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INTO THE BLUE

Securing a Sustainable Future for Kelp Forests

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INTO THE BLUE

Securing a Sustainable Future for Kelp Forests

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INTO THE BLUE

Securing a Sustainable Future for Kelp Forests

Foreword

Protecting ocean's gold, kelp forests

Covering a quarter of the world's coastlines, kelp forests are one of the most widespread and valuable marine ecosystems on the planet, providing a range of important ecological, economic, and cultural benefits.

They help draw carbon from the atmosphere, produce oxygen, reduce damage from storms, improve water quality, and attract tourists to their rich biodiversity. Kelp and seaweed farming has become the fastest-growing aquaculture industry globally, with an increase of 6.2 per cent per year over the last two decades.

However, kelp forests across every continent are in decline, and over the past 50 years, 40–60 per cent of kelp forests have been degraded. A multitude of local pressures and climate change are threatening the survival of this vital ecosystem.

This global synthesis report, provides the world's first comprehensive information on the status of kelp forests, aims to improve our understanding of the value of kelp forests and provides recommendations to protect and sustainably manage them.

Kelp forests can help countries achieve several global goals in terms of climate, biodiversity, and sustainable development.

Despite their importance, kelp have received little attention in ocean governance. To date, no global legal or policy instruments have focused explicitly on kelp. Additionally, many international frameworks, national laws and policies, and local and traditional knowledge could be considered, engaged, and channeled for the successful management, protection, and conservation of kelp forests.

Maintaining healthy kelp ecosystems is important for marine life and communities around the world. In doing so, they represent strong nature-based contributions in addressing the climate challenge and the biodiversity crisis, and in supporting sustainable development and growth worldwide.

Leticia Carvalho
Head of Marine and Freshwater Branch
United Nations Environment Programme

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Norwegian Blue Forests Network

Executive summary

The term "kelp" is commonly used to refer to just over 100 species of large brown seaweeds that represent some of the most productive and diverse habitats on Earth. Kelp dominate approximately one quarter of the world's coastlines, throughout polar and temperate regions, making them the most extensive marine vegetated ecosystem in the world. Kelp create complex and three-dimensional underwater forests rich in biodiversity. These unique coastal environments provide nursery habitat, shelter and foraging grounds for a wide range of marine organisms, including fish species of commercial importance, such as cod and pollack, and other species such as crab, octopus and lobster. Kelp forests can mitigate carbon emissions by storing carbon in standing biomass and by facilitating the long-term removal of carbon dioxide (CO_2) through the export and burial of kelp carbon in the deep sea. Indigenous and coastal people have used kelp as medicine, food and material for generations, with kelp forming part of their identities and fostering the development of a sense of place and connectedness with nature.

However, kelp have been declining globally over the past 50 years. As cool-water species, kelp are stressed by ocean warming, marine heatwaves and other climate-related extremes, with extensive losses recorded at their warm range-edges. Overfishing, reduced water quality from excess nutrients, pollution and sedimentation, and unregulated and unsustainable kelp harvesting also pose major threats to kelp forests. This global synthesis report is the most comprehensive knowledge review on kelp to date, revealing the state of science on the world's kelp forests and providing recommended actions to build the recovery of the world's kelp forests through increased public awareness and institutional support for advancing conservation, management and restoration. The report also provides a range of policy and management interventions and options that can be used to maintain these remarkable ecosystems now and in the future and to support the people and economies that have depended on them for generations.

The state of kelp forests, their values and key challenges

Kelp is the most extensive marine vegetated ecosystem in the world. Kelp are predominantly cool-water species of large brown seaweeds that are found growing on rocky reefs throughout temperate, Arctic and sub-Antarctic regions, along 25–30 per cent of the world's coastlines. They cover 1.5–2 million km^2, an area up to five times greater than that of coral reefs.

Kelp forests are threatened by both local and global stressors. Kelp have suffered widespread losses across much of their range, at a global rate of decline of 1.8 per cent per year. The trajectories of change across regions are variable, reflecting the variety of factors affecting kelp ecosystems. Over the past 50 years, 40–60 per cent of kelp forests have been degraded, with climate change, poor water quality and overfishing being the prominent causes. In severe cases, these stressors can cause full-scale shifts to ecosystems that are difficult to reverse, turning kelp forests from complex habitats to structurally simple turf-dominated reefs or sea urchin barrens.

Climate change is a major threat to kelp forests and requires urgent action. Projections for climate change impacts on kelp forests reveal extensive losses in temperate regions. A key strategy for climate change adaptation would include addressing all other stressors that can be managed locally or regionally, such as by improving water quality and controlling overfishing, in order to reduce multiple pressures acting simultaneously and cumulatively and increase kelp resilience.

Kelp forests are among the most diverse and productive ecosystems in the world and provide many valuable ecosystem services. These ecosystem services include supporting coastal fisheries, providing food, medicine and materials, mitigating climate change, protecting biodiversity, buffering ocean acidification, improving water quality and providing a range of cultural services such as recreation and support for traditional identities.

Kelp can provide important nature-based solutions to tackle climate change. Kelp forests are essential contributors to the carbon cycle; they can take up CO_2 and convert it into organic biomass for short-term storage. Kelp carbon that is not grazed, consumed or decomposed can be buried in sea floor sediments or transported to the deep ocean, thus facilitating long-term carbon removal.

Kelp provide services with economic and existence values. Economic frameworks, such as the total economic value or cost–benefit analysis, can be applied to reveal the different types of economic values that kelp provide and to support management decisions. Although these economic tools are useful, many services linked to traditional uses, spiritual practices, support for identities and broader ecological function cannot easily be monetized. Economic tools should therefore be coupled with general biophysical data on ecological function and sociocultural knowledge in order to acknowledge the full breadth of values associated with kelp ecosystems.

Kelp forests can help countries achieve several global goals in terms of climate, biodiversity and sustainable development. These forests are at the core of delivering Sustainable Development Goal (SDG) 14 Life below Water, while the conservation and sustainable use of kelp forests align with many other SDGs, including SDG 1 No Poverty, SDG 2 Zero Hunger, SDG 6 Clean Water and Sanitation, SDG 8 Decent Work and Economic Growth, SDG 12 Responsible Consumption and Production and SDG 13 Climate Action.

Kelp have received little attention in ocean governance. To date, no global legal or policy instruments have focused explicitly on kelp. This lack of attention has perhaps resulted in limited protection of kelp forests, and vice versa, with an approximate first-order estimate of less than one third of known distribution falling within marine protected areas. There are, however, many international frameworks and national laws and policies in place that could, in principle, support the conservation and effective management of kelp.

Demand for kelp for human consumption and for industry is growing. In recent decades, demand for kelp for human consumption, alginate production, aquaculture feed and potentially biofuel has increased, and will almost certainly continue to grow. Growing demand for kelp globally has mainly been met by cultivation, which now delivers 27 times more than harvesting of wild kelp. Kelp and seaweed farming has become the fastest-growing aquaculture industry globally, with an increase of 6.2 per cent per year over the last two decades.

Opportunities and recommendations

Knowledge and data generation

Invest in mapping and systematic and long-term monitoring of the world's kelp forests. The most comprehensive study of historical trends in kelp abundance covers only about one third of the world's regions where kelp forests exist, as data within these regions are spatially and temporally sparse. Assessing the trends and condition of kelp forests – especially in the many unmonitored regions – is key to evaluating the need for management actions.

Support the development of a coordinated network of global kelp observations and a data-sharing platform. Improved information on, and understanding of, kelp forests may in turn support the development of transformative policies, which are often a prerequisite to effective management and investment.

Invest in further understanding and prediction of individual stressors and their combined effects on kelp abundance and distribution. Extreme events (including marine heatwaves and storms), overfishing leading to outbreaks of grazers, eutrophication, coastal darkening and invasive species can all affect multiple life-history stages of kelp and interact to reduce their growth and survival. It is critical to understand how these drivers interact in order to predict future kelp abundance and distribution and make informed management decisions.

Quantify the ecosystem functions and services provided by kelp, and understand how these will be affected by climate change and human activities. Most data on ecosystem services – both the biophysical measures and their value – are limited to a few well-studied regions and direct-use benefits, but every kelp habitat can function differently. It is therefore critical to have specific knowledge for different ecosystems.

Incentivize kelp protection and restoration through their carbon value. One promising tool to protect and restore kelp could be the use of kelp forest "blue carbon" credits. However, operationalizing such credits would require improved scientific estimates and tools to measure kelp carbon sequestration, as well as changes to carbon market policies and frameworks.

Develop a toolbox of management interventions. By compiling examples of best practice, a toolbox of management interventions and their effectiveness (e.g. the 2022 Global Kelp Restoration Guidebook) could be developed, which could then be tailored to the needs of individual nations and local scales.

Management and policy responses

Take immediate and global action to address climate change. Increasingly warm waters have driven, both directly and indirectly, the majority of recent kelp loss. The long-term provision of services and benefits by kelp forests depends on ocean warming being held in check. Global action to tackle climate change is therefore needed to mitigate the effects of ocean warming on kelp forests and ensure their resilience in the coming decades.

Follow an ecosystem-based approach to sustainably manage kelp forests. Ecosystem-based management can act as an "umbrella" framework, whereby a number of different management approaches are applied and integrated, including initiatives for addressing individual pressures, area-based management such as marine spatial planning and marine protected areas, and sustainable management of harvesting of kelp and associated species.

Ensure an explicit focus on kelp when designating management measures and setting targets. As kelp can be affected by both land-based and sea-based human activities, managing for the cumulative impacts from various uses and users calls for a holistic approach, whereby kelp is registered as an "ecosystem in focus", and for strategic plans to address current and future stressors through appropriate regulations.

Ensure capacity-building and sustained investment for kelp management at national and local scales. Well-intentioned initiatives may not be effective if their implementation remains underfunded and inadequately managed. For management plans to be effective and for kelp-specific goals and targets to be achieved, continuous funding and sufficient technical expertise and human resources are needed for implementation and monitoring of activities.

Assess harvesting practices regularly and adapt as needed. In many countries, kelp harvesting is managed through a combination of domestic and regionalized approaches. To ensure regrowth of kelp and kelp ecosystem resilience, obtaining regular and accurate information on kelp standing stock, monitoring harvest levels and assessing harvest impacts are critical to mitigating impacts on kelp populations and associated communities. In light of significant uncertainty around impacts on kelp forests and associated ecosystem recovery (e.g. the lack of a systematic evaluation of the effectiveness of approaches to manage kelp harvesting), it is necessary to apply an adaptive and learning approach.

Combine sociocultural knowledge with economic valuations to strengthen the case for devoting resources to the conservation, sustainable management and restoration of kelp. Economic frameworks are important to identify which kelp conservation or restoration projects are likely to deliver benefits overall and how those benefits are distributed. Decision-making should also consider sociocultural frameworks that take into account whether the distribution of resources is fair and equitable, particularly when minority groups are identified as being negatively impacted by kelp management practices.

Use existing global frameworks more effectively. Existing international law could be more widely utilized to recognize kelp forests and address threats to them. Kelp could also be better acknowledged and recognized within World Heritage Sites, the Ramsar Convention, the Sendai Framework for Disaster Risk Reduction, the Convention on Biological Diversity, national biodiversity strategies and national action plans. Within the framework of the Paris Agreement and nationally determined contributions, there is also potential to catalyse the protection and restoration of kelp forests in the context of blue carbon and nature-based solutions to climate change mitigation and adaptation. Kelp restoration also provides countries with opportunities to achieve their pledges as part of the United Nations Decade on Ecosystem Restoration.

Expand partnerships and ensure stakeholder engagement and involvement. Many stakeholders have interests in kelp forests, including governments, non-governmental organizations, local and indigenous communities, local women representatives and women's groups, and businesses. Good governance requires the engagement and involvement of all relevant stakeholders. In particular, the integration of local and traditional knowledge, respect for indigenous customary laws and practices, community-based management, and formal recognition of traditional governance institutions that are empowered to make rules for local communities are all important.

Support the development of a global alliance among kelp nations. Such an alliance could raise the profile of kelp ecosystems and provide a platform for sharing best practices, discussing concerns and gathering legal, policy and management solutions at all governance levels. Similar to alliances for mangrove and coral reef ecosystems, a global alliance among kelp nations could work to provide greater visibility and commitments for kelp ecosystems in multilateral environmental fora, including the Convention on Biological Diversity and the United Nations Framework Convention on Climate Change.

PART 1

THE EVIDENCE

Chapter 1. Ecology of kelp forests and their main threats

Coordinating authors: Thomas Wernberg, Alejandro H. Buschmann, Kira Krumhansl, Kyle Cavanaugh
Contributing authors: Mads Thomsen, Dan Smale

Highlights

- **Kelp forests are one of the most extensive coastal habitats in the world, covering 25 per cent of the world's coastlines and 1.5–2 million km^2.**
- **These highly diverse ecosystems are created by a variety of large brown seaweed species, which thrive in cool high-energy environments and form forests with a dense canopy and shaded understorey.**
- **Human activities have had a profound influence on kelp forests across their range, with increasingly negative impacts during the past 50 years.**
- **Climate change and warming temperatures are among the main threats facing kelp forests, and often interact with other pressures such as eutrophication, reduced water quality, overfishing, invasive species and kelp harvesting.**

What are kelp forests?

Kelp do much the same underwater as trees in a forest do on land: they create three-dimensional structures that moderate their local environment, providing an abundant food source and a unique habitat for scores of associated organisms. Indeed, the forest analogy, and the role of kelp in creating habitat for marine organisms, has been recognized for centuries. Famously, Charles Darwin compared the giant kelp forests of South America to tropical rainforests, asserting that they support an equal number of species (Darwin 1839). Even if this is not strictly true, the biodiversity and productivity supported by kelp forests is truly remarkable (e.g. Teagle *et al.* 2017; Pessarrodona *et al.* 2021).

While there is no definitive definition of kelp (Bolton 2016), all kelp species have a common form consisting of three main parts: a blade or blades that take in sunlight and nutrients from the surrounding water, a stipe that supports the blade(s), and a holdfast which anchors the organism to the sea floor. Some kelp are rigid, held up by a stiff stipe, whereas others are highly flexible, either draping across the sea floor or being held upright or floating close to the surface by gas bladders. The majority of kelp species range in size from about half a metre to several metres, but a few species can grow to more than 30 m in length.

Many scientists use the term "kelp" to refer to brown seaweed (Ochrophyta) of the order Laminariales only, whereas others use it more broadly to also include some members of the orders Fucales, Tilopteridales and Desmarestiales (Fraser 2012; Wernberg and Filbee-Dexter 2019). Both uses are correct and have a long history. For example, the common name "bull kelp" can refer to *Nereocystis luetkeana* (Laminariales) in North America and to *Durvillaea antarctica* (Fucales) in New Zealand (Fraser 2012). While our definition of kelp forest (Box 1.1) is deliberately inclusive, here the focus is primarily on the Laminarian kelp as they, as a group, constitute the bulk of forest-forming species along most coastlines. There are just over 100 species of Laminarian kelp – around half of which are forest-forming either on their own or as part or multi-species canopies (Druehl 1970; Lane *et al.* 2006; Bolton 2010).

There is also no set definition of what constitutes a kelp forest. On land, where there are hundreds of definitions of specific types of forests, a "forest" is intuitively understood simply to be areas with lots of trees. Similarly, kelp forests are areas dominated by kelp that form a three-dimensional vegetated habitat with a canopy that either floats on the surface or is submerged with erect or draping canopies. Sometimes kelp forests are referred to as "kelp beds". However, as this term has been used inconsistently across kelp species and canopy types, it may be best to simply use the term "kelp forests" because they all provide multilayered habitat similar to forests on land (Wernberg and Filbee-Dexter 2019).

Kelp forest structure and environment

There are three broad forms of kelp forests: surface canopies where the blades float on the surface held up by gas bladders (e.g. *Macrocystis pyrifera*, *N. lutkaena*, *Ecklonia maxima*), stipitate subsurface canopies where the blades are suspended in the water column, usually by a rigid stipe (e.g. *Laminaria hyperborea*, *Lessonia trabeculata*, *E. cava*) and prostrate canopies where the blades and flexible stipes are draped over the bottom (e.g. *Saccharina latissima*, *E. radiata*) (Figure 1.1). These forms (morphologies) are not always clearly distinct and intermediate forms also exist even within species due to different environmental conditions (e.g. Kennelly 1989). Some kelp forests are made up of a single species, but often several forest-forming species co-occur in mixed-species and multilayer canopies (Dayton *et al.* 1984; Maxell and Miller 1996; Connell and Irving 2008).

Box 1.1. Definition of kelp forests

Kelp forests can be defined as subtidal stands of large brown macroalgae that modify their physical environment to create distinct environmental conditions and habitat.

This definition recognizes that kelp constitute ecologically similar species from several phylogenetically distinct orders that usually spend a significant part of their life cycle fully submerged. These kelp species have a common structure, consisting of a holdfast, stipe(s) and blade(s) that create a canopy. It also recognizes that "forests" are emergent properties of kelp aggregations when these are extensive and dense enough to modify their biophysical environment and create a unique multilayered habitat.

Figure 1.1. Examples of kelp with (A) surface canopy (*Ecklonia maxima*, South Africa; photo credit: T. Wernberg), (B) stipitate canopy (*Laminaria hyperborea*, Norway; photo credit: K. Filbee-Dexter) and (C) prostrate canopy (*Saccharina latissima*, Canadian Arctic; photo credit: R. Scheibling)

Kelp are ecosystem engineers that modify their surrounding environment due to their large size, complex form, high density and the area they cover. They can reduce light penetration (Wernberg, Kendrick and Toohey 2005; Pedersen *et al*. 2014), dampen currents and waves (Mork 1996; Gaylord *et al*. 2007) and affect sedimentation (Eckman, Duggins and Sewell 1989; Wernberg, Kendrick and Toohey 2005) and the recruitment of marine organisms (Duggins, Eckman and Sewell 1990; Almanza *et al*. 2012). For example, the removal of kelp in both California and Australia resulted in a reduction in species richness of around 30 per cent (Graham 2004; Ling 2008). Kelp can reduce nutrients in the water column (Jackson 1997) and provide surface area on which epiphytic organisms can grow (e.g. Teagle *et al*. 2017). Kelp can also transfer carbon (via drift kelp, fragments and dissolved organic carbon) within kelp forests and to surrounding habitats (Bustamante, Branch and Eekhout 1995; Wernberg *et al*. 2006; Vilas *et al*. 2020). High rates of carbon fixation and export emphasize the potential for kelp carbon sequestration (Krause-Jensen and Duarte 2016).

Global distribution of kelp forests

Laminarian kelp likely originated in the cool waters around Japan about 100 million years ago and diversified into their current forms around 25–30 million years ago (Silberfeld *et al*. 2010). Complex morphologies (including branching patterns, gas bladders and other structures) evolved several times over the past 15–20 million years, highlighting the importance of morphological convergence in establishing modern upright, complex kelp forests (Starko *et al*. 2019). Despite evidence that they crossed the equator on four separate occasions, the evolutionary history of Laminarian kelp is still apparent today, as there are many more species in the northern hemisphere than in the southern hemisphere (Bolton 2010) (Figure 1.2), and very few species are found in both hemispheres. The most diverse region is the North Pacific, with over 40 species in Asia and nearly 40 species in North America (Lane *et al*. 2006).

Today, Laminarian kelp forests are found along around 25 to 30 per cent of the world's coastlines. They are the largest marine biome in the world, covering 1.5–2 million km^2 which is 5–10 times more ocean area than coral reefs (Wernberg *et al*. 2019b; Starko, Wilkinson and Bringloe 2021) (Figure 1.2). Temperature is a strong driver of kelp biogeography. Given their evolutionary history, kelp are predominantly cool water species found at temperate, Arctic and sub-Antarctic latitudes. There are no Laminarian kelp in Antarctica (Lüning 1990). Kelp forests can also be found at tropical latitudes (e.g. Galapagos Islands) on deep seamounts in clear water where there is still enough light to sustain photosynthesis and upwelling provides low temperatures and high nutrient concentrations (Graham *et al*. 2007a).

Most kelp forests are subtidal and found from the water's edge down to 15–25 m and in places with particularly clear water down to 40–60 m (Graham *et al*. 2007a; Marzinelli *et al*. 2015b; Ramos *et al*. 2016). However, several species of Laminarian kelp can be found in the intertidal zone, such as *Postelsia palmaeformis* in the North-East Pacific coast and *L. spicata* in the South-East Pacific coast (González *et al*. 2014). Kelp are also found depths in excess of 200 m (Žuljević *et al*. 2016).

Dominant and iconic kelp species

Most species of Laminarian kelp are relatively unknown and do not have common names in English. However, a few species are very well known for a variety of reasons. The genera *Macrocystis*, *Ecklonia* and *Laminaria* are probably the most widespread kelp, with species in both the northern and southern hemispheres (Bolton and Anderson 1994; Graham, Vásquez and Buschmann 2007b; Bartsch *et al*. 2008; Wernberg *et al*. 2019a). Giant kelp (*M. pyrifera*) is one of the most iconic kelp species in the world due its conspicuous floating canopy that forms tall, dense forests that support very diverse organisms (Graham, Vásquez and Buschmann 2007b). The species is distributed along the sub-Antarctic and the north-eastern Pacific coasts (Macaya and Zucarello 2010). Golden kelp, *E. radiata*, is the biological engine of the Great Southern Reef, where it forms extensive forests across thousands of kilometres of rocky reef along the south coast of Australia, in most places as the only Laminarian kelp (Bennett *et al*. 2016; Wernberg *et al*. 2019a). Bull kelp, *N. luetkaena*, is also largely distributed in the British Columbia coast, along the west coast of Canada (Schroeder *et al*. 2020).

Some kelp have been used as food and medicine for more than 10,000 years (Dillehay *et al*. 2008) and are now well known as harvested or cultivated crops (see also section B of chapter 3). *Lessonia* species are the most harvested kelp in the world and are particularly important in Chile and Peru (Food and Agriculture Organization of the United Nations [FAO] 2021), whereas *Laminaria* species are extensively harvested in the European coast of the Atlantic, especially in Norway and France (Smale *et al*. 2013). In addition to the importance of kelp for food and the polysaccharide (sugar) industry, different kelp species have been used to obtain some bioactive compounds (e.g. phlorotannins), or to produce extracts for agronomical applications (e.g. fertilizer, see Buschmann *et al*. 2017). Finally, due to its high growth potential and high tissue-sugar content, there are different ongoing large-scale research and technological programmes for cultivating kelp for biofuel production, biomitigation of anthropogenic nitrogen inputs and carbon sequestration (e.g. Chopin and Tacon 2021; Naylor *et al*. 2021).

Kombu (*S. japonica*) and sugar kelp (*S. latissima*) have become some of the most cultivated kelp species globally (Naylor *et al*. 2021). Wakame (*Undaria pinnatifida*) is another well-known and widely cultivated kelp. Native to the cooler waters around the Republic of Korea, Japan and northern China, wakame is also known to be one of the most invasive seaweed species in the world and is now found in North and South America, Europe and Australia and New Zealand (Schaffelke and Hewitt 2007; South *et al*. 2017).


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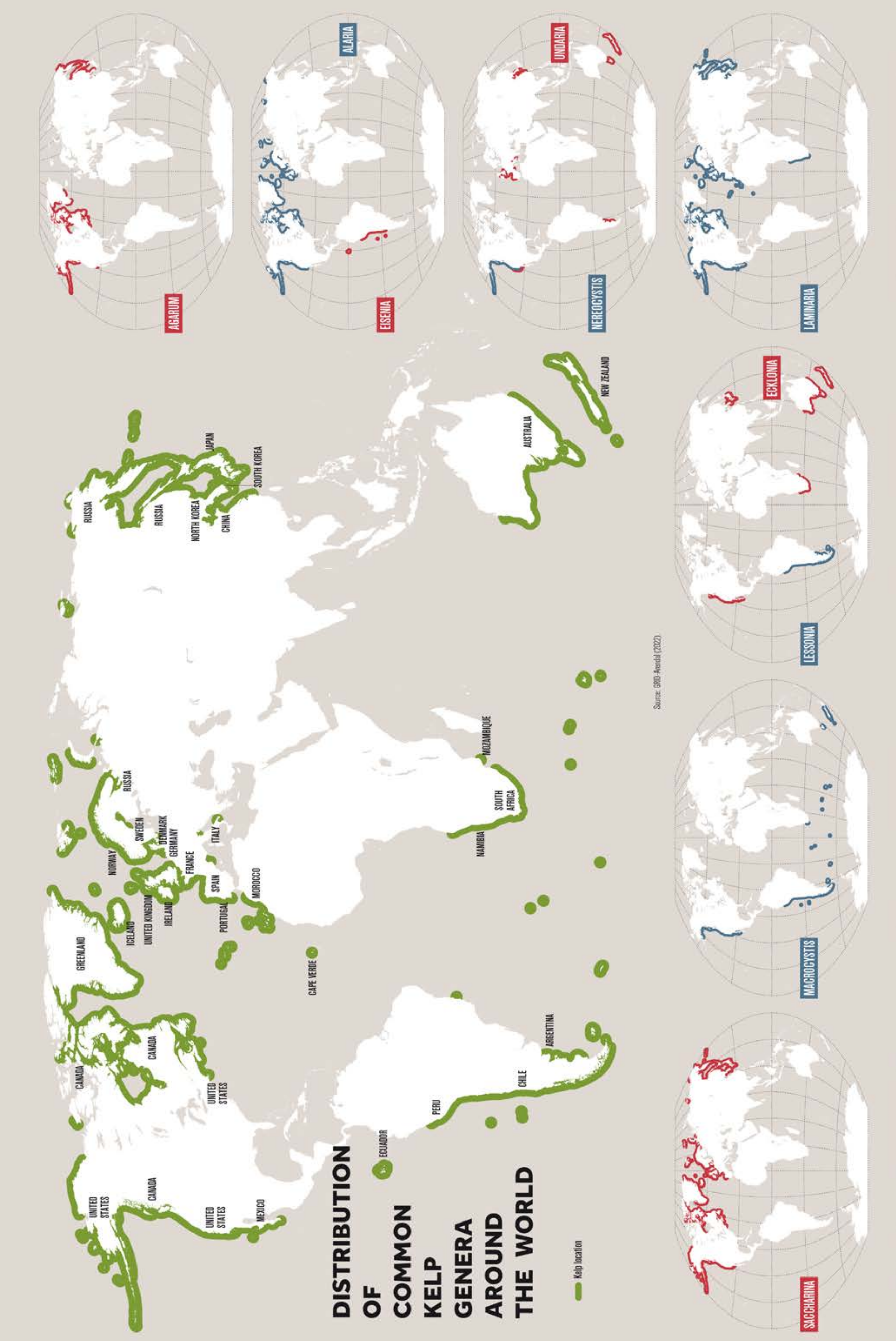
Figure 1.2. Distribution of common kelp groups around the world



Box 1.2. Kelp life cycle and abiotic requirements

Like plants on land, kelp require sunlight and carbon dioxide (CO_2) for photosynthesis and inorganic nutrients including nitrate, phosphate and several trace elements and vitamins, all of which are present in seawater. Kelp vary substantially in their capacity to store nutrients and energy. Some species (e.g. *S. latissima* and *L. solidungula*) can maintain growth under light- and nutrient-limiting conditions for weeks to months based on stores in their stipe (Dunton 1985), whereas other species (e.g. *M. pyrifera*) have a very low carbon and nutrient storage capacity and depend on a continuous supply of light and nutrients to sustain their growth (Graham, Vásquez and Buschmann 2007b). In addition, most kelp require a hard (rocky) bottom for attachment during development of both the gametophyte and sporophyte stage.

All Laminarian kelp have a life cycle with two distinct phases: a macroscopic sporophyte (the adult kelp) and a microscopic gametophyte (small life phase for sexual reproduction) (Figure 1.3). It is the sporophyte that makes up the kelp forest, but the full life cycle cannot be completed without the microscopic gametophyte, and these two life stages can have different environmental requirements and vulnerabilities. Non-Laminarian kelp, on the other hand, do not have an alternation of phases, but instead the gametes arise directly from the kelp and develop directly into a new adult.

Although all Laminarian kelp have the same basic life cycle (Figure 1.3), different species exhibit substantial variation in ecological strategies. Many species are perennial with a sporophyte that can live for anywhere between several years and more than a decade, whereas other species are annuals, where the entire life cycle lasts only a few months (Wernberg *et al*. 2019b). Some kelp show remarkable plasticity in population dynamics and can alternate between a perennial and annual strategy. For example, giant kelp (*M. pyrifera*) is usually perennial but in some populations in Chile the species is annual, relying on synchronous reproduction and microscopic stages that are able to survive for several months to connect successive time-separated generations (Buschmann *et al*. 2006).

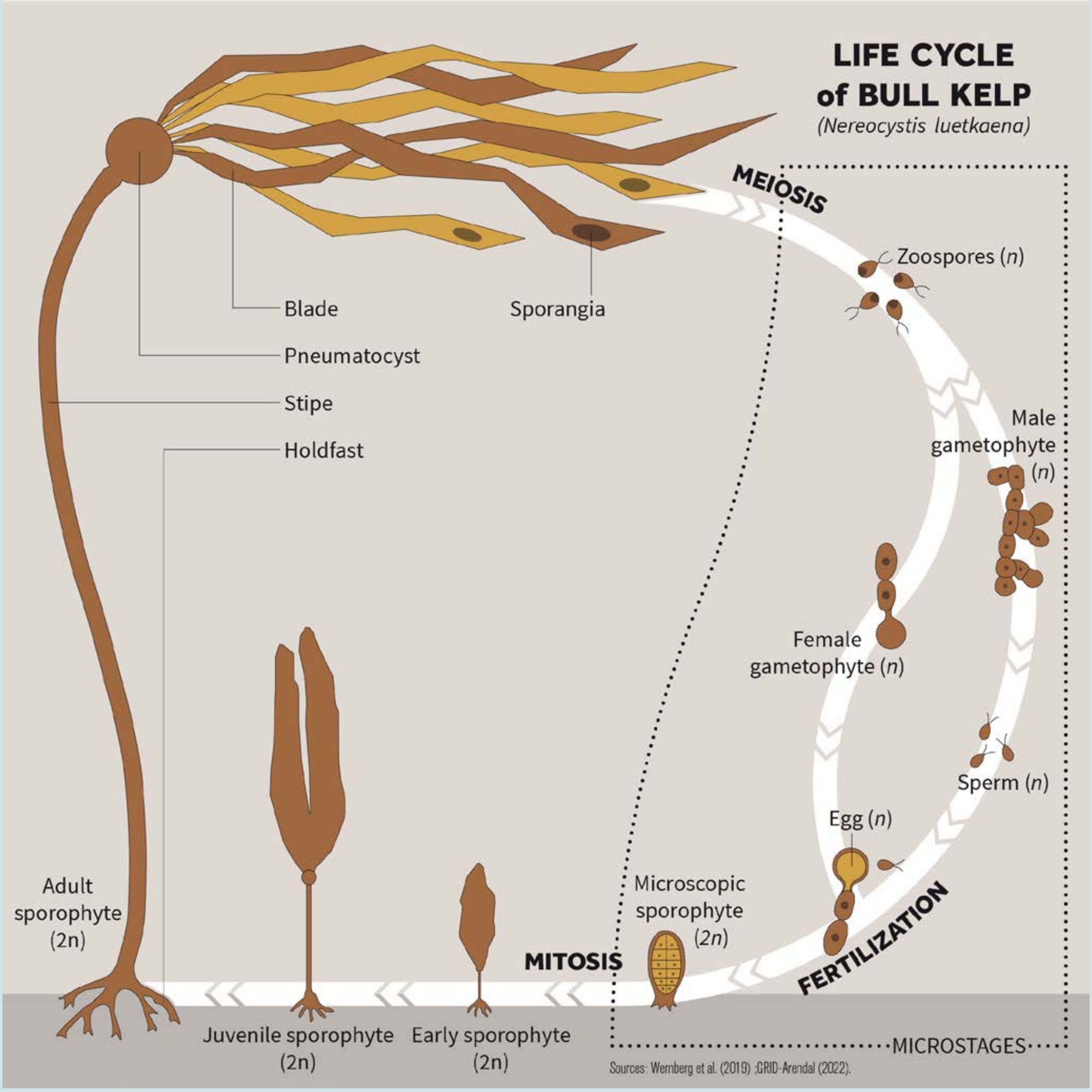
Reproduction ranges from all year round in some species such as giant kelp (*M. pyrifera*) (Graham, Vásquez and Buschmann 2007b) to seasonally in other species such as cuvie (*L. hyperborea*) (Andersen *et al*. 2011), golden kelp (*E. radiata*) (Mohring *et al*. 2013b; Wernberg *et al*. 2019a) and bull kelp (*N. luetkeana*) (Schroeder *et al*. 2020), often determined by different environmental aspects. Specifically, blue light triggers the production of spores and day length controls the production of germ cells, sexual reproduction and sporophyte growth (Lüning and Dring 1975; Dring 1984). *L. solidungula* in the high Arctic can reproduce seasonally in the winter, in the absence of light (Dunton 1990). Spore production in some species is greatly influenced by changes in seawater temperature and nutrient availability, while spore production in others is not (Reed *et al*. 1997), emphasizing that the responses of different kelp are diverse, and it can be difficult to generalize.

Dispersal and recruitment

Microscopic spores released from the adult kelp is the primary dispersal mechanism for kelp (Figure 1.3). Spores swim slowly but they can travel far with currents and waves, as evidenced by kelp recruits found hundreds of metres to several kilometres away from the nearest kelp forests (Reed, Laur and Ebeling 1988; Fredriksen *et al*. 1995). Dispersal range is mainly dictated by the spore release height, sinking rate and water motion. Up to 50 per cent of the spores released by giant kelp (*M. pyrifera*) can travel more than 1 km, and a substantial fraction might disperse as far as 10 km (Gaylord *et al*. 2002). Exceptional long-distance dispersal (hundreds or even thousands of kilometres) can occur through drifting or rafting of reproductively active dislodged individuals (Reed, Schroeter and Raimondi 2004).

Kelp recruitment (the addition of new adults to the kelp forest) is a complex process because of the two distinct life stages. For the sperm to be able to reach an egg, male and female gametophytes must settle within millimetres of one another (Reed 1990). Early life stage of kelp can persist in the kelp forest understorey for weeks to months (Hoffmann and Santelices 1991) and only start growing once stimulated by high light when the canopy is lost during storms or when harvested (Reed and Foster 1984; Santelices and Ojeda 1984; Christie, Fredriksen and Rinde 1998; Wernberg *et al*. 2020). Within weeks, dense kelp recruits emerge, with recruitment into the adult population taking anywhere from a few months to two or three years depending on the kelp species and local conditions (Reed 1990; Pedersen *et al*. 2012). Most recruits die within the first year, from predation, stress or self-thinning.

Figure 1.3. Life cycle of bull kelp (*Nereocystis luetkaena*)

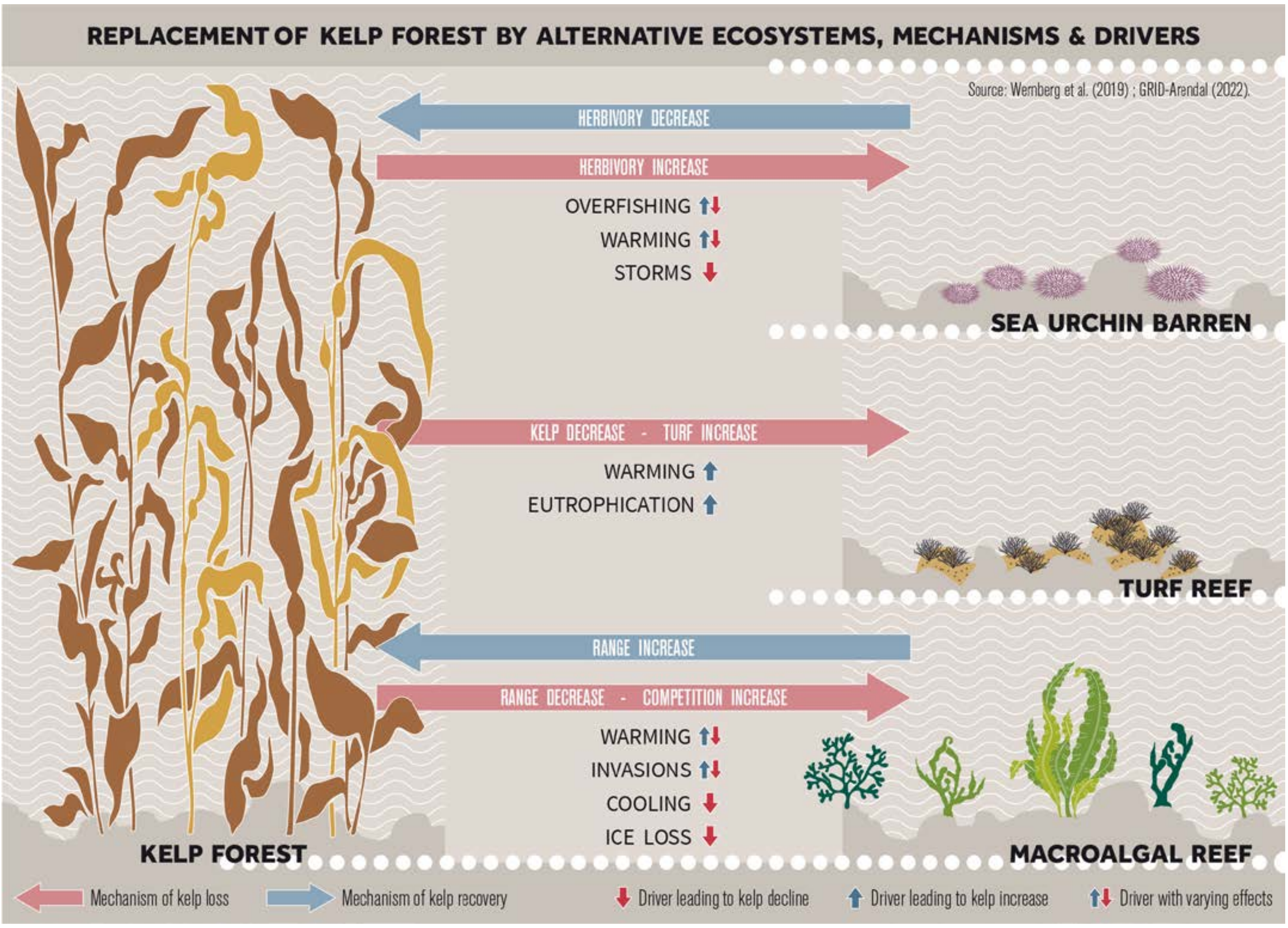


Note: All Laminarian kelp have a life cycle with two distinct phases: a macroscopic sporophyte (the adult kelp) and a microscopic gametophyte.

Threats and stressors

Human activities have had a profound influence on kelp forests, with increasingly negative impacts during the past 50 years (Dayton *et al*. 1998; Steneck *et al*. 2002; Krumhansl *et al*. 2016; Filbee-Dexter and Wernberg 2018). Many different processes are at play, operating at local to global scales and often causing a range of direct and indirect effects (Figure 1.4), leading to region-specific causes of kelp decline (Krumhansl *et al*. 2016). Many, but not all, of these threats are ultimately linked to, or compounded by, climate change and more often than not they interact in their effects (Box 1.2). These major threats include warming, marine heatwaves and other environmental extremes, ocean acidification, herbivory linked to overfishing of predators or range-shifting grazers, reduced water quality from increasing eutrophication, pollution, sedimentation and ocean darkening, harvesting and invasive species and diseases.

Figure 1.4. Impacts of human activities on kelp forests



Note: Human activities have caused decline and loss of kelp forests globally and a transition to degraded habitats (right). Several drivers (red) have been responsible for these habitat transitions.

Ocean warming, marine heatwaves and indirect effects of changing environmental conditions are probably the most pervasive manifestations of global climate change in the oceans (Oliver *et al*. 2018) and a major threat to kelp forests globally. Warming ocean temperatures have been implicated either directly or indirectly, through their effects on other drivers, in almost all major impacts on kelp forests (Filbee-Dexter and Wernberg 2018; Wernberg *et al*. 2019b; Smale 2020).

The direct effects of warming are determined by the rate and magnitude of warming, species-specific responses, and the thermal history of the kelp forest. Most multicellular species have an optimal performance within a range of tolerable temperatures (Harley *et al*. 2012). Thus, how kelp responds directly to temperature increases will be dictated by how close ambient conditions are to their thermal optimum (Bennett *et al*. 2015a). For species occupying areas with low temperatures relative to their optimum, warming seawater may increase their growth and performance (Hargrave *et al*. 2017). Conversely, warming will have direct negative effects on kelp species occupying waters at or above their thermal optimum, as seen by the massive die-offs of kelp forests in Baja California at the southern end of its range (Arafeh-Dalmau *et al*. 2019; Edwards 2019). Short-term but high magnitude increases in temperature (i.e. heatwaves) that are above the thermal limit of kelp can lead to direct mortality (Wernberg *et al*. 2013), particularly if kelp already exist above their thermal optimum.

Direct negative effects on kelp caused by water temperatures being above their thermal optimum for prolonged periods include reductions in growth rate, damage to kelp tissue, decreased resilience to disturbance, reduced reproduction and ultimately death (Bartsch *et al*. 2013; Simonson, Metaxas and Scheibling 2015; Alsuwaiyan *et al*. 2021). Cellular damage arising from warm temperatures can reduce kelp tissue strength and extensibility, and decrease the ability of kelp to withstand wave forces (Simonson, Metaxas and Scheibling 2015). Rising temperatures can also impact kelp reproduction, fertilization and the survival of early life stages (Bartsch *et al*. 2013; Mohring *et al*. 2013a). Although the impacts on these early life stages are less well understood compared to adults, they are likely very important in the population's overall response to environmental changes (Schiel and Foster 2006; Harley *et al*. 2012).

Marine heatwaves have caused kelp forests to collapse on both sides of the North Atlantic (sugar kelp, *S. latissima*, Filbee-Dexter *et al*. 2020), in the North-East Pacific (giant kelp, *M. pyrifera* in Baja California, Arafeh-Dalmau *et al*. 2019), in northern California and British Columbia (bull kelp, *N. luetkaena*, Rogers-Bennett and Catton 2019; Schroeder *et al*. 2020), in Australia (golden kelp, *E. radiata*, Wernberg *et al*. 2016) and in New Zealand (*Durvillaea* spp., Thomsen *et al*. 2019, 2021; giant kelp, *M. pyrifera*, Tait *et al*. 2021).

Changing environmental conditions can also affect kelp indirectly by influencing biotic interactions that weaken their competitive advantage. For example, warming stimulates the growth of turf algae which competes with kelp for light and space (Straub *et al*. 2019). Small grazers such as snails eat kelp faster at higher temperatures (Simonson, Metaxas and Scheibling 2015), which can lead to high loss of blades in the forest canopy (Krumhansl, Lauzon-Guay and Scheibling 2014). Similarly, warming temperatures enhance rates of kelp overgrowth by encrusting species and also cause tissue weakening and canopy defoliation (Andersen *et al*. 2011; Krumhansl and Scheibling 2011). Climate changes can also alter distribution, densities or behaviour of herbivorous (grazing) sea urchins and fish, which can in turn increase rates of grazing and heavily influence the extent and abundance of kelp (Filbee-Dexter and Scheibling 2014; Vergés *et al*. 2014a).

In terms of other environmental stressors, the increasing frequency of extreme storms has increased the dispersal range of the keystone species through rafting, such as southern bull kelp (*D. antarctica*), potentially causing an establishment of non-native taxa in Antarctica (Fraser *et al*. 2018). Changes to upwelling regimes, for example as a consequence of increasingly severe El Niño events or incursions of warm nutrient-poor currents, can cause collapse of kelp forests due to combined temperature and nutrient stress (Johnson *et al*. 2011).

Ocean acidification refers to the decreasing alkalinity of the oceans as they absorb carbon dioxide. These changes in the chemical balance of seawater are generally predicted to pose a serious threat to marine life (Kroeker *et al*. 2013). Ocean acidification is, however, unlikely to affect kelp forests directly, as studies have found minimal effects on kelp reproduction, biomass, photosynthesis and survival (Leal *et al*. 2017; Provost *et al*. 2017; Fernández *et al*. 2021). Nevertheless, ocean acidification could have indirect negative effects through increasing the virulence of diseases (Qiu *et al*. 2019) or increasing the competitive strength of filamentous turf algae (Connell *et al*. 2013). Specifically, ocean acidification stimulates growth of turf algae due to carbonate enrichment, at the same time as the lower pH impairs turf consumers (gastropods and urchins), and these effects may be further strengthened by increasing temperatures and marine heatwaves (Connell and Russell 2010; Provost *et al*. 2017; Straub *et al*. 2019).

One major question in relation to the effects of ocean acidification on kelp forests revolves around their capacity to regulate and buffer ocean pH in their immediate surroundings through photosynthesis (Krause-Jensen *et al*. 2016), creating a local ocean acidification refuge for themselves and associated species. Recently, it was suggested that this refuge effect would impose limitations on the size of sea urchin barrens, as sea urchin activity would be negatively affected due to low pH far from kelp forests (Ling *et al*. 2020).

Grazing (herbivory) is generally low in healthy kelp forests (Christie and Norderhaug 2017) but it can have devastating effects when grazers increase in abundance. Population explosions of kelp grazers have occurred on all continents except Antarctica, as a consequence of hunting and overfishing of grazer predators (Steneck *et al*. 2002) or climate-driven range expansion of grazers from warmer latitudes (Vergés *et al*. 2014a). For example, in Alaska hunting of sea otters led to increased sea urchins, a main prey of sea otters, and these sea urchins overgrazed hundreds of kilometres of kelp forests (Estes and Palmisano 1974). Destructive grazing of kelp has been recorded among many different kinds of herbivores including sea urchins, fish, crustaceans and snails (see, for example, Estes and Steinberg 1988; Vásquez and Buschmann 1997; Byrnes *et al*. 2006; Filbee-Dexter and Scheibling 2014; Vergés *et al*. 2014a; Zarco-Perello *et al*. 2017; Norderhaug *et al*. 2021).

Hunting and overfishing of sea urchin predators including sea otters (North American Pacific, Estes and Palmisano 1974), ground fish (Northern Europe, Norderhaug *et al*. 2021) and lobsters (Australia, Ling *et al*. 2009a) have been implicated in sea urchin outbreaks and the subsequent formation of sea urchin barrens. Barrens are areas of reef devoid of habitat-forming seaweed that can extend over thousands of kilometres of coastline or occur in small patches (tens to hundreds of metres) within a kelp forest. They are less productive, provide reduced habitat and support less biodiversity compared to kelp forests. Transitions from kelp forest to barrens often occur as regime shifts and can be abrupt transformations of the ecosystem. These shifts are triggered by large increases in the densities of sea urchins, which overcome feedbacks such as kelp whiplash, abundant drift kelp and high predation within the forests that usually keep sea urchins from grazing destructively. The barren state can be difficult to recover from and can exist for decades in some regions, even if the original drivers of high sea urchin densities are relaxed (Filbee-Dexter and Scheibling 2014; Ling *et al*. 2015).

Climate-driven range expansion of warm-water herbivores, which are particularly prevalent at the warm-range margins of kelp forests, has led to increased herbivory and loss of kelp forests in many regions around the world (Vergés *et al*. 2014a). In eastern Australia, sea urchins have expanded progressively further south into Tasmania in recent decades, leading to widespread formation of urchin barrens (Ling *et al*. 2009a; Ling *et al*. 2009b). Also in Australia, tropical fish have extended down the east and west coasts, resulting in the loss of between 60 and 100 per cent of kelp canopies in some areas (Bennett *et al*. 2015b; Vergés *et al*. 2016; Zarco-Perello *et al*. 2017). Similar observations have been made in Japan (Haraguchi *et al*. 2009; Nakamura *et al*. 2013) and the Mediterranean Sea (Vergés *et al*. 2014b).

In addition to sea urchins and fish, many invertebrates such as small crustaceans and snails also consume kelp. These small grazers may not have a substantial direct grazing effect on kelp (Hereward *et al*. 2018), but they can increase kelp mortality and erosion by creating perforations and weak points on blades and stipes, which break when kelp blades are under stress from wave action and currents (Haggitt and Babcock 2003; de Bettignies, Thomsen and Wernberg 2012). Further, when kelp abundance declines, grazers concentrate on the fewer remaining kelp, enhancing rates of kelp canopy loss at higher water temperatures (O'Brien, Scheibling and Krumhansl 2015).

Eutrophication, pollution and sedimentation are prominent symptoms of urbanization, human waste and food production (Airoldi 2003; Gorman, Russell and Connell 2009; Duarte 2014). The associated reduction in water quality poses a significant threat to kelp forests in nearshore areas with high human population densities and intense agriculture or aquaculture. Eutrophication darkens the water column and can stimulate phytoplankton and fast-growing opportunistic seaweed species, including some epiphytic species that grow directly on kelp (Pedersen and Borum 1997). Epiphytes may increase the drag on blades and cover kelp tissue, which may impede light conditions (even further) and affect the uptake of nutrients and inorganic carbon (Andersen *et al*. 2011). High nutrient availability may also prevent kelp recruitment by stimulating the biomass and sediment accumulation of fast-growing, mat-forming turf algae that can cover the substrate (Airoldi 2003; Gorman and Connell 2009; Pessarrodona *et al*. 2021).

Acute eutrophication and sedimentation have been shown to quickly impact kelp forests negatively, however the negative effects were transient and kelp forests recovered quickly as soon as the stressors abated (Shaffer and Parks 1994; Tegner *et al*. 1995). In contrast, persistent sedimentation can affect microscopic stages and sexual reproduction performance (Muth *et al*. 2017), with increased sediments and nutrients as a result of expanding human populations, urbanization and soil erosion having an insidious effects on kelp forests and having been implicated with habitat degradation and the loss of habitat-forming seaweed species all over the world, including in California (Foster and Schiel 2010), Norway (Moy and Christie 2012), Australia (Coleman *et al*. 2008; Connell *et al*. 2008) and Brazil (Gorman *et al*. 2020).

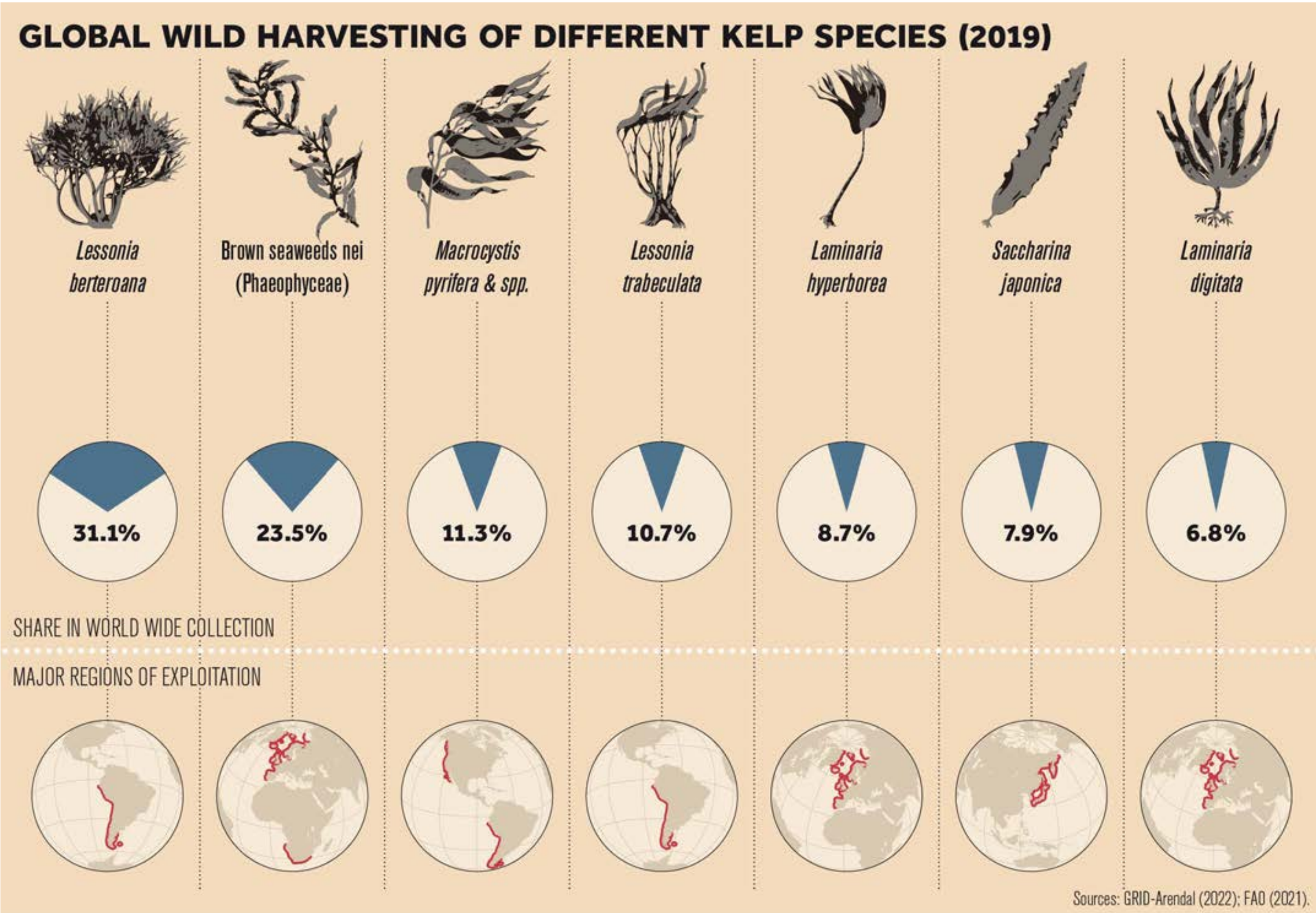
Harvesting of kelp for materials, food and fodder is probably one of the oldest direct human influences on kelp forests (Turner 2000; Erlandson *et al*. 2007, see also section B-4 of chapter 3), and has been recognized as having a negative impact on kelp in some regions (Krumhansl *et al*. 2016). Intense or prolonged harvesting can alter the structure and functioning of kelp forests (O'Connor and Anderson 2010; Geange 2014), but as many kelp forests lack baseline data for the resource, it is difficult to track the industry's impacts (Bennion *et al*. 2018). In Chile, kelp fishers now use specialized harvesting equipment, resulting in intensive removal of kelp (*L. berteroana* and *L. trabeculata*). High harvesting intensity leads to increased kelp density but reduced kelp size (holdfast diameter, number of stipes, total length) and age. In some areas, kelp do not recover within the seven-year fallow period. An increase in sea urchin barrens has been reported in heavily harvested areas in northern Chile, but no quantitative data exist.

In Norway, *L. hyperborea* is harvested on an industrial scale using small trawls (Figure 1.5A) that tear the kelp from the sea floor and leave 3 m wide tracks (Figure 1.5B). These trawl tracks have reduced ecological function and biodiversity (Steen *et al*. 2016), with substantial effects on seaweed biomass and fish communities (including on invertebrate and fish diversity, and the abundance of juvenile and small fish), which may in turn affect seabirds foraging in kelp forests (Lorentsen, Sjøtun and Grémillet 2010; Norderhaug *et al*. 2020). It can take four years for kelp biomass to return to pre-harvest levels, but at least six years for associated communities to recover (Steen, Norderhaug and Moy 2020).

In contrast, harvesting kelp (*E. maxima*) in South Africa by cropping the floating canopy above the main meristem (point of growth) resulted in minimal effects on the understorey flora and fauna communities. Within a year, kelp biomass and associated communities were indistinguishable between harvested and control plots (Levitt *et al*. 2002).

Figure 1.5. A. Wild harvesting of cuvie (*Laminaria hyperborea*) in Norway using a trawl (photo credit: H. Steen). B. A single surviving kelp standing in a trawl track (photo credit: J. Thormar)

Figure 1.6. Global wild harvesting of different kelp species



Invasive species and disease are emergent threats to kelp forests. Invasive species are predominantly associated with competition for space and light or overgrowth. For example, the decline of sugar kelp (*S. latissima*) in the North-West Atlantic is due in part to pre-emption of space by expansive covers of invasive turf algae (Dijkstra *et al*. 2017; Feehan, Grace and Narvaez 2019). Also in the North-West Atlantic, the large green alga dead man's fingers (*Codium fragile*) expanded rapidly where kelp forests declined (Mathieson *et al*. 2003) and expanding populations of the invasive brown alga japweed (*Sargassum muticum*) have been associated with declines in sugar kelp in Denmark (Stæhr *et al*. 2000) and fingerkelp (*L. digitata*) in France (Cosson 1999). In the United Kingdom of Great Britain and Northern Ireland (UK), experiments showed that competition from the invasive kelp *U. pinnatifida* suppressed growth and recruitment of native sugar kelp, fingerkelp and *Saccorhiza polyschides* (Epstein, Foggo and Smale 2019). Fouling by invasive invertebrates can also have a negative effect on kelp forests. For example, in the North-West Atlantic, kelp blades covered by the bryozoan *Membranipora membranacea* decreased reproductive output and growth and increased mortality, leading to a defoliation of kelp forests there (Saunders and Metaxas 2008).

In many cases, the effects of invasive species on kelp have been mediated or compounded by increased ocean temperatures and/or physical disturbances. Although there is both experimental and observational evidence that marine invasive species negatively affect seaweed abundances (including kelp) (Thomsen *et al*. 2009), questions remain as to the extent to which invasive species are drivers or passengers of declines in kelp forests and where and when this occurs (Didham *et al*. 2005).

Diseases can cause kelp die-off (e.g. Cole and Babcock 1996). Wild kelp species are heavily colonized by prokaryotes (Marzinelli *et al*. 2015a; Florez *et al*. 2017), viruses (Beattie *et al*. 2018) and eukaryotes including fungi and oomycetes (Li *et al*. 2010) as well as parasitic microscopic filamentous algae (Potin 2012) and invertebrates (Wahl and Mark 1999). In New Zealand, die-off of golden kelp (*E. radiata*), the dominant seaweed forest in the region (Wernberg *et al*. 2019a), was attributed to a combination of environmental stress and viral infections (Cole and Babcock 1996; Easton, Lewis and Pearson 1997), leading to the loss of pigmentation and bleaching (Beattie *et al*. 2018). In Europe, oomycete (water moulds) infections of wild kelp populations of cuvie (*L. hyperborea*), fingerkelp (*L. digitata*) and sugar kelp (*S. latissima*) produced a severe effect on kelp growth and survivorship (Eggert, Peters and Küpper 2010). Endophytic infections by a filamentous brown alga have been found in galls affecting natural populations of *L. nigrescens* (Thomas *et al*. 2009). At this point in time, reports of major pathogen outbreaks in kelp forests remain rare. However, increasing pollution and climate change (warming in particular) are likely to increase pathogen virulence (Campbell *et al*. 2012; Qiu *et al*. 2019).

"Multiple stressors" refers to the combined effects of several stressors (such as those listed above) at the same time. The coastal zone is a focal point for human activities, where broad changes in environmental conditions are superimposed onto other stressors such as pollution, coastal development, fisheries, invasive species and aquaculture. These other stressors, which are increasing with rising human population density, can have compounding effects on kelp forests. Interactions among multiple stressors can be complex (Strain *et al*. 2014) and in some cases can create abrupt and large declines in kelp forests. For example, overfishing of large predators can make kelp forests vulnerable to climate-driven threats such as range shifts of grazing sea urchins or marine heatwaves (Rogers-Bennet and Catton 2019). Warming and marine heatwaves can make kelp forests more vulnerable to additional stressors (Wernberg *et al*. 2010) and reduce kelp genetic diversity and adaptive capacity through directional selection or selective mortality, which can lower their resilience to other stressors such as pollution. Eutrophication and warming events can interact to drive increased kelp mortality due to the combined effects of reduced light and increased temperature stress. However, increased nutrients can help establish introduced kelp species such as wakame when storms create bare openings in the kelp canopy and in some regions, physiological studies on kelp show that nutrient availability can result in a higher tolerance to impacts of climate change (Fernández *et al*. 2021). Low salinity and turbidity in areas with run-off or melting ice can interact with temperature shifts to alter kelp forest extent and structure.

Knowledge gaps and priority areas for future research

Key knowledge gaps concerning the ecology of kelp forests range from small-scale issues associated with their microscopic life stages to broad-scale biogeographic questions around their distribution and abundance in many bioregions. At the smallest scale, the ecology of the microscopic gametophyte stage is poorly known, especially under field conditions. At the species and population scale, important questions remain as to how performance and sensitivity to stress vary within and across kelp forests (Muth *et al*. 2019). This includes the adaptive capacity of many kelp species to resist or respond to increased stress across all stages of their life cycle.

It is also unclear how population connectivity and dispersal can drive genetic diversity and thereby influence the adaptation and resilience of natural kelp forests. Most of the predictions for the future state of kelp forests consider only gradual change in ocean temperature as a main driver of change. However, in reality virtually all kelp forests exist in multi-stressor seascapes. Understanding and predicting the combined effects of multiple future stressors is essential for informed management of these ecosystems. Extreme events including marine heatwaves, storms and outbreaks of grazers are increasing, while coastal populations are expanding, which is leading to increased pollution, eutrophication, sedimentation, coastal darkening, invasive species and activities such as fish and seaweed farming. As we move into the Anthropocene, the coastal zone is increasingly facing multiple human pressures, from our need to expand food production, coastal infrastructure and agriculture to ocean warming and climate-driven changes.

Table 1.1. Dominant kelp species and their main threats in different regions around the world

Region	Dominant kelp species	Main threats	References
Arctic	*Alaria* spp., *Saccharina latissima, Agarum clathratum, Laminaria digitata, L. solidungula, Hedophyllum nigripes*	Arctic kelp forests may expand as sea ice retreats, with temperate species replacing endemic seaweed species. Sedimentation, turbidity and glacial melt cause kelp loss in some areas.	Filbee-Dexter *et al*. 2019; Krause-Jensen *et al*. 2020
NW Atlantic	*L. digitata, S. latissima, A. clathratum*	Warming, marine heatwaves, invasive species, overfishing	Filbee-Dexter, Feehan and Scheibling 2016; Feehan, Grace and Narvaez 2019; Steneck *et al*. 2013
NE Atlantic	*L. hyperborea, S. latissima, Alaria esculenta* and *L. digitata* (in the north) and *L. ochroleuca* and *Saccorhiza polychides* (in the south)	Warming, marine heatwaves, eutrophication, herbivory by urchins, overfishing	Smale *et al*. 2013; Filbee-Dexter *et al*. 2020; Norderhaug *et al*. 2021
NE Pacific	*Eualaria fistulosa* (Aleutians) *Macrocystis pyrifera* (Baja)	*Eualaria*: hunting of predators and population explosion of grazers *Macrocystis*: El Niño-Southern Oscillation	Edwards *et al*. 2020; Metzger, Konar and Edwards 2019; Edwards 2019
NE Pacific	Bull kelp, giant kelp	Warming, overfishing	Schroeder *et al*. 2020
SE Pacific	*M. pyrifera, L. trabeculata, L. spicata, L. berteroana*	Wild harvesting, industrial pollution in Northern-Central Chile	Vásquez 2008; Oyarzo-Miranda *et al.* 2020; Vega, Broitman and Vásquez 2014; Gouraguine *et al.* 2021
Southern Africa	*Ecklonia maxima, L. pallida, E. radiata*	*E. maxima*: harvesting *E. radiata*: warming	Bolton *et al*. 2012; Rothman pers. comm.
Oceania	*E. radiata, M. pyrifera* (around Tasmania and southern New Zealand). Diverse assemblages of subtidal fucoids	Warming, marine heatwaves, eutrophication, sedimentation, tropical fish, urchins	Wernberg *et al*. 2019a

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Chapter 2. Status, trends and future projections

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Highlights

- **Overall, there is a global decline in kelp abundance of 1.8 per cent per year (instantaneous rate).**
- **There is high regional variation in kelp forest status. However, the majority (61 per cent) of longer-term (> 20 years) data sets showed significant declines in kelp abundance, with only 5 per cent showing increases.**
- **Kelp forests at warm range-edges are declining in the North Atlantic, North Pacific and Oceania, often being replaced by mats of turf algae.**
- **Sea urchin overgrazing of kelp forests has occurred across large areas of reef in the Gulf of Maine and eastern Canada, Norway, California, Japan, Korea, Chile, Alaska and Australia.**
- **Kelp forests in Arctic regions are predicted to increase in cover and standing stock with sea ice loss, however increased turbidity may offset these gains in some regions. High Arctic kelp are also predicted to be replaced by temperate kelp.**
- **Most of the world's kelp forests are unmapped and sporadically monitored, making it difficult to detect changes.**

Status and trends

Global overview

Kelp forests have declined throughout their temperate range over the past 50 years, as documented by a combination of regional analyses and a global synthesis of available data. The most recent global assessment (Krumhansl *et al*. 2016), mainly representing temperate kelp forests, found an overall global decline in kelp abundance of 1.8 per cent per year (instantaneous rate). This decline occurred amid significant regional variation, with about 38 per cent of ecoregions experiencing declines in kelp abundance, 27 per cent experiencing increases, and the remaining regions showing no detectable change (Krumhansl *et al*. 2016). However, the majority (61 per cent) of longer-term (> 20 years) data sets in the analysis showed significant declines in kelp abundance, with only 5 per cent showing increases (Wernberg *et al*. 2019). This suggests that high short-term variability and the short duration of most kelp forest monitoring data sets included in the Krumhansl *et al*. (2016) analysis may have precluded detections of long-term change.

More recent analyses from continued regional monitoring (e.g. Feehan, Grace and Narvaez 2019; Filbee-Dexter *et al*. 2020; Wernberg *et al*. 2016; Rogers-Bennett and Catton 2019) indicate that declines have persisted and have been exacerbated in some temperate regions, often by ongoing climate-related stress (e.g. warming, marine heatwaves) (Wernberg *et al*. 2016; Arafeh-Dalmau *et al*. 2019; Filbee-Dexter *et al*. 2020) in combination with other stressors (e.g. invasive species, eutrophication, urchin grazing, trophic cascades). See chapter 1 for a detailed description of drivers of change.

There is evidence of kelp persistence in some temperate regions where climate change stressors have been less intense (Mora-Soto *et al*. 2021; Wernberg *et al*. 2013; Reed *et al*. 2016; Pfister *et al*. 2017) and/or favourable to kelp (Bolton *et al*. 2012). Furthermore, regional variation in environmental conditions and other interacting stressors may result in the persistence of refuge populations. For example, offshore ledges in the Gulf of Maine have been found to contain healthy and thriving kelp compared to degraded inshore reefs, and more exposed headlands that have cooler water temperatures and greater flushing from oceanic processes can support persistent kelp populations in regions where kelp have been lost in more wave-protected areas (Filbee-Dexter, Feehan and Scheibling 2016; Hamilton *et al*. 2020). Some regions have experienced a shift towards kelp species that are better adapted to warm conditions, resulting in little to no overall loss in kelp, but a change in habitat structure and function. Efforts to re-establish healthy kelp populations through mitigation of local stressors and kelp restoration have been successful in some areas (Watson and Estes 2011; Eger *et al*. 2020), though these efforts are expected to be most effective when combined with genetic technologies to address the ongoing and increasing effects of climate change (Coleman *et al*. 2020).

Compared to temperate regions, the trajectory of kelp in Arctic regions is generally much less well known. While poleward range expansions or increased abundance of kelp in the Arctic are predicted with climate change, documented instances of these expansions have been limited (Krause-Jensen *et al*. 2020). In most Arctic regions, limited monitoring has prevented detections of long-term change (see, for example, Merzouk and Johnson 2011), and therefore the status of kelp throughout a large part of their global range remains unknown.


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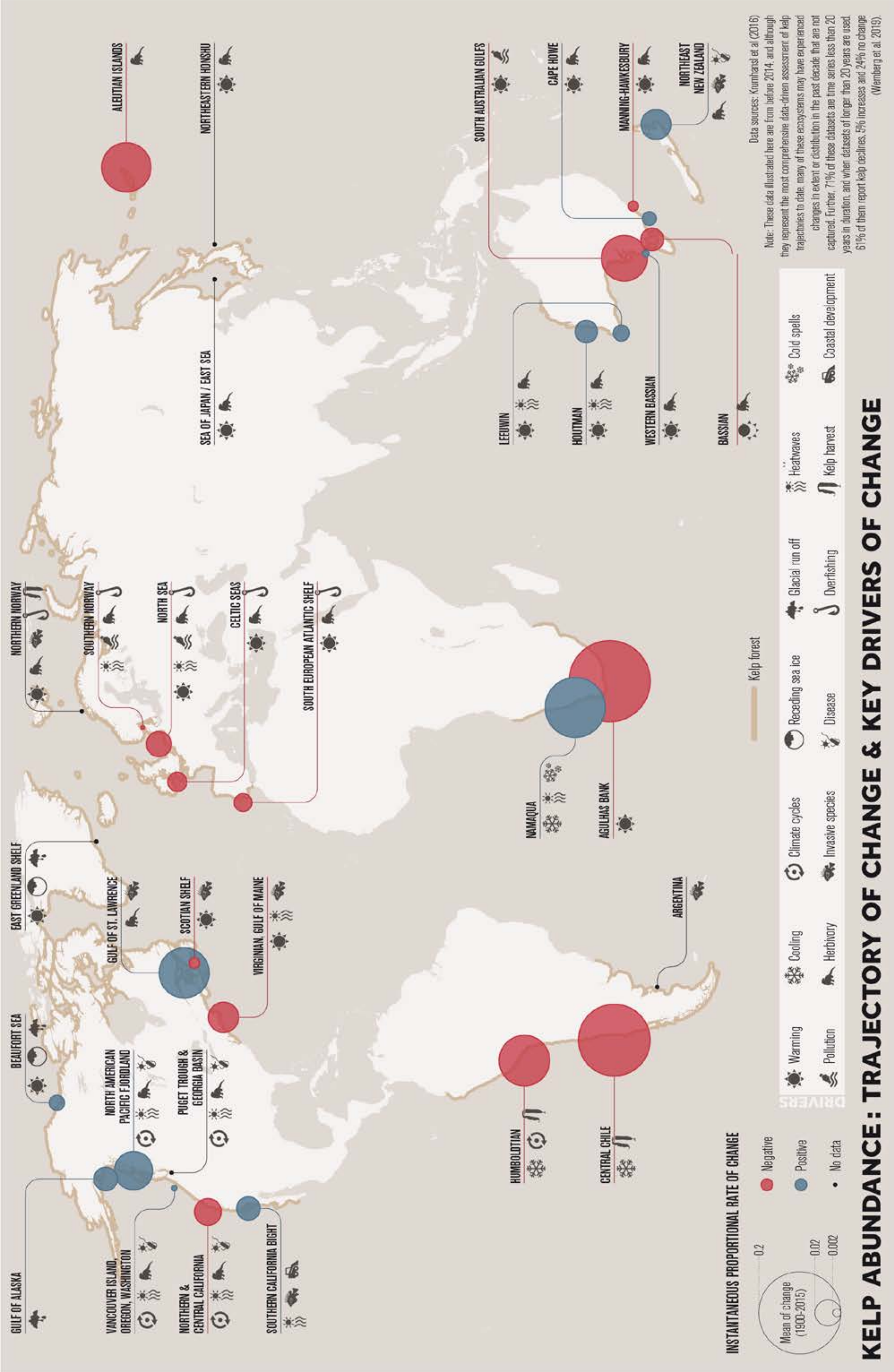
Figure 2.1. Trajectory of change in kelp abundance and key drivers of change, by ecoregion globally



The following sections describe in detail the historical trends in kelp abundance and the main drivers of change, as is currently best known for each region. Following these regional descriptions, we provide information on what has been projected for the future of kelp forests worldwide.

North-East Pacific – Baja California, Western United States of America, Western Canada

Historical trends in kelp abundance across the North-East Pacific show a large degree of variability. For example, the global analysis of kelp trends from Krumhansl *et al.* (2016) found positive change for the North American Pacific Fjordland (British Columbia), the Gulf of Alaska (2003–2013) and the Southern California Bight (2003–2013), no change for Oregon, Washington and Vancouver Island, and negative change for North-Central California, Southern California Bight (prior to 2002) and the Aleutian Islands. However, trends also vary within each of these ecoregions (Beas-Luna *et al.* 2020). In the Aleutian Islands, a long-term decline in kelp abundance has been well documented (Estes *et al.* 1998). While data are lacking for multiple species across much of the extensive coastline of British Columbia, declines in canopy-forming bull kelp (*N. luetkeana*) were recently reported for sites in the Gulf Islands (Schroeder *et al.* 2020), and substantial changes in subtidal and intertidal kelp species have been documented for two decades on the west coast of Vancouver Island, including overgrazing by sea urchins and loss of kelp during marine heatwaves (Watson and Estes 2011; Starko *et al.* 2019). Northern areas of Haida Gwaii and the West Coast of Vancouver Island in British Columbia have shown kelp persistence since the 1850s, based on an analysis of British Admiralty Charts (Costa *et al.* 2020). Meanwhile in Washington, the abundances of both bull kelp and giant kelp (*M. pyrifera*) have remained relatively stable along the outer coast of the Olympic Peninsula and the Strait of Juan de Fuca (Pfister *et al.* 2017), but substantial losses of bull kelp have been observed in the wave-sheltered areas of the South Puget Sound (Berry *et al.* 2021). There is a large amount of annual to decadal variability in the abundance of bull kelp and giant kelp from California to Oregon, making it difficult to detect directional trends in this region (Bell *et al.* 2020; Hamilton *et al.* 2020). However, beginning in 2014, northern California experienced a sudden and prolonged collapse of bull kelp, which was unprecedented in the 40 years prior (Rogers-Bennett and Catton 2019; McPherson *et al.* 2021). In Baja California, Mexico, giant kelp abundance is also highly variable, with declines occurring following marine heatwaves, including those associated with strong El Niño events (Edwards 2004; Cavanaugh *et al.* 2019).

The primary pressures on kelp abundance and distribution in the North-East Pacific include marine heatwaves and changes in the abundance of starfish and sea otters, which are predators of kelp-grazing sea urchins. In Alaska and Northern British Columbia, local recovery of kelp forests following the return of sea otters has dominated trends over the past century in certain areas (Estes and Palmisano 1974; Watson and Estes 2011). However, areas where sea otters are still absent (such as the Aleutian Islands) have not exhibited similar recovery (Estes *et al.* 1998; Gabara, Konar and Edwards 2021). Furthermore, starfish wasting disease has caused dramatic loss in the population of predatory sunflower starfish across British Columbia, leading to sea urchin outbreaks and subsequent loss of kelp (Burt *et al.* 2018). Along the coast of Washington, fluctuations in kelp abundance have been linked to climate cycles such as the Pacific Decadal Oscillation (PDO), the El Niño-Southern Oscillation (ENSO) and the North Pacific Gyre Oscillation (NPGO) (Pfister *et al.* 2017). In Northern California, the sudden collapse in bull kelp populations has been linked to a marine heatwave and a boom in sea urchin recruitment following outbreaks of starfish wasting disease (Rogers-Bennett and Catton 2019; McPherson *et al.* 2021). In Southern California and Baja Mexico, heatwaves and climate anomalies have led to temporary declines in kelp abundance, with a large degree of spatial variability in patterns of recovery (Arafeh-Dalmau *et al.* 2019; Cavanaugh *et al.* 2019). On local scales, non-indigenous tropical algae (e.g. *S. horneri, S. muticum* and *U. pinnatifida*) has invaded kelp forests at sites across southern California (Marks *et al.* 2015) and sedimentation from coastal development has been linked to declines in kelp forest abundance at localized sites in Southern California and Baja Mexico (Foster and Schiel 2010; Torres-Moye and Escofet 2014).

South America – Argentina, Chile and Peru

In recent decades, there has been a significant decrease in the abundance of kelp in northern and central Chile, despite a cooling trend in this region (Krumhansl *et al.* 2016; Vásquez 2008). Kelp abundance has been more stable in southern Chile and the South Georgia and Falkland Islands (Malvinas), an area that accounts for more than 47 per cent of the known distribution of giant kelp, *M. pyrifera* (Mora-Soto *et al.* 2020). A comparison of satellite imagery from 1984–2019 with nautical charts and surveys from the nineteenth and twentieth centuries found that most kelp forests in this region were remarkably persistent (Mora-Soto *et al.* 2021). Another study of giant kelp dynamics on the southern tip of South America found no significant change in kelp abundance and associated biodiversity over the past 45 years (Friedlander *et al.* 2020), but further north along the Argentinean coast the introduction of wakame (*U. pinnatifida*) already covers 1,850 km of the Atlantic coastline (Bunicontro, Marcomini and Casas 2018). The stands of this invasive kelp reduce native seaweed diversity (Casas, Scrosati and Piriz 2004) and can also invade giant kelp forests (Raffo, Eyras and Iribarne 2009) and modify the habitat for coastal fish (Irigoyen, Eyras and Parma 2011).

Decreases in the abundance of kelp in northern and central Chile are likely related to high extraction pressure, as this region has the highest rate of natural kelp harvest in the world (Buschmann *et al.* 2014; Camus, del Carmen

Hernández-González and Buschmann 2019; Vega *et al*. 2019). High harvest rates have also led to changes in the population structure and morphology of some kelp species (e.g. *L. berteroana, L. trabeculata*), with high harvest intensities being associated with increases in juvenile densities and smaller kelp size (Vega, Broitman and Vásquez 2014; Gouraguine *et al*. 2021). Nevertheless, territorial user rights policies and the development of strategies for marine protected areas by the Chilean Government have contributed to the conservation of wild intertidal *Lessonia* populations (González-Roca *et al*. 2021).

In southern Chile, kelp populations seem more stable, are much less impacted by direct human pressures and may not yet have experienced warming sufficient to cause regional declines in kelp abundance (Krumhansl *et al*. 2016; Mora-Soto *et al*. 2020). Moreover, recent evidence suggests that kelp (e.g. giant kelp) are adapting to the increased presence of fresh water and sediment from melting glaciers (Palacios *et al*. 2021) and that despite there being no inter-population differences in response to ocean acidification and warming, intrinsic differences exist among populations that seem to be associated with their natural variability in CO_2, NO_3 and seawater temperatures driven by coastal upwelling (Fernández *et al*. 2021). A northern shift in the polar front, intense westerlies and the cooling effect of glacier melting would keep temperatures in the normal range for kelp tolerance (Mora-Soto *et al*. 2022).

North-West Atlantic – Eastern United States of America, Nova Scotia, Gulf of St. Lawrence, and Newfoundland

Studies of long-term change in the North-West Atlantic region (1952–2014) have documented widespread and significant declines in kelp abundances (*S. latissima, L. digitata* and *Agarum cribosum*), particularly throughout the southern portion of the range, including Southern New England, the Gulf of Maine, and along the Atlantic coast of Nova Scotia (Filbee-Dexter, Feehan and Scheibling 2016; Feehan, Grace and Narvaez 2019; Filbee-Dexter *et al*. 2020). Although kelp-dominated sites remain in these parts of the region, many kelp forests have given way to carpets of turfs made up of many species of native and invasive seaweed (Pessarrodona *et al*. 2021). The loss of kelp forests from their southern range-edge (Southern New England, United States of America) is correlated with an increase in the cumulative annual intensity of marine heatwaves that have equalled or exceeded a 22.8°C thermal threshold for sugar kelp (*S. latissima*) mortality (Filbee-Dexter *et al*. 2020). The loss of kelp forests throughout the North-West Atlantic is also linked to the direct and indirect effects of rapid multidecadal ocean warming (Krumhansl, Lee and Scheibling 2011; Filbee-Dexter, Feehan and Scheibling 2016; Witman and Lamb 2018; Dijkstra *et al*. 2019). Warm temperatures are associated with reduced kelp growth rates, high mortality, and increased tissue loss associated with temperature-mediated interactions with small grazers and encrusting species, and the subsequent proliferation of algal turfs (Simonsen, Scheibling and Metaxas 2015a and 2015b; Krumhansl, Lee and Scheibling 2011; Dijkstra *et al*. 2019).

Historically, sea urchins were the main driver of kelp abundances through time in the North-West Atlantic, causing widespread barrens that persisted for years to decades along hundreds of kilometres of coastline (Filbee-Dexter and Scheibling 2014). From the late 1960s to the 2000s, the Atlantic coast of Nova Scotia (Canada) underwent decadal fluctuations between kelp-forested and urchin barren states, driven by recurrent disease-induced sea urchin (*Strongylocentrotus droebachiensis*) mass mortalities and subsequent sea urchin population recovery. Over the last decade, kelp forests have shifted to an algal turf state following the decimation of sea urchins by intensifying disease and colonization of turfs under warming sea temperatures. Beginning in the 1970s and 1980s, sea urchins destructively grazed kelp forests in the Gulf of Maine (Harris and Tyrrell 2001; Steneck, Vavrinec and Leland 2004), but their barrens collapsed in the early 1990s following the opening of a sea urchin fishery that decimated urchin populations (Taylor 2004; Steneck, Vavrinec and Leland 2004). Kelp declines have not been documented in the Gulf of St. Lawrence, Newfoundland, and Labrador, yet data from much of these areas are sparse. Although sea urchin barrens are prevalent in these areas, it is unclear if the areas were historically dominated by kelp forests that were overgrazed in the past century or if they have been persistent barrens throughout recent history (Gagnon, Himmelman and Johnson 2004; Merzouk and Johnson 2011; Frey and Gagnon 2016; Krumhansl *et al*. 2016).

North-East Atlantic – Europe, UK

Studies from the North-East Atlantic have reported variable trends with respect to kelp abundances, with documented increases and decreases over the past few decades (Krumhansl *et al*. 2016). *S. polyschides* is a native kelp species that follows the general trend of decline along its southern marginal range in Europe (Araújo *et al*. 2016). Reduction in abundance, local extinctions or range contractions for kelp have been reported in southern Norway (sugar kelp, Filbee-Dexter *et al*. 2020), Spain and Portugal (*L. hyperborea* and *S. polyschides*, Smale 2020), often associated with shifts in dominance towards algal turfs. *L. ochroleuca* has reduced in abundance in the Bay of Biscay, Spain (Araújo *et al*. 2016) but is increasing along its northern range-edge in the south-west of the UK (Smale 2020). *L. digitata* is experiencing a range shift, with declines along the southern range-edge in the English Channel (King *et al*. 2020). *L. hyperborea* has expanded in Helgoland, Germany, where it is displacing *S. latissima* and *L. digitata* (Araújo *et al*. 2016). Along the northernmost part of the Norwegian coast, kelp forests have largely been reduced, though both *Laminaria* and sugar kelp forests are recovering in mid-Norway in part of a 2,000 km^2 area that was formerly dominated by sea urchins. This recovery, starting in the 1990s, is still progressing at the southern barrens' limit and to a lesser extent around the northern barrens' limit, more than five decades after sea urchins bloomed and overgrazed the kelp forests (Christie *et al*. 2019a).

Warming and overfishing are the main drivers of kelp loss and changes in kelp distribution in the North-East Atlantic. The gradual temperature increase in coastal waters in this region has caused northward range shifts for many kelp species (Smale 2020), and the broad-scale mortality of kelp in marginal areas (e.g. sugar kelp in the Skagerrak, southern Norway) has been linked to increasingly frequent marine heatwaves (Filbee-Dexter *et al*. 2020). A sea urchin bloom on the mid- and northern Norway coast occurred around 1970 and was most likely caused by overfishing and a collapse in coastal fish stocks, leading to the release of a prominent grazer, the sea urchin *Strongylocentrotus droebachiensis* (Norderhaug *et al*. 2020). The ongoing reduction of sea urchins and recovery of kelp are consequences of gradual warming and expansion of predatory crabs (Christie *et al*. 2019b). Although sea urchin grazing is mainly reported from northern coasts in Norway, small-scale localized events have been reported widely from France, the UK and Denmark in the south to Iceland and the Russian Federation in the north (Norderhaug and Christie 2009). Other causes of kelp loss include eutrophication and freshwater run-off from land (Bartsch *et al*. 2008; Araújo *et al*. 2016; Filbee-Dexter and Wernberg 2018). Expansion of invasive species and subsequent displacement of native species is also a threat at present and will be in the future. For example, *U. pinnatifida* (wakame) was introduced to the Mediterranean Sea from Asia in the 1970s and is now expanding along the Iberian and French coast (Araújo *et al*. 2016). Finally, the growing interest in kelp cultivation in Europe poses a potential future environmental threat by increasing the risk of spreading non-native species and genes (Campbell *et al*. 2019).

Southern Africa

Cooling sea surface temperatures in western South Africa have been associated with increases in kelp abundance and kelp range expansion. While sea surface temperatures have been rising throughout much of the world, in this region increases in south-easterly winds and upwelling beginning in the 1990s have resulted in decreased annual mean temperatures (Blamey *et al*. 2015). In the mid-1990s, a floating canopy of *E. maxima* appeared at De Hoop Nature Reserve, approximately 70 km east of the documented long-term range limit of this species (Bolton *et al*. 2012). This population has persisted, but the species is still not reported at sites between the De Hoop Nature Reserve and the previous long-term range limit (John J. Bolton, pers. obs., 2007–2020). In contrast, climate change is resulting in warming and strengthening of the Agulhas Current, the major warm surface current moving southward along the east coast of South Africa (Blamey *et al*. 2015). These changes have not yet resulted in significant changes in kelp abundance, but future warming may affect the small inshore populations of *E. radiata* in this region.

Notably, there have been major changes in kelp forest fauna in South Africa since the 1970s, with almost all populations of reef fish species overexploited or collapsed, and both West Coast rock lobster and abalone populations severely overexploited (Blamey and Bolton 2018). Unlike many other regions, these faunal changes have not yet led to loss of kelp forests in South Africa, although they have been linked to other changes in kelp forest community structure. For example, the presence of sea urchins along the Cape of Good Hope has corresponded to changes in kelp forest composition, but not changes in overall kelp abundance (Leliaert *et al*. 2000). Additionally, an eastward migration of West Coast rock lobsters in the 1990s into a portion of the urchin-dominated coastline removed sea urchins and resulted in changes to the kelp forest understorey community (Blamey and Branch 2012).

North-West Pacific – Republic of Korea and Japan

Decadal scale warming trends in the North-West Pacific have been linked to range contractions of temperate kelp species such as *E. cava* and expansion of some warm-water-tolerant kelp and coral species. In south-western Japan, warming during the 1997–1998 ENSO was associated with a large decline in E. cava and a persistent expansion of tropical species (Tanaka *et al*. 2012). Declines in kelp abundance in other parts of Japan have been associated with grazing from herbivorous fish, which warming can increase (Nakayama and Arai 1999; Masuda *et al*. 2000). In the Cape Ōma region of northern Japan, seawater temperature increases of around 1°C between the 1980s and early 2000s corresponded to a decrease in the abundance of cold-temperate species including *S. japonica* (kombu) and increases in warm species such as *U. pinnatifida* (wakame) (Kirihara *et al*. 2006).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Warming has also been linked to range contractions of temperate species in Jeju Island, Republic of Korea (Kang and Chung 2015). *E. cava*, the dominant kelp species in this area, share shallow benthic habitats with soft coral species and dynamically fluctuate in response to various disturbances, including summer typhoons (Kim *et al*. 2021). There are also declines in kelp abundance and shifts towards urchin barren states along the east coast of the Republic of Korea (Jeon, Yang and Kim 2015; Hong *et al*. 2021). A recent study demonstrated that removal of sea urchins led to rapid kelp recovery as well as the stability of the food web structure, suggesting that kelp could persist in this region if grazers were reduced (Hong *et al*. 2021; Kim *et al*. 2022).

Oceania – Australia and New Zealand

South-eastern and south-western Australia have warmed faster than 90 per cent of the global ocean (Hobday and Pecl 2014). In response, these regions have experienced a poleward contraction of temperate seaweed species over the past 50 years (Wernberg *et al*. 2011a). In 2011, the west coast of Western Australia lost 43 per cent of its *E. radiata* (golden kelp) forests (Wernberg *et al*. 2016), and other habitat-forming fucoids. The marine heatwave caused an approximately 100 km range contraction of kelp forests and substantial tropicalization of associated reef communities (Wernberg *et al*. 2016). These impacts were compounded by increased grazing from range-shifting tropical fish (Bennett *et al*. 2015; Zarco-Perello *et al*. 2017). Now, more than 10 years later, these kelp forests have not recovered (Wernberg 2020). Further to the south, where the heatwave was equally intense but did not reach temperatures in excess of the thermal limit of golden kelp, forests showed little response (Wernberg *et al*. 2013).

Losses of golden kelp have also occurred in south Australia in the Adelaide gulfs and in Port Phillip Bay, Victoria (Carnell and Keough 2019) due to eutrophication and warming, and in northern New South Wales due to grazing from range-shifting tropical herbivores (Vergés *et al*. 2016). Around Tasmania, giant kelp has declined by more than 95 per cent in the past few decades, mainly due to warming, incursions of nutrient-poor warm water and grazing from range-shifting sea urchins (Johnson *et al*. 2011; Ling and Keane 2018). In New Zealand, golden kelp (*E. radiata*) has experienced local die-offs and reductions in abundance along the North Island due to diseases and grazing (Cole and Babcock 1996; Haggitt and Babcock 2003; Shears, Babcock and Salomon 2008), while giant kelp has been lost in Otago due to increased turbidity, heatwaves and urchin grazing (Glover 2021). The invasive kelp wakame has invaded some parts of the region and can outcompete some native kelp species. In 2017/18, populations of *D. poha* were lost during a marine heatwave near Lyttelton Harbour on the South Island (Thomsen *et al*. 2019).

Arctic – United States of America, Canada, Greenland, Svalbard and the Russian Federation

Arctic kelp forests have been vastly understudied relative to kelp in temperate regions (Krumhansl *et al*. 2016), but recent studies demonstrate widespread and extensive kelp coverage in the Arctic. The most recent pan-Arctic review of existing long-term monitoring and field studies on kelp ecosystems shows a general trend of increasing abundance in response to climate change (Krause-Jensen *et al*. 2020), though trends are variable across existing studies that cover some parts of the Beaufort Sea, Greenland, Norway and the Russian Federation. For example, a 40-year time series in the Beaufort Sea showed no change in kelp productivity or abundance (Krumhansl *et al*. 2016; Bonsell and Dunton 2018), while diver surveys in Arctic Norway (Svalbard) reported an eightfold increase in kelp biomass (*L. digitata*) in 2012–2014 compared to 1996–1998 (Bartsch *et al*. 2016). However, this was also associated with a loss of kelp biomass in deeper areas, which was attributed to reduced light from higher turbidity due to climate-driven increases in terrestrial run-off (Pavlov *et al*. 2019). In the Russian Federation, the recovery of kelp in sea urchin barrens has occurred in the Guba Zelenaya Fjord, but kelp forests have retreated from lower depth limits of 10–12 m in Kola Bay near Murmansk. There is also some evidence that *L. hyperborea* is extending its range east, further into the Russian Federation as temperatures increase and sea ice retreats (Krause-Jensen *et al*. 2020).

Historical changes in Arctic kelp forests have been closely linked to environmental conditions, with sea ice cover being one of the primary drivers of change. Sea ice cover has become thinner and has begun to break up earlier in the year, reaching historic lows in the last decade. As sea ice restricts the upper depth limits of kelp by mechanical abrasion and restricts the lower depth limits by light shading (Filbee-Dexter *et al*. 2019), its loss generally makes habitat more suitable for kelp. However, the coastal zone is also the main recipient of increasing sediment fluxes from thawing permafrost and eroding continental shelves (Fritz, Vonk and Lantuit 2017), as well as freshwater inputs from increased river discharge and glacier melt (Meredith *et al*. 2020). Increased freshwater run-off from glacial ice melt increases turbidity in coastal waters, which can lead to kelp shading (Bonsell and Dunton 2018; Pavlov *et al*. 2019) and offset the beneficial effects of decreasing ice cover for kelp populations. The degree to which these environmental changes have impacted kelp abundances varies regionally and depends on the extent to which melting sea ice, glacial melt, and permafrost erosion increase turbidity and freshening in coastal areas (Bartsch *et al*. 2016; Traiger and Konar 2018).

Future projections

During the remainder of the twenty-first century, anthropogenic climate change is expected to cause further increases in mean ocean temperatures and the frequency and intensity of marine heatwaves, reductions in sea ice cover in the Arctic and Antarctic, and increased glacier melt and run-off at high latitudes (Frölicher *et al*. 2018; Oliver *et al*. 2019). Increases in the uptake of atmospheric CO_2 by surface waters will result in increased partial pressure of carbon dioxide (pCO_2) levels and ocean acidification (Doney *et al*. 2009). Climate change is also expected to increase storm frequency and intensity in some regions, leading to higher levels of wave disturbance (Reguero, Losada and Méndez 2019).

In general, climate change is likely to shift kelp distributions poleward, with declines in equatorward range-edge populations and expansions at poleward range-edges (Table 2.1), a pattern that corresponds to recent observed trends in kelp abundance (Smale 2020). Warm-tolerant species are expected to replace cold water species, thus altering the diversity and community composition of kelp forests (Assis, Araújo and Serrão 2018; Sudo *et al*. 2020). In polar latitudes, reductions in sea ice will lead to lower salinity and greater sediment inputs in kelp ecosystems (Filbee-Dexter *et al*. 2019). This pattern is prevalent in the North Atlantic, which is probably the most well-studied region in terms of future projections. In this region, contractions in warm range-edges and northward shifts have been projected for numerous species (Assis, Araújo and Serrão 2018). In Australia, trends of decline in abundance and distribution are expected to continue, leading to the extinction of some species such as *M. pyrifera* and major range contractions of other iconic species, including *E. radiata* (Martínez *et al*. 2018). The Aleutian Islands are another region of particular concern as both kelp forests and the biogenic coralline habitat on which they are built are declining due to herbivory, warming temperatures and ocean acidification (Rasher *et al*. 2020).

However, there will be local to regional scale variability in how kelp forests respond to climate change. Local adaption (e.g. Vranken *et al*. 2021) and intraspecific variability in tolerance to warming (e.g. Clark *et al*. 2013) may lead to variability in the magnitude of temperature-driven declines across species' ranges (Bennett *et al*. 2015; King *et al*. 2019). These processes may also lead to populations that are particularly resilient due to their adaptation to warm conditions (Lind and Konar 2017). Local variation in ocean currents, upwelling, and bathymetry can create refugia for kelp against climate change (Davis, Champion and Coleman 2021). Changes in kelp forest community composition could alter species interactions and, in some cases, maintain ecosystem functions.

Extrapolating recent trends in kelp abundance may not provide an accurate view of the future because of non-linear responses and thresholds, complex interactions among multiple stressors (see chapter 1), and changing policies related to fishing, coastal development, and climate change mitigation. Although the majority of research focuses on climate-driven impacts, future projections for the world's coastal zones show increases of multiple other important stressors, including heavily intensified food production in these regions (wild harvest and aquaculture), growing coastal development, increased shipping activity and increased pollution and run-off. These changes have all been linked to kelp loss in various regions, yet the exact consequences of these threats are not well understood, and there are limited predictive models to show how these stressors may interact to alter kelp forests in the coming decades.


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Table 2.1. Examples of the projected impacts of climate change on the abundance and distributions of major kelp species

Region	Species	Response	References
Japan	*Alaria crassifolia, Agarum clathratum, Costaria costata, Arthrothamnus bifidus,* seven species of *Saccharina*	Declines in distribution of all species by the 2040s and 2090s, depending on the warming scenario Northern range shifts for most species	Sudo *et al.* 2020
North Atlantic	*Laminaria solidungula, A. esculenta, Saccorhiza dermatodea, L. digitata, L. hyperborea, Saccharina latissima, S. polyschides, L. ochroleuca*	Contraction of low latitude ranges with northwards expansion Under Representative Concentration Pathway (RCP) 8.5 (high-emissions warming scenario), decreases in *L. solidungula, A. esculenta, S. latissima, L. digitata, L. hyperborean* and increases in *S. dermatodea, S. polyschides, L. ochroleuca*	Assis, Araújo and Serrão 2018
North Atlantic	*L. digitata, S. latissima*	Poleward range contractions between 100 and 300 km	Khan *et al.* 2018
Europe	*L. digitata*	Declines in abundance at southern edge with poleward shift of distribution	Raybaud *et al.* 2013
Europe	*L. ochroleuca*	Declines in abundance at southern edge (Morocco and Iberian Peninsula) with poleward shift of distribution (e.g. UK)	Franco *et al.* 2018
Eastern Australia	*Ecklonia radiata*	Poleward range contraction of around 530 km by 2100	Castro *et al.* 2020
Australia	*Macrocystis pyrifera, E. radiata*	*Macrocystis* projected to become extinct from Australia by 2100 under RCP 6.0 *Ecklonia* predicted to contract by between 49 and 71 per cent and become restricted to south coast of Australia	Martínez *et al.* 2018
Eastern North America	*L. digitata, S. latissima*	Expansion at poleward limits, contractions at southern range-edges	Wilson *et al.* 2018
North-East Pacific	*Eualaria fistulosa, Nereocystis luetkeana, M. pyrifera, Eisenia arborea*	Declines in the abundance of kelp near the equatorward range limits of *M. pyrifera* in Baja California and *N. luetkeana* in Northern California Continued decline in Aleutian kelp forest abundance and degradation of biogenic habitat	Beas-Luna *et al.* 2020 Rasher *et al.* 2020
Arctic	*L. solidungula, Alaria* spp. *S. latissima*	Severe southern range contractions in endemic Arctic kelp taxa, with up to 67 per cent of suitable habitat lost by 2100 under RCP 8.5. Areas likely to experience losses regardless of climate change severity include coastlines in the Sea of Okhotsk, the Bering Sea and the White Sea. Increasing climate change severity will also result in severe losses in Hudson Bay, Newfoundland and Labrador (Canada), Svalbard (Norway), the Barents Sea (the Russian Federation) and the northernmost reaches of the Bering Sea. Arctic habitat is projected to remain stable along much of the Siberian coastline, the northern half of Greenland, and the Canadian Arctic Archipelago. In areas with projected losses in Arctic taxa, succession by temperate kelp is predicted.	Bringloe *et al.* in 2022

Knowledge gaps

The most comprehensive study to date of historical trends in kelp abundance contained data from only about one third (34 out of 99) of the world's ecoregions where kelp forests exist, and in most cases coverage within these regions was relatively sparse in space and time (Krumhansl *et al*. 2016). Most studies using these data were relatively short in duration, which may contribute to a lack of detection of directional change in many regions, as kelp forests are known to be highly variable on short timescales (Wernberg *et al*. 2019). A lack of consistent funding for monitoring has contributed to a paucity of long-term studies on kelp abundances. Funding lapses for monitoring that lead to data gaps and shifts in methodologies make detecting long-term changes difficult. The lack of data from Arctic regions is of particular concern, and consequently there is a high degree of uncertainty in the trajectory of kelp forests over a large part of the global range of kelp.

A coordinated network of global kelp observations would help address these gaps (e.g. Duffy *et al*. 2019). Remote sensing also represents a valuable tool for monitoring certain species of kelp (e.g. those that form surface canopies), especially in remote areas. Satellite imagery has been used to map giant kelp distributions on global scales (Mora-Soto *et al*. 2020) and characterize trends and variability for a handful of regions such as California, Tasmania and the Falkland Islands (Malvinas) (Bell *et al*. 2020; Butler *et al*. 2020; Houskeeper *et al*. 2022). These efforts should be expanded to map trends on global scales with increasing spatial and temporal resolution.

We also need to better understand the drivers of changes in kelp abundance, especially with respect to multiple interacting pressures. For example, kelp forests in southern California exhibited relatively high resilience to a major marine heatwave in 2014–2016 (Cavanaugh *et al*. 2019), but this same event was linked to collapse of kelp forests in northern California due to interactions between the heatwave and high levels of urchin grazing (Rogers-Bennett and Catton 2019). Understanding interactions between climate change and local pressures such as pollution, overfishing and invasive species is critical for informing management actions. Local pressures can often be mitigated by actions such as regulating coastal development and pollution, implementing marine protected areas, reducing grazing pressure and making restoration/afforestation efforts (Eger *et al*. 2020; Morris *et al*. 2020; Hamilton *et al*. 2022).

While projections of changes in kelp forest distribution have been developed for some species and regions (Table 2.1), there are major geographic and conceptual gaps in our understanding. To date, most projections have focused on the North Atlantic and Europe. There is a lack of studies for widespread surface-canopy forming species such as *M. pyrifera, N. luetkeana* and *E. maxima*, and even fewer standardized studies on subcanopy kelp dynamics. More information is needed for the Eastern and Western Pacific, including areas such as Asia (where there is high demand for harvested kelp) and the North-East Pacific (where commercial interests in seaweed harvesting are currently being developed).

Future modelling efforts should attempt to develop dynamic predictive models that incorporate adaptation, ecological interactions, multiple stressors and extreme events. To achieve this, more data are needed on intraspecific variability in environmental tolerance and variability in the tolerance of different life stages. It would also be useful to develop models that integrate experimental data on species tolerance thresholds to better characterize non-linear responses (e.g. Franco *et al*. 2018; Castro *et al*. 2020). Improved models will enable more accurate projections and give managers the tools to examine the effects of mitigating local stressors to promote kelp forest resilience in the face of climate change.

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Chapter 3. Biodiversity and ecosystem services

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Highlights

- **Kelp forests are sites of increased biodiversity. Kelp extend into the water column and create three-dimensional structures that numerous species use for shelter and food.**
- **Marine communities that live under the shaded canopy of kelp blades can be highly diverse, with hundreds of species on a single kelp. At the wider seascape scale, kelp canopies also offer shelter and foraging areas for marine wildlife such as seals, sea otters, octopus, sea birds, sharks and large predatory fish.**
- **Kelp forests also provide numerous benefits to coastal communities, through direct harvesting or farming, fisheries provision (food security), carbon storage and nutrient filtration.**
- **Humans have a long history and close relationship with kelp forests. These ecosystems provide a wide range of cultural benefits for people living on or near the coast around the world.**
- **Much of the data on these services come from a few well-studied regions, but every forest can function differently, and it is critical to have specific knowledge on ecosystem services for different systems.**

Section A: Kelp forest biodiversity and community structure

1. Kelp as foundation species

Kelp modify the environment. Kelp are habitat-forming foundation species that – like seagrass, mangroves and corals – modify environmental conditions, species interactions, community structure and ecosystem functioning. The main characteristics that make kelp foundation species are their large fronds that absorb light, remove nutrients from the water column and alter hydrodynamics (Eckman, Duggins and Sewell 1989; Schiel and Foster 2015). Furthermore, some kelp species reduce sedimentation rates on the underlying reef through frond whiplash and abrasion (Kennelly 1989; Toohey *et al*. 2004). Kelp forests typically reduce light availability on the sea floor by over 90 per cent, creating darker stratified subcanopy habitats (Wernberg, Kendrick and Toohey 2005; Schiel and Foster 2015; Smale *et al*. 2016). Kelp also assimilate inorganic nitrogen and carbon, deplete local nutrient concentrations, increase pH and alter water chemistry (Krause-Jensen *et al*. 2015; Krause-Jensen and Duarte 2016; Murie and Bourdeau 2020). Dense kelp forests can dampen wave forces and create calmer microhabitats within the forests (Mork 1996a; Wernberg, Kendrick and Toohey 2005). Nevertheless, the extent of environmental modification varies between kelp species. For example, the standing biomass and extent of shading are lower in kelp forests that are dominated by small or short-lived species such as *Postelsia palmaeformis, Hedophyllum sessile* and *U. pinnatifida* (Epstein and Smale 2017; South *et al*. 2017) compared to forests dominated by larger or long-lived species such as *Durvillaea* spp., *L. hyperborea and M. pyrifera* (Smale *et al*. 2013; Wernberg *et al*. 2019a).

Kelp modify species interactions. Through the mechanisms described above, kelp modify interactions among species that inhabit kelp forests. Kelp are strong competitors that shade and outcompete many light-dependent perennial brown seaweed and small filamentous and turfy seaweed species (Thomsen and South 2019; Santelices and Ojeda 1984; Wernberg *et al*. 2020). However, species that have low light requirements and high resistance to abrasion, such as slow-growing encrusting and calcifying seaweed and small sessile invertebrates, flourish underneath kelp canopies (Melville and Connell 2001; Thomsen and South 2019; Wernberg *et al*. 2020). These encrusting species help cement the reef, can reduce erosion of soft rocks and facilitate small slow-moving grazers such as limpets and chitons (Bosence 1983). In wave-swept environments, kelp fronds can control the abundance and grazing efficiency of larger herbivores, such as sea urchins and fish, because whiplash from fronds hinders their foraging (Kennelly 1991; Toohey *et al*. 2004).

Through these mechanisms, kelp can control system-wide biodiversity (section 3.2), ecological functions such as provision of nursery habitats (section 3.3), and trophic interactions and food-web structure (section 3.4). Kelp forests are dynamic systems, where storms, waves, sea ice scour, warming events or intense grazing can cause localized deforestation and reset successional processes (Dayton *et al*. 1984; Tait *et al*. 2021; Thomsen *et al*. 2021). The creation of gaps in the kelp canopy allows competitively inferior species to coexist with kelp species at the habitat scale, with mosaics of dense kelp forest interspersed with patches of communities at differing successional stages (Foster 1975; Benes and Carpenter 2015; Wernberg *et al*. 2020). Much like forests on land, these mosaics increase heterogeneity and functional and taxonomic diversity within the ecosystem. However, if forests become too fragmented and gaps too large, for example through natural or anthropogenic disturbances, the competitive hierarchies may switch to favour other seaweed species or small opportunistic species such as filamentous and turf algae. In other words, kelp forests are maintained through positive feedback loops of self-recruitment, fast growth into large fronds, shading, frond abrasion and whiplash (Schiel and Foster 2015; Filbee-Dexter and Wernberg 2018; Thomsen *et al*. 2021).

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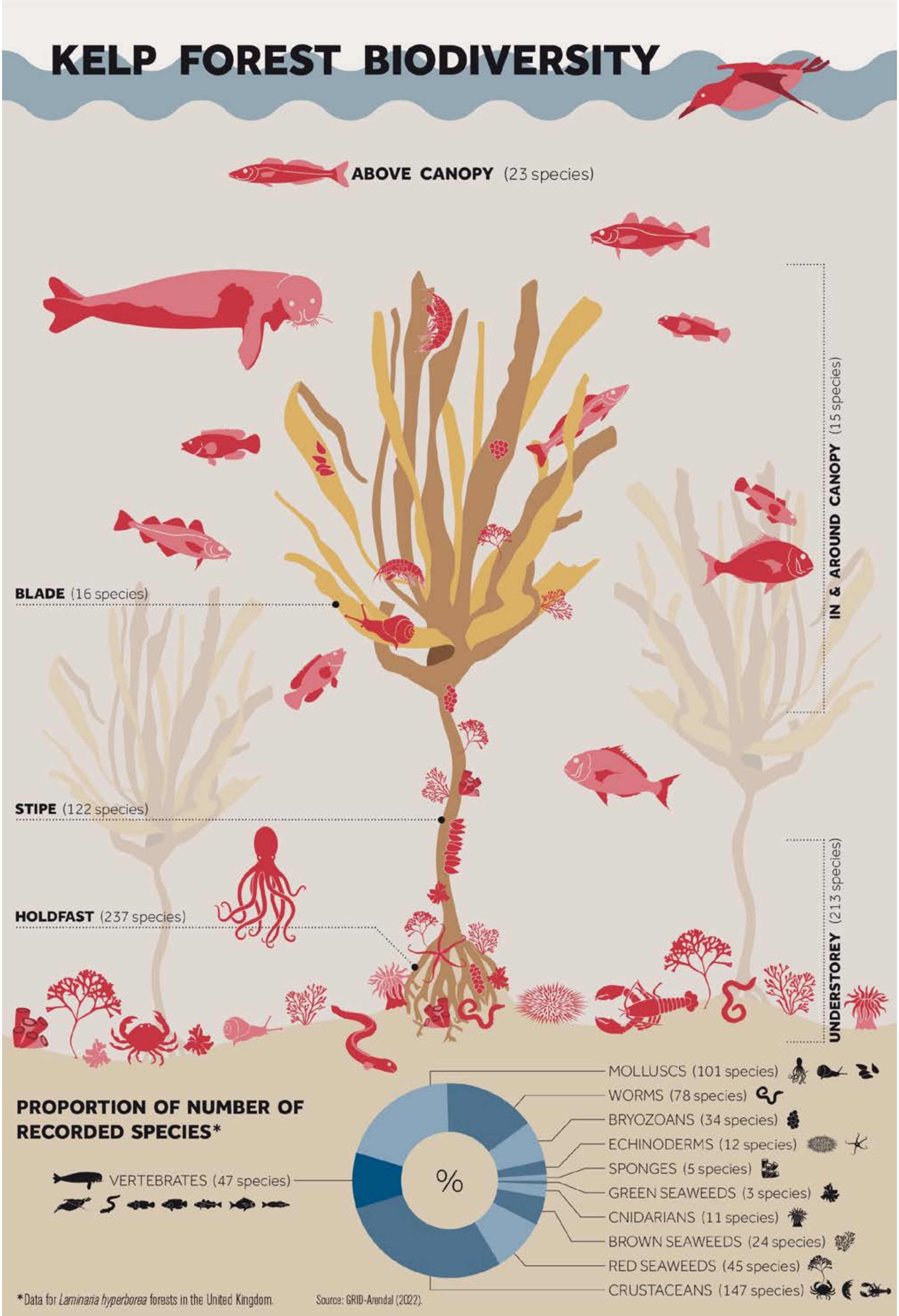
2. Kelp-associated biodiversity

Figure 3.1. Example of the biodiversity value of the United Kingdom's kelp forests



Direct habitat provision. Kelp support elevated biodiversity by increasing habitat space (volume), variability and complexity, and through the direct provision of food and shelter (Teagle *et al*. 2018). Most kelp species form large, complex biogenic structures (made of living organisms), which offer substantial area and living space for colonization by numerous species of seaweed, invertebrates and fish. Moreover, some kelp species are long-lived, reaching 20 years of age in some regions (Rinde and Sjøtun 2005). Kelp forests may have persisted for millennia along the North-East Pacific and Atlantic coastlines (Neiva *et al*. 2020), providing stable high-quality habitat for associated communities over time. A single *L. hyperborea* individual in Norway was shown to support around 80,000 organisms of more than 70 species (Christie *et al*. 2003). Similarly, extensive surveys of kelp forests in the UK have recorded over 500 species of kelp-associated plants and animals, thereby highlighting their value as repositories of biodiversity (unpublished Smale, Figure 3.1).

Different parts of the kelp offer microhabitats that support distinct communities. For example, the holdfast structure that anchors the kelp to the sea floor is typically complex and intricate, where cavities and interstitial spaces between the root-like haptera (branches of the holdfast) offer living space and refuge for mobile invertebrates and even small fish (Anderson *et al*. 2005; Teagle *et al*. 2018; Thomsen *et al*. 2018). In New Zealand, more than 350 species were associated with 80 holdfasts of *E. radiata* (Anderson *et al*. 2005) and in the UK over 260 species were recorded in 60 holdfasts of *L. hyperborea* (Figure 3.1) (Teagle *et al*. 2018). Larger fauna such as crabs, pipefish and rock fish have also been found to overwinter and take refuge in some holdfasts. Communities associated with holdfasts are typically dominated by amphipods (small crustaceans), gastropods (small snails) and polychaetes (bristle worms), although bivalves (e.g. mussels) and echinoderms (e.g. sea urchins, starfish) can also be important, and a range of trophic groups including detritivores, herbivores, filter feeders and predators are often represented (Thomsen *et al*. 2018; Schaal, Riera and Leroux 2012).

The diversity and composition of holdfast communities varies between kelp and habitats, due to differences in the morphological complexity and structure of kelp, age of the holdfast, local species pools, and predators, and variability in environmental factors such as sedimentation rates, ocean currents and food supply (Teagle *et al*. 2018). The kelp stipe is structurally simpler than the holdfasts but still offers surface area to which sessile invertebrates and other seaweed can attach (Christie *et al*. 2003). The diversity and abundance of stipe-associated communities is extremely variable among kelp species, where some species' stipes have no associated species, but other species support lush plant and animal communities. For example, some *Laminaria* species support abundant epiphytic red algae and sponges, which in turn offer additional food and living space for a wide variety of mobile invertebrates (Christie *et al*. 2003), whereas other *Laminaria* species have no stipe epiphytes. Stipe-associated mobile invertebrates are important prey items for fish and large crustaceans and form an important link in the local food web. Finally, kelp fronds or blades are typically simple leaf-like structures with a large surface area for photosynthesis. They often have high turnover, which generally supports relatively low-diversity communities. Healthy, fast-growing kelp blades tend to have few animals growing directly on them, but dying or stressed kelp may support many seaweed species and invertebrates (O'Brien and Scheibling 2016; Denley, Metaxas and Fennel 2019). Nevertheless, a few organisms, such as specialized grazers, gastropod egg casings and sea urchins, can be abundant on healthy kelp blades (Poore *et al*. 2014).

Habitat creation at the seascape scale. The structure and size of habitat provided by kelp, and consequently the diversity and shape of kelp forest communities, are influenced by a range of physical and biological factors that vary across scales. At spatial scales greater than a single kelp, multiple individuals form canopies that provide three-dimensional habitat for a vast array of larger marine organisms, many of which are of ecological importance (e.g. sea urchins) (Kitching and Thain 1983) or socioeconomic importance (e.g. lobsters, pollack groundfish, abalones) (Johnson and Hart 2001; Norderhaug *et al*. 2020). Kelp canopies alter local conditions and therefore influence which species can colonize and thrive in the understorey environment. Patchy mosaics with different kelp canopy structures and open reefs create a range of conditions for associated communities. Marine communities that live in the kelp forest understorey (under the shaded canopy of blades) can be highly diverse; over 100 species of seaweed were recorded attached to the underlying reef at a single site in Western Australia (Smale, Kendrick and Wernberg 2010), and more than 170 species of mobile invertebrates were sampled in understorey habitats in the UK (Figure 3.1) (Bué *et al*. 2020). At the wider seascape scale, extensive kelp canopies also offer shelter and foraging areas for marine wildlife such as seals, sea otters, octopus, sea birds, sharks and large predatory fish (Figure 3.1).

3. Refuge and nursery habitat

Many animals complete their life cycle within kelp forests, while other species spend only certain life stages within kelp habitats (Norderhaug, Christie and Rinde 2002). For example, the Patagonian squid *Doryteuthis* (Amerigo) *gahi* attaches eggs to giant kelp (*M. pyrifera*), and juvenile king crabs (*Lithodes santolla*) inhabit holdfasts in sub-Antarctic South America (Rosenfeld *et al*. 2014; Cárdenas *et al*. 2007). Kelp forests serve as nursery habitat for young fish (Bergström *et al*. 2016), with *L. trabeculata* and *M. integrifolia* forests in northern Chile, for example, being important for the settlement and early development of coastal fish (Angel and Ojeda 2001). Kelp canopies also offer protection from many predators (Villegas *et al*. 2019). For example, juvenile pollack (*Pollachius virens*) feed in the water column immediately above kelp, retreating to the shelter of the kelp canopy when threatened by larger predators (Norderhaug *et al*. 2005).

Several studies have shown that the abundance and identity of juvenile fish and shellfish in kelp forests is highly variable in space and time. For example, juvenile cod in Newfoundland rest in kelp forests at night-time but exhibit flexible activity patterns elsewhere during the day-time (Keats and Steele 1992). Furthermore, in Japan juvenile abalone (*Haliotis discus hannai*) inhabit crustose coralline algae beds, whereas adults are abundant in kelp forests (Won *et al*. 2013). Associations between juvenile animals and kelp are, however, context-dependent and other marine habitats may perform similar functions (Hinz *et al*. 2019). Many studies have documented associations between kelp and fish and shellfish, typically showing higher diversity within kelp forests (Metzger, Konar and Edwards 2019; Konar, Edwards and Efird 2015) but few studies have carried out experiments to test for these causal links (Bertocci *et al*. 2015). Nevertheless, experimental additions and removals of kelp have demonstrated higher abundances of juvenile fish within kelp forests compared with outside (Villegas *et al*. 2019; Norderhaug *et al*. 2020).

4. Trophic interactions

Kelp as a trophic resource. Kelp species have relatively high growth rates and large standing biomass (chapter 1), providing plentiful resources for animals that feed on marine plants (herbivores). In contrast to other foundation species such as saltmarsh grass, mangroves, seagrass and corals, kelp have fewer structural or chemical anti-grazer defences (Steneck *et al*. 2002). Instead, kelp can escape top-down control (when feeding by herbivores limits the amount of kelp) by growing rapidly to outpace grazing activity (but note the effect of sea urchin grazing), by living in wave-exposed habitats that limit grazing foraging time, and because grazers themselves are often top-down controlled by predators (Estes *et al*. 1998; Lauzon-Guay and Scheibling 2007; Kawamata 2010).

The palatability and nutritional value of kelp varies between kelp species and over time, with fresh tissue often less palatable than degrading tissue. Hence, around 80 per cent of the annual production of kelp forests enters the food web after it has broken off from the kelp as detritus (Duggins, Simenstad and Estes 1989; Krumhansl and Scheibling 2012). The high standing kelp biomass nevertheless supports many herbivores, including small grazers such as marine snails and many types of crustaceans (Davenport and Anderson 2007; Molis, Enge and Karsten 2010), herbivorous fish (Andrew and Jones 1990; Taylor and Schiel 2005) and sea urchins (Kawamata 2010; Filbee-Dexter and Scheibling 2014). Furthermore, drifting kelp, fronds or fragments dislodged during storms can support fished species such as abalones (Bustamante, Branch and Eekhout 1995), subsidize deep-sea communities (Vetter 1995) and, when cast ashore, be eaten by land animals (Colombini and Chelazzi 2003).

Large amounts of kelp fragments and leached dissolved organic material also enter the local food web through browsing, filter-feeding and deposit-feeding animals and larvae (Duggins, Simenstad and Estes 1989; Norderhaug, Fredriksen and Nygaard 2003; Feehan *et al*. 2018; Miller *et al*. 2018). These animals in turn provide food for predators such as fish, octopus, seabirds and apex predators including sea otters, seals, sharks and dolphins (Goodall *et al*. 1995; Estes *et al*. 1998; Port *et al*. 2016) and for parasites (Morton *et al*. 2021). As a result, many of these coastal habitats support a rich kelp-associated animal community.

Trophic cascades, food webs and sea urchin grazing. Kelp forests support diverse food webs due to how they modify the environment, their competitive hierarchies with other seaweed, their trophic linkages (feeding connections in a food web), the effects of wave disturbances, and their creation of biogenic habitat (habitat made of living organisms) (see previous sections). Many studies have reported complex kelp forest food-web structures from isotope analyses and natural history observations (Graham 2004; Rocchi *et al*. 2017; Vilalta-Navas *et al*. 2018). Recent analyses have shown that loss of kelp forests causes reduced complexity in coastal food and interaction webs (Gabara *et al*. 2021) and that the presence of kelp forest-associated parasites increases community diversity and food-web complexity. For example, in a Californian kelp forest over 1,000 species – represented by 492 free-living species from 21 phyla and 450 parasitic species from 10 phyla – were interlinked by over 20,000 unique trophic interactions, of which half involved parasites, demonstrating the ecological importance of this overlooked group of cryptic organisms (Morton *et al*. 2021).

The trophic linkages whereby sea otters, predatory fish and lobsters indirectly facilitate kelp by eating sea urchins, which Paine (1980) famously coined a "trophic cascade", represents a text-book example of indirect species interactions (Begon, Harper and Townsend 1986). Trophic cascade theory has applied implications where fishing bans have been heralded as a key tool to maintain kelp forests and avoid collapse to sea urchin barrens (Pinnegar *et al*. 2000; Shears and Babcock 2003).

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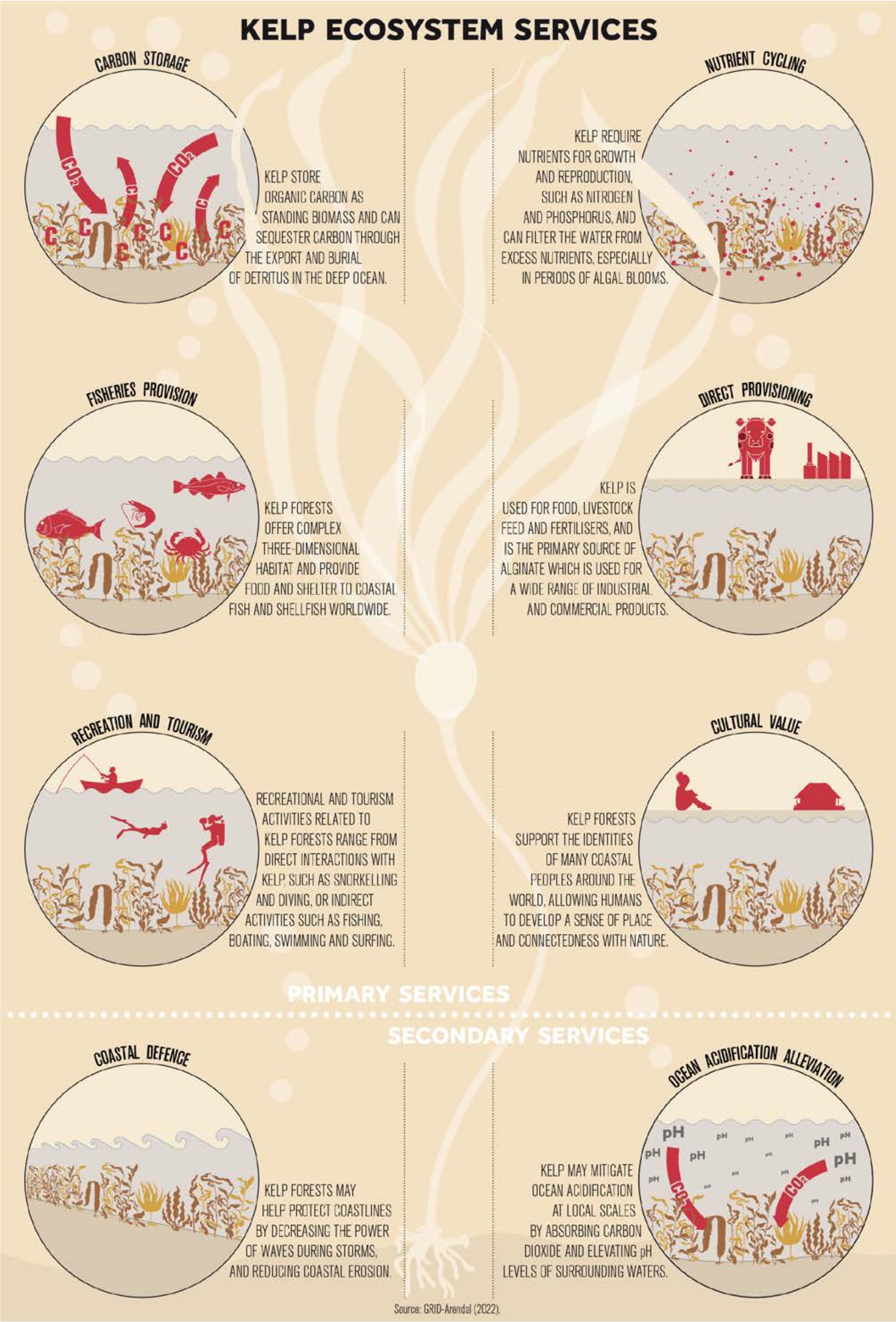
Section B: Ecosystem services and societal benefits

Figure 3.2. Ecosystem services provided by kelp forests



Source: GRID-Arendal (2022).

This section discusses the wide range of ecosystem services that kelp provide (Figure 3.2). Although relatively few studies have quantified kelp ecosystem services in detail, growing awareness of the many benefits of kelp forests to societies is creating an impetus for their management and conservation (see also chapter 6).

1. Carbon storage

Kelp carbon pathways

Kelp forests are essential contributors to the carbon cycle. These productive coastal vegetated habitats take up inorganic carbon, including CO_2, and convert it into organic carbon biomass ("blue carbon") for short-term storage (Dayton 1985; Steneck *et al*. 2002). Furthermore, living kelp are continuously exporting biomass (and hence carbon) to adjacent environments as particulate organic material (POM) through tissue erosion, shedding and whole kelp dislodgement (Krumhansl and Scheibling 2012; Ortega *et al*. 2019; Filbee-Dexter *et al*. 2020). Kelp biomass that is not grazed or consumed by bacteria can be buried in sea floor sediments or transported to depths beyond 1,000 m, where it can be stored for long timescales (thereby crossing the "carbon sequestration horizon", Duarte and Cebrián 1996; Krause-Jensen and Duarte 2016). Recent advances in carbon tracing have shown that kelp detritus is ubiquitous in all ocean basins, reaching up to 4,000 m water depth (Ortega *et al*. 2019). Kelp also excrete dissolved organic carbon (DOC) during growth, of which an unknown portion is poorly degradable and may be exported to the carbon sequestration horizon (Barrón and Duarte 2015; Baltar *et al*. 2021). Through these processes, kelp forests can contribute to long-term (centuries or millenniums) carbon removal from the ocean-atmospheric pool, thereby facilitating carbon storage and sequestration (Smith 1981; Duarte, Middelburg and Caraco 2005; Krause-Jensen *et al*. 2018). See chapter 4 on kelp forests and blue carbon markets for more information.

Global area, net primary production, and sequestration

The global extent of macroalgal forests has been estimated at between 1.7 and 7.2 million km^2 (Duarte *et al*. 2022), equivalent to the area of the Amazon rainforest. Global macroalgae net primary production is estimated at around 1,500 (1,020-1,960) Tg C per year (Krause-Jensen and Duarte 2016), corresponding to around 20 per cent of global coastal net primary production (Dunne, Sarmiento and Gnanadesikan 2007). Of this production, 40–80 per cent of the carbon (with kelp forests in the high range) is exported out of the macroalgal habitats (Duarte and Cebrián 1996; Krumhansl and Scheibling 2012; Pedersen *et al*. 2020). It has also been estimated that annually, global macroalgal carbon sequestration is around 173 Tg C yr^{-1}, corresponding to 620 million tons CO_2 and 11 per cent of the macroalgae net primary production (including the DOC pool of 8 per cent, Krause-Jensen and Duarte 2016). On a national scale, kelp forests in Norway represent a total of 158 million tons wet weight and a standing stock of 7.1 Tg C (Frigstad *et al*. 2020). In Canada, the total carbon standing stock of extensive kelp forests in the eastern Canadian Arctic is 73 Tg C, which is equivalent to the annual greenhouse gas emissions of over 5 million Canadians (Filbee-Dexter *et al*. 2022). Meanwhile, in Australia, kelp forests have been estimated to represent a standing carbon stock of 10.3–22.7 Tg C and contribute 1.3–2.8 Tg C per year in captured production, amounting to more than 30 per cent of total blue carbon stored and potentially sequestered around the Australian continent (Filbee-Dexter and Wernberg 2021). These values are, however, coarse estimates, and there are still considerable uncertainties related to kelp carbon budgets. Future research should aim to provide robust and regionally specific data on kelp carbon sequestration, cycling, export and long-term storage.

Kelp in blue carbon inventories

The Intergovernmental Panel on Climate Change (IPCC) has developed guidelines for the voluntary reporting, by states, of blue carbon habitats such as mangroves, seagrass and saltmarshes (Hiraishi *et al*. 2014); however, kelp forests are not included. Blue carbon ecosystems are also collectively included under the land use, land-use change and forestry (LULUCF) sector of the IPCC, which considers carbon storage or carbon emissions from human interventions to these ecosystems. Although the LULUCF sector is based on emissions from "land" (i.e. soil-based ecosystems), mangroves, saltmarshes and even subtidal seagrass are included in the LULUCF sector because these plants grow in sediments. However, most kelp species grow attached to rock and have therefore been omitted. Research suggests that the carbon derived from kelp forests and transported away from the rocky reef to marine sediments and the deep ocean may exceed the levels of carbon sequestered in seagrass, salt marshes, and mangroves (Krause-Jensen *et al*. 2018; Macreadie *et al*. 2019). Marine ecologists are therefore increasingly considering kelp forests in global and national carbon budgets, although much uncertainty remains around the size of these stores and the carbon fluxes involved (Krause-Jensen *et al*. 2018; Macreadie *et al*. 2019). These knowledge gaps and past perceptions that kelp forests do not store carbon because kelp attach to rock (Nellemann *et al*. 2009) have prevented kelp from being considered in greenhouse gas emission accounting and in the development of climate change mitigation strategies, such as the Paris Agreement, Nationally Determined Contributions and the voluntary carbon market to date. A review of whether to reject or include kelp in the blue carbon framework concluded that kelp and other macroalgae contribute significantly to carbon sequestration (Krause-Jensen *et al*. 2018). However, the mechanism of kelp carbon transport remains understudied and there is a paucity of data documenting kelp carbon sequestration beyond their habitats and tracing sediment carbon pools back to kelp sources (Krause-Jensen *et al*. 2018; Macreadie *et al*. 2019; Queirós *et al*. 2019). Novel methods, including

DNA techniques, are rapidly developing to address these knowledge gaps and build databases on kelp carbon sequestration potential in coastal, offshore and deep-sea sediments (Queirós *et al*. 2019; Ortega, Geraldi and Duarte 2020; d'Auriac *et al*. 2021).

2. Nutrient cycling

Kelp require nutrients for growth and reproduction and have relatively high primary production rates compared to many other photosynthetic organisms. The key limiting nutrients for kelp growth are nitrogen and phosphorus. Nutrients are absorbed by their fronds mainly as inorganic ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-) and phosphate (PO_4^{3-}), although some organic compounds can also be absorbed (e.g. urea, CH_4N_2O) (Schiel and Foster 2015). High concentrations of nutrients can result in eutrophication and are typically associated with human activities, such as sewage outfalls, rivers transporting agricultural fertilizer run-off, and oceanic fish farms. Other photosynthetic organisms can take advantage of high concentrations and influxes of nutrients and trigger algae blooms. These blooms block light from reaching benthic algae and seagrasses. As the algal blooms die, they decompose and consume oxygen from the water, and, in extreme cases, create toxic hypoxic zones. By drawing excess nutrients out of the water, kelp provide a valuable ecosystem service. Kelp genera such as *Macrocystis*, *Nereocystis*, *Laminaria* and *Ecklonia* are estimated to remove between 148 and 1.900 kilograms of nitrogen per hectare per year and between 8 and 216 kilograms of phosphorus.

Nutrient uptake is most relevant when kelp growth is high, and often overlaps temporally with potential microalgal blooms (i.e. typically in spring to summer). Further, as most kelp biomass is recycled locally (Krumhansl and Scheibling 2012), kelp-sequestered nutrients are unlikely to be removed over long timescales but may nevertheless be reduced during periods when they would support microalgal blooms. Still, when kelp biomass is removed from the system, for example through harvesting or export to offshore waters, sequestered nutrients are – like blue carbon – also removed from the coastal ecosystem over long timescales.

3. Fisheries provision

As already discussed, kelp forests offer complex three-dimensional habitat and provide food and shelter to coastal fish and shellfish worldwide. Commercial, recreational and subsistence fishery species may spawn in kelp forests, where they may spend their juvenile period before moving to deeper waters, transiting or foraging in kelp forests as adults, or they may spend most of their life in kelp forests (Norderhaug *et al*. 2020). In general, most kelp forests are linked to fisheries, many of which are in decline due to over-exploitation. Populations of abalone, sea otters, lobsters and large fish (e.g. cod) have declined during the last century in many regions (Estes *et al*. 1998; Steneck *et al*. 2013). These declines not only disrupt the fishery but also disturb the ecosystem and may cause kelp forests to shift to impoverished states, such as sea urchin barrens (Filbee-Dexter and Scheibling 2014). However, fisheries provision in kelp forests remains a critical ecosystem service, as the following regional examples highlight.

West coast of North America. Kelp forests support diving and pot-based fisheries of abalone (*Haliotis* spp.), lobster (*Panulirus* spp.), sea urchins (*Strongylocentrotus droebachiensis*, *S. purpuratus* and *Mescentrotus fanciscanus*) and juvenile salmon (Schiel and Foster 2015). These fisheries have been valued at $1 million to $33 million per species per region per year (Reid *et al*. 2016; Frimodig and Buck 2017). Furthermore, many species of commercially and recreationally important rockfish rely on kelp forests, as do edible species such as kelp bass, lingcod, giant seabass, cabezon, white seabass and sea cucumbers.

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East coast of North America. The economically most important kelp-associated fishery is American lobster (*Homarus americanus*), with a value of around $150 million in 2010 in Maine (Steneck *et al*. 2011) and 1.6 billion CAD in Atlantic Canada (Government of Canada 2022). In Maine, all other coastal fisheries species, including Atlantic cod (*Gadus morhua*), Atlantic wolffish (*Anarhichas lupus*), pollock (*Pollachius* spp.), crab (*Cancer irroratus*), mussels and algae have an estimated total value of $30–40 million. Since the 1950s, overfishing has reduced fish stocks and sea urchins (*Strongylocentrotus droebachiensis*) dramatically (Steneck, Vavrinec and Leland 2004), many of which were historically abundant in kelp forests.

Europe. Commercially important kelp-associated species in the United Kingdom and Norway include lobster (*Homarus Gammarus*), brown crab (*Cancer pagurus*), spider crab (*Maja brachydactyla*), Atlantic cod (*G. morhua*), Atlantic wolffish (*A. lupus*) and (non-native) red king crab (*Paralithodes camtschaticus*) (Smale *et al*. 2013; Christie *et al*. 2019a). Kelp forests also act as feeding and nursery areas for numerous coastal fish, including commercially important species of codfish (Bergström *et al*. 2016; Norderhaug *et al*. 2020). Experimental removal of kelp in Norway showed a 46 per cent reduction in total fish abundance and significant reductions in the abundances of juvenile fish (Norderhaug *et al*. 2020). In Northern Europe, overfishing of coastal fish from the 1950s led to stock collapse and predator release of the sea urchin grazer *Strongylocentrotus droebachiensis* (Norderhaug *et al*. 2020). Consequently, large areas of kelp forests were overgrazed in the 1970s, with little recovery. Annual catches of Atlantic wolffish declined from around 3,300 tons prior to sea urchin expansion to around 870 tons after. Similarly, coastal catches of Atlantic cod declined from around 60,000 tons before, to around 37,000 tons after (Norderhaug *et al*. 2020). Research into the impacts of kelp protection on fish production shows an increase in cod harvests in Norway. In Spain, healthy kelp forests are thought to be important for lobster, with kelp declines associated with declines of three fished lobster species (Voerman, Llera and Rico 2013). Compared to commercially fished species, very little is known about the recreational kelp-associated fisheries, but the importance of kelp forests in supporting recreational fishing is likely to be substantial. For example, there are around 8.7 million European recreational sea fishers, and fishing effort (measured as days fishing) is highest in countries with extensive kelp forests (Norway, UK, France, Portugal) (Hyder *et al*. 2018).

South America. The National Fisheries Service in Chile estimated the value of fisheries between 1998 and 2010 at approximately $82 million (Adam Gouraguine, pers comm.). Associated fisheries include rock fish, Chilean abalone (*Concholepas concholepas*), keyhole limpets and various sea urchin species. Intensive fisheries for southern king crab (*Lithodes santolla*), false king crab (*Paralomis granulosa*) and sea urchins have resulted in stock declines (Friedlander *et al*. 2020).

Asia. The waters around Japan and the Republic of Korea have more seaweed species than any other place on earth and these habitats support centuries-old fisheries. The most important fishery is for abalone (*Haliotis* spp.), which supports numerous coastal fisheries across the two countries. Sea urchins are also an important dive fishery worth $300 million per year in Japan (Sun and Chiang 2015) and local fishing for *Turbo* snail can be intense. As kelp forests are generally recognized as important habitat for healthy fisheries that support many commercially important species (e.g. *Scomber japonicus, Scomberomorus niphonius, Girella punctata, Trachurus japonicus*), kelp restoration is therefore targeted to improve stocks (Eger *et al*. 2021).

Oceania. In the South Pacific, Australia has the region's largest fisheries and kelp forests support almost $1 billion worth of lobster (*Jasus* spp.) and abalone per year. These species are also economically important to New Zealand (Fisheries New Zealand 2021). It is estimated that about 15 per cent of Australia's population takes part in recreational fishing each year and kelp forests are inhabited by many of the target species (e.g. *Cheilodactylus spectabilis, Epinephelus multinotatus, Parapercis colias, Pseudocaranx georgianus*) (Bennett *et al*. 2015).

South Africa. Historically kelp forests in South Africa have supported rock lobsters (*Jasus lalandii*), abalone (*Haliotis midae*), rock mussels, oysters, octopus and a variety of finfish (Blamey and Bolton 2018). Abalone are directly linked to kelp forests through their consumption of drifting kelp fronds and their reliance on coralline algae, which kelp facilitate through shading and scour. Kelp are also inhabited by sea urchins, a key prey item for lobster. However, these abalone and lobster populations are currently overexploited, worth less than $5 million per year and still declining (Blamey and Bolton 2018).

4. Direct provisioning (harvest)

Seaweed, including kelp, have provided direct provisioning services to coastal communities for millennia, with written records originating around 1,700 years ago (Erlandson *et al*. 2015). Historically, seaweed were mainly used for food and livestock feed (Delaney, Frangoudes and Li 2016). Kelp continue to provide important direct provisioning services, with 591,000 tons of kelp landed globally in 2019 (Food and Agriculture Organization of the United Nations [FAO] 2021). Seaweed cultivation continues to expand, whereas harvests of wild stocks have been relatively constant over the last decade, averaging around 600,000 tons since 2000 (FAO 2021). According to FAO (2021), 14 countries harvest wild kelp, dominated by Chile, which accounts for 48 per cent of harvested biomass and Norway, which accounts for 22 per cent (see chapter 6 for further details on countries and key species). Key harvested species are huiro (*L. nigrescens complex* and *L. trabeculata*), cochayuyo (*D. antarctica* and *D. incurvata*), giant kelp (*M. pyrifera*), bull kelp (*N. luetkeana*), European kelp (*L. hyperborea* and *L. digitata*), Japanese kelp (*S. japonica*), wakame (*U. pinnatifida*) and *Ecklonia* spp. Specifically, *L. negrescens* and *L. trabeculata* account for approximately 22 per cent and 7 per cent of wild seaweed harvest (i.e. kelp and non-kelp species), whereas *M. pyrifera, S. japonica* and *Laminaria* spp. together account for approximately 5 per cent (Ferdouse *et al*. 2018). In addition to generating socioeconomic benefits to coastal communities, seaweed have also provided an avenue for women's empowerment through cultivation and involvement in the value chain (Cai *et al*. 2021).

Today, harvested kelp are mainly used for food, livestock feed, fertilizers and a wide range of industrial products. The species most commonly used for human consumption are *U. pinnatifida*, *S. japonica* and *D. antarctica*, with the majority of the first two species derived from cultivation (Ferdouse *et al*. 2018). *M. pyrifera* and *E. maxima* are widely used as feedstock, especially for an expanding abalone aquaculture (Troell *et al*. 2006; Buschmann *et al*. 2014). Kelp are also the primary source of alginates that are used in over 600 products such as thickening and gelling agents in the food and feed processing industry; as bonders, stabilizers and emulsifiers in the pharmaceutical industry; for wound care in medicine; for waterproofing in the textile industry and in wastewater treatment (Lee and Mooney 2012; Ferdouse *et al*. 2018). Biorefining of seaweed, including kelp, is an emerging area of scientific and policy interest, because it can reduce impacts from terrestrial farming. Areas of particular interest include production of food, animal feed, chemicals, materials and energy (e.g. biofuels), but only a few studies have progressed beyond the laboratory (Kostas *et al*. 2021).

While wild kelp harvest has remained relatively constant in recent decades, there is increasing interest in harvesting wild stocks in some countries such as Peru and Scotland (Gouraguine *et al*. 2021). The impacts of kelp harvesting depend on the method and intensity of harvesting. They can be negligible when only parts of the frond are removed, leaving the meristematic tissue for regrowth (Levitt *et al*. 2002; Borras-Chávez, Edwards and Vásquez 2012). However, when whole kelp are removed, kelp harvesting can lead to altered population dynamics and, in extreme cases, loss of the entire kelp forest (Gouraguine *et al*. 2021). The establishment of effective management plans may, however, make wild kelp harvesting more sustainable (Norderhaug *et al*. 2021).

Box 3.1. Historical and contemporary uses of kelp

Some of the earliest evidence of human's use of kelp comes from the archaeological site of Monte Verde in southern Chile, dating back around 12,500 years (Dillehay *et al*. 2008). The findings indicate that the inhabitants travelled to distant beaches to collect seaweed, which they used for food and medicine. Another historical example comes from the blades of *Durvillaea* that Māori people in New Zealand collected to make *pōhā* – bags to hold preserved meat of mutton birds (Wassilieff 2006). Pacific Native Americans used the same kelp species to make ropes and baskets, and used their bulbs and stipes for storing fish, sharks, seals, whale oils, syrups and liquors. Contemporary uses of kelp have increased rapidly, with the main source of raw materials coming from cultivation (see special chapter on the *Global state of kelp farming and brief overview of environmental impacts*). Many of these contemporary uses are based on research into the chemical content of different kelp species, as well as the development of new methods for processing the substances into a variety of end products, from dried tissue to target compounds, and in different applications and sectors, from agriculture to pharmaceutical products. Some indicative examples of the different uses and products that derive from kelp are provided below.

From agriculture to aquaculture. Kelp can be hard to digest for many species, except for ruminants. Research suggests that adding kelp to their fodder may improve their meat and increase their milk production. Kelp additives may also reduce ruminants' emissions of methane, which is a severe climate issue related to meat production. Extracts from kelp, such as the antioxidants fucoidan and laminarin, may also be used to produce functional fodder to improve livestock health. Kelp also serve as a key part of the natural diet of abalone and are therefore used as feed in the cultivation of these commercially valuable shellfish, which are overharvested in many wild populations. Kelp can replace less sustainable ingredients in aquaculture feed, thereby reducing the need for imports of protein-rich feed such as soybean and fish meal.

Biochemicals as raw materials. During World War I, the Californian kelp industry manufactured huge amounts of iodine, potassium chloride for gunpowder, kelpchar (a deodorizing charcoal carbon) and alginates to seal grenades and for wound dressing. Many primary metabolites from kelp are capitalized on in international markets, including carrageenan, alginate and agar. For instance, alginate is used in over 600 pharmaceutical, food and industrial products, serving as an additive in common food products, such as stabilizer in ice-cream and margarine, as thickener in sauces, as preservative against rancidity and bacterial contamination of fish and meat, and to enhance the chewiness of hard and leathery food such as rings of squid and pota (Pérez-Lloréns *et al*. 2018). Alginate is also used in different membranes, water purification, sealing of cans and castings, and in textiles, i.e. as a flame retardant. Algal polysaccharides can be combined with other materials to produce packaging and plastic replacements.

Food. The most profitable kelp markets are centred on food, food-related products and feed. Throughout East Asia, seaweed, including kelp, form part of traditional diets. In Korea, Japan and China, kelp are harvested as "sea vegetables" (*Laminaria* and *Undaria*). Kombu (*Saccharina* spp.) is used to prepare dashi, an ancient Japanese stock with an umami taste that serves as a base ingredient in other dishes. Asian ways of using kelp have recently become popular in other parts of the world, and edible kelp species are often used as supplements to high-end food products in western countries rather than being the main ingredient in a dish.

Fuel and bioenergy. Kelp are considered a resource for biofuels because of their naturally abundant biomass along coastlines, their high polysaccharide content, and the reduced need for terrestrial and freshwater resources for their cultivation. The conversion of kelp biomass to ethanol (a component of biofuel) also produces high yield but may require the production of extracts or use of bacterial genes to aid hydrolysing alginic acid and laminarin and the use of mannitol as substrates for fermentation (reviewed in Adams 2016). In line with the European Green Deal and the Recovery Plan for Europe, the European Commission is currently financing various projects focusing on seaweed biofuel production in the North Sea. There are *optimal* environmental conditions for maximum production of primary metabolites in different kelp species and there is huge potential for macroalgae to contribute to a circular bioeconomy.

Pharmaceuticals, health products and cosmetics. Kelp species have been widely used in traditional medicine. In China, decoctions of *Laminaria* and *Saccharina* were used over 2,000 years ago to treat diseases such as gout, tumours, oedemas and inflammations, and as aphrodisiacs. Kelp have high mineral content, contain important vitamins and can be used for a large variety of dietary supplements and natural medicine products. For instance, an extract of oarweed (*L. digitata*) has been clinically approved in Europe as an appetite suppressant to help people lose weight. Kelp are widely used in therapies that aim to restore the body's chemical balance for people suffering from rheumatism, osteoporosis and psoriasis (Pérez-Lloréns *et al*. 2018). Kelp products are also used in cosmetics, such as body lotions, soap, hair care and bath products.

5. Coastal defence

Kelp forests, like other coastal vegetated habitats, may offer biogenic coastal defence. For example, kelp forests alter water motion and can thereby buffer storm surges through wave damping and attenuation and by reducing the velocity of breaking waves (Løvås and Tørum 2001). In doing so, these forests can reduce coastal erosion and the movement of sand and pebbles from adjacent beaches (Mork 1996b; Løvås and Tørum 2001). However, compared to structurally rigid coastal habitat-forming species such as mangrove trees and hard corals, there is less knowledge regarding how much storm protection kelp forests offer. The magnitude of wave damping will be affected by the kelp morphology, size, density, spatial extent and drag coefficient, as well as local coastal geomorphology, depth and ocean physics (Gaylord *et al*. 2007), meaning wave damping will vary between regions. Moreover, flow attenuation may also be modified by the understorey assemblages (Eckman, Duggins and Sewell 1989).

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Few studies have quantified or modelled the influence of kelp forest on wave dynamics, but in Norway, it has been suggested that *L. hyperborea* reduce wave heights by up to 60 per cent (Mork 1996a). However, *E. radiata* forests in Australia (Morris *et al*. 2020) and *M. pyrifera* forests in California (Elwany *et al*. 1995) appeared to have little effect on wave damping. Smaller-scale laboratory experiments have demonstrated wave-attenuating effects of kelp forests, although the magnitude of such effects is modified by vegetation and wave characteristics, as well as the degree of submergence (Elwany *et al*. 1995). Given that increased storminess and sea level rise related to climate change will increase the need for coastal protection in many regions, a deeper understanding of the influence of kelp forests on wave dynamics is needed to assess their importance as biogenic coastal defence.

Kelp may provide coastal protection if they are integrated into coastal infrastructure by being directly grown on concrete and other hard engineered structures. These structures can provide coastal defence as well as numerous co-benefits through some of the aforementioned services. Seaweed- and kelp-associated green-grey infrastructure can range from planting kelp forests on artificial reefs in order to enhance fisheries and improve water clarity (Eger *et al*. 2021), to seeding sea walls, piers or pilings with seaweed in order to enhance carbon and nutrient uptake (Heery *et al*. 2020). There have been proposals to i) incorporate seaweed farms into coastal protection strategies due to their capacity to attenuate waves (Zhu *et al*. 2020) and ii) grow kelp on offshore wind farms to create multifunctional infrastructure that produces clean energy and provides habitat for fish and other species. Growing seaweed on some engineered structures may also increase the lifespan of these structures, although success depends on the materials used and surrounding environmental conditions (Kuwae and Crooks 2021).

Kelp may also have an important role to play in green-grey infrastructure, which combines the protection from grey infrastructure (engineered and physical structures such as sea walls, dams, dykes, pipes and gutters) with environmental services and co-benefits from green infrastructure (nature-based physical structures created by natural vegetation, habitats and ecosystems). Organisms that live on rocky reefs, such as kelp, can integrate into coastal green-grey infrastructure by directly attaching to concrete and other hard engineered structures. Globally, the capital investment in infrastructure is approximately $2.3 trillion per year and rising. One estimate suggests that $94 trillion of capital investment will be required by 2040 for both new and replacement infrastructure (Global Infrastructure Outlook 2017; Thacker *et al*. 2019). A large range of financing options are available for coastal infrastructure projects that can deliver both climate change resilience and sustainable development, including blue bonds, adaptation finance and voluntary blue carbon credits (Thacker *et al*. 2019). Yet, these tools would need to be tailored for kelp forests before they could be implemented (Kuwae and Crooks 2021, Kuwae *et al*. 2022).

6. Alleviation of ocean acidification

At local scales, ocean acidification may be mitigated through the photosynthetic activity of submerged macrophytes, which absorb CO_2 and increase the pH levels of surrounding waters (Hurd 2015; Gattuso *et al*. 2018). As this elevated pH effect may extend to waters above and away from submerged vegetation (Krause-Jensen *et al*. 2015; Krause-Jensen *et al*. 2016), kelp may, like other seaweed, provide local refugia from ocean acidification (Hurd 2015; Gattuso *et al*. 2018). However, empirical evidence to support refugia from ocean acidification is lacking for most kelp forests. Recent work on *Macrocystis* forests in California found limited support for ameliorating against acidification, apart from within a narrow band of surface water (Hirsh *et al*. 2020). However, measurements taken within and around seaweed farms in China showed that pH was significantly higher in waters surrounding farmed seaweed (Xiao *et al*. 2021). Clearly, further research is needed to understand the influence of kelp on local biogeochemistry, and particularly whether kelp forests can offer refugia from ocean acidification.

7. Recreation and tourism

Recreation and tourism around kelp forests are important in temperate coastal regions with large human populations. However, despite millions of people having access to the coast, many can find kelp forests intimidating. For example, the reverence that many feel for kelp forests may be related to their large dark shapes and how canopies obscure what lies beneath. In addition, kelp forests typically grow in cold water that is often exposed to large swells, currents and tides (Steneck *et al*. 2002), making these forests relatively inaccessible habitats for most people. Recreational and tourism activities related to kelp forests range from direct interactions with kelp, such as snorkelling and diving, to indirect activities such as fishing, boating, swimming, surfing and various land-based activities where surrounding kelp forests provide context. Although there are relatively few systematic studies on recreational use and tourism in kelp forests, these activities are important for many cultures and peoples.

Recreational fishing is a pastime for millions of people around kelp forests and contributes to the ecotourism sector. Recreational fishing is worth millions of dollars to local and state economies each year in the form of expenditure on licences, gear, transport and accommodation. For example, in South Africa, Blamey and Bolton (2018) estimate that $83.68 million per year is generated from the sale of permits for collecting West Coast rock lobster and by the recreational line fishery. An unknown proportion of these lobsters are located within kelp forests, but the values reported in Blamey and Bolton (2018) are likely to represent temperate reefs more generally. Scuba- and free-diving represent major sociocultural values of kelp forests (including organized tours managed by recreational dive companies and ad hoc groups of individuals) for scenic enjoyment, photographic opportunities and recreational fishing. Scuba-diving is arguably the most direct interaction people have with kelp forests.

In Australia, almost 70 per cent of the population live within

50 km of a kelp forest, and millions of Australians directly and indirectly engage with kelp forests for recreation and tourism. Here, diving tourism contributes around AUD 1.25 billion per year in states adjacent to the Great Southern Reef, where most kelp diving takes place (Beaver and Keily 2015). In South Africa, Blamey and Bolton (2018) estimate ecotourism associated with the kelp-dominated coastline of the Western Cape to be around $113 million per year, although this value does not apportion revenue that is directly attributable to kelp forests, such as diving with cow sharks or foraging for kelp. Similarly, in Chile kelp-associated activities, including underwater guided trails, are also supported and have demonstrated educational values (Vásquez *et al*. 2014). Furthermore, re-created kelp forests can be a major feature in public aquaria, including the Two Ocean Aquarium in Cape Town, South Africa, and the Monterey Aquarium in California, United States of America. At the Two Oceans Aquarium, for example, visitors can pay to dive in the kelp display (Mark Rothmann, pers. comm).

However, kelp forests can also provide recreational "disservices" for some users. For example, some surfers blame kelp for interfering with waves, while rotting beach-cast kelp wrack can be an unsightly nuisance that attracts sand flies and smells. Millions of dollars are therefore spent annually on removing kelp wrack from popular beaches. Kelp removal from beaches offers opportunities to employ kelp collectors, who seal the kelp in plastic bags and take it to landfill, sometimes causing conflict between governmental agencies and local residents concerned that kelp removal might accelerate beach erosion.

8. Cultural value and supporting identities

Kelp forests are visible structural components of coastal ecosystems that create an important sense of place and have cultural value for many people. Oral histories and archaeological evidence suggest that the relationship between humans and kelp dates back millennia (Hafting *et al*. 2015; Buschmann *et al*. 2017; Erlandson *et al*. 2007). Some human histories are closely related to kelp, through the use of the kelp ecosystem as a source of food, as evidenced by the abalone shells found in caves throughout South Africa associated with the rise of modern humans (e.g. Blombos Cave, South Africa, Henshilwood *et al*. 2011). Indeed, access to the marine food web, including seafood gathered around kelp forests, has been postulated to have triggered the exponential growth of the human brain and increased cognitive capacity (Compton 2011; Duarte 2014). Elsewhere, kelp has been used as medicine, food and materials (e.g. fishing line, canoe construction) in South America for 14,000 years (Dillehay *et al*. 2008) and among Aboriginal Australians for perhaps up to 65,000 years (Thurstan *et al*. 2018). Studies also support the notion that kelp directly or indirectly influenced people's migration routes from Asia to the Americas in the late-Pleistocene (Erlandson *et al*. 2007), known as the "kelp highway hypothesis". Furthermore, people in South Africa collected intertidal organisms near the kelp forests during the mid-Holocene (Jerardino 2021), which may have contributed to prehistoric economies (Compton 2011; De Vynck *et al*. 2016).

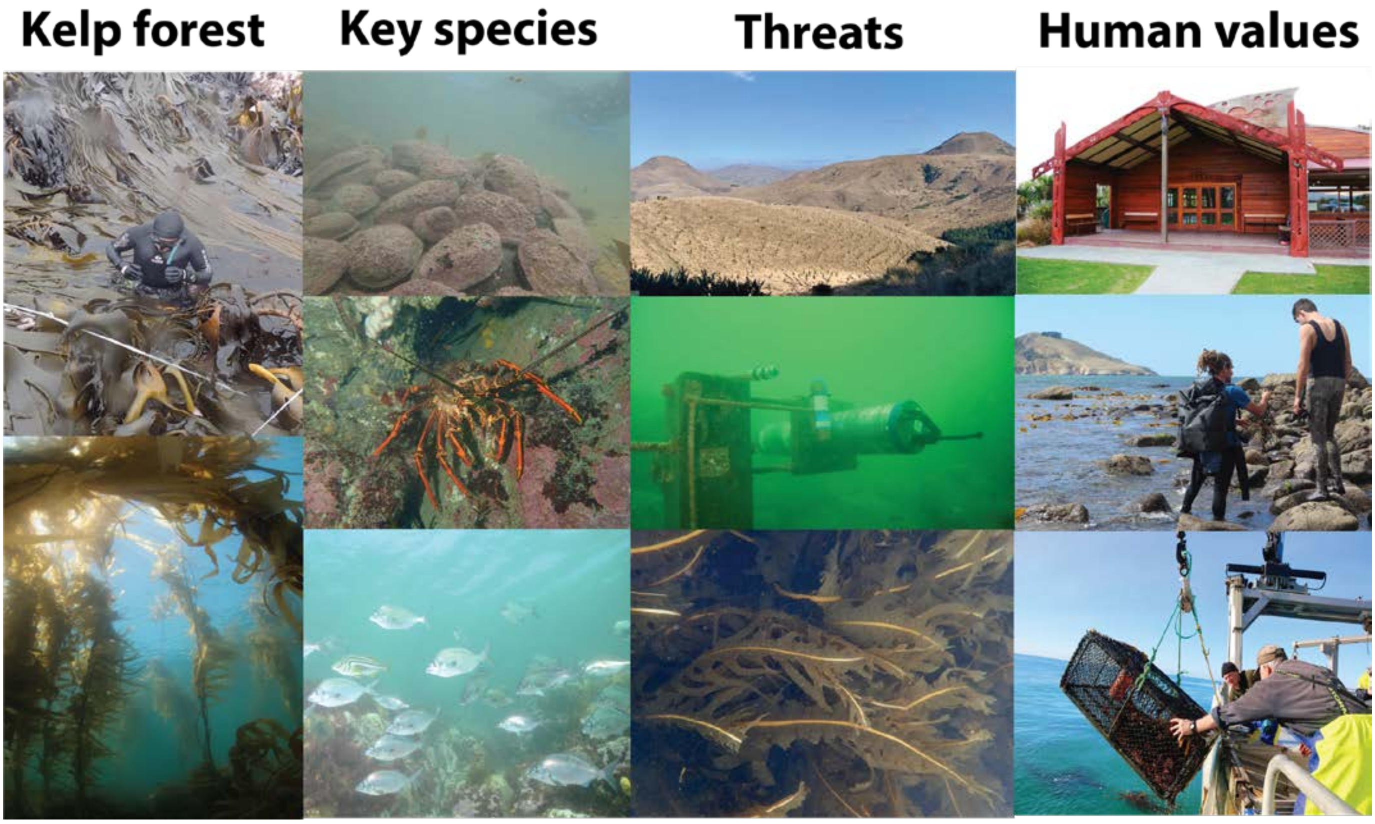
Today, kelp forests support the identities of many coastal peoples around the world, allowing humans to develop a sense of place and connectedness with nature. This connection can take the form of a practical relationship such as a livelihood, for example among the Pacific North-West Haida tribe who harvest giant kelp blades covered with herring spawn and among the abalone fishermen who dive along Australia's Great Southern Reef (Mac Monagail *et al*. 2017; Bennett *et al*. 2016). Connectedness can also be linked to seascape attributes, such as kelp canopies stretching along the water surface of California and Oregon's iconic coastlines. The cultural value of kelp forests is demonstrated by kelp's use in traditional knowledge systems, art, ceremonies, medicines and protocols by numerous indigenous communities and the popularity of various pursuits in these habitats (Figure 3.3).

Harvesting and gathering of kelp are often intrinsically linked to the cultural identity of coastal communities (Mac Monagail *et al*. 2017). However, in some regions, there are growing tensions between expanding commercial kelp harvest, and traditional smaller-scale collections of cultural significance (Mac Monagail *et al*. 2017). Furthermore, the establishment of no-take marine reserves and growing allocations of areas of wild seaweed to commercial seaweed industries may conflict with the practices and values of indigenous and coastal peoples (Bennett *et al*. 2018).

Figure 3.3. Kelp in Inuit art

Notes: 1. Seaweed (translated title), Cee Pootoogook, Cape Dorset, 2016; 2. Keeper of the kelp, Mary Pudlat, Cape Dorset, 2001; 3. Gathering kelp, Kananginak Pootoogook, Cape Dorset, 1986 (a Canadian indigenous family harvesting kelp). Dorset Fine Arts (www.dorsetfinearts.com), reproduced from the Kananginak Pootoogook image: 'Gathering Kelp' (Mac Monagail *et al*. 2017); 4. Untitled (humpback, belugas and inuk), Qavavau Manumie; 5. Kelp garden, Cee Pootoogook, Cape Dorset, 2018; 6. The kelp collector, Qavavau Manumie, Cape Dorset, 2005.

Figure 3.4. Values and threats to kelp forests in the cultural landscape of Kāti Huirapa ki Puketeraki hapū from Te Waipounamu (South Island), New Zealand



Notes: Kelp forest: (Top) *Durvillaea* spp. (Bottom) *M. pyrifera*. Key species: (Top) Cultural keystone pāua (abalone), (Mid) Kōura (Rock lobster), (Bottom) Reef fish associated with kelp forest habitats. Threats: (Top) Recent planting of exotic forestry species in coastal catchments, (Mid) Globally driven climate change and heatwaves detected by a mooring in a local kelp forest, (Bottom) *U. pinnatifida*, an invasive kelp. Human values: (Top) Carvings on Puketeraki Marae (meeting house) include pāua (abalone) and other marine species sustained by energy derived from kelp forests, (Middle) Kelp forests are living classrooms, broadly supporting education and research, (Bottom) High-value fisheries for rock lobster are supported by kelp forest habitats. Photo credits: Chris Hepburn, Suzi Flack, Lucy Coyle, Louise Bennett-Jones.

Figure 3.5. Location of case studies on the cultural value of kelp forests

1 North-East Pacific 2 Canadian Arctic 3 Great Southern Reef 4 New Zealand
5 Great African Seaforest 6 Japan 7 North Atlantic 8 Chile

Case study 1

North-East Pacific

The kelp *Egregia* (y̓ák̓a) has a cultural use among First Nations peoples along the coasts of Canada and Alaska. *Egregia* is important in ceremonies, trading and gift-giving practices. Its harvest is managed through ancestral laws and practices (Ĝvi̓ḷás) and its management is connected to traditional indigenous knowledge systems (Kobluk *et al*. 2021). In coastal Alaska, the dAXunhyuu people place kelp at the centre of cultural revitalization, using and revitalizing traditional knowledge of bull kelp (*Nereocystis*) and sugar kelp (*Laminaria*) to reclaim food sovereignty.

> “Our future depends on the healthy ecosystems of kelp which mitigates climate change and provides food sovereignty for the Salmon Nations of the Pacific. Native Conservancy is returning to our traditional ecological knowledge and relationship to kelp in these rich ocean waters of Eyak-Cordova.” Evelyn Arce Erickson, Vice-President at Native Conservancy.

Case study 2

Canadian Arctic

For the Inuit of Nunavik, kelp are defined as part of the "Tininnimiutait" (meaning "the ones that belong on the shore"). This group of organisms, like "Irqamiutait" or "Timmiat" (meaning "those that belong to the bottom of the sea" and "those that fly") are spiritually linked through the "Uumajuit" to their equivalent belonging in the spiritual order (Rapinski *et al*. 2018). Kelp also feature in legends and myths (e.g. Arnaluk, the giantess; Sedna, goddess of the sea and marine animals). Many Inuit communities from northern Alaska to Greenland use kelp as traditional medicine and food (Kuhnleini and Soueida 1992; Andersen 2005; Black, Arnason and Cuerrier 2008; Clark 2013). In addition to having nutritional value, traditional Inuit food that is hunted or gathered from the land has cultural and spiritual significance, contributing to well-being and keeping the mind and body healthy (Searles 2002).

> "You truthfully can't separate the way we get our food from the way we live. How we get our food is intrinsic to our culture. It's how we pass on our values and knowledge to the young. When you go out with your aunts and uncles to hunt or to gather, you learn to smell the air, watch the wind, understand the way the ice moves, and know the land. You get to know where to pick which plant and what animal to take. It's part, too, of your development as a person. You share food with your community. You show respect to your elders by offering them the first catch. You give thanks to the animal that gave up its life for your sustenance. So, you get all the physical activity of harvesting your own food, all the social activity of sharing and preparing it, and all the spiritual aspects as well." Patricia Cochran, Inupiat of Alaska (Gadsby and Steele 2004).

Case study 3

Great Southern Reef

In Australia, kelp forests span over 8,000 km of coastline around the southern half of the continent, in what is collectively known as the Great Southern Reef. For the past 65,000 years, kelp forests have played an important role for Aboriginal peoples across the southern half of the continent, where an estimated 46 indigenous nations border the Great Southern Reef. The diversity of seaweed species and the diversity of indigenous cultures across temperate Australia meant that seaweed had an important range of traditional uses and cultural practices. Much traditional knowledge has been lost, yet some uses have been recorded related to ceremonial activities, medicine, clothing, diet/cooking, fishing and shelter/domestic use (Thurstan *et al*. 2018). In Tasmania, for example, Aboriginal women used kelp to help them dive and catch crayfish. Tasmanian Aboriginals also used the thick leathery fronds of *Durvillea potatorum* to make water carriers, baskets and shoes (Thurstan *et al*. 2018). In contemporary Australia, kelp forests form a tacit part of the environment and coastal experience for millions of Australians who have a direct or indirect association with kelp forests through recreation, leisure and/or enterprise. Approximately 17 million people (70 per cent of Australia's population) live along the Great Southern Reef, spanning several major cities (including Sydney and Melbourne) and remote regional towns (Bennett *et al*. 2016).

Case study 4

New Zealand

> "Many of our kai Māori (indigenous foods) are either extinct or on the endangered list and are off the menu – pāua (abalone) and kōura (lobster) will go the same way as the birds, if we lose the kelp like we lost the ngāhere (native forests)."

In New Zealand, in the south-eastern part of Te Waipounamu (South Island), rimurapa (*Durvillaea* spp., Southern bull kelp) and the giant kelp *M. pyrifera* form productive kelp forests that extend from the low watermark to offshore beds up to 30 m deep in wave-exposed locations. Kelp forests provide key values in terms of local indigenous culture, economy, food security and resilience. These values are encapsulated within the cultural landscape of Kāti Huirapa ki Puketeraki hapū (Kāti Huirapa), a subtribe of a southern iwi (tribe) Ngāi Tahu. Historically, kelp forests provided a central role in the establishment and success of coastal settlements in a challenging environment for the tīpuna (ancestors) of Kāti Huirapa (Prebble and Mules 2004). Kelp forests today are critical in both maintaining kaitiakitanga (inherited spiritual and physical stewardship), manaakitanga (uplifting prestige through hospitality), rakatirataka (inherited leadership) and coastal economies in the region (Jackson, Hepburn and Flack 2018; Hepburn *et al*. 2019).

The habitat and energy provided by kelp forests support many species in coastal fisheries, including a cultural keystone, pāua (abalone, *Haliotis iris*). *M. pyrifera* canopies facilitate the local settlement of larval kōura (*Jasus edwardsii*). Without access to abundant numbers of these species, tāngata whenua (indigenous people) will lose connection to their tīpuna (ancestors). In many areas of New Zealand, mahika kai (food and resource gathering) are some of the few activities where modern Māori can engage in the natural world as their ancestors did (Phillips, Jackson and Hakopa 2016). Both kōura and pāua support local and national economies; kōura is New Zealand's largest fishery export earner and pāua the ninth largest.

Case study 5

Great African Seaforest

The Great African Seaforest stretches from the shores of Cape Town to 1,000 km north, into Namibia. While history suggests that the connection between humans on the coast of South Africa and resources from kelp forests dates back 70,000 years, today much of the historical, traditional and indigenous knowledge surrounding kelp in South Africa seems to have been lost. In recent interviews with kelp harvesters and coastal community members, only a few respondents held aspects of kelp knowledge. Those who did talked about kelp's use in "potjies" (a South African stew slow-cooked over an open flame in a cast iron three-legged pot), as a direct and natural fertilizer for marijuana and other indigenous plants, and its medicinal properties of high iodine levels that were harnessed through salves and creams. Some told anecdotes about how they had used kelp in the ocean itself, for example as an "anchor" to hold onto during strong currents, and as an oasis from predatory sharks to hide within while diving for fish (Akshata Mehta pers. comm. 2022).

Today the relational values towards kelp are especially high across their various users (including harvesters, coastal community members, government, and management officials). Kelp forests bring about a sense of place for many. Not only were relational values brought to light through qualitative responses such as, "Kelp is important and should be valued and protected as a critical and beautiful environment" or "Kelp is important to me because conserving and caring for nature is important to me," but also through actors' frequent indications that kelp "plays a role in community life" and/or "contributes to lifestyle," indicating high levels of appreciation for the social and cultural contributions of South African kelp forests. Users also report a sense of calm that is associated with observing kelp in the ocean or being immersed among kelp. Interviews with recreational free drivers who swim in the kelp forest report reduced stress and anxiety and a range of physical and mental benefits, including a profound connection to nature. Today the use of kelp in South Africa is mainly beach-cast collections, which are used for abalone feed and the production of plant-growth stimulants and soil conditioners.

The atmosphere of the Great African Seaforest is captured in the 2020 film 'My Octopus Teacher' produced by filmmaker Craig Foster, founder of the Sea Change Project. It is a visually stunning documentary about the filmmaker's journey of self-discovery and learning with a female octopus living in the kelp forest off Western Cape, South Africa. This film can be used as a learning tool for post-humanist thinking, as it introduces the concepts of humanism, anthropocentrism and post-humanism philosophy by decentring humans from the world and challenging the assumption of human exceptionalism and separation from other life forms by exploring other ways of knowing, knowledge and being (Ross 2021). These sentiments are echoed by kelp users in South Africa, encapsulated in one recreational user's response: "There is nothing like the joy of floating through a golden forest" (Akshata Mehta pers. comm. 2022).

Case study 6

Japan

In Japan, kelp plays an important role ecologically, socioeconomically, historically and culturally. Key species include kombu (*Saccharina* spp.) and wakame (*U. pinnatifida*[1]). Kombu forests are most common in the cold coastal waters of Hokkaido, the northernmost part of Japan, whereas wakame forests are distributed across Japan, except for Okinawa and southern Kyushu to the Pacific coast of Honshu and eastern Hokkaido. *Eisenia* and *Ecklonia* kelp also constitute underwater forests along the coast of Honshu to Kyushu (Terada *et al*. 2021).

The social importance of kelp forests relates to their traditional dietary use and their role in fishing culture. The dietary use of kombu and wakame is widespread throughout Japan, including in inland areas. While kombu is mainly produced in Hokkaido and the northernmost part of Japan, its dietary use has spread to Osaka, Toyama and the southernmost prefecture of Okinawa. This is because, during the Edo period (1603–1867), kombu was transported by sea from Hokkaido to the coast of the Sea of Japan and to Kyushu and Okinawa on Kitamae-bune cargo ships (Fukutome 2018). It is likely that the use of kelp in the Japanese food culture of Kyoto and the process of trade with China via Okinawa led to its use in local cuisine. Today, kelp, along with bonito flakes, remain an important ingredient for dashi (soup stock), making it a key ingredient in Japanese food culture. The glutamic acid, aspartic acid, alanine and other components in the kombu mix combine with the inosinic acid in bonito flakes to produce strong flavours. Japanese food was registered as a UNESCO Intangible Cultural Heritage in 2013 under the title "Japanese Food: Traditional Food Culture of the Japanese People" as a "custom" related to food based on the Japanese temperament of "respecting nature".

Wakame and kombu are an inseparable part of Japan's food culture, but their natural abundance has been decreasing. Due to poor harvesting conditions in Japan and imports of low-priced seaweed from China and the Republic of Korea, most of the wakame (80 per cent) and kombu (90 per cent) sold in Japan are now imported from aquaculture products cultivated abroad.

Japan's kelp forests are also culturally important for fishing. In Japan and Korea, women *ama* ("sea women") divers collect kelp and catch associated fish and shellfish (Schwerdtner-Máñez and Pauwelussen 2016). The origin of the *ama* may go back over 3,000 years, and there are still around 2,000 active *amas* in Japan. There are also *ama* divers in Korea who harvest *Eisenia* and other seaweed species, as well as abalone, shells and sea urchins while managing the resource sustainably. These divers have become a regional tourist attraction, offering tours showing divers catching shells and subsequently cooking and serving the catch in their huts.

In Japan, seaweed are used in prayers for seaweed propagation and fruitful fishing at several festivals, particularly in the western regions, such as Fukuoka, Yamaguchi and Shimane Prefectures. This ritual has traditionally taken place in regions where *ama* divers operate. Specifically, wakame is collected and offered to the gods and after the festival, it is customary to lift the ban on wakame harvesting.

1 This species of seaweed, which is native to Japan and other East Asian countries, has recently spread to various parts of the world and is considered one of the world's worst invasive species (Epstein and Smale 2017).

Case study 7

North Atlantic

Many fishing communities in the North Atlantic (Canadian Maritimes, Norway, Ireland, UK and Scotland) used kelp detritus collected from beaches or cut with rakes as fertilizer, food and materials, especially where soil and other land-based resources were limited. Kelp gathering was traditionally carried out by multiple family members and processed at home. It was rarely the main source of family income, instead providing an alternative to fishing during poor conditions and periods of over-exploitation (Rebours *et al*. 2014). Seaweed were considered a reliable resource that helped communities through times of economic hardship and lack of work.

"The seaweeds have to be there, if the children return home." Donal Hickey, director of a seaweed factory in Connemara, Ireland (Mouritsen 2013). Today, seaweed harvest still offers important part-time employment for fishermen during the off season in some regions (e.g. during months when the lobster season is closed in Nova Scotia) (Rebours *et al*. 2014).

Case study 8

Chile

In South America, the Mapuche – especially those living in the Lafken Mapu area of La Araucanía (800 km south of Santiago, the capital of Chile) – use cochayuyo as part of their culinary tradition in the preparation of stews, casseroles, pies, soups, salads and jams. Cochayuyo or cochahuasca are names for *D. incurvata* (30–43° S) and *D. antarctica* (43°–56° S). The word cochayuyo is of Quechua origin and means "sea vegetable"; it comes from kocha, which means "lagoon or sea" and "yuyu", which means vegetable. This brown seaweed species was an important food resource for indigenous Mapuche communities before the Spanish conquest in the fifteenth century.

Even though the Chilean Government introduced a policy that gives organized groups of artisanal fishers formal property rights over defined areas of seabed, with the goal of achieving sustainable exploitation of natural resources, *Durvillaea* continues to be traditionally managed, where small sectors of the exposed rocky coast are passed on from generation to generation. The Lafkenche, the Mapuche of the sea, scour the rocky cliffs to collect seaweed as their ancestors did: clearing the rocks of eventual competitors of small *Durvillaea* recruits, thinning the population, allowing the whiplash of juvenile kelp that are not yet suitable for harvesting to decrease the grazing of local herbivores (urchins and keyhole limpets), and leaving individuals of a deep brown colour, which contain the most reproductive structures but are not sold or consumed because of their appearance, thereby ensuring that harvested stocks are replaced.

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Special chapter. The global state of kelp farming and a brief overview of environmental impacts

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Kelp and seaweed farming are among the fastest growing aquaculture industries globally, with an annual increase of 6.2 per cent averaged over the last two decades (2000–2018; FAO 2020; Duarte, Bruhn and Krause-Jensen 2021). Seaweed farming supplies a growing global population with resources for food, feed, cosmetics, pharmaceuticals and biofuel (Vincent, Stanley and Ring 2020), and has recently been identified as a potential nature-based solution for climate mitigation, resulting in increased global attention for the practice. In Asia, seaweed farming has been an important coastal industry for centuries (Duarte *et al*. 2017; Duarte *et al*. 2021). Although the practice has been documented as providing positive ecosystem services, including carbon sequestration, water purification and primary production, some of these benefits have not been clearly demonstrated (Troell *et al*. 2022), and the practice may also have potentially negative impacts on coastal ecosystems (Campbell *et al*. 2019; Hancke *et al*. 2021), as discussed in the following section.

Globally, more than 31.8 million tons of seaweed (fresh weight) were cultivated in 2018, with a market price of $400 per ton of dry weight and a total value of more than $11.3 billion (FAO 2020). More than 99 per cent of global seaweed and kelp production occurs in Asia, with China, Indonesia and the Republic of Korea producing 55 per cent, 32 per cent and 8 per cent of the global market, respectively. The two most cultivated kelp species globally are *S. japonica* (kombu) *U. pinnatifida* (wakame). *S. japonica* is cultivated in China, the Democratic People's Republic of Korea, Japan, the Republic of Korea and Spain, and represents 29 per cent of global seaweed aquaculture production. *U. pinnatifida* is cultivated in China, Japan and the Republic of Korea, and represents 9 per cent of global aquaculture production (Buschmann *et al*. 2017). Despite relatively low seaweed and kelp cultivation in Europe and North America (around 20,000 tons per year), the industry receives intensive attention and is fast-growing. *S. latissima* and *Alaria* spp. are the main kelp species in this region, but other species (e.g. *M. pyrifera*) are also tested for cultivation (Camus, Infante and Buschmann 2018; Araújo *et al*. 2021). The global area occupied by seaweed farming is not officially documented but is estimated to be around 2,000 km^2 (Duarte *et al*. 2021), which corresponds to 0.04 per cent of the global area covered by wild seaweed species.


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Modern kelp cultivation was developed in the 1950s–1970s in East Asia (Hwang *et al*. 2019), the same basic principles of which are still applied in Europe and North America. The process usually involves seedling production in land-based systems or under laboratory-like conditions, with kelp grown to a harvestable size in long rows and held to the surface by buoys in coastal waters. Farming in this manner means that kelp individuals benefit from natural light and coastal water nutrients, and thus requires relatively low operational and energy costs. In Asia, advanced genetic techniques (artificial selection or hybridizations) are used to produce seedlings, which seaweed farmers then purchase from breeders or breeding companies. As a result, farmed kelp have highly different genetics than wild kelp that grow on natural reefs in Asia. This differs in Europe and other regions, where the industry is restricted to use spores from local kelp strains for cultivation purposes to avoid the genetic pollution of wild kelp populations.

Harvesting kelp and seaweed for food, feed and other low-value products is a well-established practice, and there is growing industry ambition to increase its production for high-value products (e.g. cosmetics and pharmaceuticals) that would boost the kelp farming industry's value chain. There is also a potential valuable future market for kelp and seaweed to be used as bioplastic and decomposable materials in the food and distribution industry (Buschmann *et al*. 2017; Duarte *et al*. 2017; chapters 3 and 6). At present, kelp cultivation facilities are based in coastal regions, often in bays, fjords and other environments protected from physical stress such as waves, strong winds and water currents. However, in most parts of the world, the competition for coastal region areas is high, with offshore kelp farming and its integration with offshore wind farms therefore proposed as measures to expand and increase global kelp production (Buschmann *et al*. 2017).

Despite the potential environmental benefits of kelp farming, such as an improved coastal water quality, a rapid expansion in kelp farming industries faces some risks. Proposed plans for offshore kelp farming would require new technology and infrastructure, as well as risk assessments of interactions with natural ecosystems (Campbell *et al*. 2019). Besides the risks, achieving productivity levels high enough to sustain commercial practices, the harvested biomass value and its potential demand require attention in the near future (e.g. Camus, Infante and Buschmann 2019).

A brief overview of the environmental impacts of kelp farming

Industrial seaweed and kelp farming has both positive and negative impacts on coastal ecosystems and also affects open-water (pelagic) and sea floor (benthic) ecosystems, with implications for natural flora and fauna, CO_2 uptake, oxygen availability and nutrient uptake and release (Campbell *et al*. 2019; Hancke *et al*. 2021). Kelp use sunlight as an energy source and absorb nutrients and CO_2 from the water, while releasing oxygen and exporting particulate and dissolved organic matter during growth. Seaweed and kelp cultivation are recognized as extractive species and therefore differ significantly from fish aquaculture, as no feed or other substances should be needed during production.

Positive environmental impacts include oxygen release to the water, CO_2 uptake and the stimulation of local biodiversity from increased primary production. Considerable amounts of particulate detritus are exported from kelp farms during growth (up to 60 per cent of the harvested biomass; Fieler *et al*. 2021), which can stimulate local production and biodiversity by serving as a food source for local food-limited systems. If not consumed by fauna or turned over by bacteria, a fraction of the total carbon (recalcitrant C) will be buried in sea floor sediments where it will be stored for a long period, thus contributing to carbon sequestration and climate mitigation (Duarte *et al*. 2017; Queirós *et al*. 2019). Nevertheless, these ideas have been challenged due to the need for information establishing how diverse seaweed farming systems and species capture carbon, how they transiently sequester it, and whether they could potentially permanently sequester it at a meaningful geological time scale (Troell *et al*. 2022). Also, nutrient uptake by kelp farms could potentially reduce marine eutrophication in regions that are struggling with a surplus of nutrients, which is the case for many coastal regions of the world's oceans (Xiao *et al*. 2017).

Many of the processes that have positive impacts may also negatively impact coastal ecosystems, depending on the location of the farm site, its physicochemical conditions and its initial state. Such negative impacts include reduced light availability to the water column and sea floor algae communities, a depletion of water column nutrients and a deposition of organic matter on the seafloor, which can lead to oxygen deficiency, a loss of sea floor fauna and reduced biodiversity (Hancke *et al*. 2021). As kelp cultivation expands, these effects could potentially reduce light and nutrient availability, lead to reduced primary production and increase competition for nutrients between cultivated and natural algae communities, which will in turn impact the system's carrying capacity (Campbell *et al*. 2019). The deposition of excess organic matter may lead to sea floor communities becoming organically enriched to an extent that creates local anaerobic conditions, stimulates toxic microbial releases of hydrogen sulfide and decreases species abundance and biodiversity. Given that kelp farms provide substrate (physical structures) and hideaways for a wide variety of species (Theuerkauf *et al*. 2022), they could potentially support the spread of alien and unwanted species, genetic material and diseases in coastal environments as has been reported recently in the south-eastern Pacific coast (Camus *et al*. 2022).

At small-scale kelp farms, such as those currently operating in Europe and North America, the magnitude of negative impacts is likely small, unlike in intensive Asian cultivation sites, where a comprehensive understanding of scale-dependent impacts is needed to ensure kelp cultivation remains sustainable. Adaptive management plans are also needed, especially since the global kelp farming industry is set to significantly expand (Campbell *et al*. 2019; Araújo *et al*. 2021; Hancke *et al*. 2021). At present, seaweed cultivation activities are regulated in the same way as shellfish farming, with limited explicit regulations existing on seaweed-related environmental impacts, including the sinking of seaweed in the deep ocean (e.g. Wood *et al*. 2017; Hancke *et al*. 2021).

One urgent challenge in ensuring the kelp industry's sustainability is the collection and conservation of natural kelp germplasm without genetic contamination, as knowledge about natural genetic kelp variability is limited (Barrento *et al*. 2016; Evankow *et al*. 2019). Genetic contamination between farmed seaweed species and local natural populations can occur if the farmed seaweed are from different origins, for example, non-native species or genetically distinct populations, or if farmed kelp have undergone artificial selection during aquaculture practices. Genetic contamination can cause a loss of genetic diversity among natural populations, which may possibly compromise their health, resilience and capacity to adapt to local environmental conditions (Hwang *et al*. 2019). It can also

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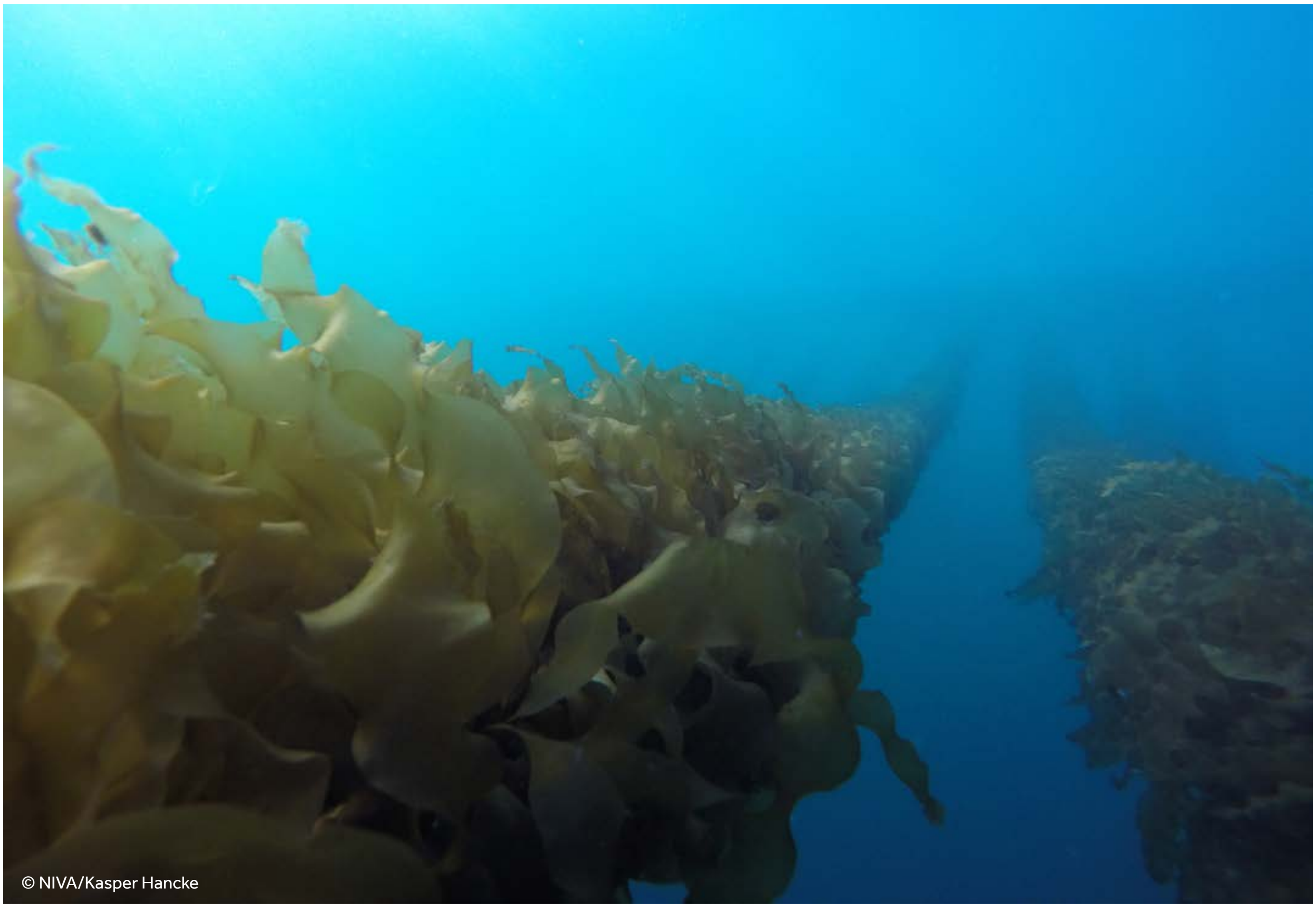

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have negative impacts on farmed kelp through the introduction of undesirable characteristics during commercial cultivation (see Box S.1). Using local natural kelp in local farming avoids genetic pollution from non-native farmed populations or from artificial selection during kelp aquaculture practices. Proper biosecurity protocols and regulations are globally required in this context for seaweed aquaculture, including kelp (Valero *et al*. 2017; Cottier-Cook *et al*. 2021).

Box S.1. Kelp aquaculture in China: germplasm conservation

Having first been brought into China from Japan and/or the Republic of Korea, the kelp species *S. japonica* and *U. pinnatifida* are now the backbone of China's seaweed industry. These species not only contribute significantly to the country's gross domestic product (yielding $4.79X10^3 million in 2017, i.e. around 0.04 per cent of gross domestic product; Hu *et al*. 2021) but also enhance water quality, in particular the biogeochemical cycling of carbon, nitrogen and phosphorus in coastal marine environments (Hu *et al*. 2021). According to estimates, kelp cultivated in China annually sequester around $3.3x10^5$ tons of carbon (since 2003), which accounts for around 82 per cent of the total carbon fixed by all cultivated seaweed (Cao *et al*. 2018).

Geographically, the cold-temperate *S. japonica* is naturally distributed in Hokkaido, north-eastern Honshu and the Siberian coast of the Sea of Japan. There is a long-term consensus that no native *S. japonica* occurs in northern China (Tseng 2001), with the Republic of Korean Peninsula's warm currents likely serving as a geographical barrier for its natural spread southward to China. In fact, farmed and natural populations of *S. japonica* in the Republic of Korea were also introduced from Japan (Hu *et al*. 2021). In comparison, natural *U. pinnatifida* populations are sparsely distributed in China, with southernmost distributions found in the Yushan archipelago in Zhejiang province. Kelp in natural habitats in northern China are currently not native, but are secondary derivatives from local cultivated populations, which were sourced in Japan and the Republic of Korea in the 1920s–1940s (Tseng 2001). Most of these kelp populations have survived and persisted in nature for decades, suggesting their long-term acclimation and adaptation to the local environment. If genetic erosion occurs on an ongoing basis due to the genetic transfer of farmed populations to natural populations, the accumulated beneficial fitness and adaptation capability of the latter may be compromised irreversibly. These genetically unique kelp populations in northern China therefore need to be collected off-site, conserved and exploited to breed cultivars suitable for local waters.

Fortunately for the natural *S. japonica* and *U. pinnatifida* populations in northern China, negligible genetic pollution has been found from currently farmed cultivars (Zhang *et al*. 2017; Shan *et al*. 2018, 2019; Li *et al*. 2020). This situation is mostly attributable to current farming and seedling production practices, particularly for *S. japonica*. Phycologists in China have pioneered a summer sporeling production system, in which farmed kelp populations mature during summer months each year (a trait resulting from recurrent artificial selection and which differs from natural populations) (Tseng 2001). This results in farmed kelp being mostly harvested before they have become reproductive. Zoospores released from parent kelp individuals that are maintained in deep waters until August can potentially reach nearby rocky substrate, but the derived gametophytes are unlikely to survive the high summer temperatures (usually higher than 27–28°C in northern China).

The flow of kelp genes from natural reefs to farmed populations is limited among *U. pinnatifida*, but relatively prominent among *S. japonica*. Nursery cultivations in the sea occur from sporophytes, but gametophytes tend to present on seedling strings, which means that if natural kelp settle on cultivation rows, they may hybridize with the farmed kelp or self-fertilize (Shan *et al*. 2019). Since genetic pollution between farmed and natural populations may negatively impact both natural and farmed kelp, accurate assessments of genetic structuring should become a routine part of kelp farming management. In addition, genome-scale comparative analyses between farmed and natural kelp populations (Köhler and Springer 2017) can potentially provide valuable insights into genome-assisted breeding, germplasm improvement and ecological resilience to environmental change, ultimately enabling the development of a sustainable kelp industry worldwide.

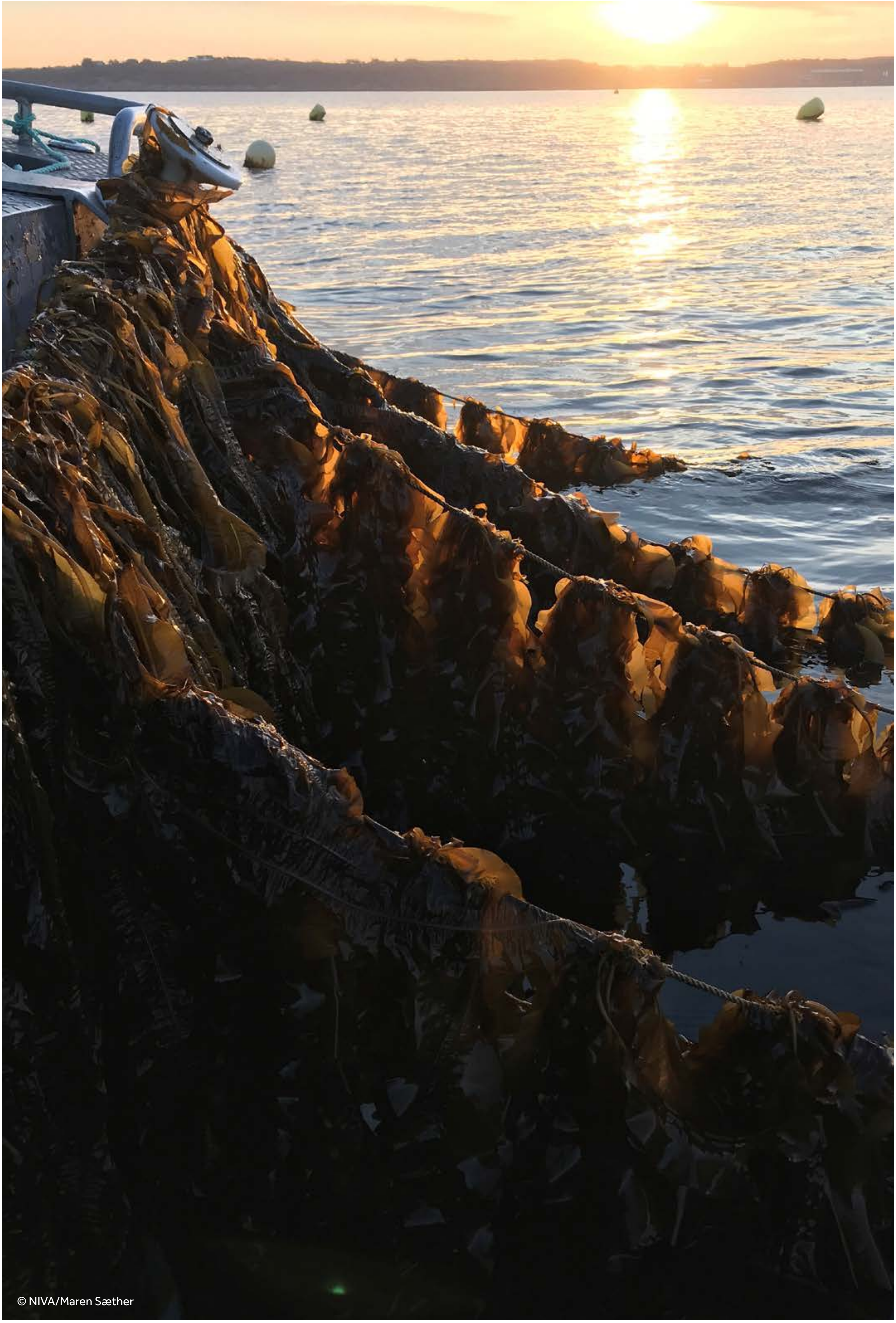
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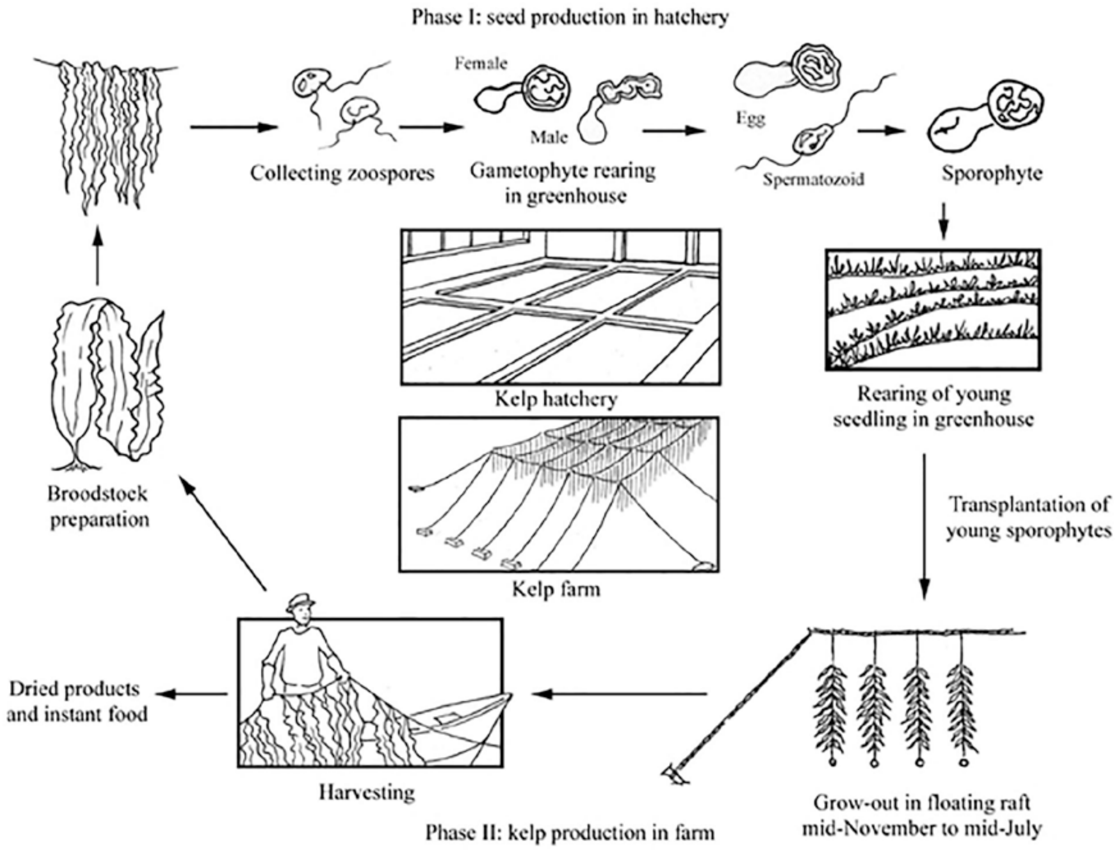
Figure S.1. Production cycle of Japanese Kelp (*Saccharina japonica*) in China



Source: FAO 2004

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PART 2

THE SOLUTIONS

Chapter 4. Economic perspectives on kelp management

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Highlights

- **Ecosystem services can help communicate the value that humans place on natural resources and are used to evaluate the benefits that they provide to humans.**
- **Economic tools, such as total economic value (TEV) or a cost-benefit analysis, can improve knowledge on the value of goods and services that kelp provide, though not the value of the ecosystem itself.**
- **Economic valuations can provide monetary values for ecosystem services, which can enable better policy design and the evaluation of trade-offs among various management options.**
- **Although existence values of kelp ecosystems cannot be easily monetized, they should be fully acknowledged and recognized in evaluation studies using the knowledge of diverse stakeholders, indigenous peoples and local communities.**

A framework for recognizing the economic value of kelp

Kelp forests provide numerous benefits to people, some of which are better understood and recognized in scientific literature than others. These benefits are both monetary (visible in the market as prices of kelp products) and non-monetary (biodiversity, cultural and/or social benefits). Some benefits, such as climate change mitigation, are of global significance, while others are more regionally or locally significant. The value of such benefits should be assessed and presented to decision makers prior to any decisions about developments that will affect kelp forests. Impact assessments provide a wide set of tools to do this, including methods based on economic theory, which have recently been applied more broadly.

Chapter 3 explored the range of ecosystem services that kelp provide, as well as their importance to many cultures around the world. This knowledge provides the basis for economic concepts and frameworks, such as total economic value (TEV) and cost-benefit analysis, which seek to determine the different types of economic values that kelp supply with a view to making rational and informed decisions about their conservation, restoration and sustainable management. This chapter aims to demonstrate how common economic tools used in environmental management can be applied to kelp to allow for a more complete balancing of the value of goods and services the ecosystem provides. There are several advantages to applying economic methods, including: i) the production of common metrics that allow for comparison across services; ii) the production of outputs that decision makers often easily understand and that can be compared for investment purposes, for example; and iii) the provision of a basis on an established economic theory (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2020). However, these tools also have some disadvantages, the most significant of which is the transfer of measurements with associated value systems into monetary terms. Many perceive this as reductionist and unable to open up broader discussions on the importance of different values in nature management decision-making. Another issue concerns the measurement of what all stakeholders find important, such as the existence values of the kelp ecosystem, which is a prerequisite for monetization (United Nations 2021). It is therefore important to acknowledge and explore existence and other values of kelp ecosystems through additional methodologies that strictly apply economic valuations. Many services linked to traditional practices, spiritual and religious life and cultural identities may be inappropriate to measure using monetary terms, with relational or sociocultural valuations often more appropriate in such cases. There is increasing recognition that researchers should embrace a fuller understanding of nature's contributions using knowledge of diverse stakeholders, indigenous peoples and local communities (IPBES 2022).

Cost-benefit analysis

Cost-benefit analysis is an economic decision-making support tool that is used to identify the net benefits of a project, such as kelp conservation or restoration, to establish whether it provides considerable market-based (e.g. commercialized ecosystem services) or non-market-based benefits (e.g. cultural ecosystem services, including nature's contribution to people) (Díaz *et al.* 2019). It can be used to prioritize projects by comparing and ranking which are most worthwhile for investment (meaning the use of financial resources from any source to fund kelp conservation, restoration or enhancement), which is particularly important when budgets are limited and the aim is to maximize benefits. Cost-benefit analysis is also commonly used to assess projects and can be used for industrial developments and other development projects that may affect kelp.

A cost-benefit analysis' key decision metrics include the net present value, which measures whether a project's total benefits exceed costs, and the benefit-cost ratio, which measures the amount of benefit produced per dollar spent. A project is economically viable if the net present value is greater than zero and if the benefit-cost ratio is greater than one. There are many guidelines available for conducting a cost-benefit analysis that explain the process and decision metrics in more detail. Guidance specifically relevant to conducting a cost-benefit analysis of kelp conservation and restoration is available in Morris *et al*. (2021), which provides an overview of cost-benefit analysis considerations for nature-based coastal defence activities.

Both market-based and non-market-based benefits and costs can be included in a cost-benefit analysis of a kelp conservation or restoration project, and it is possible to identify which benefits and costs are most influential on the analysis' outcomes. Understanding this is important for identifying which benefits are tangible and market-based (e.g. increased production for commercial fisheries, new ecotourism ventures), and which are non-market-based community benefits (e.g. improved recreational fishing opportunities, the provision of a habitat for rare marine fauna), as different stakeholders and investors may value both types of benefit.

Table 4.1. Five-step process for making the economic case to dedicate resources to the conservation, restoration or sustainable management of kelp

Step	Explanation	Expertise needed
1. Definition of alternative management actions	All relevant stakeholders and experts work together to define alternative management actions, including the conservation, restoration or sustainable management of kelp through multiple pathways. A gender-responsive, participatory approach is recommended.	Land managers, environmental planners, gender experts, legal experts, natural and social scientists, local women's groups and indigenous community leaders, among others, based on the local context.
2. Identification and description of relevant ecosystem services	The creation of an exhaustive list of ecosystem services that are relevant to the proposed management actions, with the participation of all relevant stakeholders and experts. Some of these services will be monetizable, while others will be quantifiable in biophysical terms only (at least initially). Others can only be described qualitatively.	Land managers, environmental planners, gender experts, legal experts, natural and social scientists, local women's groups and indigenous community leaders, among others, based on the local context.
3. Measurement or modelling of changes in quantifiable ecosystem services	The identification and measurement of changes in ecosystem services that are anticipated due to the proposed management actions.	Biologists, ecologists, other natural and social scientists and gender experts.
4. Total economic value	The monetization of ecosystem services for which economic tools allow a conversion from biophysical to monetary terms. These methods could include the application of market prices, a value estimated through the application of revealed or stated preference approaches or a benefit transfer.	Environmental and/or natural resource economists (including considerations for the gender dimension in the methodological guidance).
5. Cost-benefit analysis	The application of cost-benefit analysis methods that compare the economic benefits and costs of a specific set of management actions or that rank competing management options according to which options provide the largest net benefits. Impacts and values that cannot be easily measured or monetized are also presented and discussed.	Environmental and/or natural resource economists (including considerations for the gender dimension in the methodological guidance).

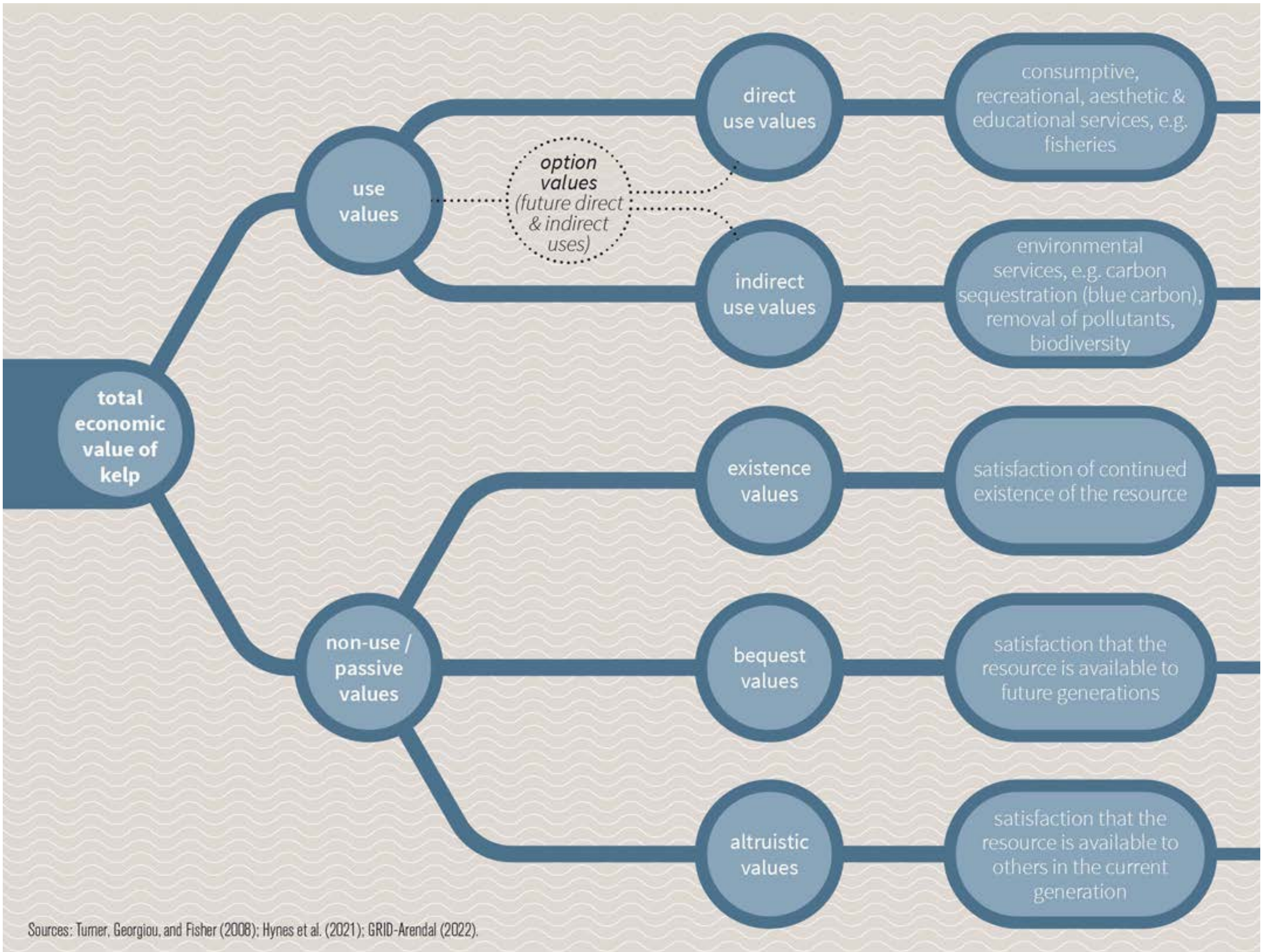
Cost-benefit analysis also has various other useful aspects that can assist in decision-making (Morris *et al*. 2021). First, the tool can account for the fact that many benefits of a project are not achieved until later in the future through the economic practice of discounting future benefits and costs to current values. Second, the tool can identify break-even points and thresholds to provide information on how long a restoration project needs to succeed to recover its costs, along with the extent to which project failure can be managed. Given the inability to control exogenous events, such as extreme storm events and heatwaves, understanding how well a project is equipped to deal with such risks is crucial. Third, by understanding what benefits and costs are driving a project's viability, it is possible to identify which stakeholders are likely to gain or lose from particular decisions. Although economic frameworks are important for identifying which kelp conservation or restoration projects are likely to deliver benefits overall, and how such benefits will be distributed, it is important for decision-making inputs to be supported by assessments that account for the wide range of impacts and values that are not captured in the cost-benefit analysis. This includes frameworks that consider issues about whether the distribution is fair and equitable, and is especially important when minority groups are identified as being negatively impacted. Due to the aforementioned limitations, it is important to note that effective pre-decision-making assessments require a multidisciplinary approach.

Total economic value

One of the main challenges in implementing the cost-benefit analysis approach is finding a single measure of heterogeneous benefits and costs. For values that can be monetized, economic platforms are valuable for their ability to integrate diverse sources of information (e.g. environmental, social and financial) and synthesize them in a commensurate way. This in turn facilitates the ability to understand the trade-offs implied from decisions that are focused on enhancing different elements of these environmental, social and financial dimensions.

The TEV framework is central to the organization of this diverse information, as it recognizes that value is not limited to the value obtained from goods and services provided solely by a marketplace. Rather, it acknowledges that value is derived from various consumptive and non-consumptive uses of environmental resources, and from simply knowing that these resources exist (i.e. non-use values). The TEV of an environmental resource is synonymous with what is commonly referred to as the economic welfare that the resource provides to people.

Figure 4.1. Total economic value of kelp



Ecosystem services help determine the value that humans place on natural resources and are used to evaluate the benefits that humans can obtain from such resources (Costanza *et al*. 1997). Boyd and Banzhaf (2007) defined ecosystem services as "the benefits of nature to households, communities, and economies". These values can be incorporated into a TEV framework and therefore supply data for a cost-benefit analysis on the benefits that ecosystems such as kelp provide. With the aim of enhancing the sustainable use of natural resources, the Millennium Ecosystem Assessment (MEA) evaluated how ecosystem changes affect human well-being (Millennium Ecosystem Assessment [MEA] 2005), classifying natural ecosystems based on the services they provide, nature's contributions to people and how human actions may change environments.

Ecosystem services are understood within a coupled socioecological system framework (McGinnis and Ostrom 2014), which consists of human and natural systems that interact in two ways. First, via human drivers, through which the human system influences the environmental status of and outcomes in ecosystems, and second, via ecosystem services (i.e. what nature provides to human systems). This report considers the kelp ecosystem as the natural system and human beneficiaries and stakeholders as the human system, with the flow of ecosystem services from kelp to people as the linkage between the two systems.

The value that kelp ecosystem services provide can be described in qualitative, quantitative or monetized terms using economic valuation techniques (as described in Champ, Boyle and Brown 2003, among others), if data allow. Economic valuations as part of TEV generally aim to provide monetary values for ecosystem services to ensure better policy design and the evaluation of trade-offs among various management options.

The economic value of consumptive products is generally captured through market prices, for example, the price paid for a kelp-based food product. Economic value is reflected in two elements of paid prices: "producer surplus", which is the profit that the producer (supplier) makes from selling the product (e.g. the profit made from kelp farming);[2] and "consumer surplus", which is the benefit or utility that the consumer gains from purchasing the product, above and beyond the price they actually paid (Hanley and Barbier 2009).[3]

Clarity around measures of consumer and producer surplus and expenditure and revenue are important to this topic, especially since large expenditure and revenue figures are often reported for marine tourism and similar industries, with marine habitats (including kelp forests) commonly viewed as sustaining such industries. These large numbers do not necessarily provide information on the welfare benefits that kelp forests generate and cannot directly assist in determining whether an investment in kelp restoration, for example, would be profitable (in terms of producer surplus for a private investor) or generate a community benefit (in terms of consumer surplus for a public investor). Nonetheless, expenditure and revenue figures are often the only information available, and still convey a good sense of the scale of benefits that a resource is producing.

Some examples of studies that have estimated the market value of kelp include the following:

- The total estimated value of the Falkland Islands' (Malvinas) kelp ecosystem is currently equivalent to approximately £2.69 billion per year (or £3.24 million km^{-2} $year^{-1}$) (Bayley *et al*. 2021). However, the true value of the kelp forest surrounding the Falkland Islands (Malvinas) is likely to be even higher, given that the estimate does not account for elements such as associated scientific research, tourism and cultural services.
- In South Africa, the current value of the kelp ecosystem, which is the main food source for abalone aquaculture, is estimated at \$434 million $year^{-1}$ (ZAR 5.8 billion $year^{-1}$), of which around \$290 million $year^{-1}$ (ZAR 3.9 billion $year^{-1}$) contributes to the country's gross domestic product. Ecotourism contributes to almost 40 per cent of this figure, followed by recreational fishing (28 per cent) and commercial and illegal fishing (15–16 per cent each) (Blamey *et al*. 2018). Income currently generated by fisheries is greatly reduced, with some sectors worth less than half of their value in the 1990s.
- In northern Chile, kelp goods and services have a total value of \$540 million. Of this total, kelp fisheries account for 75 per cent and associated-species fisheries account for 15 per cent. However, the value of these goods and services as a source of scientific information or climate regulation through carbon capture or oxygen production represents only 9 per cent of the total value, with a very low relative importance to society (Vásquez *et al*. 2014).
- Across southern Australia, Bennett *et al*. (2016) estimated that ecosystem services associated with kelp forests and their broader Great Southern Reef ecosystem contributed approximately A\$10 billion

2 This is not the revenue that producers receive, which is commonly misrepresented as a measure of welfare. Rather, it is the revenue minus the expenses incurred to supply the product.

3 This is commonly confused with measures of consumer expenditure, which is not a welfare measure. Expenditure only informs about how much money consumers have spent and not whether they considered that expenditure worthwhile given the benefits they experience from their purchase. An individual's consumer surplus from a kelp forest might relate, for example, to the enjoyment gained when scuba-diving in one, or the satisfaction gained from knowing these habitats exist.

per year to the Australian economy through tourism and commercial and recreational fishing in addition to providing substantial biodiversity.

Non-market-priced ecosystem services can be measured and valued in various ways. Non-consumptive use values (e.g. from recreation) and non-use values of such services cannot be captured in markets as they are not "bought and sold", and are therefore often equated using non-market valuation methodologies that instead estimate people's willingness to pay for them.

There are a range of tried and tested non-market valuation approaches in use (Rogers *et al*. 2015), some of which focus on revealed behaviours. For example, observing how frequently people visit a dive site and the expenses they incur in travelling to that site reveals their willingness to pay to make the trip (Zimmerhackel *et al*. 2018). Other approaches depend on stated preferences and are particularly important for revealing non-use values, among which are survey-based approaches such as discrete choice experiments, in which respondents are asked about the trade-offs they are prepared to make between different policy, management or investment options, as well as how much they would be prepared to pay for particular options (Rogers 2013). The hypothetical nature of these surveys enables the practitioner to construct scenarios that resemble a faux market for non-market environmental goods and services, from which the practitioner can then estimate how much people are willing to pay for changes in the quality or quantity of those goods and services.

Since non-market valuation approaches can be complex and costly, a common approach for decision-making is a benefit transfer, in which welfare estimates from a primary source site are extrapolated to secondary policy sites (Johnston *et al*. 2015). This approach is a feasible alternative to collecting primary data for decision-making, provided the decision contexts between sites are similar enough, including considerations such as the scale and scope of the environmental resource, the geographic location and population demographics, among others.

To date, very little attention has been placed on estimating the non-market values of kelp forests. One study by Hynes *et al*. (2021) estimates that Norwegians are willing to pay €21.22 per person per year to restore a 20,000 m^2 area of kelp forest. This study suggests the benefits of kelp restoration are substantial, but that more primary valuation studies are required to validate this estimation and to explore in more depth the full range of ecosystem services that kelp forests provide. Due to the limited primary data on non-market values attributed to kelp forests, benefit transfers will likely play an important role in estimating kelp restoration benefits and costs, at least in the short term, which will enable practitioners to draw on a (still limited, but larger) literature of marine ecosystem service values.

Non-market values can be utilized in different ways for decision-making, including conceptually as a means of advocating for a policy or investment decision, or instrumentally as a qualitative input to a formalized decision process. This could include their use in damage assessments or the determination of compensation by the court system (e.g. Exxon Valdez), or alongside financial values in decision-making support tools such as in a cost-benefit analysis. The use of payments for ecosystem services (PES) schemes could be an effective tool to trigger investment from both the public and private sectors in kelp forest conservation and restoration. While valuation studies are key to setting prices for different ecosystem services, PES schemes offer another way to capture some of the non-market values that natural ecosystems provide, specifically, how much a buyer is willing to pay to maintain or improve the provision of ecosystem services.

Although non-market valuations are an important tool for quantifying a vast majority of intangible kelp ecosystem service values that can be integrated into decision-making, they can be limited in their representation of particular value sets, such as those of some traditional owner communities. Non-market valuations rely on the assumption that people can consider some form of trade-off when prioritizing preferred outcomes (e.g. spending or receiving money in lieu of more or less kelp habitat, or trading off public investments in a kelp forest for a terrestrial forest). However, traditional owners, such as Australia's Aboriginal people, are connected to the country in a holistic way, acting as custodians of a complete ecosystem where the concept of trading off components within an ecosystem, or even one ecosystem with another, may not be an acceptable framework. Again, it is important to note that effective decision-making that recognizes all values can be supported by coupling economic frameworks with other sociocultural frameworks.

The TEV and cost-benefit analysis framework can ensure that limited conservation resources are efficiently allocated, justify the allocation of more resources to conservation and restoration and contribute to the inclusion of broader values of kelp ecosystems in decision-making and economic developments. However, to obtain reliable outcomes from this framework, all market and non-market benefits of kelp ecosystems must be identified and accurately measured, which cannot be fully completed at present as additional benefits are still being discovered. In the meantime, before a relatively complete TEV analysis can be performed for kelp, existing individual measures of value should instead be relied upon in decision-making processes. Using the various existing approaches to measure kelp values, especially those that make the benefits of kelp both tangible and visible, can still result in strong advocacy for kelp conservation and restoration policy and investment.

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Chapter 5. Kelp forests in law and policy

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Highlights

- **There are no global law or policy instruments focused explicitly on kelp, but kelp forests do benefit from some international regimes.**
- **Many national laws and policies provide for the protection, management, restoration and use of kelp, although approaches vary in different jurisdictions.**
- **Awareness of the value and status of kelp forests is growing, with further research needed to identify ways to enhance laws and policies.**
- **Holistic governance is crucial to ensuring that cumulative impacts are addressed, ecosystem approaches are embedded and all stakeholders are engaged.**

Introduction

Laws and policies that support the sustainable use (harvesting), conservation, management and restoration of kelp forests are vital if the ecosystem services they provide are to be maintained. Kelp ecosystems (or forests) have a physiological need for sunlight, which commonly limits their distribution to shallow waters (mostly 5–40 m depth) (Wernberg *et al*. 2019). These marine areas fall under the control and management of coastal States, meaning national laws and policies are crucial. International laws can also provide a much-needed platform for global discussion, knowledge-sharing, awareness-raising and capacity-building. More specifically, international law regimes can sharpen the focus on kelp ecosystems, set global standards, create obligations common to all nations and establish incentives, including binding funding mechanisms. Global soft laws (non-binding or informal law) and/or policy-based initiatives can establish overarching goals, action plans, non-binding targets and indicators, while also providing a vehicle for voluntary commitments by a broad range of stakeholders. To effectively implement laws and policies, mitigate threats to kelp forests and reverse their global decline, significant institutional support is also needed (Eger *et al*. 2020).

As is the case with most natural ecosystems and associated species, kelp forests do not always respect national boundaries, with some interconnected and interdependent coastal ecosystems straddling several countries. For example, the Great African Sea Forest extends north from Cape Town in South Africa into Namibian waters. Similarly, pressures and impacts upon kelp forests often cross jurisdictional boundaries and the land-water interface. Integrated and ecosystem-based approaches, as well as regional, transboundary and bilateral agreements, are therefore also relevant (Llewellyn, English and Barnwell 2016).

At present, there are no global law or policy instruments focused explicitly on kelp, although kelp forests do benefit from some international regimes. This lack of attention has resulted in limited global drivers for the sustainable utilization and protection of kelp forests, as evidenced, for example, by the under-representation of these species and ecosystems in marine protected areas (MPAs) (Table 5.1). Nevertheless, global attention is being increasingly drawn to the value of kelp forests, which may catalyse further action in the near future (Hutto, Brown and Francis 2021).

Domestic laws and policies for sustainable harvesting, protection, management and restoration of kelp forests differ considerably between nations, driven by national interests and local contexts. Specific legal tools can include species and area-based listing approaches, conservation and management measures, utilization/harvesting regulations, restoration obligations, as well as decision-making processes for the approval and administration of developments that may have impacts upon them (Richardson 2016). However, in many jurisdictions there is a divide between environmental (conservation and restoration) and natural resource management (utilization, including harvesting) laws and policies, which hampers integrated approaches to the sustainable conservation and utilization of kelp forests. Furthermore, traditional laws, practices and management systems remain relevant at local and provincial levels, highlighting the importance of applying a broader governance lens.

To sustainably conserve and utilize kelp forests in a more comprehensive manner, improved law and policy options must be identified at all governance levels and across various sectors. This includes finding ways to use existing laws and policies more effectively, as well as developing new instruments and initiatives to address gaps in ways that recognize different governance approaches. The following sections explore the relevant international frameworks that benefit kelp forests or may do so in the future. Selected examples of national laws and policies are highlighted to demonstrate the different approaches taken, the focus of which is on the sustainable conservation and utilization of natural kelp forests. Cultivation is not considered in these examples.

Table 5.1. Coastal and marine ecosystems within marine protected areas

Ecosystem	Globally recorded area (km^2)	Percentage within marine protected areas
Kelp	1,469,900	30*
Seagrasses	324,248 (potentially up to 1,650,000 based on model projections)	26
Mangroves	152,233	43
Saltmarshes	54,661	42
Cold-water corals	18,993	32
Warm-water corals	150,045	40

*Please note that this is a rough estimate based on clipped coastlines (www.naturalearthdata.com) where kelp distributions have been recorded.
Sources: Adapted from United Nations Environment Programme (UNEP) World Conservation Monitoring Centre (WCMC) data; UNEP 2020

International treaties

Although there are no global laws or policies related specifically to kelp species or forests, several international treaties have been used to support kelp forest protection, utilization, management and/or restoration. These international treaty frameworks include the law of the sea, biodiversity, climate change and disaster risk reduction. The instruments use different legal mechanisms or tools for conservation and utilization: area-based, species-focused, ecosystem-based and natural resource-use approaches. There is evidently a wealth of laws that could potentially be used more widely to benefit kelp forests.

United Nations Convention on the Law of the Sea

The United Nations Convention on the Law of the Sea (UNCLOS) takes a holistic approach to ocean management, for which it has established binding principles. These principles should be detailed in other contexts according to carefully circumscribed mandates set out in the Convention. UNCLOS has catalysed significant international agreements and organizations, as well as national governance agreements, and continues to act as a foundation for further initiatives that can facilitate the sustainable conservation and utilization of kelp forests. Annual debates and resolutions on the law of the sea and fisheries are held and made at the United Nations under the Convention, which could be used to increase the attention given to kelp forests and to call for action.

The most relevant provisions for kelp are found in Part XII and include the obligation to protect and preserve the marine environment (articles 192 and 193), the requirement to prevent, reduce and control pollution (e.g. article 194), as well as mandates for assessments, monitoring and research (articles 200, 204–206). There are also relevant provisions for conservation and the utilization of living resources (e.g. articles 61–62).

UNCLOS highlights the importance of cooperation, including at the regional level (e.g. article 197), which has contributed to the establishment of the Regional Seas Programme. Although not globally comprehensive, such programmes, conventions and action plans seek to protect the marine coastal environment and can benefit kelp forests by establishing standards and creating obligations for Member States at the regional level (UNEP no date). For example, the Commission established under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention) has adopted recommendations to strengthen the protection of kelp forests and to improve their conservation status. This includes encouraging the adoption of legislation to protect kelp forest habitats, conservation management measures, restoration programmes and the designation of protected areas (OSPAR Commission 2021).

The provisions in UNCLOS on living resources have resulted in the development of an implementation agreement (the Straddling Fish Stocks Agreement of the United Nations), many regional fisheries management organizations (RFMOs) and significant domestic legislation. The ecosystem-based management and precautionary approaches found in fisheries regulations (e.g. articles 5 and 6 of the Straddling Fish Stocks Agreement) may benefit critical habitats such as kelp forests by protecting them from fisheries-related damage, with such regulations also establishing standards for kelp harvesting. RFMOs may launch further initiatives to protect kelp, as evidenced through the example of the Indian Ocean Tuna Commission, which has undertaken a study to identify ecologically or biologically significant marine areas, some of which include kelp forests (Indian Ocean Tuna Commission 2018).

Convention on Biological Diversity

This Convention aims to ensure the conservation of biological diversity and the sustainable use of its components (article 1). It seeks to achieve these goals through encouraging Member States to identify and monitor biodiversity, adopt conservation, management, recovery and rehabilitation measures for species and ecosystems, protect threatened species, promote environmentally sound and sustainable development, and balance conservation and the sustainable use of natural resources. The Aichi Biodiversity Targets and the broader Strategic Plan for Biodiversity 2011–2020 focused on five strategic goals and 20 targets, with kelp relevant to several of them. These strategic goals and targets will be replaced by a post-2020 global biodiversity framework. The draft 2050 goals and 2030 milestones are less specific than the Aichi Biodiversity Targets in mentioning ecosystems such as kelp forests, despite kelp being relevant to the achievement of several of them (Convention on Biological Diversity 2021). Kelp forests currently feature explicitly in 11 national reports (Australia, Bangladesh, Canada, China, Ghana, Japan, Namibia, Norway, Oman, South Africa and Thailand), but only one national biodiversity strategy and action plan (the Republic of Korea, and only in relation to cultivation). Several initiatives of the Convention refer explicitly to kelp, including the programme of work on marine and coastal biodiversity (UNEP/CBD/COP/DEC/VII/5), but not in relation to law and policy activities.

Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat

The Ramsar Convention is an international agreement that both promotes the conservation and wise use of wetlands, and that requires Member States to nominate at least one wetland through its area-based mechanism. Although the Convention does not specifically refer to kelp forests, they are included within its definition of wetlands (though marine wetland areas are limited to a maximum depth of 6 m, which thus may not protect an entire kelp forest). Despite the term “wise use” not being defined in the Convention, its subsequent *Handbook on the Wise Use of Wetlands* refers to conservation, sustainable use and development, and restoration. Neither kelp nor seaweed are mentioned in *Ramsar Briefing Note 7. State of the World’s Wetlands and their Services to People: A compilation of recent analyses* (2020). Although there have been no specific initiatives for kelp, nine wetland areas in the Ramsar listing acknowledge the ecosystem (in Japan, Norway, Portugal, South Africa and the United Kingdom), 16 sites included in national submissions refer to (but do not directly mention) kelp (including Argentina, Canada, Chile, Denmark, New Zealand, Peru, South Africa, Spain and the United Kingdom) and 24 listed sites (e.g. in Australia, Denmark, Ireland, Norway, the Russian Federation, Sweden and the United States of America) may have a kelp presence based on environmental conditions and scientific literature, though kelp forests are not referred to specifically.

World Heritage Convention

The World Heritage Convention is an area-based treaty that focuses on the identification, protection, conservation, presentation and rehabilitation of areas of “outstanding universal value”. Kelp forests have not been referred to in any specific programmes under the World Heritage Convention, but 16 World Heritage sites contain kelp systems (in Argentina, Australia, Canada-the United States of America, Ecuador, France, Iceland, Japan, New Zealand, Norway, the Russian Federation, Sweden, South Africa and the United Kingdom), several of which are highlighted as part of the sites’ outstanding universal value (including some sites on the Tentative List: Breiðafjörður Nature Reserve in Iceland, Hazar State Nature Reserve in Turkmenistan and the California Current Conservation Complex in the United States of America). Importantly, several global sites are listed under both the Ramsar and World Heritage Conventions, providing such areas with greater protection.

Box 5.1. Case study: Shiretoko, Hokkaido, Japan

The Shiretoko Peninsula was listed as a World Heritage site in 2005 and is one of the richest integrated marine and terrestrial ecosystems in the world. The waters around the Shiretoko Peninsula contain unique and diverse ecosystems, including kelp forests comprised of *L. ochotensis* Miyabe and *L. diabolica* Miyabe (Minami *et al*. 2010). These kelp forests play important ecological and economic roles, including as fishing resources. Areas within the Shiretoko Peninsula are protected through several national laws and regulations, including the Onnebutsedake Wilderness Area established under the Nature Conservation Act 1972, the Shiretoko National Park established under the National Parks Act 1957, the Shiretoko Forest Ecosystem Reserve established under the Act on the Management of National Forests 1951 and the Shiretoko National Wildlife Protection Area established under the Wildlife Protection and Hunting Act 1918 and the Act for the Conservation of Endangered Species of Wild Fauna and Flora 1992. The management of this World Heritage site is considered a best practice due to its integrated Shiretoko approach to governance, which involves a bottom-up approach, scientific council, self-management measures and the involvement of local communities and stakeholders through the Shiretoko World Natural Heritage Site Regional Liaison Committee (World Heritage Convention no date).

Photo credit: Eiichi Kurasawa (taken from the World Heritage Convention's website)

The Paris Agreement and nationally determined contributions

The United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement (2015) have provisions that encourage the strengthening of the world's sinks and reservoirs. Kelp forests are essential contributors to the carbon cycle (see chapter 3 for more information) and their role in alleviating acidification in the surrounding environment is well-established (Hirsh *et al*. 2020), though research continues on the role such forests can play in mitigation interventions (Macreadie *et al*. 2019). The Paris Agreement requires Member States to prepare nationally determined contributions (NDCs), which identify the ways in which they will contribute to global mitigation and adaptation within their territories. Although many NDCs refer explicitly to other coastal and marine ecosystems, such as mangroves, seagrasses and tidal marshes, only one specifically mentions kelp forests, with Namibia including "kelp beds" as a biological option for adaptation actions (see Box 5.2 on Namibia's updated NDC).

The Katowice climate package requires States to use the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and encourages the use of the *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. The wetlands supplement does not include kelp forests, which may explain why these ecosystems are not recognized alongside other coastal and marine ecosystems that fix and store carbon (e.g. mangroves, seagrass meadows and saltwater marshes as blue carbon and blue forest ecosystems). However, the 2022 Working Group II contribution to the IPCC Sixth Assessment Report identifies kelp, along with other ocean and coastal taxa, as proposed blue carbon ecosystems, noting that "there is increasing evidence about the coverage and carbon content of macroalgal, planktonic, and faunal taxa, but *low agreement* about their long-term carbon storage potential and manageability" (Pörtner, H.-O. *et al*. 2022). Kelp forests are also referred to in several climate-related intergovernmental reports, such as the *Yearbook of Global Climate Action 2019*, which note that their role as fisheries habitats is at risk as ocean temperatures increase.

Table 5.2. Analysis of nationally determined contributions made as of April 2022

Nationally determined contributions and the inclusion of key coastal and marine ecosystems	
Parties to the Paris Agreement	193
Countries that have submitted a first, revised/updated and/or second NDC	194*
Parties that have submitted a new or updated NDC	158**
Parties that have made an explicit reference to **mangroves**	55
Parties that have made an explicit reference to **seagrasses**	16
Parties that have made an explicit reference to **tidal marshes** or **saltmarshes**	8
Parties that have made an explicit reference to **kelp**	1

*Eritrea has submitted its first NDC but has not yet become a party to the Paris Agreement.
**Representing 157 countries.
Sources: Climate Watch no date; UNFCCC no date

Box 5.2. Namibia's updated nationally determined contribution (2021)

From section 3.2.3 on coastal areas:

"...other options are new interventions or investments, additional to the business as usual and existing efforts, designed to improve wellbeing, maintain the environment, and ultimately counter sea-level rise. These options can be classified into physical, biological, and institutional responses. Physical options are hard engineering techniques such as seawalls, groynes, detached breakwaters, and revetments. Biological options are more natural, less likely to produce adverse consequences and more cost-effective than most physical options. They include dune cordons, estuary and wetland rehabilitation, and kelp beds."

Source: Republic of Namibia 2021

The Sendai Framework for Disaster Risk Reduction

The Sendai Framework (led by the United Nations Office for Disaster Risk Reduction) seeks to substantially strengthen resilience to natural hazards by increasing preparedness for response and recovery to reduce disaster risk and human and environmental losses through integrated and inclusive measures. The framework includes seven global targets and 13 guiding principles. Kelp forests can mitigate the effects of storm surges, flooding and may be important for other extreme weather events, therefore contributing to the four targets focused on reducing risk (through nature-based solutions to natural disasters) and the goals that seek to strengthen resilience (by encouraging the inclusion of kelp as part of disaster reduction strategies). The framework has resulted in 77 voluntary commitments, including 323 deliverables by 354 organizations, some of which could benefit kelp forests (United Nations Office for Disaster Risk Reduction no date a).

To summarize, existing international law frameworks currently benefit kelp forests to a limited extent (see Table 5.4) but could be used to much greater effect.

Table 5.3. Summary of the Sendai Framework targets and priorities

Sendai Framework targets						
Substantially reduce global disaster mortality by 2030	Substantially reduce the number of affected people globally by 2030	Reduce direct disaster economic loss by 2030	Substantially reduce disaster damage to critical infrastructure and disruption of basic services by 2030	Substantially increase the number of countries with national and local disaster risk reduction strategies by 2020	Substantially enhance international cooperation to developing countries by 2030	Substantially increase the availability of and access to multi-hazard early warning systems, information and assessments by 2030

Sendai Framework priorities for action			
Priority 1	**Priority 2**	**Priority 3**	**Priority 4**
Understanding disaster risk	Strengthening disaster risk governance to manage disaster risk	Investing in disaster risk reduction for resilience	Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction

Source: Adapted from United Nations Office for Disaster Risk Reduction no date b

Table 5.4. Analysis of key international treaties and their potential to facilitate kelp conservation, management and restoration

Type	Treaty	No. of parties	No. of kelp sites and programmes	Protection	Management	Restoration
Area-based treaties	Ramsar Convention	170	27 Ramsar areas refer to kelp in the listing or submissions	Obligation to "promote the conservation of wetlands" (article 3)	Commitment to "wise use" (article 3)	"Wise use" has been interpreted as including restoration and rehabilitation
	World Heritage Convention	194	12 World Heritage sites include kelp forests	Obligations for listed sites include "protection and conservation" (article 4)	Obligations for listed sites include "protection and conservation" (article 4)	Implied
Species- and ecosystem-based treaties	Convention on Biological Diversity	196	None, but eight national reports mention kelp	Commitment to the "conservation of biological diversity" (article 1)	Commitment to the "sustainable use of its components" (article 1)	Obligations to "rehabilitate and restore degraded ecosystems" (article 8(f))
Climate change	UNFCCC/ Paris Agreement	197/194	One NDC mentions kelp (please see Box 5.2.)	Obligations include the "conservation [...] of sinks and reservoirs" (article 4(d)) and preparations for adaptation, including the "protection [...] of areas" (article 4(e))	Commitments to "promote sustainable management [...] of sinks and reservoirs" (article 4(d)) and "coastal zone management" (article 4(e))	Obligations include the "enhancement [...] of sinks and reservoirs" (article 4(d)) and preparations for adaptation, including the "rehabilitation of areas" (article 4(e))
Law of the sea	UNCLOS	168	None	General obligation to "protect and preserve the marine environment" (article 192)	Comprehensive general obligations on ocean management to be implemented and specified by all relevant parties	Restoration is not specified but is in accordance with general obligations, such as in article 192

Other	Sendai Framework	187	None	Implied in the goal to prevent and reduce disaster risk "legal [and] environmental [...] measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness [...] and thus strengthen resilience"	Implied in the goal to prevent and reduce disaster risk "legal [and] environmental [...] measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness [...] and thus strengthen resilience"	Implied in the goal to prevent and reduce disaster risk "legal [and] environmental [...] measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness [...] and thus strengthen resilience"

International policy frameworks and institutions

International institutions

Several international intergovernmental organizations (IGOs) can play a powerful role in kelp forest protection, management and restoration. The United Nations Environment Programme (UNEP) and Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) have relevant mandates focused on environmental protection and global ocean science, respectively. Food and Agriculture Organization of the United Nations is also relevant because of its focus on food security and fisheries, which includes seaweed and kelp harvesting. In fact, FAO has been instrumental in preparing a Code of Conduct for Responsible Fisheries and an Ecosystem Approach to Fisheries, and has also produced several relevant reports, such as *The Global Status of Seaweed Production, Trade and Utilization*. Kelp forests are only briefly mentioned in *The State of the World's Aquatic Genetic Resources for Food and Agriculture* and *The State of World Fisheries and Aquaculture*, partly because seaweed are not included in the FAO food balance sheets (FAO 2020). Beyond these institutions, there are global soft laws and international policy initiatives of relevance to kelp, discussed further in the following sections.

Box 5.3. United Nations ocean voluntary commitments and kelp

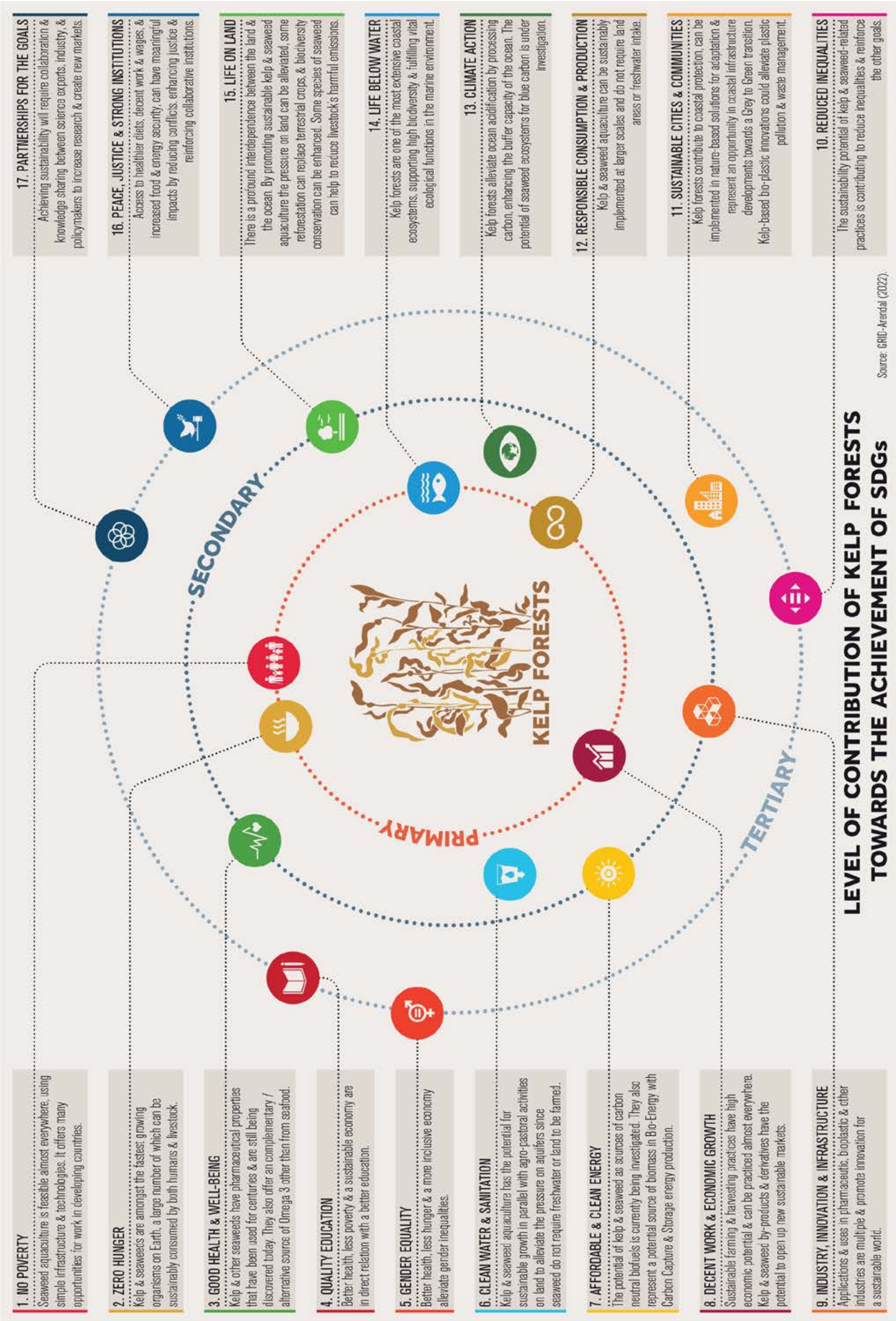
The United Nations Ocean Conference – a high-level conference to support the implementation of Sustainable Development Goal (SDG) 14 – was convened at the United Nations Headquarters in 2017. Ocean stakeholders (governments, civil society, the scientific community, etc.) were requested to make voluntary commitments, representing initiatives that aim to contribute to the implementation of SDG 14. By January 2022, 1,653 voluntary commitments had been submitted, 29 of which relate to mangroves, three to seagrass and zero to kelp forests.

Source: United Nations Department of Economic and Social Affairs no date

The Sustainable Development Goals

Kelp can benefit from soft law targets set by the Sustainable Development Goals (SDGs) and can also contribute to their achievement. Resilient kelp forests are at the core of SDG 14 on life below water, directly contribute to several other SDGs and indirectly support the achievement of others. While the conservation and sustainable use of kelp forests align with the overall objective of the SDGs, they do not specifically apply to all SDG targets (Figure 5.1). In particular, kelp forests can assist in meeting SDG targets 14.2 (sustainably manage and protect marine and coastal ecosystems), 14.5 (conserve at least 10 per cent of coastal and marine areas), 13.1 (strengthen resilience and adaptive capacity to climate-related hazards and natural disasters), 6.6 (protect and restore water-related ecosystems) and 2.4 (ensure sustainable food production systems).

Figure 5.1. How kelp forests can contribute to the Sustainable Development Goals



Note: The size of each ring indicates the SDGs' relevance for kelp forests.

Kelp forests and the United Nations decades for ecosystem restoration and ocean science

In 2021, two United Nations decades were launched, which despite not being policy frameworks or legal instruments, have the potential to raise awareness about kelp forests and ensure that they are properly appreciated for their ecosystem values and services. The UN Decade on Ecosystem Restoration (2021–2030) led by UNEP and FAO and the UN Decade of Ocean Science for Sustainable Development (2021–2030) led by UNESCO-IOC both have missions, objectives and initiatives that could enhance the global status of kelp forests, generate crucial knowledge to underpin policy development and decision-making, facilitate their integration into policies and incentivize their sustainable conservation and utilization as well as the recognition and application of kelp-based initiatives as solutions. Although United Nations decades are not legally binding on nations (having emerged from General Assembly resolutions), they incorporate strategies, aims and the general direction that United Nations IGOs and numerous non-United Nations non-governmental organizations (NGOs) should focus on throughout the following decade. They incentivize action, provide guidelines, include processes to finance and launch movements to be joined. They also provide a platform for discussion and facilitate the exchange of knowledge, expertise and methods across geographies, disciplines, industry sectors and populations. The UN Decade of Ocean Science for Sustainable Development has already seen strong levels of engagement from private sector actors engaged in kelp-related activities. Both decades have the potential to be strong drivers of communication messages that can enhance awareness, build support for kelp conservation, sustainable utilization and restoration, and demonstrate practical applications for sustainable development worldwide.

National laws and policies

Since kelp forests are found in coastal waters, domestic laws and policies provide them with the most direct protection under national jurisdiction. Although legislation tends to differ between jurisdictions, it can be separated and grouped into five categories based on the legal mechanisms or tools utilized in the law: (1) area-based conservation laws, such as MPAs; (2) species-based protection mechanisms, such as a threatened species listing; (3) kelp as a resource with licensing regimes for harvesting and use; (4) regulations linked to the ecosystem services that kelp forests provide, including fish habitats; and (5) climate change-related measures. The following sections provide some examples of national legislation that are representative of these five categories and highlight the diverse range of approaches.

In Australia, a species-based approach has been taken at the national level through the Environment Protection and Biodiversity Conservation Act 1999, which protects the giant kelp (*M. pyrifera*) marine forests of south-east Australia, a threatened ecological community. In Japan, a combination of mechanisms is used, including species conservation measures, licensing regimes and area-based protection. Laws have also been established to implement species-based measures (the Act on the Conservation of Endangered Species of Wild Fauna and Flora 1992) and protect kelp forest marine areas (the Nature Conservation Act 1972, National Parks Act 1957 and Act on the Management of National Forests 1951). Kelp harvesting is regulated separately under the Fisheries Act 1949 and the Act on the Protection of Fishery Resources 1951.

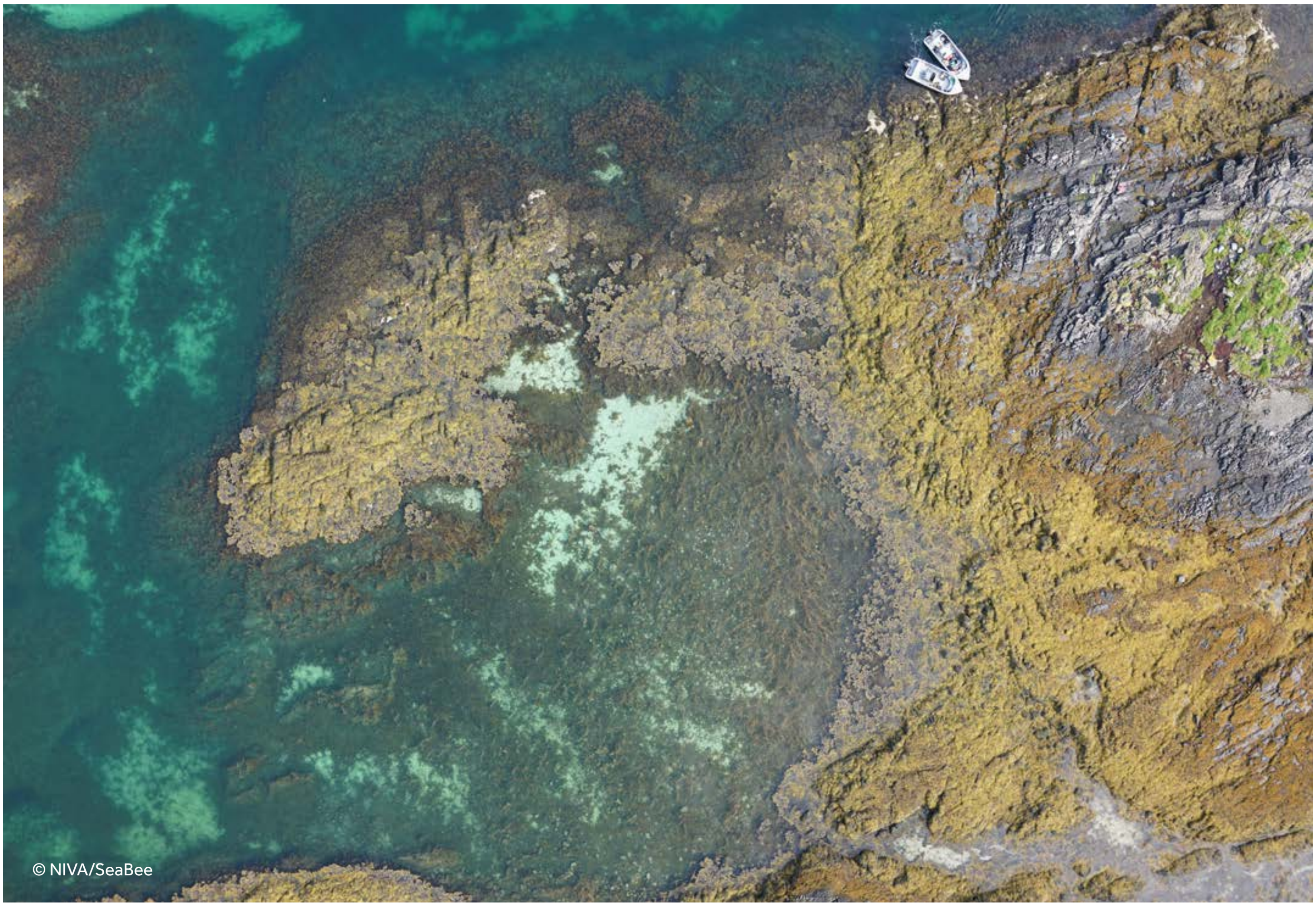
In New Zealand, the Marine Reserves Act 1971 preserves areas that contain “underwater scenery, natural features, or marine life, of such distinctive quality, or so typical, or beautiful, or unique, that their continued preservation is in the national interest” (section 3(1)), and could therefore cover kelp forests. Under the Resource Management Act 1991, kelp are offered some protection via the New Zealand Coastal Policy Statement (NZCPS) and/or regional coastal plans. Policy 11 of the NZCPS, for example, aims to “protect indigenous biological diversity in the coastal environment” and avoid “significant adverse effects of activities on [...] habitats of indigenous species that are important for recreational, commercial, traditional or cultural purposes” (New Zealand Government 2010). The Fisheries Act 1996 provides for the utilization of fisheries while ensuring their sustainability (section 8) and under its environmental principles requires that the “biological diversity of the aquatic environment should be maintained” and that “habitat[s] of particular significance for fisheries management should be protected” (section 9). Under the Fisheries Act, seaweed populations are defined as all kinds of algae and seagrasses, and therefore include kelp. In general, the Fisheries Act prohibits the commercial cutting of true kelp populations (*M. pyrifera, E. radiata* and *Lessonia* spp.) and the habitat-forming fucoid *Durvillaea* spp., but the cutting of *M. pyrifera* is permitted in two fishery areas managed under the Quota Management System (with an annual allowance of 1,500 tons), following a 2008 legal settlement on historic seaweed permitting decisions (Fisheries New Zealand no date). Fisheries (Commercial Fishing) Regulations 2001 are also being considered under the Fisheries Act as a means of closing areas of high-value kelp forests in southern New Zealand by classifying them as Type 2 MPAs (Department of Conservation and Fisheries New Zealand 2020).

In other domestic contexts, the approaches taken highlight national interests. In Norway for example, kelp harvesting is a significant activity (see Box 6.3), with *L. hyperborea* the main source of production of high-range alginate (around 15,000 tons have been harvested per year for the last decades). The harvesting and cultivation of macroalgae is an important strategic area for the Norwegian Ministry of Trade, Industry and Fisheries, the value creation of which is expected to reach NOK 40 billion by 2050. As a wild, living marine resource, kelp are regulated in Norway under the Marine Resources Act 2008, in which it is defined as belonging to “Norwegian society as a whole”, while being governed by the Ministry of Trade, Industry and Fisheries. Decree No. 642 of 1995 on regulating the harvesting of seaweed and kelp stipulates harvesting conditions, stating that seaweed and kelp are to be “exploited sustainably as part of a holistic management of the coastal resources and natural environments” (Greenhill, Sundnes and Karlsson 2021), and while prohibited in general, can be permitted at depths of less than 20 m by regional regulations defined by the Directorate of Fisheries. The 1995 decree also facilitates area-based harvesting management, whereby allocated harvesting areas are open for one year, followed by four fallow years until the next harvesting period to ensure kelp regrowth.

In the United Kingdom, different approaches have been taken to prevent the removal of entire wild kelp (in particular through prohibiting mechanical dredging) and to only allow harvesting using methods that allow the kelp to regrow. In Scotland, environmental legislation recognizes kelp as a protected environmental feature. In 2019, following extensive public objection in response to proposed industrial harvesting, a legal restriction was adopted as an amendment under the Scottish Crown Estate Act 2019 on prohibiting the industrial harvesting of whole kelp (section 15). This process bypassed the marine licences legislation that typically regulates marine activities, and the regulatory regime remains under review (Greenhill, Sundnes and Karlsson 2021). Similarly, in England, the Sussex Inshore Fisheries and Conservation Authority’s Nearshore Trawling Byelaw prohibits trawling to allow natural regeneration (Sussex Inshore Fisheries and Conservation Authority no date). The United Kingdom is also beginning to recognize the value of kelp forests as blue carbon initiatives (Stewart and Williams 2019).

Subnational law and policy approaches (at the national, provincial or local levels) are often the most relevant to kelp forests found in inshore waters. For example, in California (the United States of America), kelp forests are the subject of specific laws, including a combination of area-based, species-based and licensing regulations. The California Code of Regulations Title 14 (Natural resources) section 165 Harvesting of kelp and other aquatic plants, includes licensing rules for commercial harvesting (Title 14 section 165.5). In addition, section 632 provides for the creation of MPAs, marine managed areas and special closures, which may be used to conserve and manage kelp forests.

In several Canadian jurisdictions, First Nations people have been conserving and utilizing kelp for millenniums. For example, in British Columbia (Canada), the Heiltsuk people use kelp to collect herring spawn. In *R v. Gladstone* ([1996] 2 S.C.R. 723), the Court held that the Heiltsuk people have a traditional (Aboriginal) right to continue the practice of fishing for herring, and to sell spawn in commercial quantities (Gauvreau *et al*. 2017). Traditional laws and practices remain relevant, not only for local communities but also for the long-term conservation, management and restoration of kelp forests.



Box 5.4. Case study: New Zealand customary law

In New Zealand, species that are deemed to be of value to Māori people (because of acknowledged historic/continued use) are afforded some protection (e.g. rimurapa/bull kelp, *Durvillaea* spp.), though this is not the always case for other species that may also have cultural or ecological significance (e.g. *M. pyrifera*). Despite guarantees in the Treaty of Waitangi 1840 (*Te Tiriti o Waitangi* in Māori) – New Zealand's founding document – Māori fishing rights were gradually eroded in law and in practice, and did not become legally recognized until the 1980s–1990s. The Fisheries Act 1996 and customary fishing regulations (for the North and South Islands) included provisions for the creation of *taiāpure* local fisheries and *mātaitai* reserves (Bess 2001; Jackson 2013). These mechanisms enable the local management of fisheries resources through bylaws and regulations, the most significant of which are those that specifically prohibit the harvesting of attached kelp. In the East Otago Taiāpure area in southern New Zealand, for example, the harvesting of seven species of attached kelp (including *E. radiata, M. pyrifera* and *L. variegata*) and other habitat-forming brown seaweed (*Durvillaea* spp., *Marginariella boryana* and *M. urvilliana*) cannot be harvested (Fisheries (Amateur Fishing) Regulations 2019 and Fisheries (South-East Area Commercial Fishing) Amendment Regulations 2019).

Several *iwi* (tribes) have initiated settlement claims against the Crown. Ngāi Tahu is the largest *iwi* in southern New Zealand, for whom explicit provisions were made regarding the recognition of culturally important kelp species as "non-commercially harvested species" as part of their settlement (section 306 of the Ngāi Tahu Claims Settlement Act 1998). Notably, this includes rimurapa, a species that was, and still is, used for various purposes, including *pōhā* (kelp bags) for preserving food, karengo (*Porphyra/Pyropia* spp.) and *Ulva* spp. Rimurapa is also designated a taonga species in Schedule 97, which means that any activities that affect these species (e.g. harvesting under the Fisheries Act 1996 within the Ngāi Tahu claims territory) require consultation and advice from Te Rūnanga o Ngāi Tahu (the tribal council of Ngāi Tahu). In contrast, the wider values of *M. pyrifera* for the Ngāi Tahu are not yet recognized, despite the species providing the foundations of fisheries that support the tribe's ways of life. In parts of the Ngāi Tahu *rohe* (territory), *M. pyrifera* is known as a *kōauau* (flute), as its bladder is used to make a musical instrument. As an ecosystem engineer and a cultural keystone, *M. pyrifera* has significant cultural and economic importance for the coastal communities of southern New Zealand, yet the law still only provides for its management in a way that ignores the value it provides.

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Chapter 6. Approaches to managing kelp forests

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Highlights

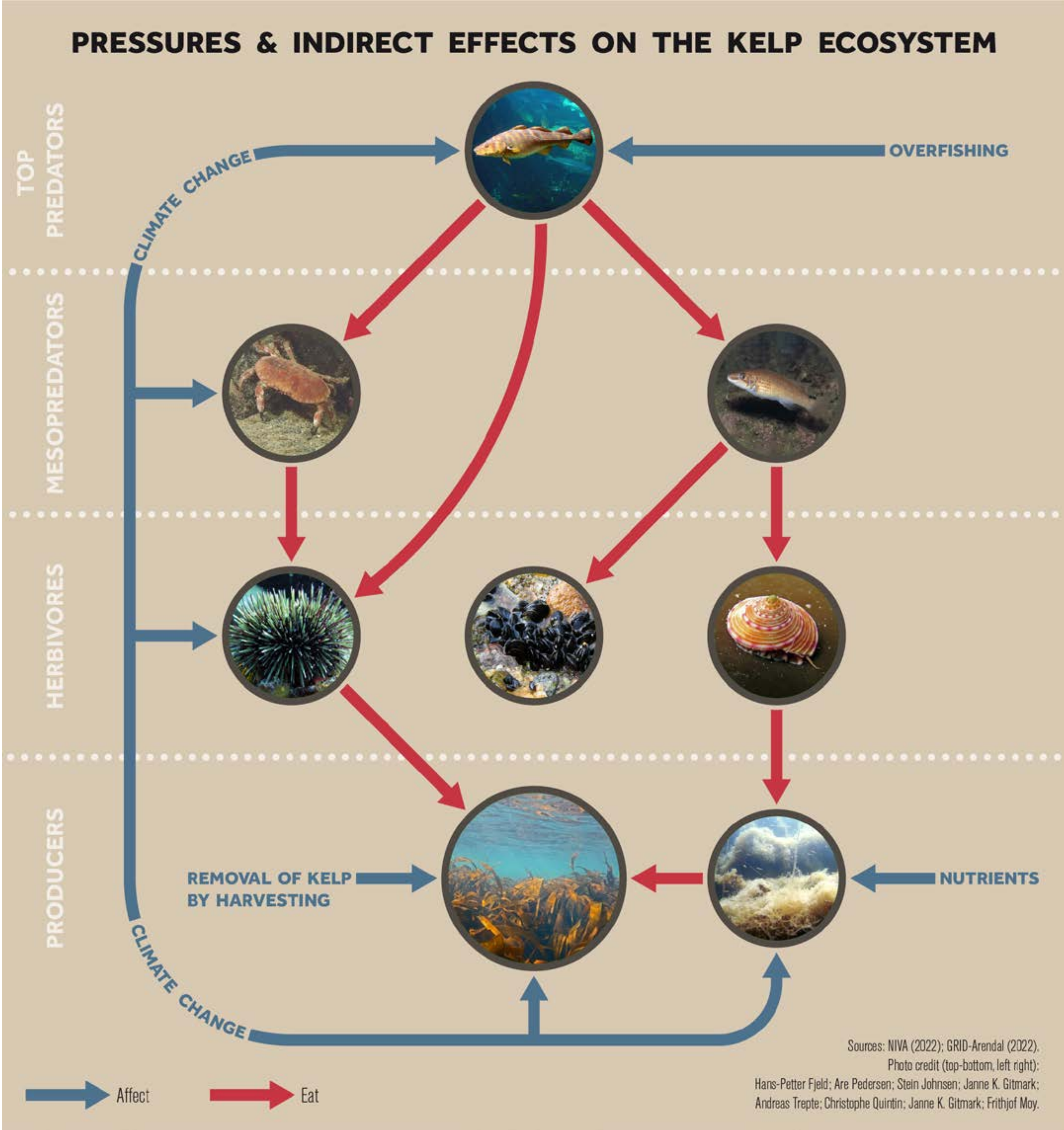
- **Managing the harvesting of wild growing kelp is still the most developed form of kelp management.**
- **Humans' intensifying use of the ocean is exposing kelp to many pressures in addition to harvesting. The cumulative impacts of these pressures need to be addressed in an integrated manner.**
- **Ecosystem-based management is a strategic approach to integrated ecosystem management that can act as an umbrella for other approaches, including marine spatial planning, MPAs and initiatives towards individual activities that affect kelp ecosystems.**
- **The management of kelp as ecosystems is usually not specific and tends to be included in more general approaches to ocean management.**

Management in this context is understood as the active controlling of human activities that affect kelp forests, either directly or indirectly through ecosystem interactions. Kelp forests can be managed according to different objectives using a range of approaches and strategies. This chapter broadly distinguishes between the management of kelp harvesting and protection of kelp forests as ecosystems, which is often embedded in wider ocean management systems. As discussed in chapter 5, various laws and policies create management frameworks and contain legal tools that can be adopted and applied in different situations.

Humans of different cultures have used kelp for various purposes, such as food, medicines and fodder, for centuries (chapter 3). Typical issues that need to be addressed by a harvesting regime include the allocation of harvesting rights, the creation of mechanisms to avoid overexploitation of resources and to prevent ecosystem damage, and the resolution of conflicts with other activities. Traditionally, kelp harvesting was managed at the local level, with systems built on local knowledge and activities conducted based on both formal and informal social norms (Berkes 2015; Ostrom 2008). In modern societies, national governments have the primary responsibility for the conservation and utilization of living resources according to the law of the sea. However, national management systems may build upon and coexist with local and traditional management institutions, as case studies in this chapter illustrate is common for kelp harvesting, with rules often formalized in legislation, but mixed with other social norms and ideals on how people should interact with kelp (Berkes and Turner 2006; Lertzman 2009). Another difference from traditional systems is that the knowledge underpinning the harvesting of living marine resources should build on the best scientific evidence available according to the law of the sea. Traditional knowledge often complements such evidence in practice.

Increasing knowledge about the role of kelp in the wider ecosystem and the many ecosystem services it provides (chapter 3) has led to a growing focus on the need to protect kelp forests and set new goals for kelp management. The challenges faced by this ambition are much more complex than simply addressing potentially unsustainable harvesting. As humans' use of the world's oceans intensifies, more pressures are placed on kelp forests, among which are climate change, coastal development, overfishing, nutrient overloading and the introduction of other species (chapter 1). These interact and have cumulative impacts (Figure 6.1). Many degraded kelp ecosystems have been subjected to interacting pressures over time, in some cases with a triggering event having caused a rapid collapse of an ecosystem and a new stable ecological state in its place that is hard to reverse (known as a regime shift) (Steneck *et al*. 2002; Filbee-Dexter and Scheibling 2014). It is necessary to identify the most relevant pressures of each situation and to address those most prominent through targeted management actions, especially those maintaining collapses in situations where this has occurred. This is the key aim of ecosystem-based management (also referred to as the ecosystem approach), which can act as an integrated umbrella for kelp management (Norwegian Blue Forests Network 2021; Hamilton *et al*. 2022). Within this, different management approaches may be applied, including initiatives to address individual pressures, area-based management by marine spatial planning and MPAs, and the management of harvesting.

Figure 6.1. Pressures and indirect effects on a kelp ecosystem



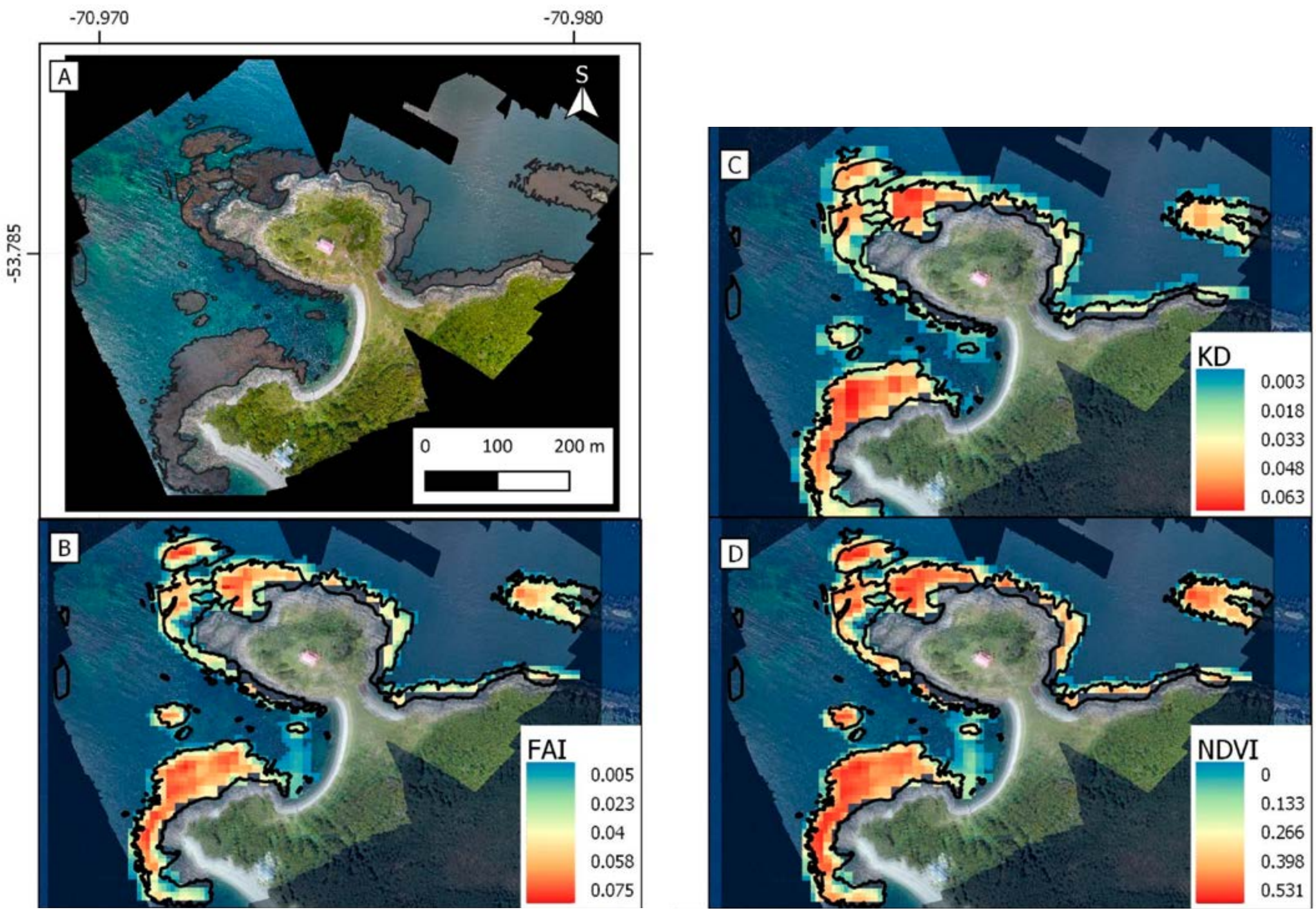
Management geared towards protecting kelp forests faces many challenges. Firstly, when assessing for cumulative impacts, an ecosystem perspective is needed to understand the trophic interactions that lead to indirect effects on kelp (Figure 6.1). Such an understanding makes it possible to identify causal factors that are not immediately apparent, affecting any level of the food web. Ecosystem-based kelp management may therefore involve rebuilding populations of top predators as well as controlling pressures that affect primary production. Secondly, many pressures that kelp forests face do not originate locally. For example, water quality in coastal areas tends to be highly influenced by land-based sources of pollution, some of which are located upstream in watersheds. Similarly, the open ocean system connects local water conditions to wider regional and global stressors. Such connections require consideration as they may extend the need for management geographically beyond a confined management area. Thirdly, the management of all these activities occurs in different sectoral administrations that operate at different levels of governance, often in interplay with each other. Many private stakeholders, including industries and civil society, may play an important role. Effective involvement of the relevant public and private actors is challenging, but is a prerequisite for mobilizing those who have knowledge, rights and vested interests, and who control possible solutions. Lastly, management that aims to protect kelp forests may form part of more general marine management approaches that could positively contribute to kelp forest protection, even in cases where this is not the specific focus. A key challenge for future kelp forest management is to define measures that more specifically and directly address kelp issues and incorporate these within wider ocean management approaches.

This chapter reviews kelp management through exploring broader ocean management approaches that may be applied to protect kelp forests, and then examines the management of kelp harvesting.

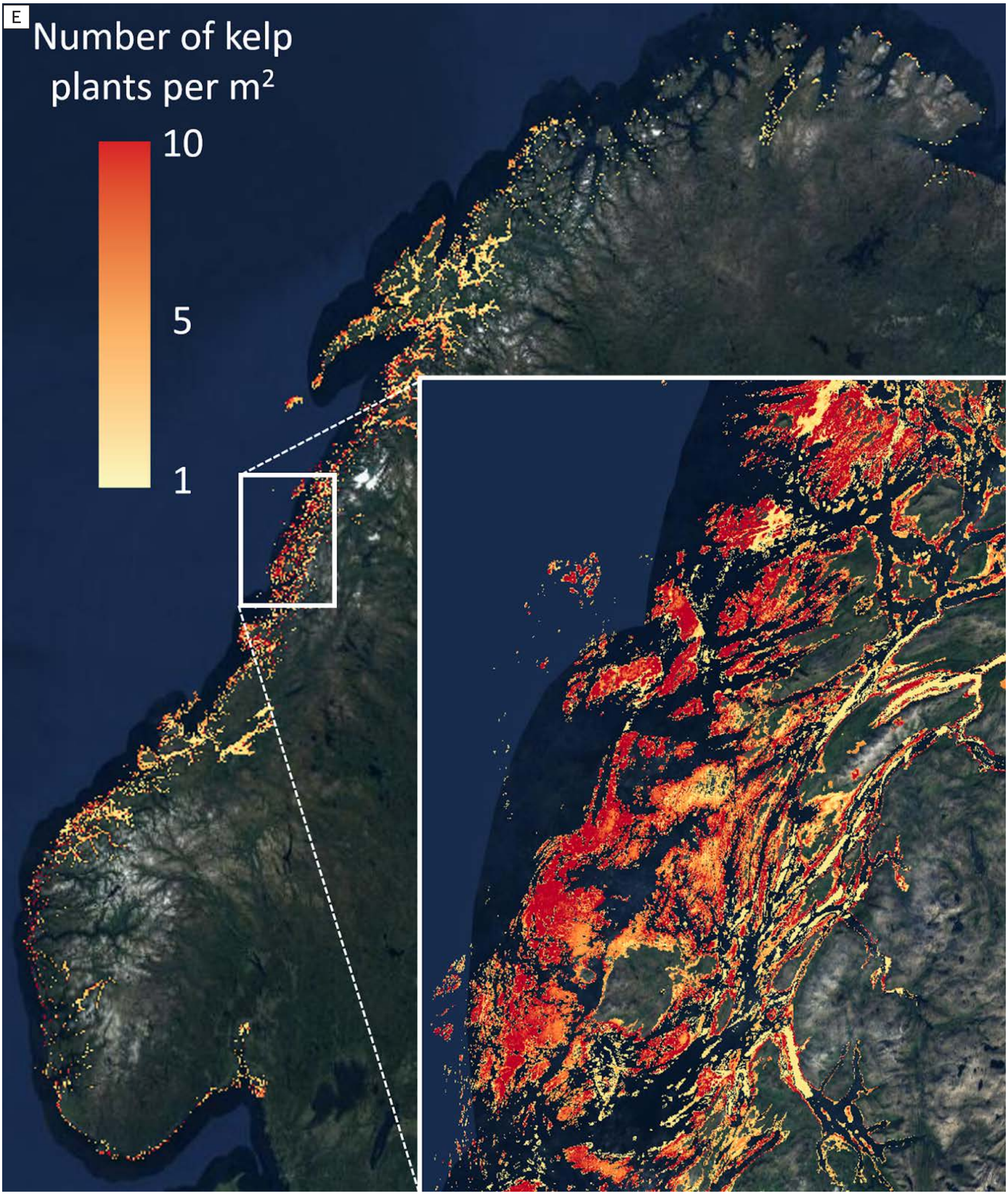
Assessing and monitoring kelp ecosystems

Mapping the distribution and biomass of kelp forests is a key starting point for any attempt to manage kelp forests. Traditional scientific methods have relied on field observations, including underwater surveys conducted from boats and by divers, as well as aerial photographs. Information from users of the marine areas can be an important additional source of information, especially when systematic scientific mapping is scarce. Such a combination of data sources was applied to map the extension of kelp forests in Canada as part of an initiative to identify ecologically or biologically significant areas. Modern advances in remote-sensing techniques offer new possibilities for covering large areas much more efficiently and accurately (Bennion *et al*. 2018), especially when combined with artificial intelligence and machine-learning algorithms. This enables a better delineation of coastal habitats such as kelp forests and the detection of spatial variability. Satellite images can capture intertidal occurrences and floating kelp canopies in upper surface waters fairly well (Figure 6.2), while aerial images from light aircraft and drones can create habitat maps with very fine resolution down to depths of a few metres. Autonomous underwater vehicles can be used in deeper waters, which is necessary to capture the typical kelp forest distribution down to around 30 m, as well as species that extend deeper. The use of spatial distribution modelling, validated with observations, also has unused potential for large-scale mapping, upscaling and the guiding of priority management areas (Figure 6.2). A general problem in the mapping and monitoring of kelp, however, is the wide variety of often incomparable methods and poor coordination of efforts (Duffy *et al*. 2019). A significant amount of standardized baseline information on standing stock and extent is missing for many areas.

Figure 6.2. Mapping the distribution of kelp using different methods. A-D: Satellite-based maps obtained using an algorithm for giant kelp forests in the Strait of Magellan, South America. E: High resolution model showing estimated kelp (*Laminaria hyperborea* and *Saccharina latissima*) density along the coast of Norway

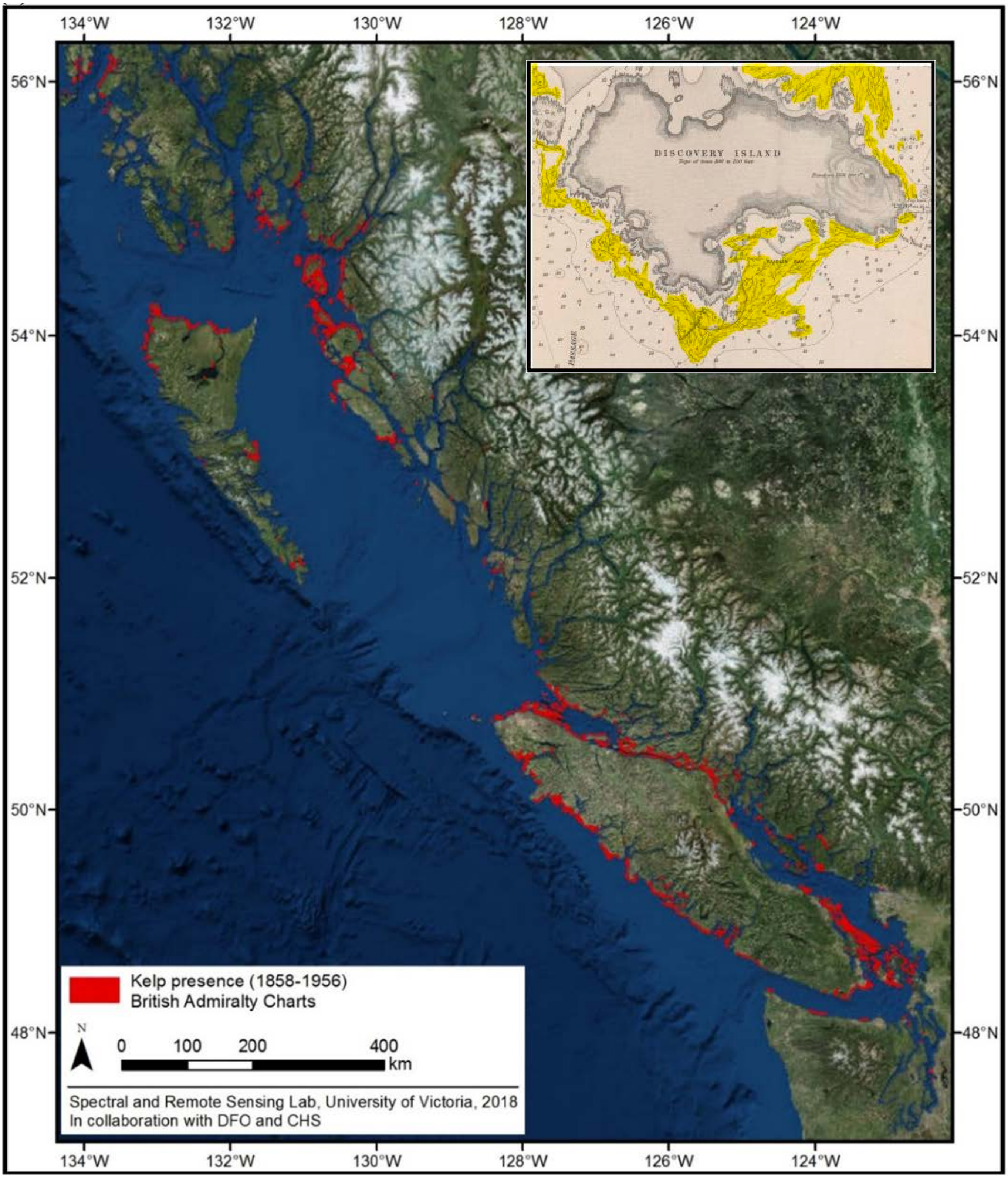


Source: Mora-Soto *et al*. 2020



Source: Frigstad *et al*. 2020

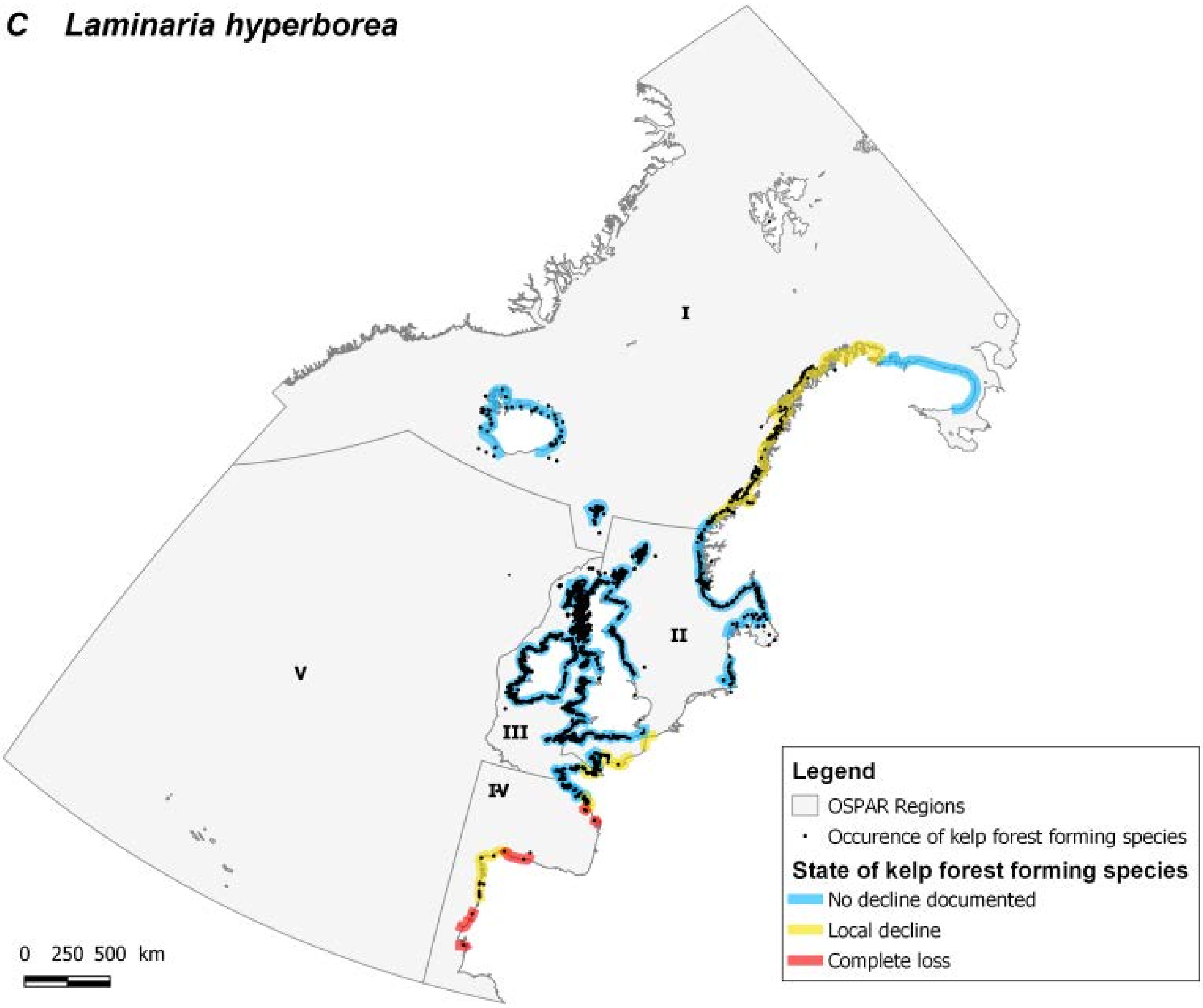
Figure 6.3. Map of historical kelp forest distribution in British Columbia, Canada, made from digitizing charts from the British Admiralty created between 1858 and 1956



Source: Adapted from Costa *et al*. 2020

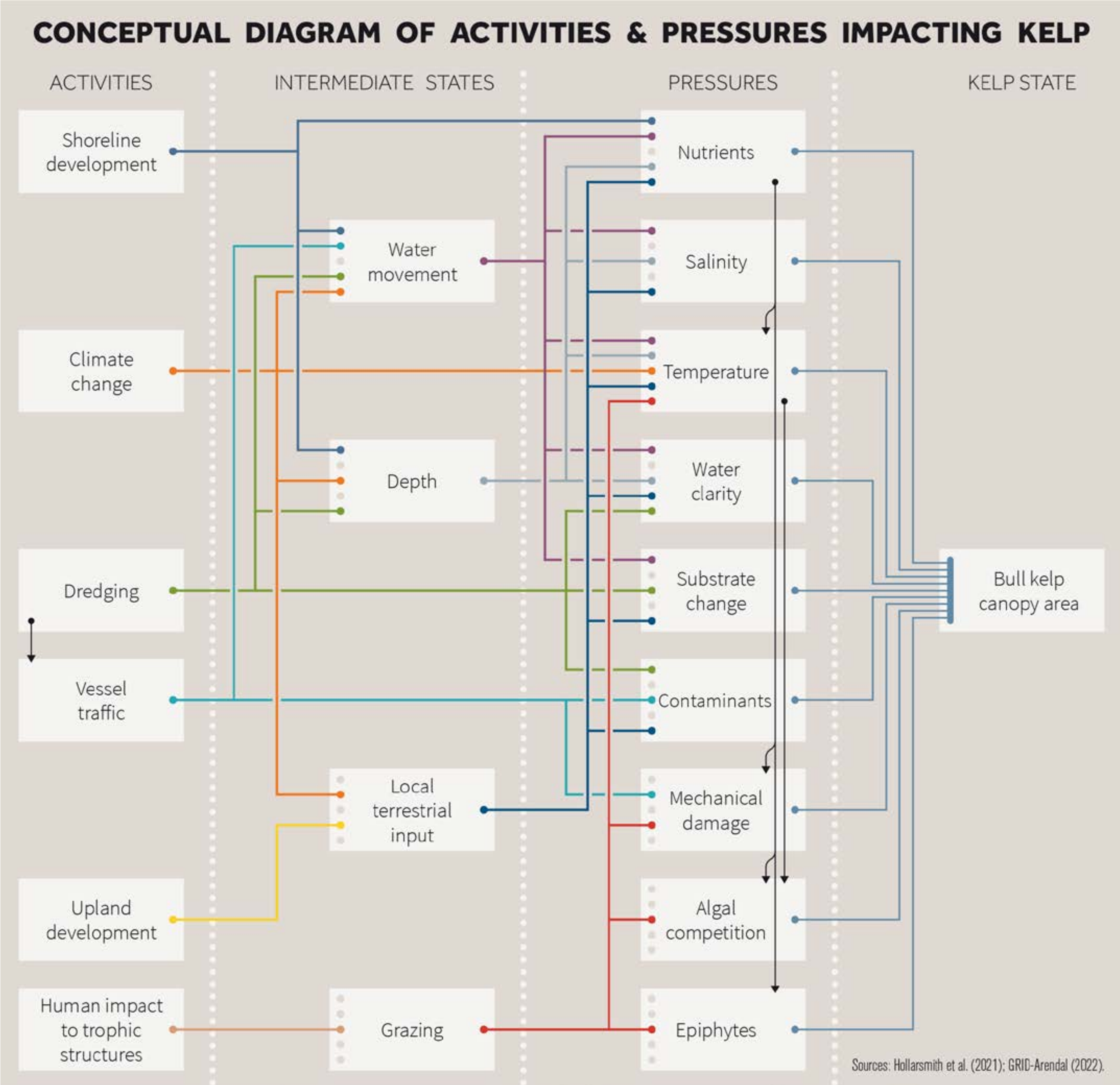
Assessments on the state of kelp forests provide key information that is necessary for evaluating the need for management actions. Such assessments require more data than just current distributions. There is a need to establish a baseline for evaluation of the state of kelp that also can be applied to set management objectives. Data on forests' historic status and analyses of temporal variability and trends are a common approach for establishing a baseline for comparisons and setting management objectives. However, monitoring with consistent data collection over time is rare in ecological literature, meaning that historical data may need to be assembled and reassembled (Simkanin *et al.* 2005). Figure 6.3 shows an example from British Columbia (Canada), where British Admiralty charts created between 1858 and 1956 were used to produce a digital historical baseline map of kelp presence (Costa *et al.* 2020). If a state assessment has demonstrated unsatisfactory conditions compared with management objectives, it can, for instance, be used to advocate for the listing of kelp forests. This was done for the OSPAR area (Figure 6.4), where strong evidence of the decline of six kelp species has led to their nomination for inclusion on the OSPAR list of threatened and/or declining habitats (de Bettignies *et al.* 2021a; de Bettignies *et al.* 2021b).

Figure 6.4. Map of kelp forests in the North-East Atlantic



Note: Kelp forests in the North-East Atlantic were assessed against criteria that included global and regional importance, rarity, sensitivity, ecological significance and status of decline. Major declines have occurred in the southern parts of the OSPAR area.
Source: de Bettignies *et al.* 2021a

Figure 6.5. Model of how activities combine to create pressures that affect the state of kelp in the Salish Sea



To manage kelp forests effectively, it is necessary to identify how pressures from various human activities contribute to cumulative impacts. It is also useful to estimate the relative importance of each pressure and to identify the activities behind them to develop a clearer understanding of what needs to be addressed. In the Salish Sea bordering Canada and the United States of America on the west coast, data gaps and a lack of long-term monitoring has hampered efforts to identify the reasons for a rapid decline in kelp forests (Hollarsmith *et al*. 2021). A focus group of experts was gathered to identify the potential causes, resulting in the production of a conceptual model of how various human activities combine to produce pressures on kelp forests (Figure 6.5). Following this, the experts conducted a structured literature review that refined the model. When supported by existing quantitative information, this approach can guide management decisions, as well as initiatives for research and monitoring, which may produce data that can then help to modify the initial model and evaluate management interventions taken (Hollarsmith *et al*. 2021). Although there are many approaches to conducting a diagnostic ecosystem assessment (Borja *et al*. 2016), they are underused for kelp forest management.

When initiating assessments, it is important to compile all existing and reliable information, rather than focusing on data deficits. In Norway, for example, the Government instructed planning teams to only use existing knowledge when it started preparing for ocean management plans in 2002 (Box 6.1). After a system for the integrated monitoring and assessment of the marine ecosystem was established in a first plan (2006), new research and monitoring activities were launched to address identified relevant knowledge needs for management. Similar evaluations have been included in later plans, resulting in many new initiatives for acquiring new knowledge (Sander 2018).

Uncertainty in the knowledge base and judgements should be evaluated to inform later decisions on the management of kelp forests. High uncertainty justifies an adaptive management approach and greater precaution in decision-making. This is especially relevant for kelp forests given that these ecosystems are dynamic and may therefore face rapid shifts in their state (Hamilton *et al*. 2022).

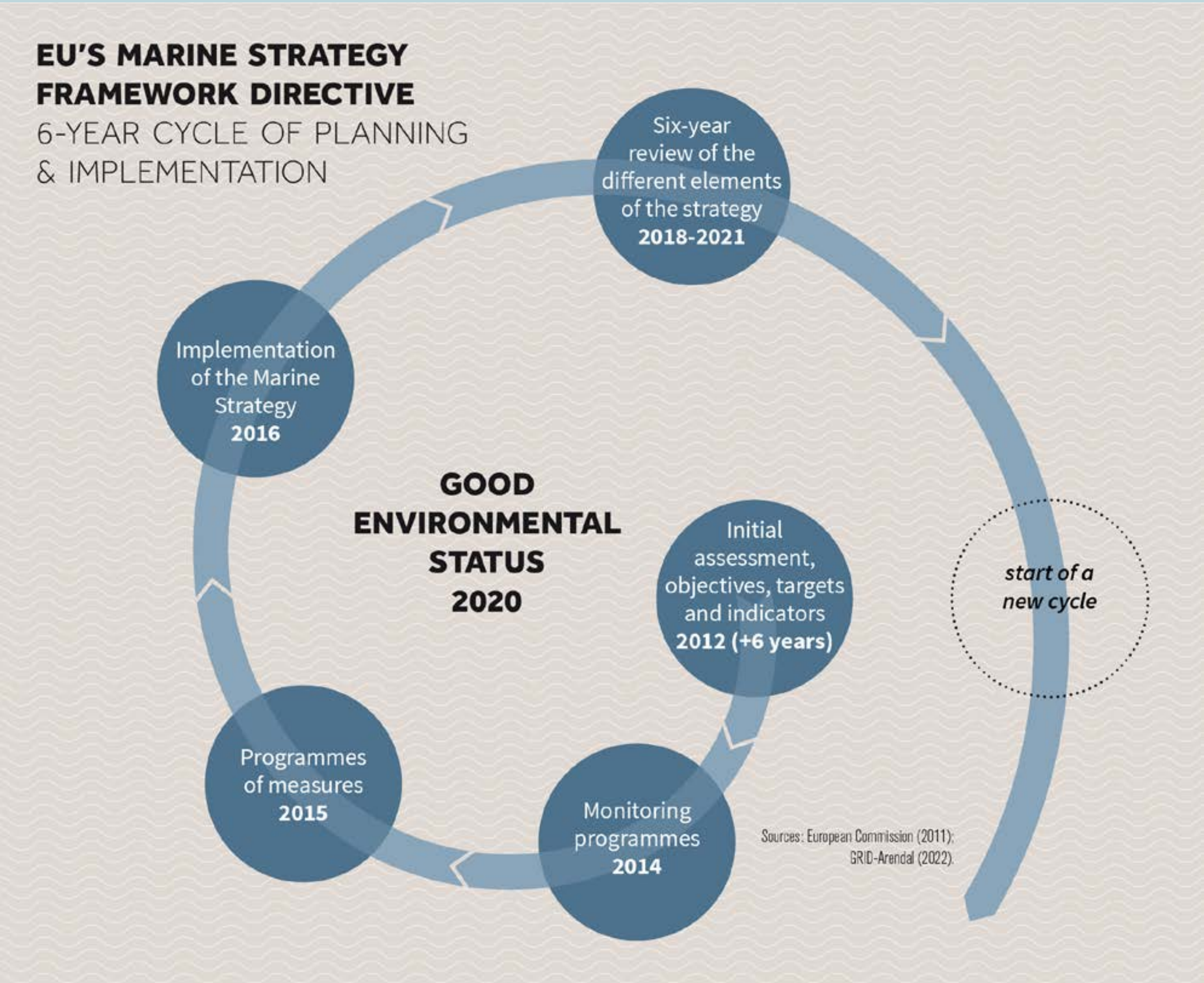
Ecosystem-based management

Ecosystem-based management is an integrated approach for managing the human activities that cause cumulative impacts on ecosystems such as kelp forests. The aim is to ensure that cumulative impacts from all human activities are kept within thresholds that ensure healthy, productive and resilient ecosystem conditions, thereby providing desired ecosystem services to humans. The approach enables the sustainable use of ecosystems if such thresholds are not exceeded. Balancing conservation and the use of ecological resources may therefore form a part of ecosystem-based management.

Box 6.1. Case study: Ecosystem-based ocean management in Europe

The European Union has legislated ecosystem-based management in two directives that have established the framework for national implementation in Europe. The Water Framework Directive (2000) takes a river basin approach to the integrated management of freshwater and associated waters in coastal zones, while the Marine Strategy Framework Directive (2008) takes a similar approach for Europe's oceans. Norway began initiating ecosystem-based ocean management prior to the European Union's directive and has already updated its ocean management plans several times. These plans share many key characteristics with the Marine Strategy Framework Directive (Sander *et al*. 2022).

Figure 6.6. Example of marine strategy cycle per the Marine Strategy Framework Directive



Both the European Union and Norway divide oceans into management units that can be referred to as large marine ecosystems. Achieving a good environmental status in these ecosystems is a key goal for both approaches. The definition of such a status must be based on an assessment of the state and trends of the ecosystem, into which kelp forests may be included according to both the Marine Strategy Framework Directive and the Water Framework Directive (de Bettignies *et al*. 2021b). The overarching goal is broken down into a hierarchy of objectives and targets that gradually becomes more concrete, with properties that can be used for evaluation and comparison purposes. Both state variables and pressures from human activities are included in assessments, which highlight the extent to which a good environmental status has been achieved, along with challenges that need to be addressed. The same system for measuring the state of an ecosystem is applied in monitoring programmes that can follow future developments and assess the results of measures taken.

The initial assessment – or those updated in later planning cycles – acts as the basis for creating a programme of measures. During this phase, the challenge is to find a combination of measures that can contribute to achieving or maintaining the good environmental status, while also taking future developments into account. All relevant measures may be included, such as regulations of activity levels, on the use of ecosystem services and on where and when activities may take place, as well as economic incentives or restoration initiatives. The Marine Strategy Framework Directive requires the assessment of the measures' impacts, side effects and effectiveness, in addition to a public review of a suggested programme of measures. The Norwegian management plans have no such requirements for assessing measures. Rather, they are prepared in closed governmental processes under the guidance of the Cabinet, and are presented as white papers to Parliament. After their approval, the Government is responsible for implementing the measures, which has been an effective practice (Sander 2018). The development, approval and implementation of such plans in other European countries vary since the Marine Strategy Framework Directive only requires countries to designate responsible authorities and ways in which collaboration can occur.

Ecosystem-based management should start with a diagnostic assessment of the state of an ecosystem and the human activities placing pressures upon it. However, following up a diagnosis with treatment is a key challenge in ecosystem-based management. Measures to reach or maintain the desired good environmental status need to be identified, while also taking into account scenarios for future developments. Such measures should also be assessed to determine their effectiveness, with those that are most feasible and acceptable to relevant ocean users, stakeholder and management units taken into account (Box 6.1). The processes require the involvement of many sectors at various levels of governance, in both public and private organizations, sometimes also in neighbouring States. The programme of measures that results from deliberations between the involved parties and a political decision is the key component of a management plan (Figure 6.7). The plan should also include mechanisms for implementing the measures and subsequent monitoring, which would be input to adaptive management in a new cycle of planning.

Ecosystem-based management plans at the scale applied in Europe are strategic and coordinate the actions of many actors. All types of management approaches and legal instruments may be included, enabling such plans to serve as an umbrella mechanism for managing kelp ecosystems. Ecosystem-based management challenges include the mobilization of knowledge and stakeholders, as well as the politics involved in decision-making, including on who has responsibility for which actions (Sander 2018). Building up an ecosystem-based management system may take time and evolve over several cycles of planning and implementation.

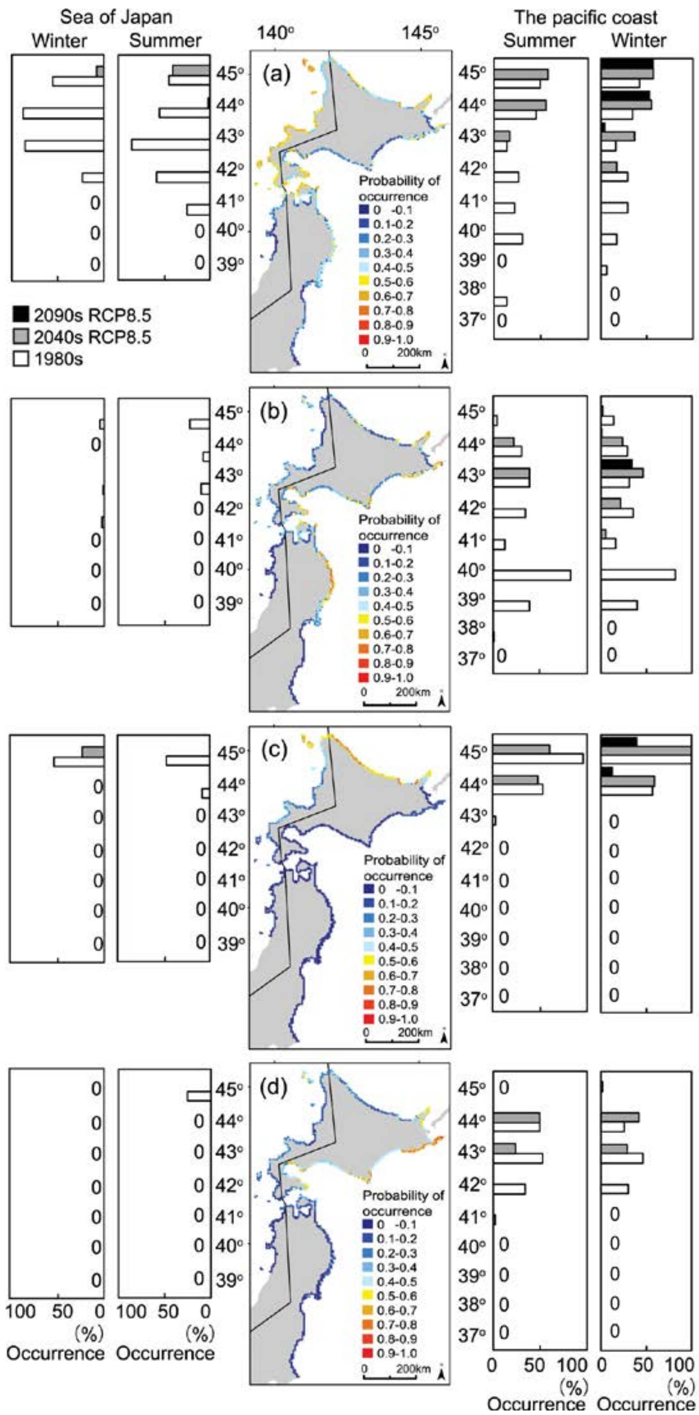
Figure 6.7. Ecosystem-based management involves preparing a programme of measures (blue arrows), based on assessments of the cumulative impacts upon the ecosystem to be managed (red arrows)

Sources: NIVA (2022); GRID-Arendal (2022).
Photo credit (clockwise, left to center): Christof Kemman; Ole André Rekkedal; Halvard Alvik; Caleb Woods; Sam Lehman; Olejk; Are Pedersen; Frithjof Moy; Janne K. Gitmark; Hans Petter Fjeld; Janne K. Gitmark.

Managing pressures on kelp ecosystems through non-spatial approaches

Different approaches are needed to deal with the individual pressures that affect kelp ecosystems. Addressing these requires the mobilization of a wide range of measures and stakeholders, many of whom may not be among those traditionally involved in ocean management.

Figure 6.8. Future shifts in major kelp species in northern Japan calculated for two IPCC scenarios for 2040 and 2090



Note: The model predicted that 6 of 11 cold-temperate kelp species may become extinct around Japan by the 2090s under the scenario with the most severe warming (RCP 8.5).
Source: Sudo *et al*. 2019

Long-term changes and extreme events caused by global warming are already major threats to kelp forests in temperate regions (chapter 1). So far, there have only been regional studies on the sensitivity of kelp species towards various climate scenarios (see Figure 6.8, for an example). Under likely future climate projections, kelp forests will continue to shift their distribution poleward, with extinction or reduced abundance expected in areas where they used to be a key ecosystem species (chapter 2). The solution to the problem is to reduce carbon dioxide emissions and other causes of climate change according to the UNFCCC and the Paris Agreement. However, the continued functionality of kelp forests is an important nature-based solution to mitigate climate change, making the threats caused by global warming to the ecosystem even more concerning (World Business Council for Sustainable Development no date). Analyses of the carbon sequestration potential of kelp forests can therefore provide an important motivation for local kelp forest management (Hutto, Brown and Francis 2021). An adaptation strategy to preserve kelp forests threatened by climate change is to abate local pressures on the kelp ecosystem (Hamilton *et al*. 2022). Such efforts include the whole suite of approaches referred to in this chapter. For example, reducing the overfishing of lobster preying on sea urchins would significantly increase the resilience of kelp forests to projected climate stressors in Tasmania (Ling *et al*. 2009). A toolbox of approaches that can be applied as part of local and regional climate change adaptation should be developed, including breeding and out-planting of more heat-tolerant kelp species (chapter 7) and the special protection of kelp climate refuge areas (Hamilton *et al*. 2022).

Poor water quality is a significant pressure on kelp in many regions, especially the overload of nutrients, which leads to eutrophication and particles darkening waters, thereby hindering photosynthesis. Certain contaminants such as herbicides, metals and oil products have been found to have some direct negative impacts on kelp forests but may also have some indirect impacts through altering other species in the food web (de Bettignies *et al*. 2021b). Addressing water pollution is usually a part of general environmental policies, from which kelp forests will also benefit. However, the specific sensitivity of kelp towards pollution could be better accounted for in such policies. Sources of nutrients are diverse and include sewage, industrial pollution, aquaculture and agriculture (Figure 6.7). Managing these may require applying specific legislation in addition to general pollution legislation, different types of technologies and measures, and different sources of funding. For example, preventing run-off from agriculture includes regulating the use of fertilizers and manure, building retention dams and developing green belts towards watercourses. The responsibility for such actions may lie with agricultural management authorities, which may apply sectoral regulations and offer economic stimuli to farmers. Reducing nutrient flows from aquaculture includes site selection, feeding practices and the development of semi-enclosed and closed facilities. For industries and sewage, better cleaning technologies that reduce phosphorus and nitrogen are important. Nutrients and particles may also stem from run-off from both natural and artificial surfaces, so efforts to curb soil erosion and manage land use and coastal constructions may be necessary to integrate land-use management and the marine environment.

There are many examples of the negative impacts of so-called trophic cascades on kelp forests, created by the top-down effects of imbalances in predator populations (chapter 1). The factors controlling the sizes of such populations are diverse and may include direct harvesting, pollution, climate change, diseases and competition or predation from other species. Trying to optimize the composition of species in a food web to restore an ecosystem is a complex undertaking with many unknowns. It may, for instance, include trying to increase stocks of top predators, such as sea otters, lobsters and fish that control sea urchins grazing on kelp. Actions to achieve this could involve stopping hunting, reducing the total allowable catch of predator fish or listing species and making action plans to protect them against relevant pressures. The ecosystem approach to fisheries mandates fisheries managers to limit fishery-related impacts on the ecosystem and to ensure that ecological relationships between species are maintained (FAO 2005). RFMOs and individual States may therefore set quotas to maintain stocks of predator fish at levels needed to indirectly protect kelp, close fishing in areas that are crucial for such fish or kelp, or introduce technical measures that reduce negative impacts.

Area-based management: marine spatial planning and marine protected areas

Area-based management presents other options for protecting kelp forests. In contrast to the previous measures mentioned, area-based management approaches focus on regulating ocean uses in terms of space and time. Marine spatial planning is a tool that allocates the use of ocean space to achieve ecological, economic and social objectives (Ehler and Douvere 2011). Balancing ocean use and non-use is therefore a core aspect of this tool. MPAs aim to conserve marine habitats and species by restricting specified ocean uses in an area. Mapping the distribution of kelp forests is crucial for area-based management. Various approaches for assessing the values of the different areas and sub-areas are also key for prioritizing between areas and for analysing conflicts with other uses.

Marine spatial planning

Marine spatial planning is a tool for balancing multiple and often competing demands on marine space. In its simplest form, it relates to functional zoning, i.e. the allocation or exclusion of specific human activities in certain areas. At the other end of the scale, marine spatial planning may create a complex system for planning, management, licensing and enforcement (Jones *et al.* 2016). Spatial measures may then be supplemented by policies that should be taken into account in sectoral regulatory regimes that affect the marine area. In this way, marine spatial planning may provide an overarching, cross-sectoral framework.

The extent to which marine spatial planning functions as a comprehensive and coordinating instrument depends on its relationship to sectoral management. This varies between countries. Depending on legislation, marine spatial planning may not apply to all sectors and its bearings on sectoral policies can be weak or strong. For example, Scotland's National Marine Plan sets out general and sectoral policies and supports economic development where it can be demonstrated as sustainable (The Scottish Government 2015). At the same time, the plan specifically protects kelp and associated ecosystem services and, in addressing coastal protection, recognizes the protective role of "kelp beds, biogenic reefs and sandbanks". Such policies are intended to ensure that any planning or decisions consider the potential of marine activities to affect kelp forests and the ecosystem services they provide.

Marine spatial planning may be used to directly protect kelp forests by not allowing or restricting activities that are detrimental or damaging in kelp forest areas. Such activities may include those that cause physical destruction, such as the construction of various installations, dredging, dumping, anchoring and the extraction of minerals (de Bettignies *et al.* 2021b). Even when such activities are conducted outside the kelp forest itself, sediment depositions and pollution may still impact the kelp forests, meaning protection zones may be required. In coastal areas, regulations on land reclamations and coastal constructions in or near kelp forests may be imposed (de Bettignies *et al.* 2021b). A marine spatial plan may also permit kelp harvesting in a particular area and for a defined period of time, subject to more detailed regulations of a harvesting regime.

Marine protected areas

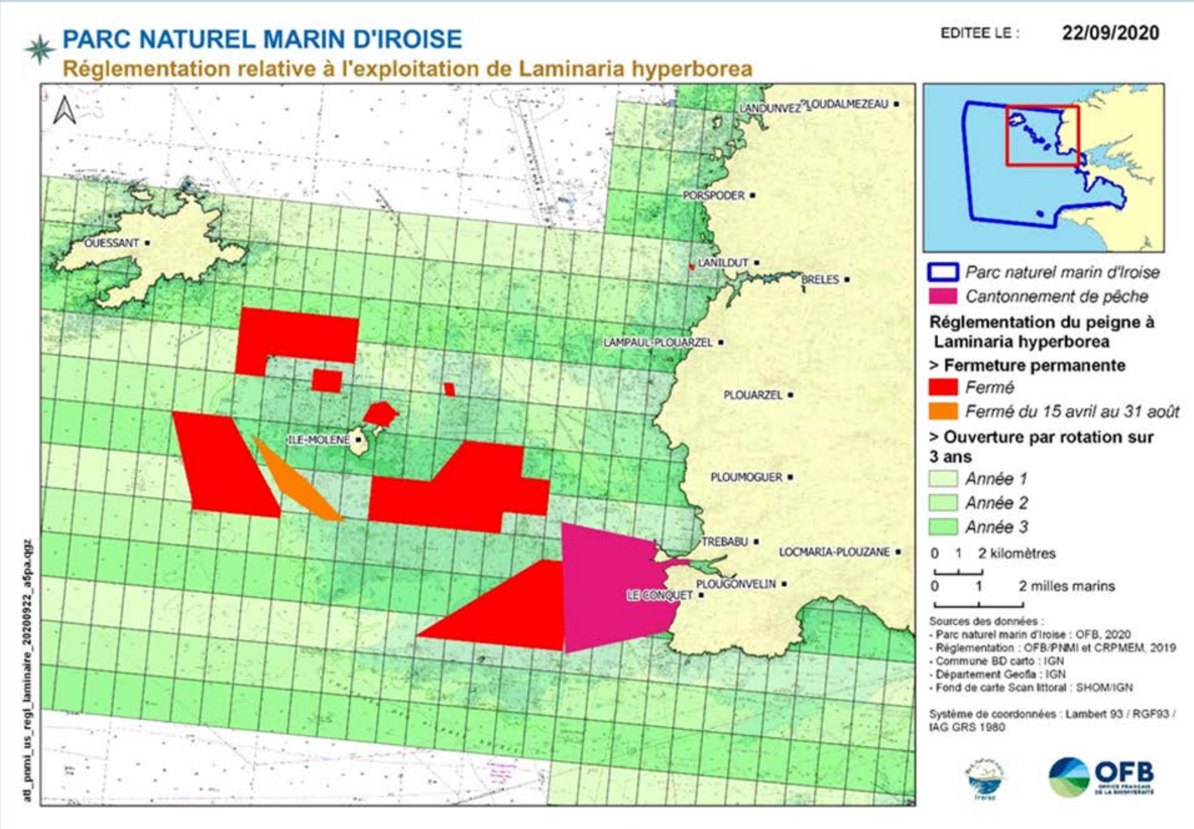
MPA is a broad term that refers to a wide range of measures applied for the conservation of biodiversity or cultural heritage in coastal and ocean areas. The level of protection varies from no-access zones to areas where most activities are permitted under certain restrictions. While fishing and kelp harvesting are banned in no-take zones, MPAs may permit kelp harvesting in zones with more specific restrictions (Box 6.2).

© Wildlife Conservation Society/Mauricio Palacios

Box 6.2. Case study: Kelp harvesting in Iroise Nature Marine Park, France

In the Iroise Sea in Brittany, kelp forests, rocky areas off the coast and shallow bays provide spawning grounds and nurseries for many marine species. In 2007, the Iroise Natural Marine Park was established as France's first MPA (Frangoudes and Garineaud 2015).

Figure 6.9. Zoning of the Molène archipelago in the Iroise Marine National Park



Notes: The zoning closes certain areas seasonally (orange areas), permanently (red areas) or according to a three-year fallow period (green-scale grid) for *L. hyperborea* harvesting. The pink area is closed for fishing and the perimeter of the park is marked in blue on the top-right insert image.
Source: Office français de la biodiversité and Iroise Marine National Park 2020, Available at https://parc-marin-iroise.fr/

The local population has harvested seaweed (*L. digitata*) and tangle (*L. hyperborea*) for centuries and used kelp for heating, livestock feed and food in times of famine, as well as for manufacturing. Industrial processes based on algae have previously included glassmaking and iodine production and now alginate production. Harvesting methods have evolved from manual collection on foot, which still occurs, to modern fishing vessels equipped with mechanical gears.

After becoming an MPA, park authorities had to tailor biodiversity conservation objectives for the park to existing and traditional activities, including kelp harvesting. The park considers kelp forests as natural heritage, and kelp harvesting as intangible cultural heritage, with both therefore protected under the park's mandate. Although the park has no authority over fisheries or kelp management, it works towards balancing the objectives of conserving kelp forests and safeguarding the know-how of kelp harvesters.

In France, kelp harvesting has been regulated since 1681 through national ordinances, bylaws and laws. All regulations primarily target the avoidance and mitigation of conflicts between harvesters rather than resource management. Despite having been harvested for a few centuries, kelp forests were and are still abundant according to scientists responsible for kelp stock assessments. Kelp harvesting is exclusively reserved to professional fishers and requires a specific harvesting licence. According to the Rural and Fisheries Act, the Regional Fisheries Committee of Brittany has granted this licence since 1993. The Committee manages all fisheries activities, including kelp harvesting, that take place in territorial waters (12 miles) and the public maritime domain (foreshore), in collaboration with regional fisheries administrations. All regulations related to *L. digitata* and *L. hyperborea* are discussed within the fisheries committee's working group, which is composed of kelp vessel owners (30 active vessels), the park authority, representatives of the processing industry, representatives of the regional and district fisheries administrations and scientists. The kelp harvesters have the decision-making power in the working group, but all decisions must receive the approval of scientists first and then the fisheries administration. The park authority has an advisory role within the working group. The park's council can oppose the kelp harvesters' decisions if they will considerably impair kelp forest sustainability and biodiversity conservation. Key features of the park's local management include the limitation of harvesting to 20 per cent of the estimated biomass and its division into harvesting areas with maximum out-take. A rotational system is in place for access to areas according to the species. Each harvesting area is open for three years and then closed for three years.

Collaboration and co-management between the fisheries committee and the park have both positive and negative impacts for kelp harvesters: on the one hand, projects can help increase scientific knowledge on kelp forests to improve the resource's management, but on the other, new knowledge can lead to harvesting restrictions. So far, no major conflicts have arisen between the fisheries committee and the park as both seem to be achieving their objectives. However, while the positive impact of no-take zones for kelp forests is clear, the seasonal closure and three-year fallow period remain a debate in the scientific community in terms of kelp forest resilience and the sustainability of harvesting.

MPAs can be designated through marine spatial planning processes with comprehensive planning and balancing towards other interests. MPAs can also be designated through separate processes that aim to identify and protect valuable and vulnerable marine areas. Initially, MPAs were created for single areas, but now there is increased interest in designating networks of protected areas to ensure connectivity between different marine habitats and ecosystems. Recently it has also been opened up to designate "other effective area-based conservation measures" as a supplement to formally protected areas (Convention on Biological Diversity 2018).

Although MPAs are rarely designated solely for the protection of kelp forests, kelp can be an important ecological feature that influences an MPA's establishment. MPAs that contain kelp forests can be found in most temperate regions. For example, in Scotland, kelp habitats are considered as priority marine features, and were therefore included in nature conservation strategies that led to the protection of kelp beds in 17 MPAs (NatureScot 2017). In South Africa, important kelp ecosystems are included in three MPAs with complex conservation targets (Marine Protected Areas South Africa no date). An example from Japan can be found in chapter 5. California in the United States of America has designated a network of 124 MPAs based on scientific advice and extensive stakeholder participation, in which kelp forests are recognized as iconic marine ecosystems (California Department of Fish and Wildlife no date). In Europe, the Natura 2000 sites form a network in which human activities must be managed to conserve biological features listed in European Union directives, including kelp forests. OSPAR has suggested that management plans for the protection of kelp forests be specified and supplemented with additional areas that are important for kelp forests to ensure that they are better considered and managed within the network (de Bettignies *et al*. 2021b).

There are several examples of how MPAs may support kelp forests. In New Zealand, the cessation of fishing in marine reserves drove the recovery of kelp forests, as top predators such as fish and lobsters increased in abundance and started to feed on smaller sea urchins, thereby decreasing grazing pressure on kelp (Leleu *et al*. 2012). MPAs can also strengthen interconnections among a kelp ecosystem's components by increasing the abundance and size of key species, as found in the northern Channel Islands marine reserve network in California (Murray and Hee 2019). This may in turn increase an ecosystem's resilience to withstand other stressors such as climate change (Leleu *et al*. 2012). MPAs that contain kelp forests can also be used to promote and manage tourism, such as in the Poor Knights Marine Reserve in New Zealand, for example, where kelp forests form part of popular dive sites, or the Kosterhavet National Park in Sweden, where visitors can follow snorkel trails through kelp forests. Nature-based tourism can provide incomes to local economies, with MPAs being an educational tool to teach visitors about the importance of kelp ecosystems. In France, pupils of primary and secondary schools can adopt and complete a project on an educationally-managed marine area, which can include kelp forests (Agence française pour la biodiversité 2020).

Effective management plans are essential for the success of MPAs. Such plans should ensure the required control of human activities and conservation actions, along with their enforcement and monitoring (Murray and Hee 2019). As an example, California has an MPA monitoring programme in place that evaluates the effectiveness of its MPA network through combining historic and new data, including on kelp forests, prior to conducting a management review (Scully

2022). MPAs can support and complement general marine planning and management when reserves or non-extractive areas function as reference areas (Ballantine 2014). This can help distinguish how kelp ecosystems react to local pressures compared with pressures that affect larger ocean areas, such as ocean warming and nutrient loading, thereby assisting the development of management strategies. Although effective MPAs can protect biodiversity, including kelp forests, against pressures that occur in the designated area, they should be used in combination with ecosystem-based management approaches to address more distant threats.

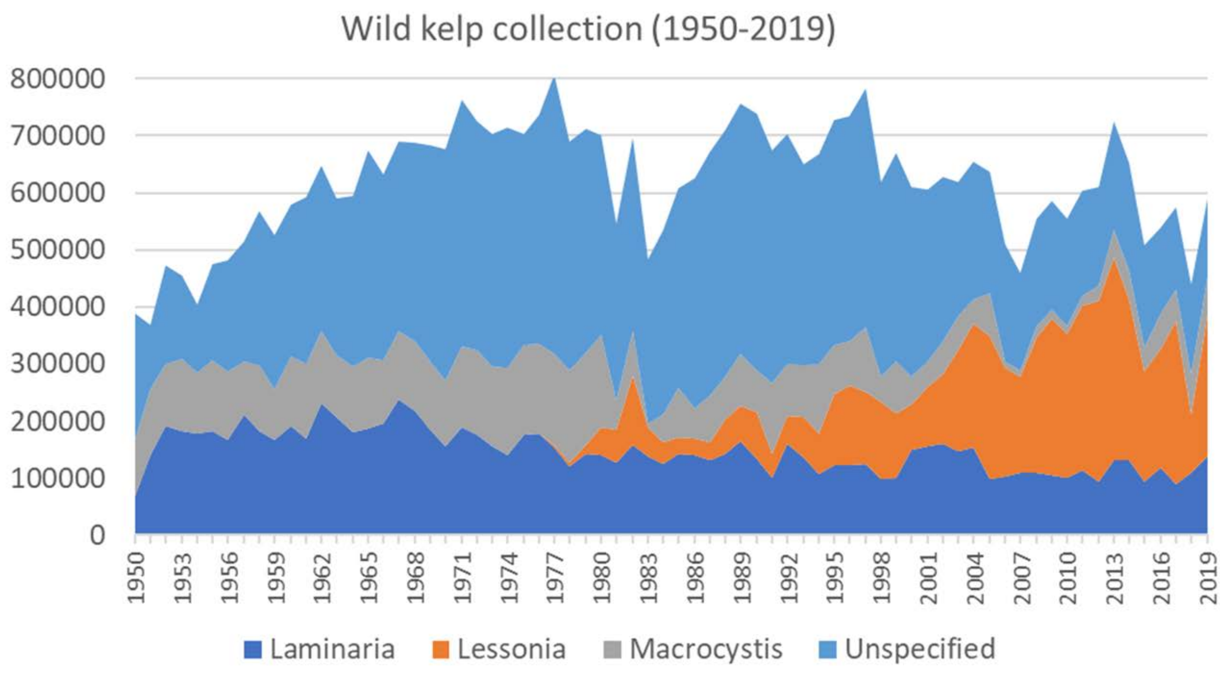
Management of kelp harvesting

Statistics on harvesting

Statistics on kelp harvesting are often mixed up with data for species that belong to other groups of brown algae. Even though there is no clear definition of kelp (chapter 1), this report has tried to make a narrower selection of groups of species that are clearly defined as kelp. The following figures have been produced using data extracted from FAO data sets and reflect countries' reporting and the categorization of species applied. The data have been used as they were reported, without any attempt to evaluate their quality and consistency.

The global production of wild harvested kelp more than doubled from 387,578 tons in 1950 to a peak of 806,658 tons in 1977 (Figure 6.10). Production for the next six years fell, before rising again to between 650,000 and 787,000 tons in the early and mid-1990s. Since then, there has been a variable but decreasing trend towards 591,259 tons, as reported in 2019. *Lessonia* species have become the main group harvested today. Throughout the period, *Laminaria* species have dominated, assuming that the majority (79 per cent) of unspecified recordings from Norway are *L. hyperborea*.

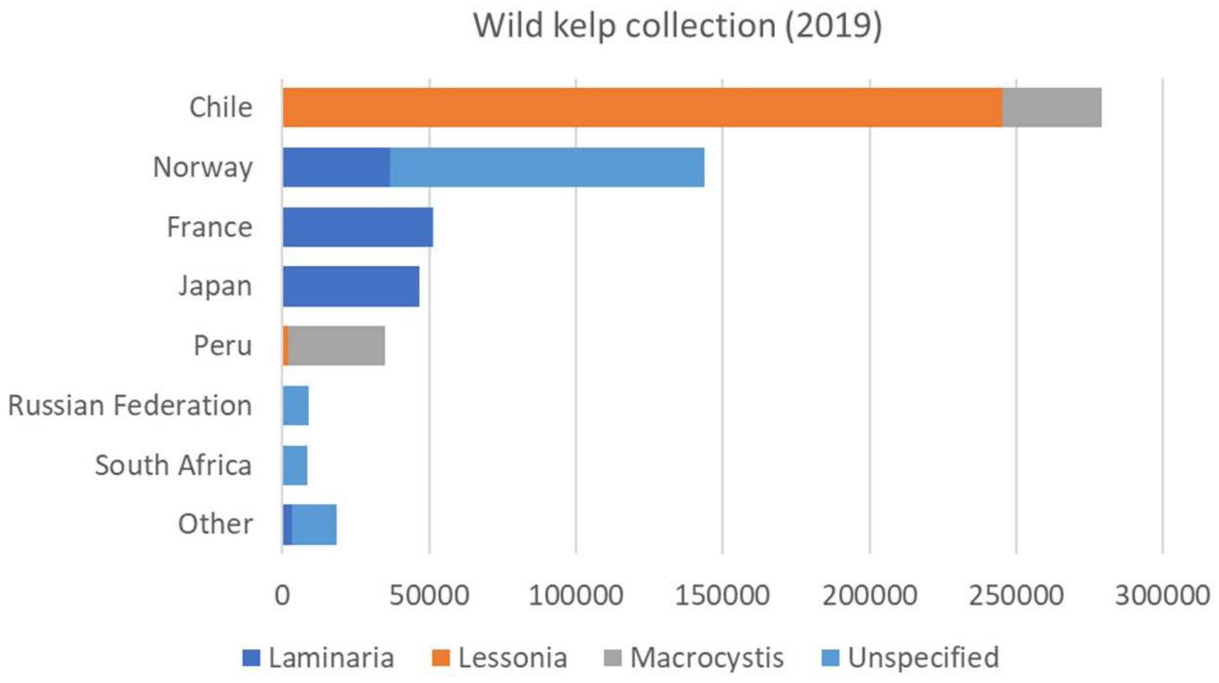
Figure 6.10. Global wild kelp harvests (1950–2019)



Notes: Data as reported to the FAO since 1950. The species included are marine aquatic plants categorized as "brown seaweeds" excluding the non-kelp *Ascophyllum nodosum* (5.4 per cent of the total) and *D. antarctica* (0.3 per cent of the total). The "Unspecified" group includes *Undaria* (0.26 per cent), *Cystoseira* (< 0.01 per cent) and other brown algae with no genus or species reported, though it is assumed to mostly consist of *Laminaria* (as 79 per cent of the records are from Norway and *L. hyperborea* is the only species harvested in large quantities in that country). The other primary contributing countries to the "Unspecified" group were the Russian Federation (6 per cent), South Africa (6 per cent), Mexico (4 per cent) and India (2 per cent). By focusing on the category "brown seaweeds" only, some (< 0.4 per cent) of records reported as "algae" under the category "miscellaneous aquatic plants" could be missed.
Source: FAO 2020

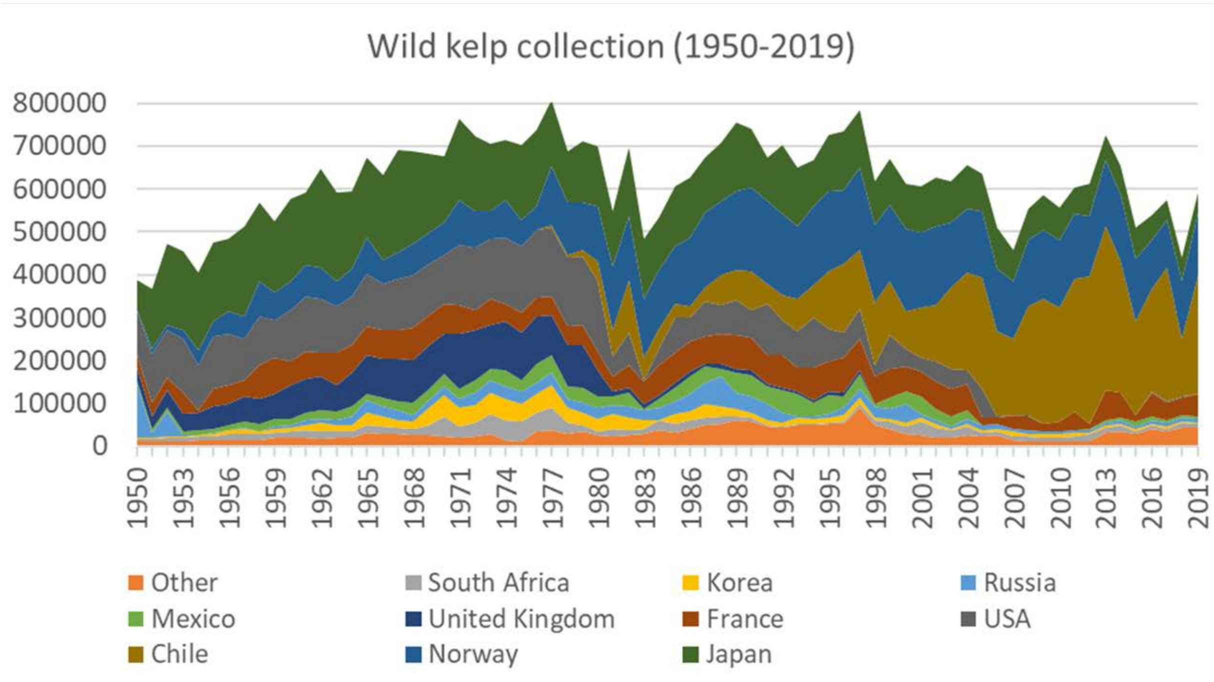
Figure 6.11 ranks the main kelp harvesting countries according to 2019 production volumes. Chile is the largest producer with a harvest of 288,486 tons, which is almost double that of Norway (143,875 tons), which had the second largest production that year. France (51,142 tons), Japan (46,500 tons) and Peru (34,837 tons) are the three other countries with significant production. The few Asian countries included in the "Other" category reflect that kelp cultivation is the most significant source of kelp in that region.

Figure 6.11. Major countries that harvest kelp according to catches in 2019



Note: "Other countries" constitute 3.1 per cent and include (in decreasing order) Mexico, the Republic of Korea, India, Iceland, Australia, Ireland, Spain and the United States of America.
Source: FAO 2020

Figure 6.12. Main kelp harvesting countries from 1950 to 2019



Notes: "Other" countries constitute 4.8 per cent for the whole period and include (in decreasing order) Iceland, Australia, India, Peru, Ireland, Spain, New Zealand, Argentina, Tonga and Ukraine.
Source: FAO 2022

Since 1950, 20 countries have reported wild kelp harvesting to FAO. The expansion of the industry in Chile has been a main characteristic of global harvesting in the last decade. Japan, the United Kingdom and the United States of America all used to have a substantial portion of the global production, but have reduced their harvesting significantly.

Harvesting methods and ecological impact

Kelp are harvested through various techniques (Buschmann *et al*. 2014; Lotze *et al*. 2019; Norderhaug *et al*. 2020). The collection of drift kelp that accumulates on shores is an ancient and widespread method (Boxes 6.2 and 6.3). Different types of nets and devices to carry kelp fronds exist and have been used, with manual work assisted by horses and more recently bulldozers, tractors and cars. Such methods are typical among subsistence or low-intensity harvesting. In South Africa, however, the amounts collected from beaches are enough to sustain a local industry (Amosou *et al*. 2013). Beach collections typically have a low impact on kelp as it does not harm live kelp forests. Despite this, such collections could impact the stability of coasts and the food web of coastal ecosystems, where kelp wrack frequently accumulates (Polis, Anderson and Holt 1997).

Harvesting kelp from water requires access, either by utilizing low waters, wading in the water, diving or using boats. Various cutting tools have been used to harvest kelp, such as the *barreteo* in Chile and the *nejrii* in Japan (Box 6.5). Manual cutting using such tools makes the selective removal of individual kelp possible. Harvesters must cut kelp carefully so as not to damage the plant. Parts of the kelp, such as the holdfast or meristem of the blade, must be left undisturbed so that regrowth can occur as it would after the natural loss of tissue at the ends of the kelp blades. Non-destructive harvesting can actually increase production in some cases (Krumhansl *et al*. 2016). However, cutting below a kelp's meristem at the top of its stipe will cause the death of the individual for many species. This problem has been reported in Chile, Namibia and South Africa, which means that even manual cutting can be lethal for kelp (Omoregie, Tjipute and Murangi 2010). Other tools used include various forms of rakes with long handles and a cutting device. These discriminate less and may more easily cut off kelp in inappropriate places or detach entire kelp individuals from the sea floor, as is the case with the Chilean *barreto* (González-Roca *et al*. 2021).

Box 6.3. Case study: Evolving kelp harvesting management in Norway

Kelp and other marine algae have historically been important for human settlements along the Norwegian coast, either as farm resources (Brox 1963; Bratrein 1974) or as raw material for the production of iodine, soda and potash from the eighteenth century into the twentieth century (Drøsland 2014). Until the 1960s, a common harvesting practice of marine algae was to manually cut individuals or collect drift kelp from the foreshore. Title deeds and historical court cases are testament to the fact that these marine algae were generally considered farm resources and privately owned. There are also examples along the coast of more communal arrangements, as well as tensions and conflicts over access and rights to collecting and harvesting kelp (Øvereng 1970).

After Norway's first alginate plant was built in 1961, kelp were increasingly harvested mechanically by the end of the decade, by purpose-built dredging vessels (Vea and Ask 2011). This approach also gradually saw kelp harvesting shift from privately owned foreshore areas to coastal waters outside of the low watermark, where tangle (*L. hyperborea*) tends to grow. In the beginning, there were no specific regulations for kelp dredging, with just a mutual understanding established between the industry and the Directorate of Fisheries on limiting the dredging to particular areas. However, conflicts with other coastal and marine interests and users soon emerged, which were primarily related to space. Fishers voiced concerns over the impacts on traditional coastal fisheries and were met with provisions for shared access (Johannessen 1989). As kelp harvesting expanded to new areas, concerns were also expressed about the destruction of fishing gear by the remaining kelp stipes, and the impact on the marine ecosystems, such as crab and lobster populations and spawning grounds for fish.

In 1972 a first regulatory measure was implemented specifically for kelp harvesting, which introduced a management regime with harvesting cycles for separate "harvesting areas". This management regime, which was set up to ensure the recovery of the kelp and sustainable yields, is the precursor for the country's current kelp harvesting management, as presented in chapter 5. Key characteristics include the opening of allocated harvesting areas for one year, followed by four fallow years until the next harvesting period. However, this practice is controversial, and harvesting regulations have been criticized for not being sufficiently geared towards the protection of kelp ecosystems, including seabirds (Greenhill, Sundnes and Karlsson 2021).

Mechanical kelp harvesting methods are more efficient than manual methods, as they increase outcomes per unit and areas covered. The development of an alginate industry was a driver for mechanization due to the need for large kelp volumes. From the late 1960s, an iron sledge with forks was placed on purpose-built vessels for kelp trawling in Norway (Box 6.3). In France, a curved iron hook mounted on a hydraulic arm that rotates and uproots kelp fronds was introduced in the 1970s (*a scoubidou*), with dredging starting in 2000. These methods remove entire kelp individuals and are therefore the most destructive.

The magnitude of kelp harvesting impacts on a specific kelp species depends on the gear type and cutting methods used and the intensity and extent of the harvesting (Lotze *et al.* 2019), all of which are issues that can be managed. Moreover, there is a need to distinguish between the impacts on kelp species, which are the resource base for harvesters in the same way that targeted fish are for fishers, and the impacts on the wider kelp ecosystem (chapter 1). The collection of kelp that has drifted ashore may only indirectly affect living kelp forests, while traditional manual harvesting tends to only have a few impacts on kelp ecosystems if conducted correctly. Traditional and artisanal harvesting methods have managed kelp resources well for centuries, which is still the case in some instances, as demonstrated by First Nations along the north-eastern Pacific coast in Canada (Mathews and Turner 2017; Kobluk *et al.* 2021). However, manual methods have also resulted in overharvesting historically (Box 6.5), particularly when not applied carefully and too many harvesters operate. The risk of overharvesting and detrimental damages increases with the use of less discriminatory and mechanical methods. However, if managed properly, mechanical extraction can be sustainable (Burrow *et al.* 2018). Key issues tend to concern harvesting intensity in an area and the implementation of sufficient fallow periods for kelp populations and the associated ecosystem to recover.

Management systems

Kelp harvesting is often managed through approaches that are based on adaptable traditional fisheries management methods. These include licensing requirements, total allowable catch, catch shares, territorial user rights for fisheries, limitations on the numbers of harvesters and boats, and restrictions on harvesting gear/technologies, times and areas (e.g. MPAs, seasonal closures, fallow rotations).

In many countries, kelp harvesting is managed through a combination of state-led and regionalized approaches. Area and rights-based systems are examples of community-based and regional management approaches used in Chile and Japan. Such systems allocate exclusive rights for a group to harvest in a certain area, which may promote a stronger sense of ownership among the harvesters and their stewardship of the resources. The inclusion of harvesters in this way can improve management compliance rates. In South Africa, kelp harvesting is managed through a combination of output and area management, with individual companies holding the right to collect a specified amount of beach-cast kelp within an area. A maximum harvested quantity of 6–10 per cent of the standing biomass is set and combined with a non-harvesting zone in the same area to protect older kelp and their associated organisms (Blamey and Bolton 2018). In the state of Maine in the United States of America, oarweed (*L. digitata*) harvesting is permitted year-round, for which management plans require the kelp to be cut carefully to ensure a healthy repopulation. The size of the entire oarweed population in Maine determines the total allowable catch, since only 30 per cent of the standing biomass can be harvested annually. In Scotland, the mechanical removal of entire kelp populations was banned in 2019 as it inhibits the regrowth of individual kelp. There is significant public resistance and a lack of national policy on harvesting beyond this gear/technology restriction (Greenhill, Sundnes and Karlsson 2021).

Table 6.1. Overview of kelp harvesting and methods in different countries

Country	Key species	Administrative level	Management tools	Purpose	Harvesting method	Source
Argentina*	*Lessonia vadosa, Macrocystis pyrifera, Undaria pinnatifida*	Local	Limited entry	Alginate, artisanal consumption	Beach collections, subtidal harvesting, diving	Rebours *et al.* 2014
Australia	*Ecklonia radiata, U. pinnatifida*	State	Limited entry, licensing, catch limit	Agriculture, fodder, alginate	Beach and drift gathering, subtidal harvesting (limited to species)	Mac Monagail *et al.* 2017; Tasmanian Government, Department of Primary Industries, Parks, Water and Environment 2017; Velásquez *et al.* 2020

Canada	*Saccharina latissima, Egregia menziesii, M. pyrifera, Laminaria setchellii*	Province	Limited entry, time restrictions, size limits	Agriculture, fodder, commercial consumption, promotion of herring habitats	Beach collections, hand-cutting	British Columbia no date; Lindop 2017; Kobluk *et al*. 2021; Hamilton *et al*. 2022
Chile	*L. spicata, L. berteroana, L. trabeculata, Duvillaea antarctica, M. pyrifera*	National legislation/ regional management plans	Territorial user rights for fisheries, limited entry licences and divers, open-access zones, MPAs, size limits	Alginate, consumption, abalone feed	Diving, *barrateo*, beach and drift gathering, cultivation	Vásquez 2008; González-Roca *et al*. 2021
France	*L. digitata, L. hyperborea*	National legislation, regionally issued licences	Total allowable catch, limited entry, time restrictions, MPAs, gear restrictions, time/area closures	Alginate (food to a lesser extent)	Mechanical harvesting dominates, foreshore harvesting that also include other species	Alban, Frangoudes and Fresard 2011; Frangoudes and Garineaud 2015
Iceland	*L. digitata, L. hyperborea*	National	Limited entry, licensing, size limitations, rotation of harvesting areas	Seameal	Mechanical harvesting (not taking the holdfast)	Maack 2019
Ireland	*L. hyperborea*	National, local	MPAs, gear restrictions, limited entry, foreshore licensing or traditional landowner rights	Colloids, artisanal usage	Beach and drift gathering, foreshore harvesting (non-mechanical), boat and rakes	Mac Monagail and Morrison 2020
Japan	*S. japonica, S. latissma, S. longissima, Ecklonia* spp., *Eisenia* spp., *U. pinnatifida*	National legislation /local cooperative fishing rights	Co-management system, limited entry, total allowable catch, gear restrictions, time restrictions, time/area closures, size limits	Commercial consumption	Non-mechanical harvesting	Fujita 2011

Mexico*	*M. pyrifera*	Federal	Time/area closures, limited entry licensing, rotation of harvested areas	Agriculture, fodder, colloids	Small vessels, non-mechanical harvesting, hand-cutting of fronds	Vázquez-Delfín *et al*. 2019
Namibia*	*L. pallida*	National	Maximum 10 kg wet weight can be harvested per day, beach-cast collection and industrial use is not regulated	Abalone feed	Blades collected from detritus washed on shore	Omoregie, Tjipute and Murangi 2010; Rothman *et al*. 2020
New Zealand	*D. antarctica, U. pinnatifida, M. pyrifera, E. radiata*	National	Limited entry licences, total allowable catch	Food, alginates, fertilizers, health supplements	Beach-cast, non-mechanical harvest	White and White 2020
Norway	*L. hyperborea*	National legislation/ county-specific harvesting regulations	Time/area closures, rotations of harvested areas	Alginate	Mechanical harvest	Greenhill, Sundnes and Karlsson 2021
Peru	*L. nigrescens, L. trabeculata, M. pyrifera*	National	Time/area closures, total allowable catch	Alginate, agriculture	Beach and drift gathering, diving and *barrateo* harvesting	Avila-Peltroche and Padilla-Vallejos 2020; Carbajal *et al*. 2021
Portugal*	*L. hyperborea, L. ochroleuca, S. latissima, Saccorhiza polyschides*	National, local	Time restrictions, limited entry	Agriculture	Beach collections	Gaspar, Pereira and Sousa-Pinto 2019
Republic of Korea	*U. pinnatifida, Sargassum* spp. (*S. japonica* is no longer harvested)	Local	Limited entry, legally prohibited species (wild *E. cava, E. bicyclis* for forest conservation)	Foods, food ingredients, feed ingredients for cultured abalones	Cultivation	Hong *et al*. 2021; Kim *et al*. 2022
Russian Federation	*S. japonica, L. digitata, S. latissima*	Federal, oblast (regional)	Size restrictions, time/area closures, MPAs	Food, alginates	Non-mechanical, manual pools from boats, diving, beach collections	Kawai *et al*. 2015; Shushpanova and Kapralova 2021

South Africa	*E. maxima, L. pallida*	National	Concession areas with catch limit for each based upon a time restriction, time/area closures, MPAs	Abalone feed, alginate, agriculture	Beach collections and boat-based activities, non-mechanical harvesting methods	Blamey and Bolton 2018
Spain (Galicia)	*U. pinnatifida, L. ochroleuca*	Regional	Licence only for individuals, exploitation plan for industries and fishers' associations with zones and intensity of harvesting	Food, some health products; former alginate industry has ceased	Knives and sickles allowed, used from boats or by divers	García Tasende and Peteiro 2015; Araújo *et al.* 2021
United States of America	*M. pyrifera, L. digitata, S. latissima, Nereocystis luetkeana*	State	MPAs, limited entry, time restrictions, licensing, leasing of kelp beds (California)	Alginate, food, agriculture	Hand-cutting, small-scale mechanical harvesting from boats	California Department of Fish and Wildlife no date; Marine Seaweed Council 2014

*Those that did not report to FAO in 2019.

Box 6.4. Case study: Managing kelp harvesting in Chile

In Chile, kelp are exploited from natural populations through two methods: 1) the collection of dead algae that are washed ashore; and 2) the cutting of kelp by hand in shallow waters. Most of the kelp landings are exported to Asian countries for alginate extraction, with only a small percentage used in the national food industry (Vásquez 2008). In the past 30 years there has been a sustained increase in production due to international demand (Vásquez *et al*. 2012; Vásquez *et al*. 2014; Krumhansl *et al*. 2016). In 2020, almost 300,000 dry tons of kelp were landed, generating returns of over $10 million from exports. The genera *Lessonia*, *Durvillaea* and *Macrocystis*, which occur from the south of Peru along Chile's coast to 55°S, make up most of the Chilean kelp fishery, with more than 80 per cent of the kelp landings coming from the intertidal *L. nigrescens* complex (*L. berteroana* and *L. spicata*). Despite this wide distributional range, the fishery is centred in northern Chile due to its proximity to the driest desert in the world, which reduces drying-related production costs (Vásquez *et al*. 2014). *Lessonia* spp. do not grow after pruning and require a sexual reproduction strategy. Despite the high production of sporophytes under laboratory conditions, neither the cultivation of brown algae in general nor the repopulation of *Lessonia* after pruning have been successful.

Due to the large volume of brown seaweed landings in northern Chile, kelp harvesting has been managed primarily based on bioecological knowledge: 1) collection is restricted to kelp individuals with a holdfast diameter of over 20 cm; 2) whole individuals are collected since there is no regrowth after pruning; 3) when harvesting, space should not be created between individuals of over 1–2 m; and 4) the same area should not be harvested for the next 6–8 months (Vásquez 2008). Chile does not regulate the amount of kelp that can be collected, but regulates harvesting according to two different strategies, each of which apply to approximately half of the Chilean coast: firstly, the territorial user rights policy, which allocates exclusive rights to a fishers' union for using several benthic marine resources in a defined area (Gelcich *et al*. 2017), with individual management plans setting extraction quotas and harvesting rules for each area;

and secondly, open-access areas, which are available to all fishers from neighbouring areas, with harvesting regulated according to regional management plans that define control rules. Conservation is also sought through the designation of MPAs, where harvesting is prohibited.

Although kelp densities have improved in all areas with management strategies in the past 11 years, biomass is greater in areas that are managed through territorial user rights and in MPAs than in open-access areas where regional management plans have been implemented (González-Roca *et al*. 2021). Within the MPAs, kelp stipe numbers and diameters were also all higher than in the areas managed by territorial users (Gouraguine *et al*. 2021).

The bioecological regulation of good harvesting practices and the use of management strategies contribute significantly to the conservation of wild kelp populations. However, enforcement and compliance are key problems due to the length of and difficult access to the South-East Pacific coastline. Other management innovations such as rotational harvest strategies could also be an important complementary measure to improve the sustainability of wild brown seaweed populations.

Box 6.5. Case study: Managing kelp harvesting in Hokkaido, Japan

The most important kelp (kombu) in Hokkaido and north-western Honshu is *S. japonica* (Figure 6.13). In lands north of Honshu (formerly known as Ezo), kelp were collected by Ainu communities who inhabited the area as early as the fourteenth century. As Japan's population grew and territories expanded, kelp collection and trading increased in the country via the "kombu road" across the Sea of Japan and to China. In 1692, the local government prohibited non-locals from harvesting kelp to avoid poaching, as well as the overharvesting of yearling kelp in the early season to maintain wild populations.

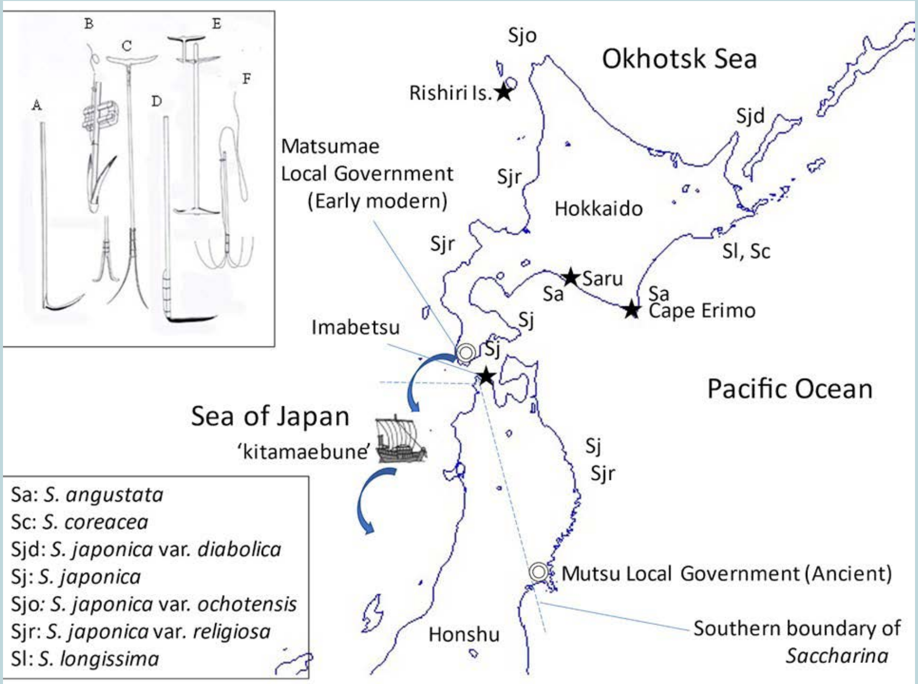
By the early eighteenth century, kelp were harvested using a sickle (*kama* – curved blade) after the closing of the herring fishery in April. Some parts of collected kelp were paid as a tax to local governments. A century later, merchants had extended kelp harvests to the north-east of Hokkaido, where they managed harvests as place contractors. The use of boats, prohibition of sickles and hatchets, and the introduction of new tools, such as a forked twister (*makka*), a torsion bar (*nejiri*) and a hook with a rod or a rope (*kagi*), increased the efficiency of harvesting. Annual varieties of *S. japonica* growing in south-western Hokkaido, which were thinner and paid less, could earlier be collected without any regulation.

Nowadays, kelp harvesting is controlled by laws such as the Fisheries Act 1949 and the Act on the Protection of the Fishery Resources 1951. The harvesting of wild kelp requires a cooperative fishing right, which is granted to fishery cooperatives (*gyokyo*) by the prefectural governor. Fishers can collect drift or stranded kelp on shore by hand or harvest kelp with manual gear nearshore. Prefectures specify further rules (e.g. target species, harvesting period, methods), the details of which are discussed, decided upon and practised in each fishery cooperative to reduce excess competition among fishers. During the harvesting period, a flag keeper (*hatamochi*) judges and announces the opening or closure of daily operations based on wave heights to ensure a safe harvest, and weather conditions for complete drying. Kelp harvesting by the public is prohibited and fishers are responsible for maintaining kelp stock. These acts and rules provide the fundamental legal frameworks for kelp management in Japan, where neither mechanical fishing nor underwater diving have been permitted anywhere in the country.

Since 1716, deforestation of kelp due to overharvesting has been met with restoration efforts (see chapter 7). The methods of such efforts have included addressing direct pressures on kelp through cleaning competitive turf algae from surfaces and removing sea urchins. Around Cape Erimo, fishers started to restore terrestrial meadows and forests in 1953 to reduce the exposure of soil to shallow waters, which was causing high turbidity and resulting in the loss of kelp, fish and shellfish. The first attempts failed due to a loss of seeded soil that was displaced by strong winds. From 1957, algal garbage was placed as a soil-stopper, which led to the recovery of 187 ha of meadows and forests (2009), which in turn led to an increase in kelp, fish and shellfish. This is one of the long challenges started and faced by fishers, which has lasted for over half a century.

Article 17 of Japan's Fisheries Basic Act 2001 provides that the State will take measures, for example, water quality conservation, the protection and development of aquatic plant and animal breeding grounds, and the conservation and development of forests, to improve and conserve the growing environment for aquatic plants and animals. This Act lays the foundations for subsidization by the Government and prefectures.

Figure 6.13. Map of the distribution of kelp species in northern Japan



Note: The top-left insert shows the following kelp harvesting gear: hooks with rod (A) or rope (B), forked twister with rod (C) or rope (F), sickle (D) and twister (E).
Source: Authors' own elaboration (credit: Daisuke Fujita)

Employment generated by kelp harvesting

It is challenging to estimate the number of people that are engaged in wild kelp harvesting because many only engage seasonally, part-time and informally as a part of subsistence. Kelp can serve as an important additional source of income for rural and at times marginalized populations (Mac Monagail *et al*. 2017) or as a diversification opportunity for fishing communities where their activities have been otherwise negatively affected (Burrows *et al*. 2018). Opportunities in other economic sectors also matter; when unemployment in Chile rises due to falling copper prices, people go to the coast and start kelp harvesting. Such harvesters usually operate independently without a fishing licence and are less prone to consider good harvesting practices. The level of mechanization also influences the number of people and livelihoods engaged. Chile and Norway both harvest large amounts of kelp. In Norway, industrialized extraction methods employ less than 150 people in harvesting and post-harvesting activities, in contrast to Chile, where more than 150,000 depend on the Chilean kelp fishery. Harvesting is also a gendered activity, with women especially engaged in collecting kelp from shores (Gustavsson *et al*. 2021). The socioeconomic benefits that wild kelp harvesting and kelp products can provide need to be assessed more specifically so that they can be taken into account in management (Frangoudes 2011).

Best practice guidelines

There are very few evaluations of the effectiveness of different approaches for managing kelp harvesting. This makes it difficult to draw general conclusions on management approaches that may be successful across the peculiarities of each national management regime, as illustrated in the previous case studies. The following section highlights some advice on how to manage harvesting beyond beach collection and small-scale cutting, drawing from scientific literature and the authors' expert opinions.

The most important measure to promote sustainable kelp harvesting is the accurate mapping of kelp forests' extent and standing stock within a harvesting region, along with assessments of the forests' state. Since kelp are structuring species of coastal ecosystems, assessments should consider the kelp ecosystem, including fish, seabirds and marine mammals, and not just the resource base of individual kelp species. To enable the determination of sustainability thresholds for any harvesting operations, harvesting should be embedded into a wider ecosystem-based management system that is founded on an understanding of the cumulative impacts and recovery time of kelp ecosystems. It is important to consider the extent to which the cumulative impacts of existing activities accommodate (increased) harvesting activities. Addressing this requires an assessment of how kelp harvesting with the relevant technology and intensity impacts kelp species and the ecosystem's associated habitats and species. Similar assessments are needed for the impacts of other current and future activities, and predicted changes associated with climate change. The socioeconomic benefits of extracted kelp to society, including gendered aspects, should also be assessed so decision makers can balance predicted ecosystem impacts. Decisions should set key parameters for sustainable harvesting, such as the total extracted volumes of each species, the areas to be harvested and harvesting technologies to be used. Preferably, decisions on kelp harvesting should be a part of broader systems for ecosystem-based management or marine spatial planning that also incorporate measures for other activities that affect the kelp ecosystem. The implementation of such measures may in turn have consequences for defining sustainable harvesting levels.

When both mapping and risk assessments are appropriate, suitable management measures adapted to existing national governance traditions must be applied. Although national legislation and governments usually establish basic rules for harvesting, there is a choice in how much of the more detailed management should be delegated to local administrations or collectives of harvesters through co-management. Another important choice is how to limit access to harvesting. This is an important mechanism that can be used to avoid kelp forests becoming victims of "the tragedy of the commons" (Ostrom 2008), and has major implications for the equity of a management regime. Access can be limited through the granting of licences to individual harvesters, as well as through the allocation of exclusive rights to certain areas to private companies of harvester collectives. Decisions must be taken to ensure that fisheries harvest kelp according to the principles of the ecosystem approach to fisheries and aim to manage harvesting to limit its impacts on the ecosystem (FAO 2005). Setting a total allowable biomass to be harvested for each species is a mechanism that is especially important when harvesting large volumes for industrial purposes. However, temporal and spatial harvesting restrictions may have a similar effect. Temporal restrictions during vital seasons should limit negative impacts on associated species. Spatial restrictions should establish areas to be harvested and the density of harvesting in these areas, as well as no-take zones. When mechanical harvesting is applied, there should be fallow periods of a duration that is long enough for the ecosystem to recover. For manual harvesting, restrictions on gear and cutting methods should be applied to limit the destruction of habitats and allow for the rapid regrowth of individual plants. When the measures are implemented, activities must be monitored to check for their compliance and impacts. Compliance can be enhanced when harvesters consider the regulating system to be legitimate, which can be ensured through their engagement in its development. Graduated sanctions should be applied when breaches occur (Gunningham 2010). Given the significant uncertainty around impacts on kelp forests and associated ecosystem recovery, an adaptive and learning-based approach to the management of harvesting is needed. The effectiveness of management measures to maintain the structure and ecological functions of kelp forests should be assessed, revising the measures taken as necessary to ensure the sustainability of harvesting operations.

Harvesting prospects

Kelp and kelp-derived refined products have a wide range of uses that can meet major human needs, with novel products in development (chapter 3). Research on how to utilize more species will be an additional driver for the collection of new raw material. The cultivation of brown seaweed in 2019 delivered 27 times more than harvesting and is likely to be the primary provider that can meet increased demand. However, it is likely that harvesting may also increase, as interest in Peru and Scotland, for example, is increasing (Greenhill, Sundnes and Karlsson 2021). One of the reasons for this is that there are certain species that cannot easily be cultivated yet, such as tangle (*L. hyperborea*) in Norway and three species of *Lessonia* in Chile, all of which are harvested for alginate production. New species with specialized applications may also be targeted. Against these prospects for growth are the realities of wild kelp being under severe pressure from climate change, which could undermine the resource base in countries where kelp could have been an attractive industry under stable climate conditions. It remains to be seen whether shifts in species distribution will introduce other species of macroalgae that could be harvested instead. For the harvesting industry to grow, it must overcome the obstacles created by the lack of basic data on standing stocks. It also depends on there being more reliable access to resources, more efficient production that can reduce costs (e.g. through more mechanical harvesting and more efficient drying and transportation), the employment of a skilled workforce and the ability to create regional development (Mac Monagail *et al*. 2017). The ability to harvest with socially acceptable consequences for ecosystems, which could be achieved by adhering to the aforementioned guidelines, also plays a role. Lessons learned from prior harvesting experience demonstrate that overharvesting is a risk but that it can be avoided if an effective management system is in place.

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Chapter 7. Restoring kelp forests

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Highlights

- **Kelp forest restoration has a long history, spanning 16 countries and over 300 years of practice. The field is diverse with representation in many sectors of society, including academia, governments, communities, indigenous groups and businesses. The field is accelerating with more projects in the 10 years between 2009 and 2019 than ever before.**
- **Several projects have achieved large-scale success (hundreds or thousands of hectares) in restoring kelp forests, which shows that large-scale restoration is currently possible and a reasonable goal.**
- **The most successful restoration projects are those undertaken near existing kelp forests. Preventing the decline of kelp forests aids kelp recovery, thus indicating that actions to ensure kelp are not lost from an ecosystem are crucial.**
- **Current barriers to restoration and needed research areas include low-cost restoration methodologies, financing mechanisms for restoration, standardized project data entry and adaptation to changing and warming oceans.**
- **Kelp forest restoration has the potential to create ecological, social and economic benefits for coastal societies, which are directly linked to the United Nations SDGs. Collaboration between groups will help achieve these results.**

A historical overview of kelp restoration efforts

In its broadest sense, kelp forest restoration includes any management action that enhances kelp forest abundance following an initial decline or disappearance. This chapter focuses on practical approaches to restoration, which include transplanting kelp individuals or removing kelp consumers such as sea urchins (Layton *et al*. 2020b; Morris *et al*. 2020). Approaches aimed at addressing the environmental or social conditions linked to kelp declines, such as poor water quality or overharvesting, are covered in more detail in chapter 6.

Kelp forest restoration has a long history, dating back to the eighteenth century and spanning 16 countries and numerous methodologies (Eger *et al*. 2021b). Although the field has developed in relative isolation, with users in each country responding to local threats, such as water pollution (Coleman *et al*. 2008), overharvesting (Fujita 2011; Buschmann *et al*. 2014), overgrazing (Johnson *et al*. 2011), and ocean warming events (Wernberg *et al*. 2016), restoration methods have converged, with similar principles now applied around the globe. However, the philosophies, motivations and scale of restoration efforts vary substantially across countries. This chapter briefly reviews how kelp forest restoration has evolved and examines its current situation.

The first documented attempts at kelp restoration or enhancement can be traced to 1718 in Japan, when a monk named Saint Teiden instructed fishers to throw stones into deforested coastline areas to encourage kelp growth in north-western Honshu (Ueda, Iwamoto and Miura 1963). Additional efforts to enhance kelp populations and offset harvest pressures followed, with hundreds of hectares of artificial reefs being installed by 1950 (Kuroda *et al*. 1957). This practice of using artificial reefs remains widespread. Sea urchins, a common cause of kelp forest decline, are also a prized food item in Japan, with many fishers in the 1930s realizing that these “pests” could be of potential value. These efforts are the first recorded instances of combining sea urchin and kelp forest management to create a sea urchin fishery that not only helps kelp forests but also generates economic gains (Kinoshita 1933). To date, Japan has attempted the most restoration projects, with over 700 recorded from 1970 to 2014. Many of these projects are now financed by a split funding scheme of the country’s federal, prefectural and municipal governments, and have restored around 100 ha
of kelp forests (and some other algae) (Box 7.1).

Across the sea, projects in the Republic of Korea experimented with their own system of artificial reefs, marine stocking programmes and restoration areas from 1971 to 2009 but did not actively introduce kelp into the sea at first. This changed with the creation of the first marine forest programme in 2009, run by the Korea Fisheries Resources Agency (FIRA), which used artificial reefs to provide new substrates for kelp propagules in combination with kelp transfers from wild donor populations and kelp spore seedlings and grazer control activities to create or restore 50,000 ha of kelp forest by 2030. In 2020, more than 20,000 ha of kelp forests had been installed. As the programme expands, it aims to move away from the use of artificial reefs in favour of installing kelp species on natural reefs (Box 7.2; Lee 2019).

In the English-speaking world, kelp restoration projects were first initiated following the large declines of the giant kelp (*M. pyrifera*) forest in California (the United States of America) in the late 1950s and early 1960s (Wilson and North 1983).

Following initial transplantation trials, these projects worked to remove herbivorous sea urchins, distribute seeds and improve water quality, all to restore kelp forests. Although these projects had initial success and restored thousands of hectares of kelp forests (North 1968), the stressors persisted, resulting in continued restoration efforts in the state ever since (Eger *et al*. 2021b).

The twenty-first century has seen a significant increase in the number of restoration projects in Australia, Canada, Chile, Norway, the United States of America and the Mediterranean region (Eger *et al*. 2021a). Although most projects are small-scale and often experimental, the continued decline of kelp forests, greater recognition of their value and contribution to services such as fisheries production, nutrient cycling and carbon capture potential has spurred restoration efforts around the world, resulting in the recovery of thousands of hectares (Eger *et al*. 2021a). Most recently, several networks, non-profit organizations and citizen science initiatives have formed to help track projects, accumulate lessons learned, spread information on restoration and connect people working in kelp forest ecosystems (e.g. Kelp Forest Alliance, SeaForester, Oregon Kelp Alliance and Hidden Deserts).[4] With accumulating knowledge and strong motivation, there is significant potential for kelp forest restoration worldwide.

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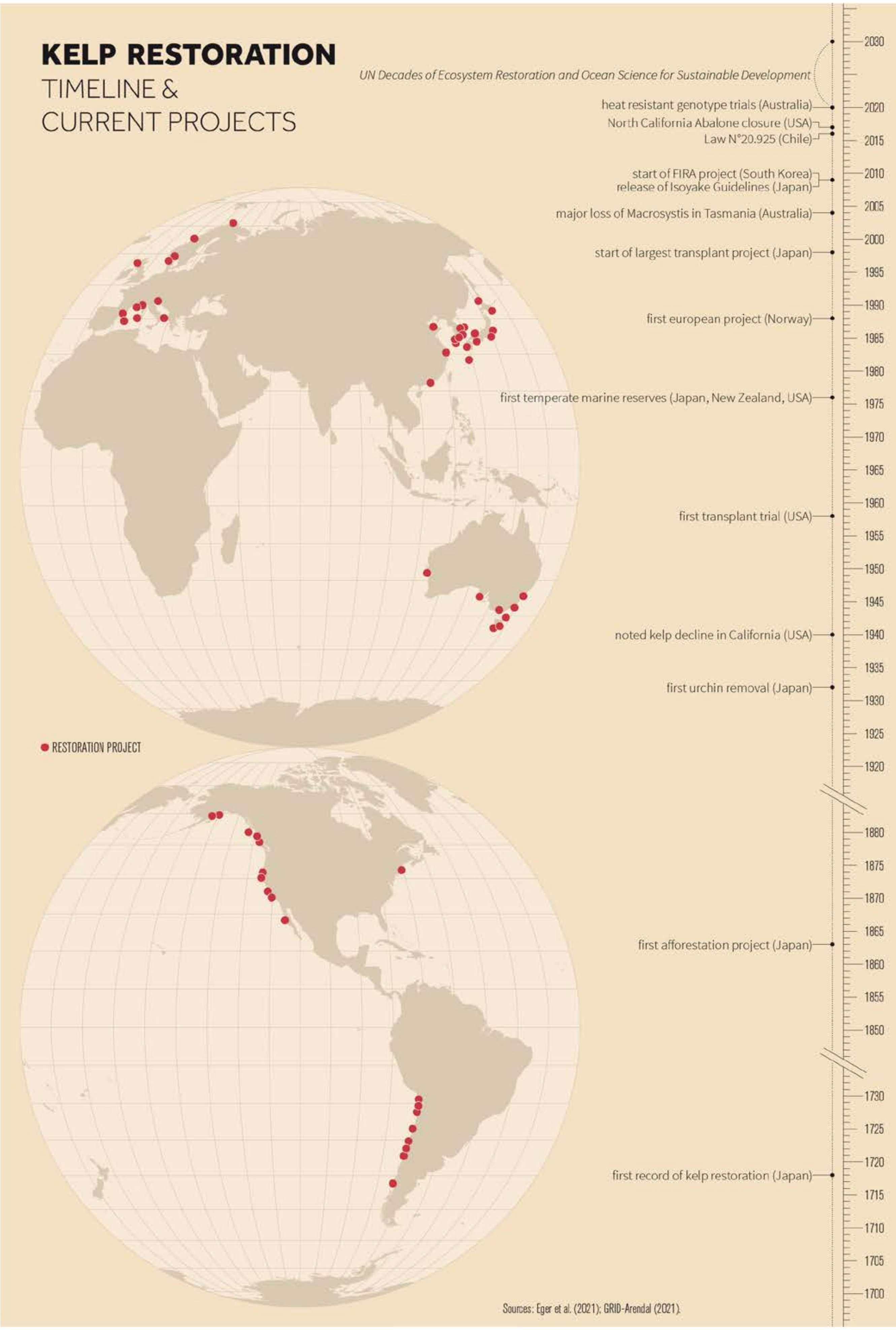
4 See https://kelpforestalliance.com/; https://seaforester.org/; www.oregonkelp.com/; and https://hiddendeserts.com/.

Figure 7.1. Kelp restoration timeline and current projects



Deciding when and where to restore kelp

Although kelp forests are generally in decline worldwide (chapters 1 and 2), it is still important to confirm that kelp populations have declined locally or regionally before beginning restoration. Such an assessment is complicated, as kelp forest monitoring is costly (see chapter 6), many species may naturally fluctuate in population (Buschmann, Graham and Vásquez 2007) and historical baselines are limited.

If it is not possible to determine kelp population trends, it is safest to prevent any further declines. Active restoration is a costly enterprise and environmental shifts to low kelp populations are difficult to reverse. While this chapter covers active restoration approaches, preventative approaches should be prioritized if possible, particularly those that manage enabling environment conditions and work to prevent kelp declines before restoration efforts are required (chapter 6).

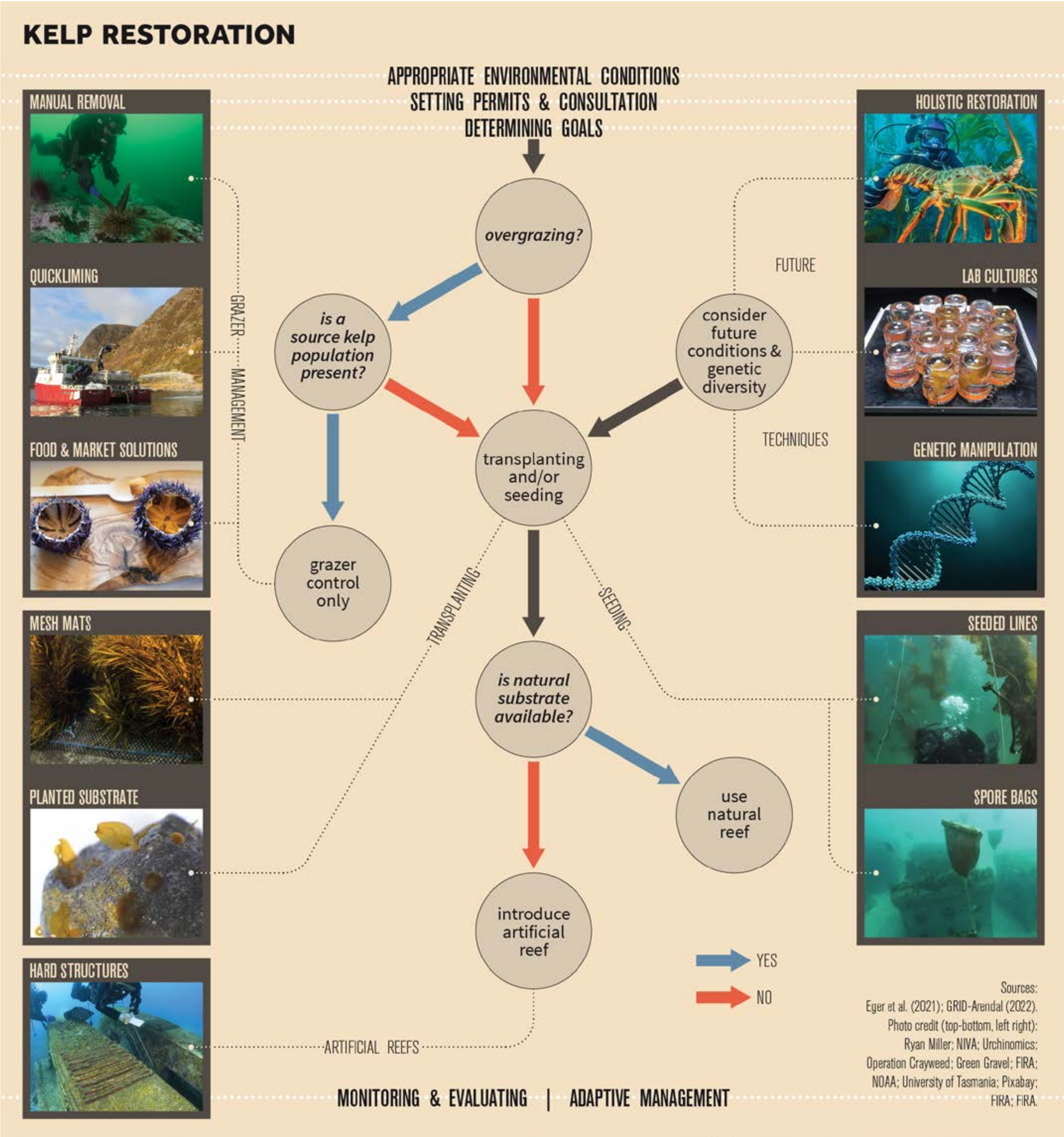
If a decline has occurred, projects should identify and address the drivers of the decline prior to any restoration efforts (Bekkby *et al*. 2020). If projects fail to mitigate the drivers of the decline, there is a high risk that restoration efforts will fail, resources will be wasted and/or continual site maintenance will be required. Mitigation may include, for example, a reduction of coastal pollution through the installation of sewage plants or the removal of herbivorous sea urchins (see chapter 6 on managing water pollution). In some instances, amelioration may be all that is needed for kelp forests to become re-established. Conversely, if it is not possible to locally address the causes of the initial decline, restoration may not be feasible or wise (Layton *et al*. 2020b).

Once a decision has been made to restore kelp populations, it is crucial to decide where to do so. Such a decision depends on multiple factors, including the reproductive biology of the target species and oceanographic processes that affect dispersal and recruitment at relevant spatial scales (Coleman and Kelaher 2009). A recent review of almost 200 kelp restoration projects concluded that proximity to nearby kelp forests is a key predictor of restoration success, which starts to decline at distances greater than 1,000 m (Eger *et al*. 2021a). This link suggests that restored sites benefit from a propagule supply from nearby populations, that existing populations facilitate the survival of new generations (e.g. via facilitation mechanisms) and/or that current environmental conditions are suitable for restoration. Such projects are also a societal undertaking, making it important to consider local and cultural values in selecting restoration sites (e.g. recreational areas, fishing zones, places of cultural significance).

Herbivory is an important and common factor that also needs to be considered when deciding where and when to restore kelp. Overgrazing by consumers such as sea urchins is both a leading cause of kelp decline and one of the most common factors limiting kelp restoration success (Eger *et al*. 2021b). Herbivore populations are a natural part of marine ecosystems and only become problematic when their consumption rates are larger than kelp growth rates. This imbalance may be caused by an overfishing of sea urchin predators such as fish and lobsters (Filbee-Dexter and Scheibling 2014) or through invasions facilitated by warming water temperatures (Johnson *et al*. 2011). As discussed in chapter 6, reducing fisheries quotas or establishing MPAs can lead to more abundant predators and consequently kelp forests (Babcock *et al*. 2010; Hamilton and Caselle 2015). Restoration is more difficult if herbivore numbers have increased due to range or population expansions facilitated by altered oceanographic conditions (see the following review of herbivore management for solutions). Other potential strategies to minimize the impact of herbivores may include selecting sites with low herbivore abundance, undertaking the restoration at times of the year when herbivores are less active (typically in winter months) and/or focusing on life history stages that are more resilient to consumers (e.g. adults instead of juveniles).

To properly assess kelp restoration efforts and learn from kelp restorative efforts, it is important to define success against clear objectives using measurable indicators. This should involve comparing restored sites with native reference kelp forests or conceptual reference models based on native ecosystems (Gann *et al*. 2019; Gleason *et al*. 2021).

Figure 7.2. Kelp restoration decision chart



Review of existing kelp restoration approaches

There are four main approaches to kelp forest restoration: transplantation, seeding, herbivore management and the installation of artificial reefs. These methods may be done alone or in combination with one or more other methods. The correct method for restoration will depend on the initial cause of decline (e.g. overabundance of herbivores or a lack of suitable substrate) and whether the kelp population can re-establish itself without further interventions once the cause of decline has been mitigated. Transplantation or seeding is required if there is no nearby parent population to provide propagules for new growth.

Transplantation

Transplanting adult or juvenile kelp individuals typically involves adhering the holdfast (similar to a root in plants) to an artificial material, which must then be added to the sea floor. The intention is for the holdfast to migrate to the benthos or for the kelp to act as a seed source for new kelp. Restorationists have trialled many different methods, including gluing holdfasts to rocks attaching them to small concrete blocks (Oyamada *et al*. 2008), tying them to ropes (North 1976; Hong *et al*. 2021), attaching them to existing holdfasts (Hernández-Carmona *et al*. 2000) and attaching them to mesh mats that are anchored to the sea floor (Campbell *et al*. 2014) or to artificial substrata (Marzinelli *et al*. 2009). Layton and Johnson (2021) provide a recent review of transplantation methods.

The key limitation with transplantation is its scalability and how well the kelp can attach to the sea floor. The physical transplantation of kelp is a laborious process and manual installation will likely prove cost prohibitive for large-scale restoration projects. The benefit of transplanting kelp is that it immediately introduces kelp individuals into an environment, which can then create conditions that are more suitable for new recruits (Layton *et al*. 2019). Transplantations may therefore be a necessary first step in establishing source populations that can then self-propagate. However, analysis shows that these patches need to be close to other existing populations to survive (Eger *et al*. 2020a; Layton *et al*. 2020a).

Seeding

Kelp seeding has received much less attention than transplantation. This bias may be due to the extremely high mortality of kelp propagules (Schiel and Foster 2006) and the perceived advantage of focusing on sporophytes, for which there is a much higher rate of survival. Projects that implement seeding approaches most often place weighted bags filled with fertile kelp material on the bottom of the sea floor (Westermeier *et al*. 2014). Such projects have had some success in the Republic of Korea but limited success elsewhere. Although the approach is more cost-efficient than transplantation, it still requires divers to install and remove the weighted bags from the ocean.

A new seeding approach, termed "green gravel"[5] is being developed to address the need for divers in restoration. In this approach, kelp spore cultures are first added to small stones, which are then grown to a juvenile life stage in a laboratory. The seeded stones are then dispersed over large areas at much lower costs than other transplantation or seeding approaches (estimated at $70,000 per hectare) (Fredriksen *et al*. 2020).

Success using a seeding approach is highly dependent on environmental and ecological factors that affect the kelp propagules. If abiotic conditions (e.g. sedimentation, temperature, salinity, pH levels) are unfavourable for growth there will be high propagule mortality. Kelp propagules are also highly susceptible to competition from other benthic species such as turf algae, crustose coralline algae and tunicates, and are also vulnerable to grazing from gastropods, sea urchins and fish (Schiel and Foster 2006).

Coral reef ecosystem restorationists are currently trialling the use of ships to disperse propagules into the ocean (Doropoulos *et al*. 2019), an approach that could be trialled for kelp and which would likely be most cost-efficient due to extensive cultivation knowledge. If successful, seeding methods can be applied at a much larger scale and much lower cost than other transplantation methods, meaning there is potential for seeding to lead future kelp restoration efforts (Saunders *et al*. 2020).

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5 See www.greengravel.org/.

Herbivore management

Controlling herbivores relies on manually removing, chemically attacking or excluding the animal from the targeted restoration area. For sea urchins this can involve relocating them (Mead 2021), harvesting them (Piazzi and Ceccherelli 2019), crushing them (Leinaas and Christie 1996) or killing them with quicklime (Bernstein and Welsford 1982). However, these methods are restricted by their high labour investments (Tracey *et al*. 2015) and feasibility in a spatially explicit location. Although physically killing or removing sea urchins is labour-intensive, with exact removal rates depending on the density and depth of the sea urchins, water conditions and the location's typography, it is a less costly approach than seeding, transplantation and artificial reefs (Eger *et al*. 2021b).

Though sea urchin management is more scalable than transplantation, it still requires substantial resources. To make removal more efficient, sea urchins can be baited to group them for collection (James *et al*. 2017) or can be killed using quicklime, which is poured over sea urchin barrens. Although the collateral damage of quicklime is low, it is possible that other echinoderms (e.g. starfish, sand dollars, sea cucumbers) and juvenile abalone could be damaged or killed (Keane 2021). The moral implications of this approach therefore need to be evaluated by the community, but technically, it can work over large areas.

The second challenge is to maintain sites that have had sea urchins removed. Many projects have demonstrated that if sites are not maintained, sea urchins will often return and once again remove kelp transplants or recruits. A global review of 13 barrens found that an average sea urchin biomass of less than 71 grams/m^2 is required for kelp regrowth and that an absence of sea urchins will best facilitate recovery (Ling *et al*. 2015). An additional or alternative solution to ongoing site maintenance is the restoration of healthy sea urchin predator populations in kelp forests, which can not only keep sea urchin numbers low, but can also help create self-sustaining ecosystems (Eger *et al*. 2020a). Regardless of the solution, restorationists will need to address this problem to ensure long-term viability.

Alternative solutions can also be applied to manage grazer populations. The establishment of a fishery or ranching programme that will remove grazers from the ocean either for food and/or profit is one such solution. As a market-based solution, it has the added benefit of providing employment and increasing the perceived value of kelp forests, which will hopefully spur further conservation efforts. A limited number of companies are currently exploring this type of solution in Japan, Norway and California (the United States of America). Another solution involves the restoration of natural sea urchin predators, either through marine reserves, which may allow them to recover without further intervention (chapter 6; Shears, Babcock and Salomon 2008; Sullivan and Emmerson 2011) or through planned reintroductions (Eger *et al*. 2020a). Managers could combine these reserves and reintroductions with active restoration efforts for maximum chances of success, though it should be noted that there have been some instances where increased predator populations did not always result in kelp forest recovery (but in any case, can support their resilience) (Ling *et al*. 2009). Similar solutions can also be applied to control the issue of grazing fish populations, which despite being a less common problem than sea urchin grazing, consistently occurs in areas such as southern California, eastern Japan, regions of Australia (Vergés *et al*. 2014), Portugal (Franco *et al*. 2017) and Spain (Peteiro and Freire 2012). As sea temperatures rise, there will likely be an increase in the interaction between kelp and fish, meaning solutions will need to be explored further (Vergés *et al*. 2019).

Artificial reefs

Although poorly documented, artificial reefs are likely the most common kelp restoration approach worldwide, with most projects undertaken in Japan and the Republic of Korea. Artificial reefs have a long history, with materials used ranging from rock to street trolley cars, bombs and ships to materials specifically designed to enhance algae growth (Reis *et al*. 2021). Projects can install reefs to provide substrates for kelp settlement if a donor population is available and substrate is limited or can supply existing kelp materials (adult, juvenile, propagules) with reef. Though popular, artificial reefs often work to replace a habitat (typically sandy sea floor) with a hard rocky reef, and subsequently, kelp. When replacing other habitats in this way, artificial reefs work to create kelp forests where they did not previously exist and can therefore be considered afforestation as opposed to restoration. This trade-off remains a societal decision and one that may be increasingly considered (Paxton *et al*. 2020).

A key benefit to artificial reefs is that managers can place them in areas where they can be easily maintained and where transplants can be more easily attached than on the natural sea floor. New materials for artificial reefs include those that structure the concrete to enhance its rugosity and provide an additional settlement area (Ishii *et al*. 2013; Bishop *et al*. 2017), and that infuse the concrete with iron, nitrates and other growth-enhancing nutrients that are slowly excreted over time (Oyamada *et al*. 2008). However, the materials required to build artificial reefs are very expensive (around $707,300 per hectare; 2020 dollar value) and require substantial investment, which governments have typically provided.

Optimizing kelp restoration

Although kelp are the dominant habitat formers in kelp forests, hundreds of other algae and animal species are found in such forests and are therefore integrated with and adjacent to human activities. To date, most projects have only focused on actively restoring the target kelp species and not on restoring associated biodiversity or synergizing with parallel human activity. It will be important for future projects to address this gap as positive species interactions can improve the likelihood that a restoration project will be successful and help species expand their niche during altered conditions such as sustained ocean warming (Eger *et al*. 2020a).

Potential synergies in kelp restoration range from kelp populations to humans. Projects can take advantage of positive density dependencies within kelp (Layton *et al*. 2019), among other kelp or seaweed species (Konar and Estes 2003) and with other habitat formers such as oysters to modify the environment and encourage growth rates and survival (McAfee, Larkin and Connell 2021). As previously discussed, predators are well known for their role in the ecosystem, an effect that is prominent in kelp ecosystems. Species such as lobster, fish and starfish consume sea urchins, which helps kelp populations to flourish across the globe. Protecting and restoring these predators will be a key step in ensuring stable kelp populations.

More manipulative technologies (e.g. genetic and microbial manipulation) may increase the tolerance of target species to warming and other stressors and should be considered for future restoration activities (Coleman *et al*. 2020). Aquaculture and sea urchin fisheries can also play an important role, as can reproductive materials, which provide a useful source of kelp spores when they enter the water column during growing seasons (Eger *et al*. 2020a). Furthermore, cultivation techniques can be adapted to advance kelp restoration (North 1976) and sea urchin fisheries can help maintain healthy sea urchin population numbers (Lee *et al*. 2021).

The incorporation of positive species interactions into future restoration practices can help promote a more holistic form of restoration that will also increase the likelihood of success in a shifting seascape.

Community engagement

Ecosystem restoration is tied to the people that value and use the ecosystems being restored. Outside of Japan, previous work on kelp restoration has not heavily involved local communities, as much of the work being done was experimental and had less opportunity for community involvement. It will be important to rectify this as projects become larger in scale and work to restore the marine ecosystems with which people interact. The question of where and what to restore requires significant community input as personal beliefs about a desired state motivate restoration, the values of which should be informed by consultation with local community members (Elias *et al*. 2021). In particular, land rights and the interests of local indigenous groups must be respected and incorporated into restoration decision-making (Lee *et al*. 2021).

Restoration education and outreach can work to create connections with restoration projects and increase community support for them (Vergés *et al*. 2020). Such support can help motivate government funding, as observed in the Republic of Korea, where the FIRA project was launched in direct response to the community's desire for healthy oceans. Other projects may even involve community members in restoring kelp forests (e.g. divers removing sea urchins; Watanuki *et al*. 2010) or monitoring activities (e.g. reporting kelp cover by snorkel; Edgar and Stuart-Smith 2014). The benefits of such involvement are twofold, with project costs somewhat mitigated and stewardship over the local marine environment increased. Working with and for the community can therefore increase the chances of success and provide multiple benefits for different users of the marine environment.

Financial and institutional support

Kelp restoration is a costly and lengthy process that can consume thousands to millions of dollars and span decades (Eger *et al*. 2020b). Even the best-researched projects are likely to fail if they lack the resources to sustain their efforts. Historically, costs for transplantation, seeding and the construction of artificial reefs have averaged between $526,000 and $707,000 per hectare (2020 dollar value; Eger *et al*. 2021a), though recent large-scale projects have reduced this number substantially to tens of thousands of dollars per hectare (Eger *et al*. 2020b). Such successful kelp restoration projects have taken place in Japan and the Republic of Korea, where governments have committed millions of dollars over decades and worked to enable local groups to perform restoration (Boxes 7.1 and 7.2).

Convincing governments or other bodies to invest in restoration remains a significant barrier to large-scale success. Recent reviews (Bennett *et al*. 2016; Blamey and Bolton 2018; Eger *et al*. 2021a) highlight the economic contributions of kelp forests to society (discussed in previous chapters), with United Nations-led initiatives, such as the UN Decade for Ecosystem Restoration and the UN Decade of Ocean Science for Sustainable Development, helping to motivate groups. In fact, declines in kelp-associated fisheries, namely abalone, were largely behind the multimillion-dollar investments made into Korean and Japanese kelp forest restoration projects (Eger *et al*. 2020b). Furthermore, if properly validated and established, programmes such as carbon or biodiversity credits can also help finance and incentivize greater and larger restoration efforts. Although momentum to support kelp forest restoration is growing, further advocacy is needed.

Standardizing monitoring and reporting

There have been hundreds of kelp forest restoration attempts, yet no two have reported the exact same information about their outcomes. This lack of standardized reporting prevents the accurate tracking of global restoration progress, the numeric analysis of restoration effectiveness and the consideration of restoration elements beyond ecological factors, and also limits information-sharing across projects. A standardized framework for restoration that records the same variables in the same units can help address these issues and further researchers' understanding of the field (Baggett *et al*. 2015; Eger *et al*. 2022). Although the development of such a framework is time-intensive, it will continue to be useful for years and should therefore be prioritized immediately. One group, the Kelp Forest Alliance, is working to achieve this goal through helping to consolidate restoration information with an open-source project database and standardized data-entry platform.[6]

Future-proofing restoration efforts

Marine environments are changing rapidly in response to global climate change, with modelling predictions indicating that these increases are likely to continue for decades, even under the most optimistic greenhouse gas emission scenarios (Gattuso *et al*. 2015). These changes include ocean warming, ocean acidification, increased frequency of marine heatwaves and extreme storm events (Masson-Delmotte *et al*. 2021), as well as biotic responses to these changes.

As cold and temperate water species, kelp have an affinity for cooler temperatures and are adapted to interact with other cold-water species. Short or prolonged increases in sea temperatures may therefore kill kelp adults (Liesner *et al*. 2020), lower their resistance to other disturbances (Wernberg *et al*. 2018) or interfere with their reproductive processes (Muth *et al*. 2019). Movements of warm-water species such as herbivorous fish and sea urchins into cool water environments also often result in kelp loss due to overgrazing (Vergés *et al*. 2014).

These rapid rates of environmental and biotic change are outpacing the ability of many species to adapt. As a result, there is a clear need for restorative initiatives to future-proof efforts by explicitly considering an ecosystem's past and current characteristics as well as its future expected conditions (Wood *et al*. 2019). The genetic composition and structure of populations underpins their ability to adapt to environmental changes and recover from disturbances such as extreme events (Wernberg *et al*. 2018). New restoration strategies may therefore use genetic tools to inform the sourcing of donor materials or to manipulate genetic traits in an effort to maximize the adaptive capacity and resilience of restored populations (Coleman *et al*. 2020). Simply considering the genetic makeup of the kelp used in restoration can help ensure the effective preservation of genetic diversity (Wood *et al*. 2020) and could also enhance overall levels of diversity. More proactive methods involve "assisted evolution" approaches, whereby specific genotypes are selected and introduced in restored populations (van Oppen *et al*. 2015). This approach is currently being developed experimentally in Tasmania (Australia), where warm-adapted genotypes of giant kelp (*M. pyrifera*) are being selectively bred and used for restoration (Layton and Johnson 2021). More interventionist approaches, including synthetic biology and gene editing tools, such as CRISPR-Cas9, could be used to either create or spread specific beneficial genetic elements such as warm-tolerance or herbivore-resistance within restored populations (Coleman and Goold 2019). However, the application of genomic tools and the implementation of different levels of interventions raises profound ethical questions that need to be considered and discussed in the public sphere (Coleman *et al*. 2020).

Box 7.1. Case study: Kelp restoration in the Republic of Korea – Korea Fisheries Resources Agency project management

Kelp forest restoration in the Republic of Korea is conducted via the centralized marine afforestation and reforestation project, launched in response to continued kelp declines caused by coastal development and overgrazing (Sondak and Chung 2015). Korea Fisheries Resources Agency (FIRA) and the Ministry of Oceans and Fisheries oversee the project, which is the world's largest kelp afforestation and restoration programme. The project was initiated in 2009 and will run until 2030 with a yearly budget of approximately $27 million (Korea Fisheries Resources Agency [FIRA] 2021) and the aim to restore 50,000 ha of kelp forest. Since 2019, more than 20,000 ha have been established across 173 sites (Lee 2019).

The project covers all of the Republic of Korea but is focused on the east coast and Jeju Island, where much of the country's kelp forests are found. On Jeju Island, Haenyo women play a leading role in seaweed and seafood harvesting and are also known as the "sea women of Jeju". Initially, FIRA relied on protocols developed for projects carried out earlier in the decade and used transplants or seeds on artificial reefs. However, there was some protest around the widespread use of artificial reefs and their replacement of other habitats (i.e. afforestation), with efforts now directed towards funding the best ways to restore forests on rocky reefs where they were once present (Yang *et al*. 2019). Aside

6 See https://kelpforestalliance.com/.

from artificial reefs, the project benefits from the country's strong aquaculture knowledge and rearing of kelp individuals to be planted as adults on seeded string or in bags and zoospores to be dispersed directly onto benthos. There is also growing interest in sea urchin management as a method for restoration, as it is often a cause of failure for initial projects.

The project has developed a systematic approach to selecting, installing and monitoring restoration sites. Municipal and state groups first identify and propose potential project sites informed by guidelines provided by FIRA and the Ministry of Oceans and Fisheries. These guidelines include consultation and support from local marine users (e.g. fishers), budget restrictions, site access, desirable ecological features such as low sea urchin density and appropriate currents, and synergies with other marine management strategies. Each year, sites are selected by a committee and funds are distributed to implement the project. After a project has been completed, FIRA inspects the site twice a year and monitors its progress. If a project does not meet its goals, adjustments are made to try and facilitate project success (e.g. sea urchin removal, water clean-up, supplemental transplants). This process of monitoring and maintenance is carried out for at least four years and is also run by FIRA. Such monitoring also allows projects to learn from past efforts so that they can be improved in the future. These lessons are compiled into a technical document titled *The Process for Marine Forest Creation*, which is available in Korean from the Korean National Library and in English from the Kelp Forest Alliance's website.[7]

Sustained project funding has also allowed for the development of new restoration approaches and innovations. This includes, for example, aerial hyperspectral imaging, which is used to track kelp forest populations and allows for large-scale evaluations of the project, and autonomous drone technology that can be used in water, which enables sites to be monitored without divers. The project has also invested heavily in mapping the marine environment and ensuring that projects do not impact other activities, such as fishing and development.

Although the Republic of Korea's Government leads the kelp restoration work, there has been considerable input from local universities and communities. University research often drives different restoration techniques, provides historical baselines and advises ongoing management efforts, while local communities are regularly consulted for input into where restoration should occur. The FIRA marine afforestation project will likely be responsible for most kelp restoration work carried out in the Republic of Korea for the foreseeable future, with input from universities and community consultations continuing. This project is a good model of how funding, applied research and interest in marine restoration can achieve success at ecologically meaningful scales.

Box 7.2. Case study: Fisheries Multifunctional Demonstration Project in Japan

Japan has an extensive history of seaweed cultivation and restoration, with marine management typically carried out at three levels: federal, prefectural and locally with fishery cooperatives. In 2013, the Fisheries Multifunctional Demonstration Project (FMDP) was established through the cooperation of these three cooperatives. The FMDP builds off a previous initiative – the Environment and Ecosystem Protection Project (EEPP) – and provides funds for preserving and restoring marine and coastal habitats across Japan. To date, most projects have focused on seaweed and kelp forests (303), followed by tidal flats (183), saltmarshes (35), and coral reefs (18).

Activities that fall within the scope of protecting and restoring seaweed beds include: transplanting adult algae; producing algae spore stocks; seeding algae; removing sea urchins; removing herbivorous fish; creating protected areas; translocating sea urchins; fertilizing seawater; cleaning marine substrates; and carrying out follow-up project monitoring.

The EEPP has created a national structure for new projects to apply for funding (Figure 7.3), which are initially set up by local action groups of different community members, such as fishers, residents, experts, non-profit organizations, schools, universities and businesses. Once a plan has been developed for a project, the action group then lodges an application with their relevant city, town or village office. The application goes through an assessment to ensure

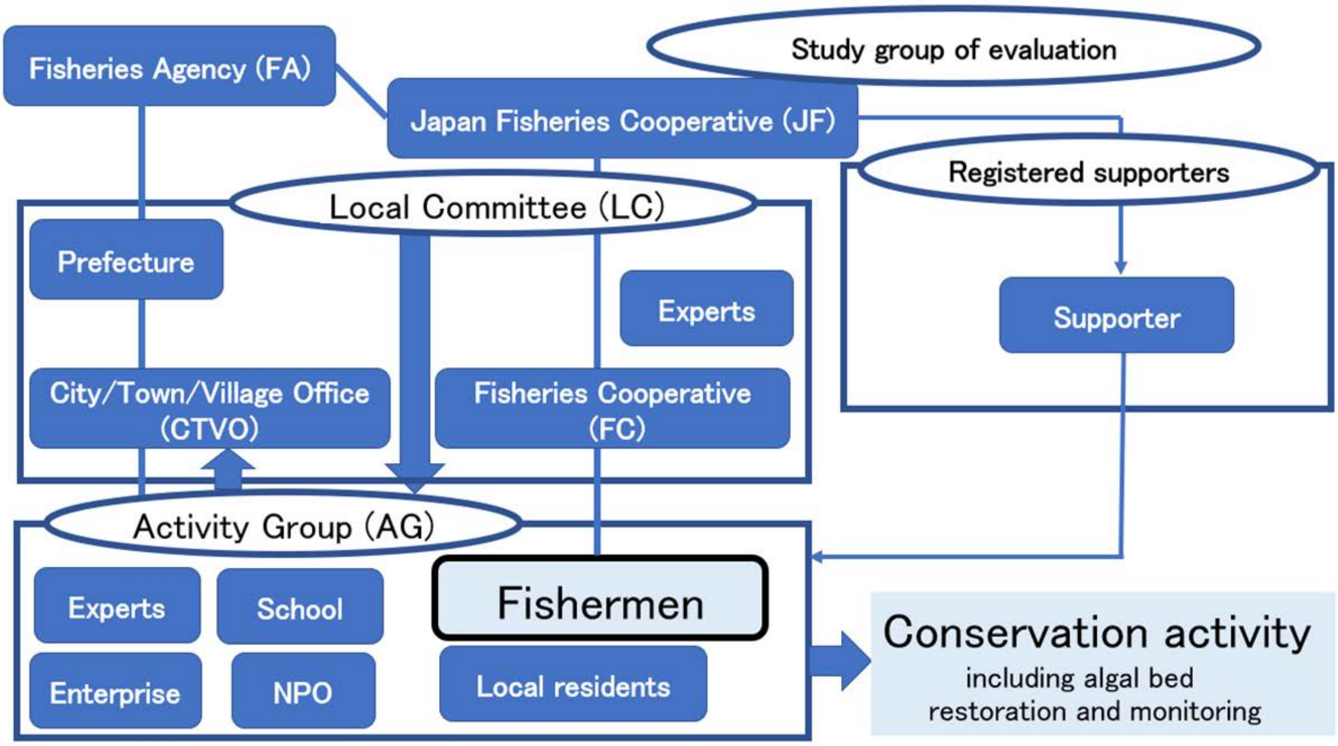
7 See https://kelpforestalliance.com/.

that it meets the aims of the EEPP, has the necessary local support and is properly planned. If the project is deemed appropriate, a funding agreement is signed between the relevant office and the action group. Project funding is split between the national government, which provides half of the funding amount, the prefectural government, which provides a quarter, and the relevant office (represented by a local committee of experts), which also provides a quarter. These funds can be spent on restoration activities, monitoring and reporting or education and promotion. The EEPP can also provide experts to support the action group if further advice is needed.

Projects are continually monitored and the action group is required to provide an annual report of updates to the committee of experts, detailing allocations of funds, activities undertaken and project outcomes. After receiving the annual report, each prefecture holds a meeting during which the committee of experts discusses project outcomes and selects successful examples to be highlighted at a national symposium hosted by the Japan Fisheries Cooperative.

It is generally straightforward for action groups with well-designed projects to access funding through this initiative, which has resulted in the restoration of some kelp forests. Overall, 288 groups have accessed support and restored around 100 ha of kelp forests since the initiative's launch. However, ocean warming and more frequent and stronger storms and floods are making restoration difficult in some instances. It can also be difficult for projects to continue work in rural areas due to their depopulation and loss of fishery cooperative members. It is therefore essential that similar initiatives ensure applications have long-term plans, are rigorously monitored and evaluated, and, as is necessary for all restoration efforts, address the root cause of decline.

Figure 7.3. Structure of the Fisheries Multifunctional Demonstration Project



Note: The concept of these projects appeared in article 32 of Japan's Basic Fisheries Act (2001) as follows: The State shall take necessary measures to gain a better public understanding and interest in the role of the fishery industry and fishing villages for the stabilization of citizens' life and national economy, and to exert appropriately and fully the multifunction of the fishery industry and fishing villages other than the supply of marine products for the future.

Chapter 7 references

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