

INTO THE BLUE

**Securing a Sustainable Future
for Kelp Forests**



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

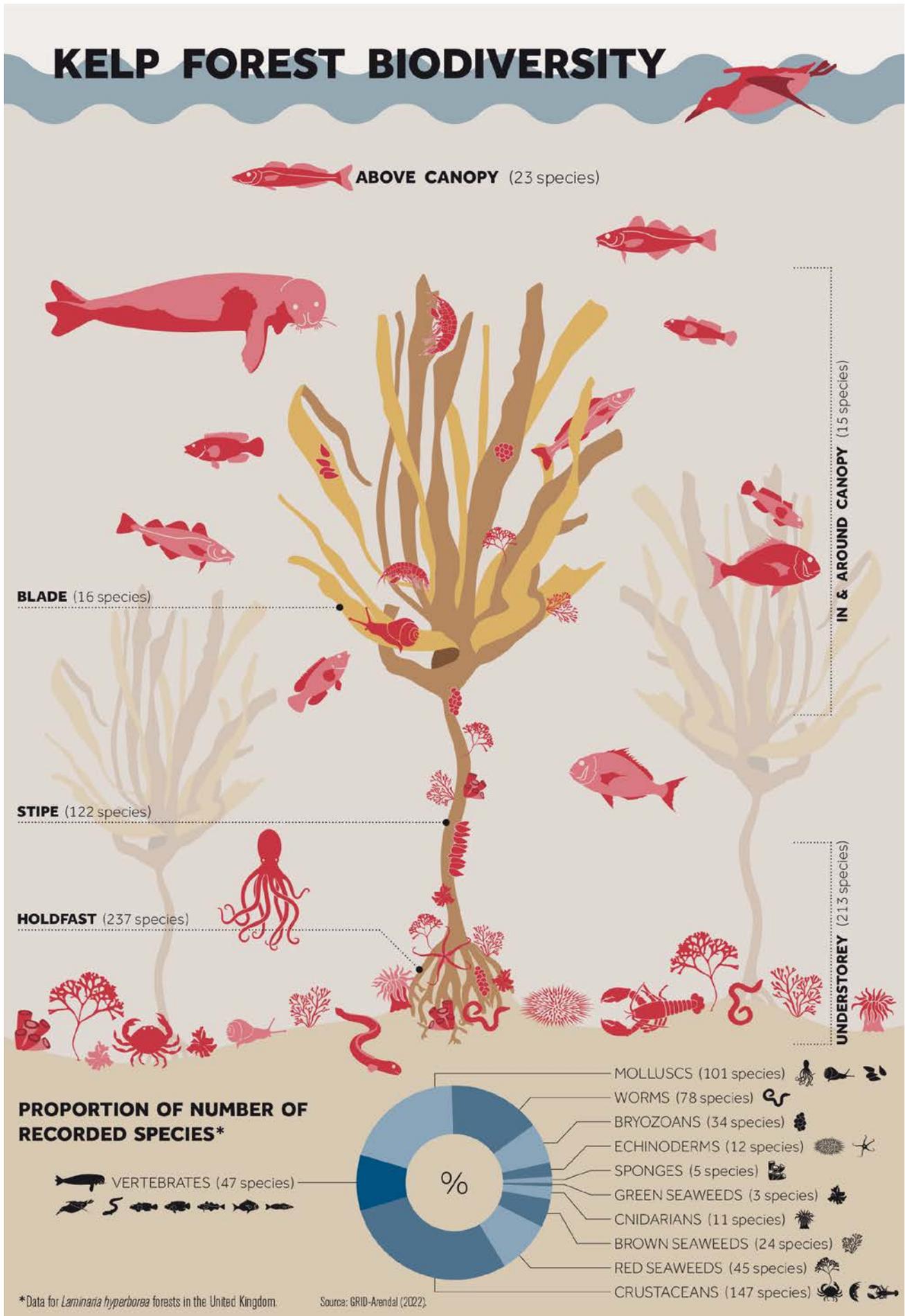
disturbances, the competitive hierarchies may switch to favour other seaweed species or small opportunistic species such as filamentous and turf algae. In other words, kelp forests are maintained through positive feedback loops of self-recruitment, fast growth into large fronds, shading, frond abrasion 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 understory 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 understory (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 understory 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 hanna*) 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 Efirid 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).

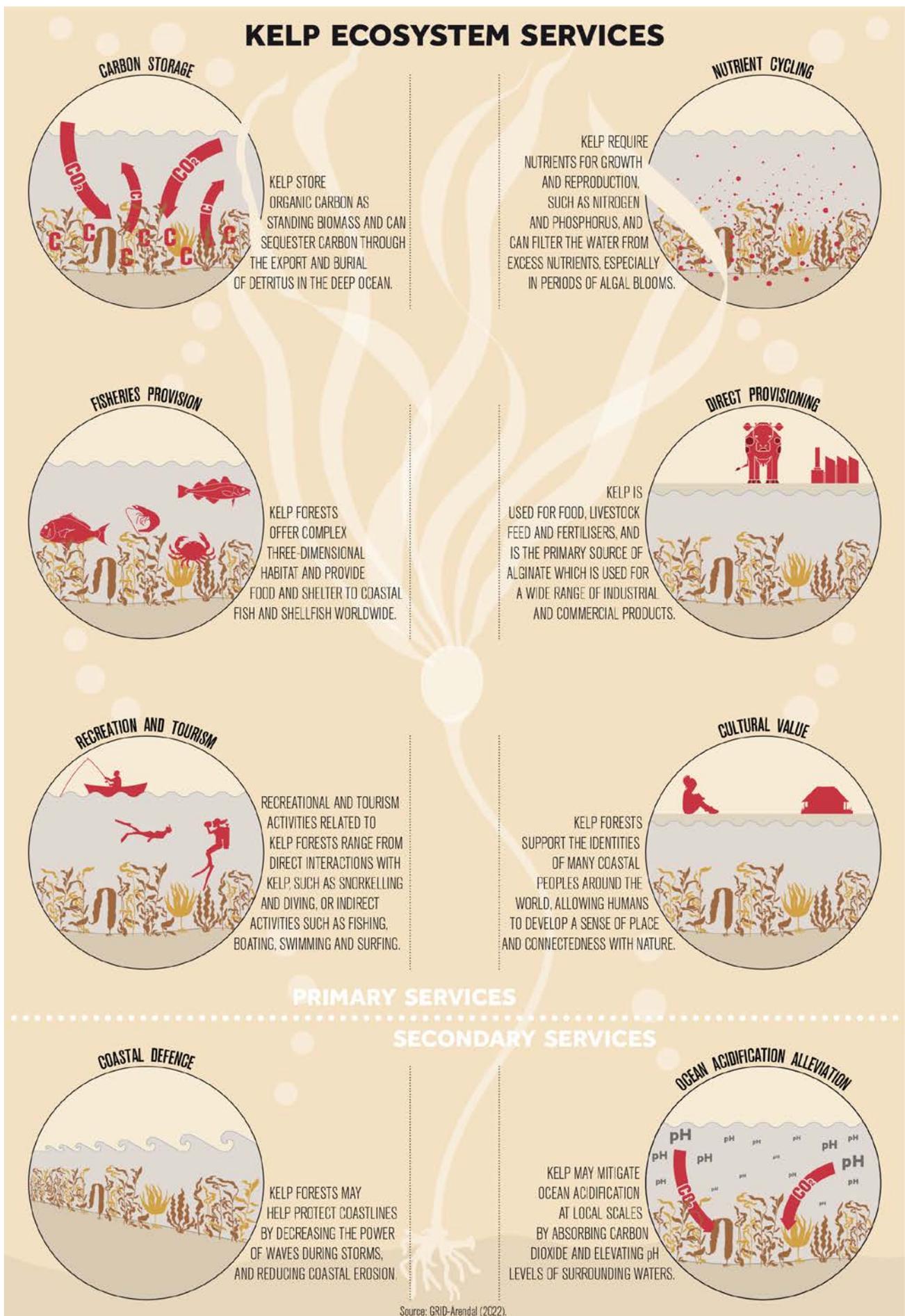
The trophic linkages whereby sea otters, predatory fish and lobsters indirectly facilitate kelp by eating sea urchins, which Paine (1980) famously coined a “trophic cascade”, represents a text-book example of indirect species interactions (Begon, Harper and Townsend 1986). Trophic cascade theory has 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



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 CO₂, 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 km² (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 CO₂ 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, Geraldini 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, $\text{CH}_4\text{N}_2\text{O}$) (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 *Mesocentrotus 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; Fridmodig 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, Vavrinc 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*, *Paraperis 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; Borrás-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 fucoxanthin 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



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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 understory assemblages (Eckman, Duggins and Sewell 1989).

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 (Kuwaie 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 (Kuwaie and Crooks 2021, Kuwaie *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 CO₂ 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



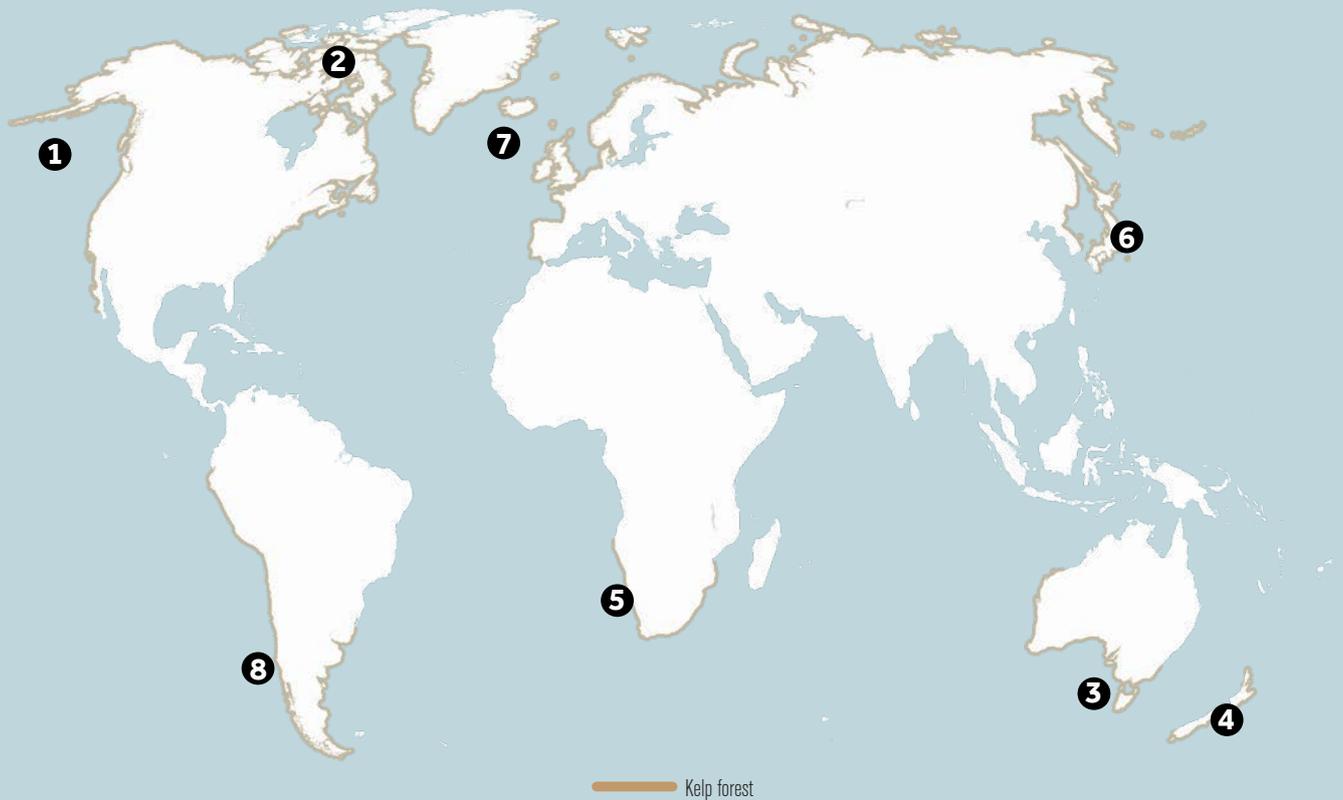
Notes: 1. Seaweed (translated title), Cee Pootoogook, Cape Dorset, 2016; 2. Keeper of the kelp, Mary Pudlat, Cape Dorset, 2001; 3. Gathering kelp, Kananginak Pootoogook, Cape Dorset, 1986 (a Canadian indigenous family harvesting kelp). Dorset Fine Arts (www.dorsetfinearts.com), reproduced from the Kananginak 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* (yáka) 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 (Ĝvĩłás) 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 divers 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).

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.

Chapter 3 references

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