
Management and policy approaches	Lack of control options for marine invasive alien species and invasive alien microbial fungal pathogens of plants and animals {5.6.1.1}	purple	purple	grey	orange
	Lack of agreed-upon methods of supporting management decision-making for invasive alien species with both positive and negative impacts {5.6.1.2}	orange	orange	grey	orange
	Lack of methods of managing pathways for invasive alien species arriving as contaminants, or through shipping containers, e-commerce (legal/illegal), biofouling or ports, and across land borders and along trade supply chains {Table 5.11, 5.6.2.4}	purple	purple	purple	orange
	Lack of methods for adaptive management of invasive alien invertebrates and plants using alternative approaches given the declining number of chemical control options {5.6.2.5}	teal	teal	purple	orange
	Lack of eradication guidelines and strategies for generalist invasive alien invertebrates, diseases and hard-to-detect freshwater and marine invasive alien species {5.6.2.1, Table 5.11}	orange	orange	purple	teal
	Lack of scenarios and models of invasive alien species that consider interactions with other drivers of global change {2.6.5, 6.6.1.6}	light green	teal	orange	teal
	Missing information on the implementation of adaptive-collaborative governance for biological invasions and factors important to the success of that governance strategy {6.4.4.5}	orange	orange	purple	orange
	Incomplete data on the effectiveness of policies, management strategies and actions related to biological invasions {6.1.3, 6.6.3}	orange	orange	purple	purple
Gaps to fill to support the implementation of policy and management	Lack of tools and frameworks to predict biological invasions {6.2.1, 6.6.1.6, 6.7.2.7}	orange	orange	purple	purple
	Lack of tools to reduce the barriers to information-sharing within and across countries {6.6.2}	orange	orange	purple	grey
	Lack of research and data on how best to implement integrated governance systems to manage biological invasions {6.6.1.3, 6.6.1.4, 6.6.2}	orange	orange	grey	purple
	Design principles for an integrated governance system to manage biological invasions {6.7.2.3, 6.7.3}	orange	purple	purple	orange
	Lack of mechanisms that allow effective collaboration among different elements of the socioecological systems {Figure 6.7, 6.7}	orange	orange	purple	orange

CATEGORY	GAP	IMPLEMENTATION CHALLENGE		POTENTIAL GAIN	
		Estimated research cost	Estimated scientific challenge	For taking management action	For better understanding biological invasions
Gaps in biomes, units of analysis and species groups	Incomplete or lack of inventories of invasive alien species in marine, tropical and Arctic ecosystems {2.5.2.1, 2.5.2.4, 2.5.2.5, 2.5.4}	● (orange)	● (purple)	● (purple)	● (purple)
	Incomplete or lack of inventories of invasive alien microorganisms and invertebrates {2.3.1.11, 2.3.3.3}	● (purple)	● (purple)	● (purple)	● (purple)
	Lack of understanding of the drivers of change that facilitate biological invasion for some animal groups (notably invertebrates), fungi and microbes {3.6.1}	● (orange)	● (orange)	● (purple)	● (purple)
	Lack of understanding and synthesis of the impacts of invasive alien microbes {4.7.2}	● (orange)	● (orange)	● (purple)	● (purple)
	Poor understanding of drivers of change that facilitate biological invasions in aquatic and marine systems {3.6.1}	● (orange)	● (orange)	● (purple)	● (purple)
	Lack of data on successful restoration attempts in terrestrial and marine systems {5.5.6, 5.6.2.1}	● (teal)	● (teal)	● (purple)	● (teal)
Regional gaps in data and knowledge	Comparatively incomplete inventories of invasive alien species in Africa and Central Asia {2.4.2.5, 2.4.5.5}	● (orange)	● (purple)	● (purple)	● (purple)
	Comparative lack of understanding of the drivers of change that facilitate biological invasions in developing economies {Box 3.12}	● (orange)	● (orange)	● (purple)	● (purple)
	Lack of data and knowledge of the drivers of biological invasions in sub-Saharan Africa, tropical Asia and South America {3.6.1}	● (purple)	● (orange)	● (purple)	● (purple)
	Incomplete data on the impacts of invasive alien species across Africa and Central Asia {4.7.2}	● (orange)	● (teal)	● (purple)	● (purple)
Interoperable data for monitoring invasive alien species and effects of drivers of biodiversity change	Lack of standardization of terminology for invasive alien species monitoring {2.4.4.5, 6.6.2.3, 6.6.2.7}	● (light green)	● (light green)	● (orange)	● (orange)
	Lack of information on the role of indirect drivers, especially governance and sociocultural drivers, in affecting biological invasions {3.1.5, 3.6.1, Box 3.13}	● (teal)	● (teal)	● (purple)	● (purple)
	Lack of understanding of the net effects of multiple interacting drivers in shaping and promoting biological invasions {3.5, Box 3.10, 3.6.1, Box 3.13}	● (light green)	● (orange)	● (purple)	● (purple)
	Lack of knowledge on interactions and feedback across drivers in promoting invasions {3.1.5, 3.6.1}	● (teal)	● (orange)	● (purple)	● (purple)
	Lack of integration of impact data and knowledge sources across languages {4.7.2}	● (teal)	● (light green)	● (orange)	● (orange)
	Incomplete data to undertake risk management, cost-effective species-based surveillance and detection of fungi, microbes and marine pests {Table 5.11}	● (purple)	● (purple)	● (purple)	● (purple)
	Incomplete data to prioritize biological invasion management under climate, sea- and land-use change {5.6.1.3}	● (teal)	● (orange)	● (dark grey)	● (orange)
	Lack of inventories at fine scales and for specific taxon and biome contexts to support decision-makers in determining when to implement species-based or site-based management (or both) {5.6.2.1, 5.7}	● (teal)	● (teal)	● (purple)	● (teal)
	Incomplete data to develop pathway risk assessments and management for different taxonomic groups and biomes {Table 5.11, 5.6.2.5}	● (orange)	● (orange)	● (purple)	● (purple)
	Incomplete data and understanding of site-based and ecosystem-based management concepts {5.6.2.1}	● (teal)	● (teal)	● (orange)	● (teal)

CATEGORY	GAP	IMPLEMENTATION CHALLENGE		POTENTIAL GAIN	
		Estimated research cost	Estimated scientific challenge	For taking management action	For better understanding biological invasions
Gaps in knowledge on invasive alien species of particular relevance to Indigenous Peoples and local communities	Lack of information on invasive alien species status and trends on land and water managed by Indigenous Peoples and local communities {Box 2.6}	High	High	High	High
	Lack of information on Indigenous and local knowledge, values and culture regarding the drivers and impacts of invasive alien species on land and water managed by Indigenous Peoples and local communities {1.6.7.1, Box 3.12}	High	High	Very high	Very high
	Lack of understanding of and mechanisms for sharing knowledge on invasive alien species and their drivers, impacts, management and governance among Indigenous Peoples and local communities and researchers and other outsiders {6.6.1.5}	High	High	Very high	Very high
	Lack of consideration of the knowledge and perceptions of Indigenous Peoples and local communities in scenarios and models {1.6.7.3, 4.7.1, 6.6.1.6}	High	High	High	Intermediate

Very low Low Intermediate High Very high

* A headline indicator has been adopted for planning and tracking of progress towards Target 6 of the Kunming-Montreal Global Biodiversity Framework, with opportunities to build on existing indicators for biological invasions {6.6.3}.

Supplementary material 6.3. Some examples of professional networks working towards the collection of empirical data related to biological invasions across geographic scales and habitats

This supplementary material complements **section 6.6.2.2**.

Name of professional networks (website and key citations)	IPBES regions	Biomes	Nature of data	Year of establish ment	Impacts
Mountain Invasive Research Network (MIREN) (https://www.mountaininvasions.org/)	All except Antarct ica	Terrestri al (Mounta in regions)	Change in species occurrence over time (repeat sampling) and space (elevation)	2005	Greater understan ding of biological invasions in mountains which are otherwise considered as immune to biological invasions
Global Garlic Mustard Field Survey (GGMFS) (Colautti et al., 2014)	Americ as, Europe and Central Asia	Terrestri al	Field survey data for performan ce analysis, and collection of germplasm of a single invasive species: *Alliaria petiolata* (garlic mustard) across its native and introduced range	2009	Greater understan ding of the traits responsibl e for higher invasivene ss of species and test of Evolution ary Increased Competiti ve Ability (EICA) hypothesis

Phragmites Network (PhragNet) (Hunt et al., 2017)	Americas	Freshwater	Environmental and genetic samples, habitat data, and management information	2012	Improved understanding of invasion ecology of one of the most problematic wetland invasive grass *Phragmites australis* (common reed) in Americas, and inform adaptive management decisions
Global Invader Impact Network (GIIN) (Barney et al., 2015)	All	Terrestrial	Experiments for the study of ecological impacts of invasive plants	2013	Development and use of standardized methods for impact studies.
International Plant Sentinel Network (Mainly focused to botanical gardens and arboreta) (https://www.plantsentinel.org/introduction/, Barham et al., 2016)	All	Terrestrial	Providing early warning system for new and emerging plant pest and pathogens	2013	Early detection of plant pest and pathogens in botanic gardens
InvaCost	All	Terrestrial,	Global estimate of	2014	Most up-to-date

(http://invacost.fr/en/accueil/; Diagne et al., 2020)		Freshwater, Marine	the economic cost associated with biological invasions		data, and standardized methods for estimating economic cost
SynHab (Macroecology of Plant Invasions: Global Synthesis across habitats) (https://www.synhab.com/)	All	Terrestrial, Freshwater	Global database of habitat affiliations of naturalized and invasive alien plants in their native and introduced range	2019	Data not yet published

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