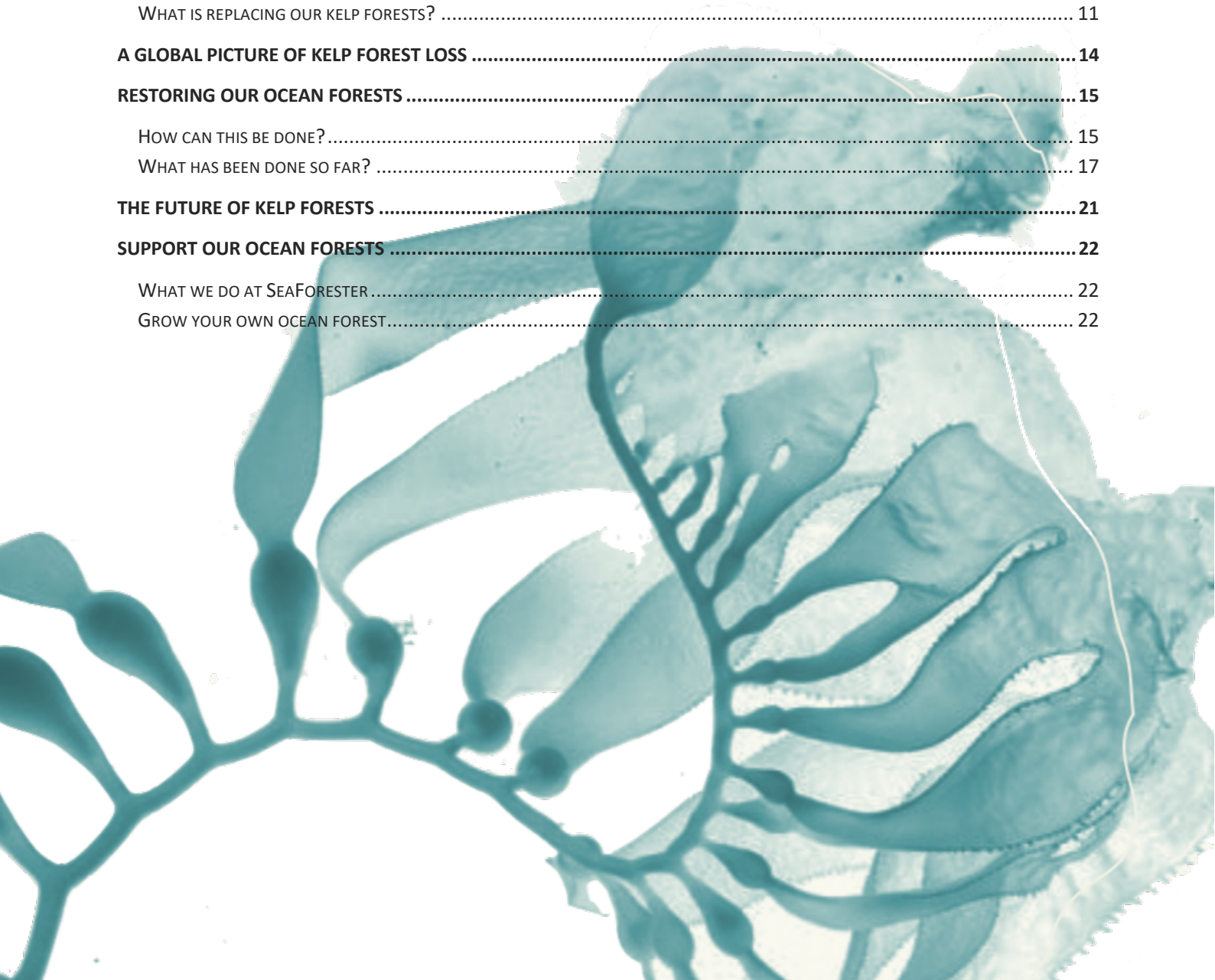


The Forgotten Ocean Forests



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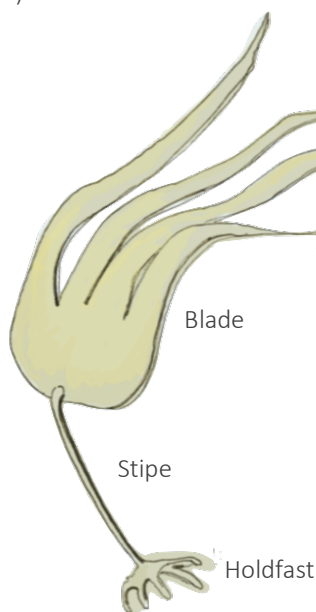


Kelp forests: The cradle of the ocean

'I can only compare these great aquatic forests with the terrestrial ones in the intertropical regions. Yet if in any country a forest was destroyed, I do not believe nearly so many species of animals would perish as would here, from the destruction of the kelp. Amidst the leaves of this plant numerous species of fish live, which nowhere else could find food or shelter; with their destruction the many cormorants and other fishing birds, the otters, seals, and porpoise, would soon perish also; and lastly, the Fuegians would decrease in numbers and perhaps cease to exist.'

Charles Darwin, 1 June 1834, Tierra del Fuego, Chile (Darwin 1909, pp. 256–257).

Charles Darwin had early realised the immense value of kelp forest ecosystems to support a diverse animal community from fish over seabirds and marine mammals to human societies themselves that rely on these coastal habitats for subsistence and various economic activities. Kelps are a type of large, brown seaweed that dominate shallow rocky coasts in temperate and arctic regions worldwide (Figure 1) where they form the largest biogenic structures found on the bottom of the ocean (Dayton 1985). Deep-water kelp habitats have also been reported in tropical regions where colder, more nutrient rich water can sustain kelp populations that are otherwise unable to thrive in tropical conditions (Graham et al. 2007). Kelp is a non-taxonomic term but is often reserved for species of the order Laminariales, whereas others use the term more broadly to include fucalean and other large seaweeds that provide similar functions (Bolton, 2010; Fraser, 2012).



Kelps come in many different shapes and sizes with 112 species of laminarian kelp currently known. They all follow the same general body plan, consisting of one or more flat blades that originate from the stipe. The stipe is attached to a holdfast that anchors the kelp plant to the seafloor. Some species form a single blade at the upper end of the stipe, while others grow multiple stipes with multiple blades. Species, such as the winged kelp, *Alaria esculenta*, even form wing-like structures along the length of the stipe.

The stipes of some kelp species are flexible, causing the kelps to form a sweeping canopy over the seafloor (prostrate kelps), while others have rigid stipes that lift the kelps up into the water column and create dense canopies several meters above the bottom (stipitate kelps) (Dayton 1985). The largest type of kelps has gas-filled bladders that allow them to reach the ocean's surface where they form floating canopies (canopy kelps).

Giant kelp (*Macrocystis* spp.) is by far the largest species of kelp and can reach heights of up to 45 meters, forming impressive underwater seascapes and floating canopies. This species dominates kelp forests on the west coast of North and South America as well as several locations in the South Pacific Ocean (South Africa, Southern Australia, New Zealand and subantarctic islands) (Steneck et al. 2002). Smaller canopy kelps include bull kelp (*Nereocystis luetkeana*) which forms productive underwater forests from Central California to Alaska, and its Southern Hemisphere counterpart, *Ecklonia maxima*, that is typically found along the southern Atlantic coast of Africa (Steneck et al. 2002). Smaller kelps such as *Laminaria* sp. dominate kelp forests across much of the Northern Hemisphere on both sides of the Atlantic

Ocean and Pacific North-west coasts of China and Japan.
Other morphologically similar species are *Ecklonia*

found in Australia, New Zealand and South Africa, and
Lessonia in Chile.

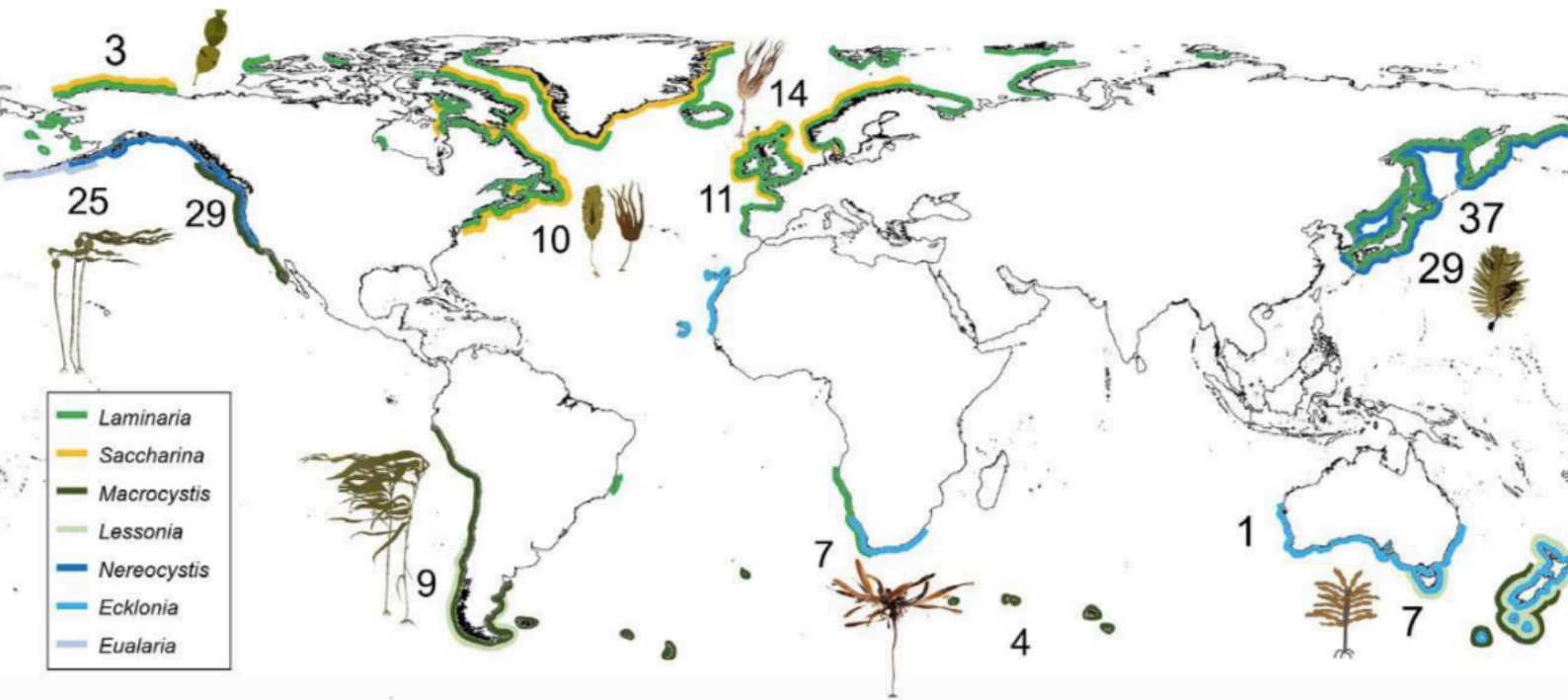


Figure 1. Distribution of laminarian kelps globally. Coloured lines and numbers indicate the main distribution of major kelp general and number of kelp species, respectively (Source: Wernberg et al. 2019).



Benefits of kelp forests to nature and society

Kelp forests are among the most important and valuable habitats on the planet, providing humans with ecosystem services worth billions of dollars annually (Figure 2) (Beaumont et al. 2008). Kelps, and the underwater forests they create, are a powerhouse for the climate, sequestering carbon and deacidifying our oceans, while functioning as important nutrient filters (Duarte et al. 2017, Filbee-Dexter 2020). They form highly complex habitats that support incredible biodiversity and provide nursery and feeding grounds for a variety of commercial fish species (e.g. abalone, lobster, sea urchin, cod, salmon) (Teagle et al. 2017). Kelp also has many and wide applications in today's society, as it can be processed for human consumption, animal feed, fertilizers, pharmaceuticals and other sustainable materials (Seaweed Manifesto 2020, Mouritsen et al. 2021). These coastal ecosystems also hold a significant recreational and cultural value to the tourism industry and local communities.

almost any other community of marine organisms. In the NE Atlantic, densities of more than 100,000 individuals of snails, crustaceans, bivalves, polychaetes and other invertebrates were observed per square meter in *Laminaria hyperborea* forests (Christie et al. 2003). The high productivity of kelp provides an abundant food source for herbivores such as sea urchins, small crustaceans, snails and fish that feed directly on the kelp. In turn, these species are targeted by larger predators that use kelp forests as foraging grounds (Christie et al. 2009; Teagle et al., 2017). These range from larger predatory fish, over seabirds, to marine mammals such as otters, seals and dolphins that are all intricately connected to these productive ecosystems. Among the stipes and blades, under the protection of a dense kelp canopy, animals seek shelter from these predators that would otherwise be vulnerable in its absence (Bertocci et al. 2015).

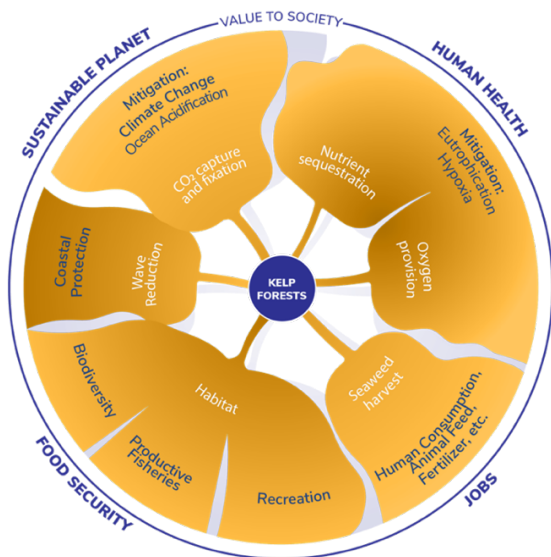


Figure 2. The benefits of kelp forests for nature and society.

Habitat for wildlife

Kelp forests are one of the most productive ecosystems on earth that form highly complex underwater habitats and are hotspots for biodiversity (Reed and Brzezinski 2009; Teagle et al. 2017). These vegetated habitats tend to have a greater diversity of plants and animals than



A swarm of fish gliding through a giant kelp forest.

Kelp forests also support productive fisheries through an increased abundance of many valuable target species such as abalone, lobsters, sea urchins, cod and salmon, that use these habitats as nursery and feeding grounds as well as for protection (Bertocci et al. 2015). Once reaching a more mature life stage, some species leave the kelp forest and migrate to other coastal or offshore habitats where they replenish local fish stocks.

In Norway, kelp forests play a key role in maintaining fish stocks and sustainable regional fisheries. It was estimated that Norwegian kelp forests support 1–2

million tons of cod (Moy and Steen 2014). To put this number into perspective, landings of the Norwegian cod fishery varied between 2.2-2.6 million tonnes per year over the last decade (Fiskeridirektoratet, 2021), highlighting the large contribution of kelp forests in supporting Norway's cod fishery.



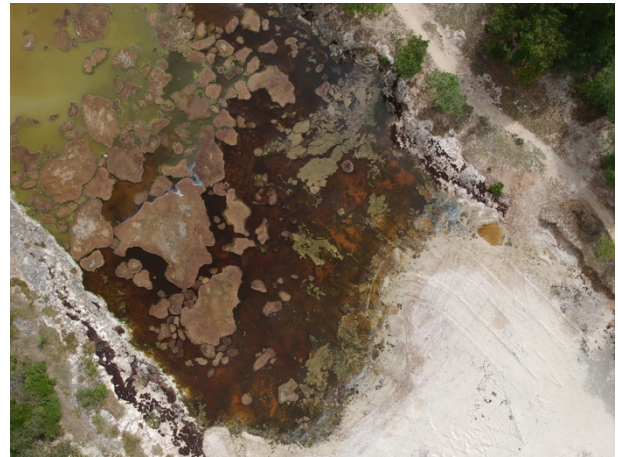
Cod in Norwegian kelp forest. © Hartvig Christie

Another example are bull kelp forests in Northern California that used to support a productive recreational red abalone fishery and a commercial red sea urchin fishery. Since 2014, kelp forest abundance has decline dramatically due to a combination of overgrazing and heatwaves that reduced kelp forest by more than 95% (Rogers-Bennett et al. 2021). The recreational red abalone fishery is now closed as a result and is only expected to reopen in 2026. The commercial sea urchin fishery has also been impacted by this environmental disaster, as urchins are starving with so little kelp remaining and are of no value to the fishery.

Ocean filters

Many of the world's coastal oceans are impacted by excess nutrients and other pollutants from human activities (e.g. aquaculture, urban and agricultural runoff and industrial discharges) (Horta et al. 2021). Excess nutrients can cause eutrophic conditions with detrimental effects on coastal ecosystems, maritime industries (e.g. capture fisheries and aquaculture) and recreational activities. Eutrophication is a process in which excess nutrients entering the coastal marine environment cause blooms of unicellular algae, also called phytoplankton, that reduce water clarity and the light reaching the seafloor. These phytoplankton blooms will eventually die off and sink to the bottom of the ocean where bacteria decompose the accumulated biomass, using up large volumes of oxygen in the

process. This drastic reduction in oxygen levels causes hypoxic (i.e. low oxygen) conditions and in the most severe cases create dead zones that are inhabitable for marine life. In the EU alone, the excessive use of industrial fertilizers was estimated to costs member countries between 70 to 320 billion euros each year in environmental and economic damages (EC 2022).



Eutrophication in coastal marine system.

Photo: Tim Oun on Unsplash

Kelp forests are important ocean filters that can sequester excess nutrients as well as other pollutants from the surrounding seawater. One square kilometre of kelp forest, for instance, can sequester nitrogen in excess of 35 tonnes during one growth season and can thereby significantly contribute to improving coastal water quality (e.g. Hasselström et al. 2018; Varela et al. 2018)

Kelp forests as blue carbon sinks

About one-third of our excess CO₂ emissions are taken up by the world's oceans (Hill et al. 2015). Global warming and ocean acidification related to rising CO₂ levels have profound consequences for our natural environment as well as our economies and livelihoods. Rising ocean temperatures and sea level rise contribute to the widespread disappearance of marine and coastal ecosystems, change biological processes and shift the distribution of species impacting fisheries and marine aquaculture (Gilson et al. 2021; Serpetti et al. 2017). When CO₂ is absorbed by the ocean from the atmosphere, it reacts with the seawater to form carbonic acid. The increase in ocean acidity can negatively impact marine life, causing the shells and skeletons of organisms made from calcium carbonate,

such as oysters and corals, to dissolve (Doney et al. 2020).

Marine vegetated habitats such as mangrove forests, seagrass beds and kelp forests play a key role in sequestering large amounts of CO₂. The carbon stored in our oceans and coastal habitats is also referred to as blue carbon. Kelp forests were long overlooked as significant contributors to blue carbon storage but have gained increased attention in recent years (Raven 2018).

Kelps take up CO₂ and sequester the carbon in its living biomass through photosynthesis, while producing oxygen. Kelp forests can sequester an average of 1000 g of carbon per square meter each year which is at least five times more efficient than the sequestration by tropical forests. Much of this production is consumed by herbivores, fuelling complex marine food webs. The continuous rapid growth of kelps is responsible for the high rates of primary production in kelp-dominated habitats, making them one of the most productive ecosystems on earth (Reed and Brzezinski 2009). As the kelp grows the blade acts like a conveyor belt of biomass production, forming in the basal area (also called the meristem) and moving towards the end of

the blade where the kelp tissue is rapidly or gradually eroded to generate detrital fragments.

Through this process of production and loss, kelp forests can store on average 500 g of carbon per square meter in its standing stock biomass (Reed and Brzezinski 2009). Globally, kelp forests cover an estimated 1.5 million km² (Filbee-Dexter et al. 2022) which amounts to around 0.75 gigatons of carbon (or 2.75 gigatons of CO₂) that is stored within these biogenic habitats. To put this into perspective, this is about half of the U.S. annual household emissions.

Some of the fragments of kelp that detach during the growing period become sequestered in marine sediments on the continental shelf and the deep sea, where the carbon contained in the biomass can be locked away for hundreds to thousands of years (Krause-Jensen and Duarte 2016) (Figure 3). Carbon sequestered in the deep ocean will remain trapped, even if the source ecosystem disappears. In contrast, the carbon stored over centuries in soils and sediments of e.g. seagrass beds, tidal marshes or land forests, is released back into the ocean and atmosphere when the ecosystem is destroyed.

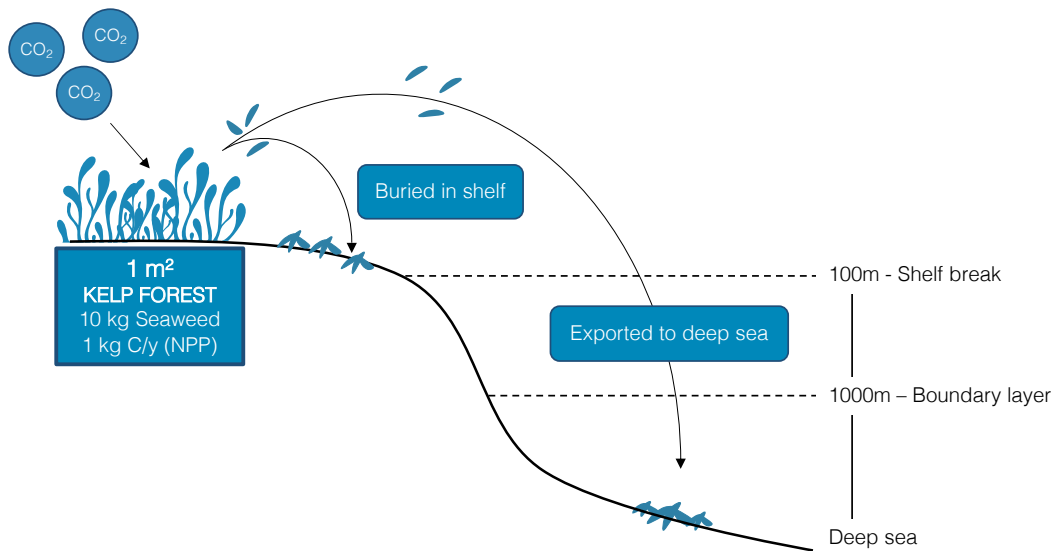


Figure 3. Carbon export from kelp forests that is stored in sediments on the continental shelf and deep sea.

Coastal protection

Coastal erosion and flooding due to sea level rise and intensification of storms pose increasing risks to coastal communities. In fact, 100 to 300 million people are at risk of floods and hurricanes because of the loss of

coastal habitats and their protective function (IPBES, 2019). Kelp canopies alter water motion and provide a buffer against storm surges by dampening wave energy and exerting drag in the water column, thereby reducing the velocity of breaking waves. It was

suggested that large, floating-canopy kelps, such as *Macrocystis* (giant kelp), provide only a negligible effect on wave attenuation, whereas stipitate kelps (e.g. *Laminaria*, *Ecklonia*) withstand wave energy through increased strength, rather than flexibility, which makes them potentially more effective in attenuating wave energies (Morris et al. 2020a). Experiments conducted along the Norwegian coast with the native kelp *Laminaria hyperborean* showed that kelp canopies have the potential to reduce wave energy by up to 70-85% (Mork 1996; Løvas and Tørum 2001).



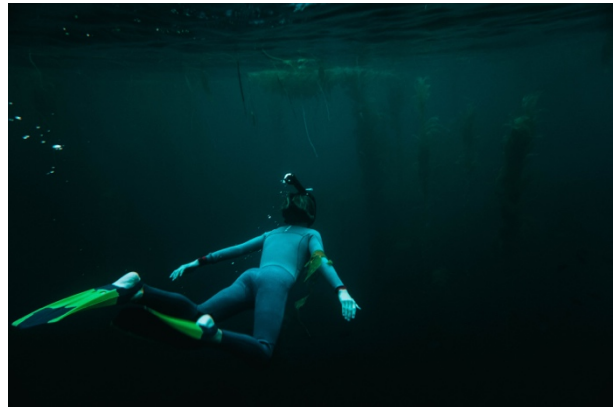
Reduction of wave energy by a shallow water kelp canopy.

The cultural value of kelps

Cultural services are the non-material benefits that people obtain from the natural environment. They include aesthetic appreciation and inspiration, cultural identity, spiritual experience, sense of place as well as opportunities for recreation and tourism (FAO 2022). Small-scale artisanal fisheries, for instance, benefit from kelp forests through increased food and income, while at the same time, these habitats play an important role in traditional fishing cultures and the fisher's way of life.

Nature-based recreational activities play an important role in supporting people's physical and mental health, where kelp forests provide attractions for recreational ocean users (e.g. wildlife watching) and indirectly affect other recreational activities such as swimming by increasing coastal water quality. In regional coastal communities along the Great Southern Reef in Australia, for instance, reef-related activities such as fishing, scuba diving, whale watching and other ecotourism ventures, have a total tourism expenditure of around AU\$9.8 billion per year, representing ~15% of the total

economic activity in some regional areas (Bennett et al. 2016).



A free diver gliding through the canopy of a kelp forest.
Photo: Shane Stagner on Unsplash

These ecosystems are also a source of inspiration for culture, art and design, and hold great value to inspire new scientific achievements (FAO 2022). Since the beginning of human civilization, nature and wildlife played a crucial part in ancient cultures, spiritual beliefs and a sense of belonging. In Chile, algae, shellfish and fish have been a major part of people diets since prehistoric times, with evidence of macroalgal use for food and medical purposes (Vásquez 2016).



Artisanal fisherman harvesting kelp in Pisagua (Chile). Photo: Claudia Pool (OCEANA)

Kelp forests under siege

We all think about deforestation and the devastating disappearance of forests on land, from the burning of the Amazon to wildfires in California, southern Europe and Siberia. But something similar is happening under the ocean completely out of view, destroying marine vegetation and our 'forgotten forests'. Many kelp forests have completely disappeared, destroyed by pollution, overgrazing, coastal developments, heatwaves, ocean warming and other factors. They used to cover most coastlines in temperate climates but are now under threat as our planet catapults towards increasingly rapid environmental degradation. The long-term consequences of their decline are a decrease in biodiversity, fewer fish, less carbon sequestration and poorer water quality. Coastal communities that rely on these vegetated habitats for subsistence and various economic activities are the ones most affected by their loss.

Ocean warming and heatwaves

Rising ocean temperatures can have profound consequences for the health and resilience of kelp forests. Kelps are adapted to cold-water environments with varying levels of thermal tolerance, i.e. the temperature range that they are able to thrive in. Temperature rise beyond their thermal limit has direct impacts on kelp performance, leading to reductions in growth rate, damage to kelp tissue, lower reproductive capacity, decreased resilience to disturbance, and eventually lead to kelp mortality (Wernberg et al. 2019).

These changes can cause a shift in species composition, where kelps are replaced by turf algae or other invasive species (Laffoley and Baxter 2016). In 2002, researchers in Norway witnessed large areas of sugar kelp (*Saccharina latissima*) being replaced by filamentous red algae, a likely consequence of the combined effects of ocean warming and coastal eutrophication, causing dramatic reductions in marine productivity (Moy and Christie 2012). Rising temperatures are also one of the main reasons as to why herbivorous species are moving poleward, causing kelp forests to decrease or disappear due to overgrazing (Laffoley and Baxter 2016).

Marine heatwaves, which are short periods of abnormally high ocean temperatures, are also

increasing in frequency and severity (Wernberg et al. 2013). In contrast to more gradual ocean warming, heatwaves can cause abrupt and severe mortality events from which many kelp forests have been unable to recover in affected regions worldwide.

Other climate-driven stressors

Climate change does not only cause global temperatures to rise but is also associated with changes in the frequency and severity of storms as well as rising ocean acidity. Due to their rapid recruitment and fast growth rates, kelp forests have been quite resilient to the effects of storms but with increasingly stronger and more frequent events that cause breakage and even removal of entire stands of kelps (Wernberg et al. 2019), natural populations will progressively be unable to cope in the future.



*Kelp washed up on beaches after storm event.
Photo: Tertia van Rensburg on Unsplash*

The impact of ocean acidification, a consequence of increasing levels of CO₂ in our oceans, on kelp forests is not yet fully understood and studies have, so far, only reported little to no effect on kelp reproduction and survival (Leal et al. 2017). It was, however, suggested that turf algae may gain competitive dominance over kelps and take over the available habitat (Connell et al. 2013).

Pollution and eutrophication

Nutrient pollution in coastal waters represents a major human-driven threat to kelp ecosystems as excess nutrient levels can lead to eutrophic conditions that reduce water clarity and the availability of sunlight for photosynthesis (Reed and Brzezinski 2009). High

nutrient levels can also trigger the excessive growth of fast-growing filamentous turf algae that outcompete kelps for space and light, while epiphytes (i.e. organisms growing on the blades of the kelp) can increase drag and reduce the availability of light even further (Sogn Andersen et al. 2011).

Fishing and overgrazing

Kelp forests form the foundation of complex marine food webs, supporting many species of fish, invertebrates, birds and even mammals that are directly or indirectly depending on these habitats for their survival. Sea urchins are a natural component of kelp-associated communities where they feed on kelps and other seaweeds, playing a significant role in kelp distribution globally (Filbee-dexter and Scheibling 2014). Urchin densities are naturally controlled by their predators such as cod, sea otters, crabs and some fish that are often of high commercial value. Where the abundance of such predators is reduced due to overfishing, sea urchin populations can dramatically increase in abundance and eradicate kelp forests across large coastal areas.



Kelp forest eradicated by voracious sea urchins. © NIVA

But overgrazing events might not be exclusively caused by fishing down predator populations, as there is evidence that warming can also affect the geographical distribution of herbivores. In Portugal, for instance, intense fish and urchin herbivory was documented in warm locations, whereas colder regions were unaffected (Franco et al. 2015).

Kelp harvesting

Kelps and other seaweeds have been harvested by indigenous communities for millennia but with the emergence of new markets the demand for commercial seaweed harvest has increased substantially (Buschmann et al 2014). Seaweed biomass has many applications in today's society where it can be processed for human consumption, alginate production, animal feed, fertilizers, pharmaceuticals and potentially even biofuels (Smale et al. 2013).

The removal of large quantities of biomass from natural populations can, however, have profound consequences for the structure and functioning of kelp ecosystems, their associated biodiversity and the benefits that these habitats provide. As kelps have high levels of recruitment and growth, industrial scale harvesting of wild populations can be done sustainably as long adequate management regimes are in place to avoid overharvesting. Kelp forests can regrow within just a few years after harvesting, whereas its associated biota requires significantly longer periods to re-establish (Steen et al. 2016).



*Kelp trawler harvesting from wild populations.
© Eli Rinde (NIVA)*

Kelp harvesting in Chile represents 10% of the world's supply and until 2002, the harvested biomass was taken from kelps washed ashore. With an increased global demand for biomass, wild harvesting has, however, increased with negative impacts on Chilean natural kelp forests (Vásquez et al. 2012). In Europe, commercial harvesting of wild kelp is well established in Norway, where fallow periods of around 3-4 years allow the ecosystem to recover before harvesting continues (Burrows et al. 2018).

Coastal development and habitat modification

The intensive urbanisation of coastal areas worldwide is influencing the connectivity between land and sea (Smale et al. 2013). Increased sediment and nutrient loading from human activities in the coastal zone are the leading cause for the widespread disappearance of kelp populations (Morris et al. 2020b) as suitable settlement substrate is buried under a layer of fine sediment and higher water turbidity from suspended particles is decreasing light penetration that impacts the kelp's photosynthetic activity (Smale et al. 2013).



Developments impacting coastal habitat health.

Furthermore, the construction of coastal defences, maritime infrastructure and other in-water constructions modify the natural habitat and make it uninhabitable for kelps. Between the 50s and the 70s, for instance, California witnessed a decrease in their giant kelp populations, primarily driven by a decrease in water quality, increased sedimentation as well as unfavourable oceanographic conditions (Foster and Schiel, 2010).

What is replacing our kelp forests?

Stressors that cause kelp loss can trigger sudden but persistent shifts in the state of marine communities. These so called 'regime shifts' happen when the kelp ecosystem is pushed beyond a threshold that fundamentally changes its structure and functioning. These alternative states cannot easily be reverted as the ecosystem is locked in a self-perpetuating state. The two most common alternative states that have received increasing focus are sea urchin barrens (Filbee-Dexter and Scheibling 2014) and turf reefs (Filbee-Dexter and Wernberg 2018) (Figure 4).

The replacement of kelp forests by these degraded habitat states has serious consequences for the goods and services the marine environment can provide to local livelihoods, fisheries, tourism and other maritime industries.

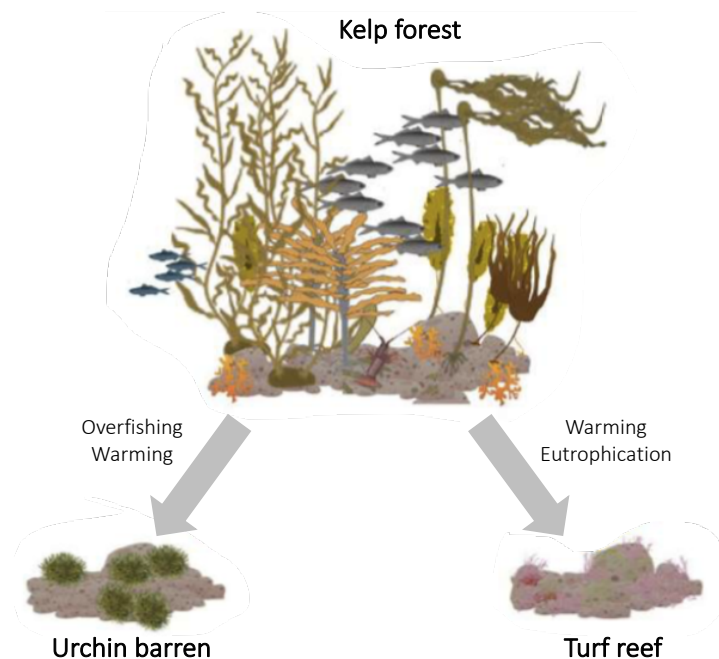
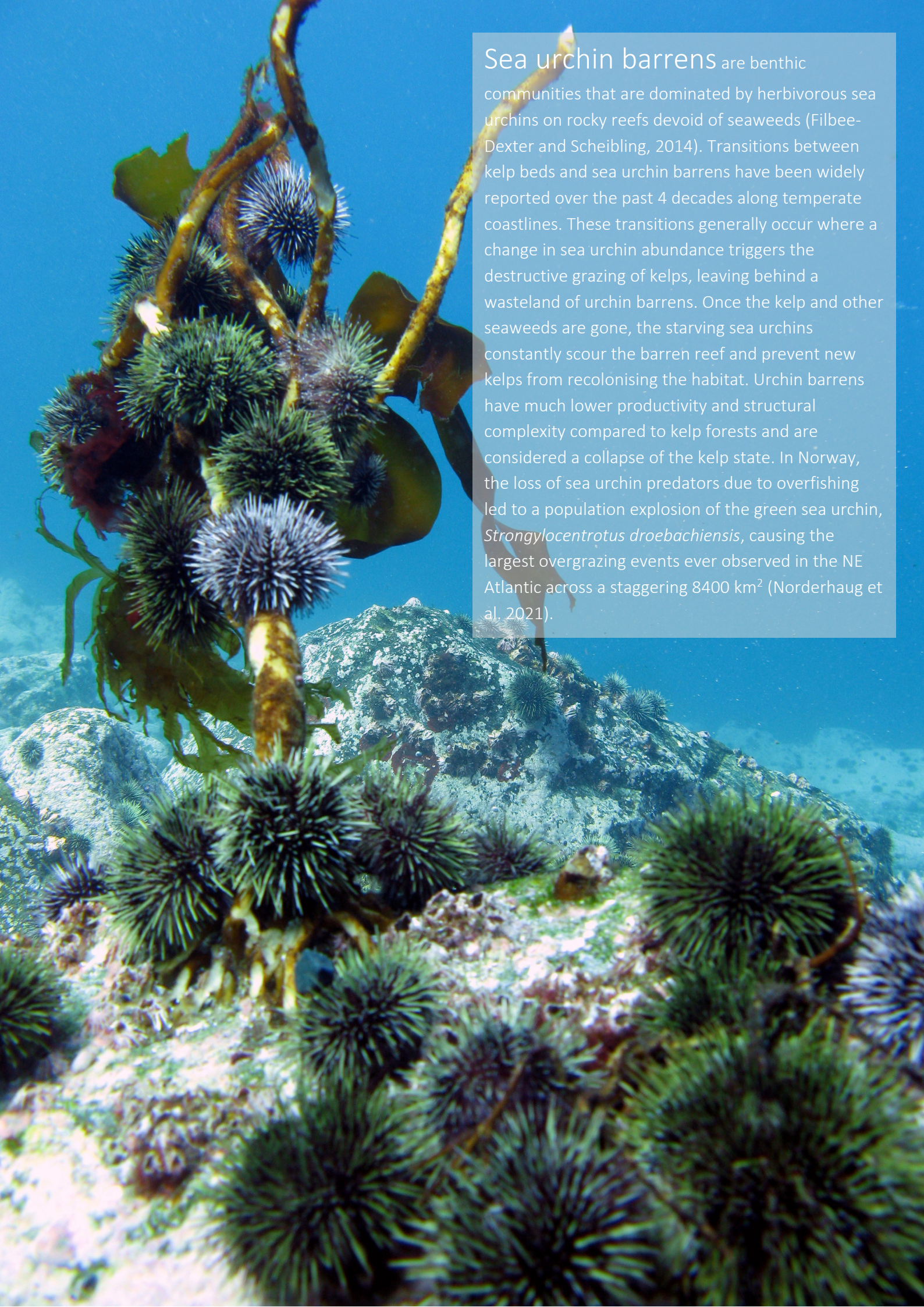
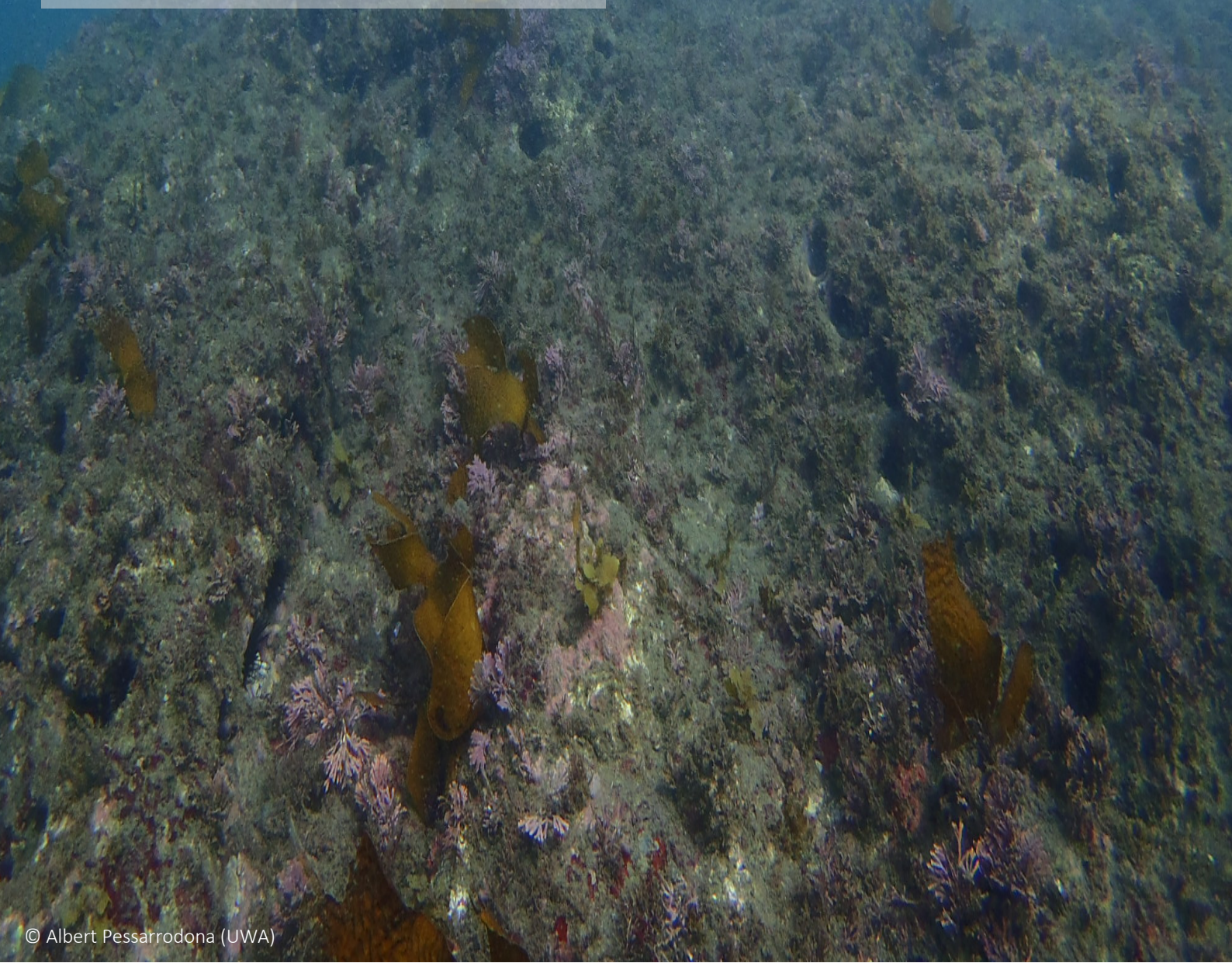


Figure 4. Replacement of kelp forests by two alternative ecosystem states: urchin barrens & turf reefs (Adapted from Wernberg et al. 2019)



Sea urchin barrens are benthic communities that are dominated by herbivorous sea urchins on rocky reefs devoid of seaweeds (Filbee-Dexter and Scheibling, 2014). Transitions between kelp beds and sea urchin barrens have been widely reported over the past 4 decades along temperate coastlines. These transitions generally occur where a change in sea urchin abundance triggers the destructive grazing of kelps, leaving behind a wasteland of urchin barrens. Once the kelp and other seaweeds are gone, the starving sea urchins constantly scour the barren reef and prevent new kelps from recolonising the habitat. Urchin barrens have much lower productivity and structural complexity compared to kelp forests and are considered a collapse of the kelp state. In Norway, the loss of sea urchin predators due to overfishing led to a population explosion of the green sea urchin, *Strongylocentrotus droebachiensis*, causing the largest overgrazing events ever observed in the NE Atlantic across a staggering 8400 km² (Norderhaug et al. 2021).

Turf reefs are rocky reefs covered by small, filamentous or foliose algae (Filbee-Dexter and Wernberg 2018). These turf algae are more stress tolerant than kelps and can monopolise the habitat after kelp forests are lost. Excess nutrients in coastal waters, causing eutrophic conditions, and the rise in ocean temperature are two key stressors triggering a shift to the turf state. The dense mats build by these algae trap high loads of sediments which further reduces the kelps capacity to recolonise the habitat. Unlike for urchin barrens, there has, so far, been no observed transitions back to the kelp state. The large-scale replacement of kelps by turf algae is a relatively new phenomenon and has increased within the past decade. Hundreds of kilometres of coastline in Atlantic Canada, Europe and Australia are already affected. Along 100 km of coastline in Western Australia, for instance, *Ecklonia radiata* kelp forests were completely wiped out during an extreme heatwave in 2010/11 and replaced by turfs.



A global picture of kelp forest loss

The trajectory of change, both in magnitude and direction, can often vary substantially between regions across the world. In a global assessment, 38% of regions with sufficient data showed declines in overall kelp abundance, whereas 27% had observed increases and the remaining regions indicated no detectable change (Krumhansl et al. 2016). But the overall picture remains unchanged; there is an on average 2% decline per year in global kelp forest abundance that may likely increase with future projections of increased global warming and further intensification of human impacts (Wernberg et al. 2019).

The main drivers for their alarming decline can be quite different depending on the part of the world (Figure 5) (Wernberg et al. 2019). In Japan, 75,000 ha of *Ecklonia* and *Sargassum* forests have disappeared between 1999 and 2018 due to coastal development, temperature rise and other extreme climate-fuelled events (Eger et al. 2020). A marine heatwave in the summer of 2010/11, following four decades of gradual warming, has caused an extensive loss of almost 90% of the kelp forests along

the western coast of Australia (Wernberg et al. 2013). Along the southern coast in Tasmania, 95% of giant kelp forest (*Macrocystis pyrifera*) has also disappeared (Wernberg et al. 2016).

In northern California, warming sea temperatures caused extensive kelp mortality and a population explosion of purple sea urchins grazed down kelp forests along hundreds of kilometres of coastline (Rogers-Bennett and Catton 2019).

Norway has lost a staggering 9800 km² of *Laminaria hyperborea* and *Saccharina latissima* due to sea urchin grazing and fouling by filamentous turf algae, a likely consequence of increased eutrophication and changes in climatic conditions (Gundersen et al. 2011).

These are only a few examples illustrating the immense loss of kelp ecosystems around the world. Many other regions are affected and without drastic changes to how we use our natural environment, we will likely see a substantial increase in habitat loss at this magnitude.

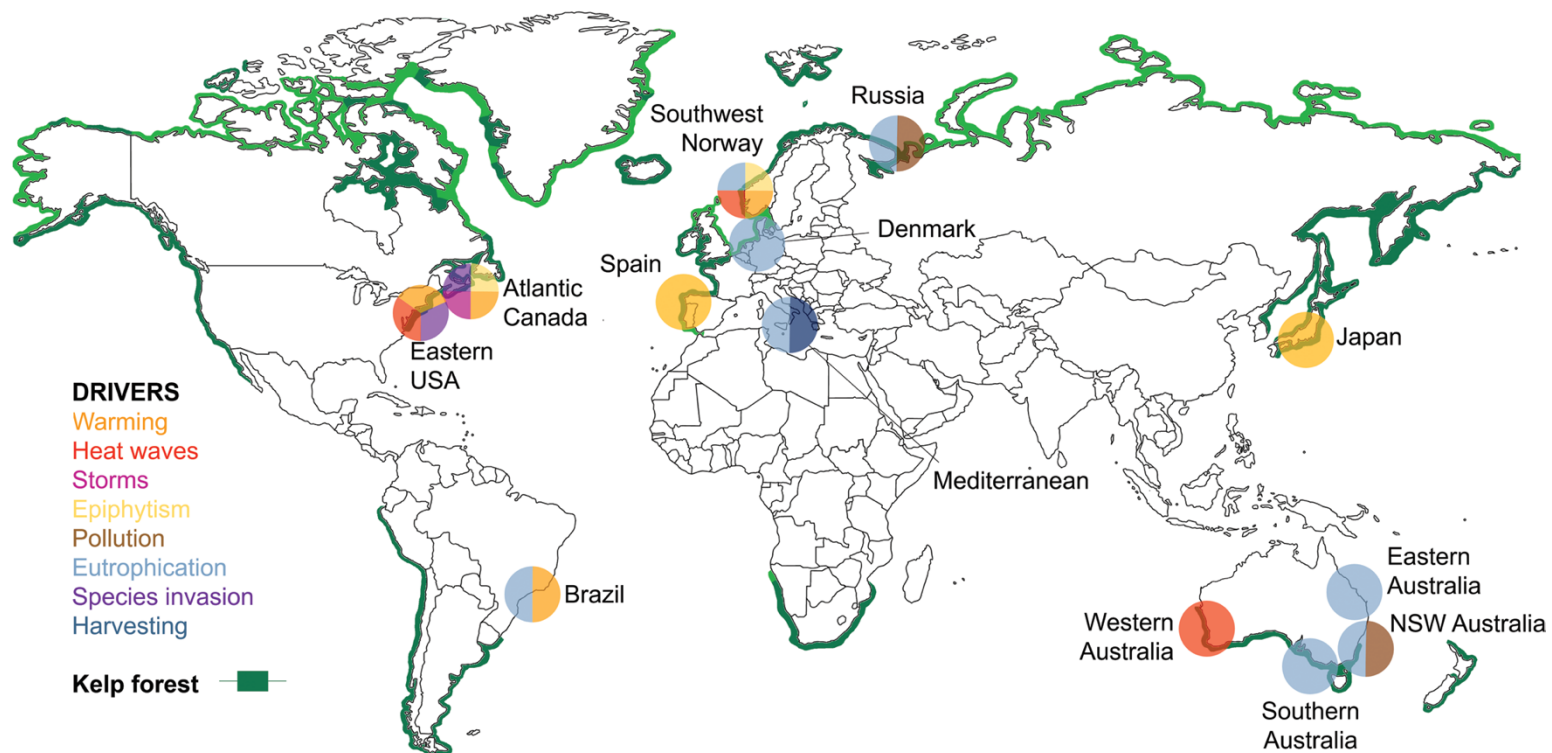


Figure 5. Geographic distribution of kelp forests and drivers of decline. Dark green: known distribution; Light Green: Distribution inferred from habitat requirements. The coloured pie charts illustrate the relative contribution of different drivers of kelp forest decline in various parts of the world (Source: Filbee-Dexter and Wernberg 2018)

Restoring our ocean forests



“There has never been a more urgent need to revive damaged ecosystems than now.”

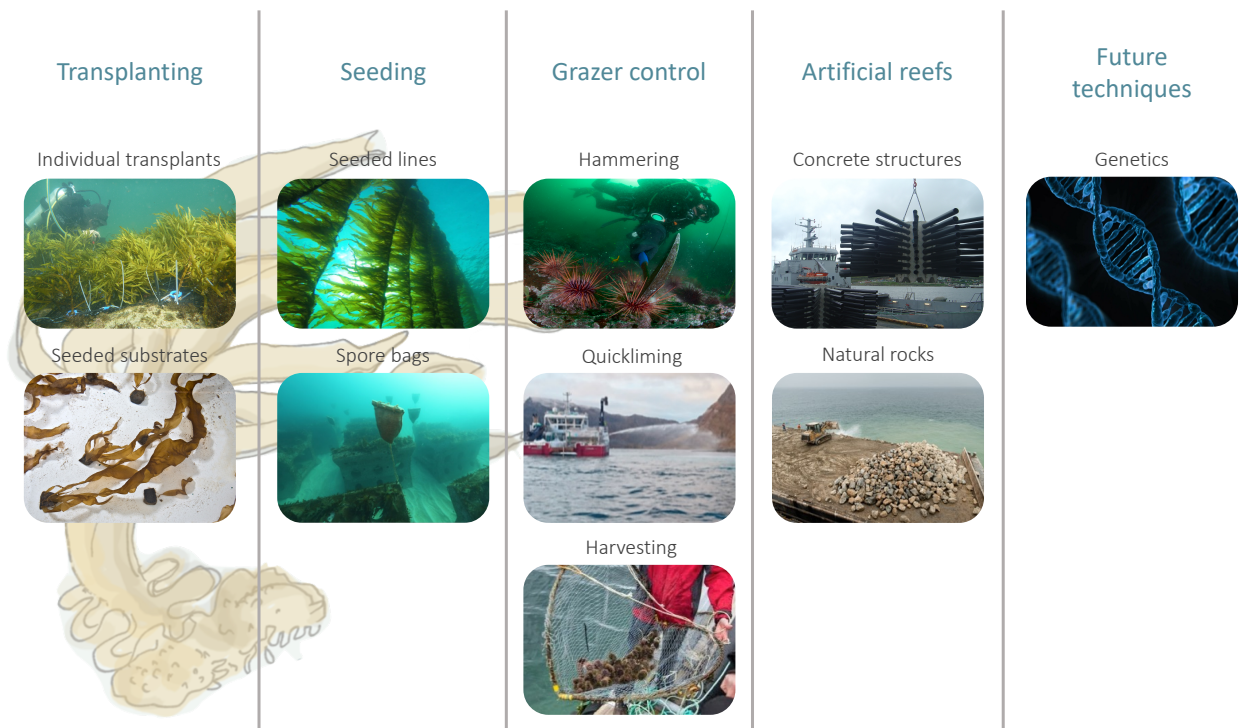
UN Decade on Ecosystem Restoration (2021-2030)

The UN Decade on Ecosystem Restoration (2021-2030) is a call for the protection and revival of ecosystems all around the world to address our current climate and biodiversity crisis and achieve the Sustainable Development Goals. While much of the current effort is focused on land forest restoration, restoring kelp forests presents a unique opportunity to tackle key climate and environmental challenges by revitalising our coastal ocean.

Restoring kelp forests comes with many advantages compared to other ecosystems. Seaweeds are among the fastest growing habitat-forming species in the world, making it possible to recover full forests in only 2-3 years, compared to land forests which can take several decades to recover. As seaweeds are ‘super spreaders’, with a single individual producing billions of spores per year, restoration areas can quickly expand due to natural dispersal.

How can this be done?

The aim of kelp restoration is to recolonise the habitat and recover its biological productivity, associated biodiversity, and ecosystem services. As a fundamental step to restoration, we first need to identify the drivers that caused the kelp decline as well as the measures that can be taken to manage them (Eger et al. 2022). Where kelp forest degradation is not too extensive or severe, the removal of stressors may be sufficient to restore the ecosystem. Extensive losses of kelps on the other hand may likely require additional actions such as active reseedling as areas void of parent plants cannot recover through natural processes alone. In fact, many successful kelp restoration projects have combined several methods, including kelp transplants, seeding kelp propagules, implementing grazer control measures and deploying artificial reefs.



Transplanting

A widely tested restoration approach is to take entire kelp plants from wild populations and transfer them to restoration sites. Various attachment methods can be used to anchor them to the seafloor and thereby create a new kelp canopy that provides spores for a new generation and creates more favourable conditions for the new kelp recruits to thrive (Layton et al. 2019). Scalability is, however, a limitation of this technique as the process of installing transplants is laborious and costly and does not provide a cost-effective solution for large scale restoration efforts.

Another approach is the seeding of natural or artificial substrates that are grown out in nursery facilities before deploying them at sea. The green gravel method (Fredriksen et al. 2020) is one such solution that is being increasingly tested in various locations around the world (see <https://www.greengravel.org/action-group>). The technique involves the seeding of small rocks with kelp spores that are then incubated in a nursery and scattered across the degraded reef. As green gravel can be produced at large quantities and easily distributed over the seafloor, the technique provides a promising new pathway to restore kelp forest at the needed scale.



Kelp restoration trial in Norway using green gravel.
© Jonas Thormar (IMR)

Seeding

This approach involves dispersing or growing microscopic life stages of kelps in the ocean. The spore bag is a seeding technique that introduces the reproductive structures of kelps (blades with spores), contained in mesh bags, into the environment (Westermeier et al. 2014). Natural cues will trigger the kelps to release their spores that will travel in the water column and settle on available habitat. This technique

requires the presence of sufficiently large donor populations as it relies on larger quantities of reproductive material from the wild.

Another restoration approach is the use of seeded lines that are commonly used in seaweed cultivation but have recently been adapted and tested for the restoration of kelp forest habitats. For aquaculture purposes, the lines are typically made of nylon but for the deployment in natural habitats, biodegradable materials are increasingly being tested. Just like the green gravel method, seeded lines are inoculated with kelp spores and grown out in nurseries until being deployed at sea. When suspended in the water column, the growing seaweeds, protected from benthic grazers, will form “kelp trees” that will eventually serve as mother plants, releasing their spores across the reef.



Kelps growing on horizontal cultivation lines (“kelp trees”).
© Seaweed Solutions (SES)

Grazer control

The management of grazers such as sea urchins is a crucial element to consider in kelp restoration. Urchin density control was identified as one of the most effective management measures to rebuild kelp ecosystems today (Frigstad et al., 2021). Seeding or transplanting kelps without controlling the intense pressure from grazers will unlikely result in successful restoration outcomes. A solution to the grazer problem is to mimic natural mass mortality events to reduce grazer abundances to levels that allow kelps to recolonise the habitat. Urchin densities can be managed by culling or harvesting.

Culling can be done by hammering urchins underwater or using quicklime that kills urchins upon contact by dissolving their outer skeleton. Urchins can also be harvested by hand-picking, mechanical removal or

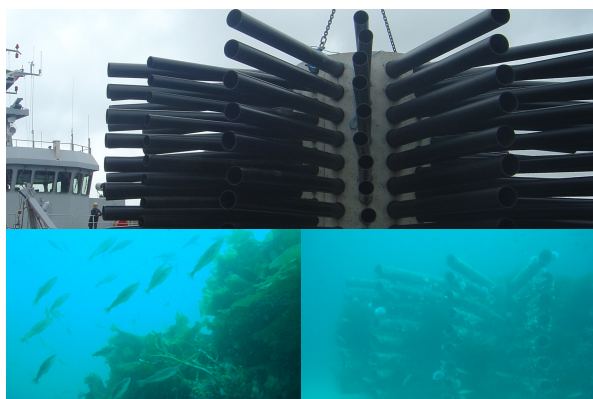
passive traps and potentially sold as a valuable seafood product (Verbeek et al. 2021). The artificial removal of grazers should, however, only be a temporary solution. To safeguard restored kelp forest in the long run, we need to restore the natural balance between grazers and their predators which can be achieved through a change in fishing regulations or protected areas. When predator populations have recovered, they can once again keep the balance in this dynamic ecosystem.



Urchin collection by diver in Norway. © Urchinomics

Artificial reefs

Artificial reefs can play a key role where there is a lack of kelp habitat, or the conditions of the natural habitat are unfavourable for kelp reestablishment. Whatever the reason, artificial reefs allow to enhance kelp forest abundance by creating new colonisable habitat for nearby kelp forests or to act as installation sites for transplanting or seeding. Artificial reefs can be constructed from concrete structures as well as natural rocks to create a boulder reef. A key consideration is to design the artificial reefs in a way that mimics ideal substrate conditions that can often vary between species of kelps. Some opportunistic kelp species may thrive on more dynamic reefs with less stable substratum whereas perennial species that live for several years may favour more stable environments.



Kelps growing on artificial reefs. © Hartvig Christie (NIVA)

Future techniques

Designing restored kelp populations with their genetics in mind will become an increasingly important restoration approach to boost the resilience and adaptive capacity of kelp forest in the light of climate and environmental changes. Several techniques are being investigated and tested with promising results and concepts to future-proof kelp ecosystems. Present day restoration projects that aim to revive lost/degraded kelp populations should, at a minimum, aim to replicate natural genetic baselines as restored populations will be more adapted to local environmental conditions in which they have evolved.

An important question has, however, been raised as to whether it is even desirable to replicate exactly what was lost or whether we should reinforce or redefine populations to make them more resilient to current and future changes (Coleman et al. 2020). An emerging approach is to improve the genetics of a population through selective breeding or boosting genetic diversity. Selective breeding can amplify specific traits that increases the kelp's resilience to stressors such as increasing ocean temperatures and heatwaves – "Assisted evolution".

Another way to improve genetic baselines is to increase the genetic diversity of a population to provide a larger set of genes that may increase the population's adaptive capacity – "Genetic rescue". Recent scientific advances in synthetic biology and gene editing have also provided us with previously unimaginable solutions to redefine natural populations. Genetic manipulation through gene editing and other approaches has the potential to create new genetic baselines that make kelps more resilient to environmental stressors.

What has been done so far?

Projects to restore declining kelp forests have been implemented in many regions across the world, with the first record of kelp restoration in Japan dating back as far as the 1700s (Eger et al. 2022) (Figure 6). Modern day restoration projects started in the second half of the 20th century and have steadily increased until today. Most of this work was done in Japan and the United States (California) and has therefore focussed on a limited number of kelp species present within these countries. Kelp restoration outside of Japan and Korea has largely been undertaken by scientists and

researchers, meaning that relatively few projects have been led by governments, NGOs, industry or community groups. To date, there have only been a small number of projects that managed to successfully restore larger

areas of kelp forests, such as those documented in California (United States), Norway, Korea, Japan and Australia

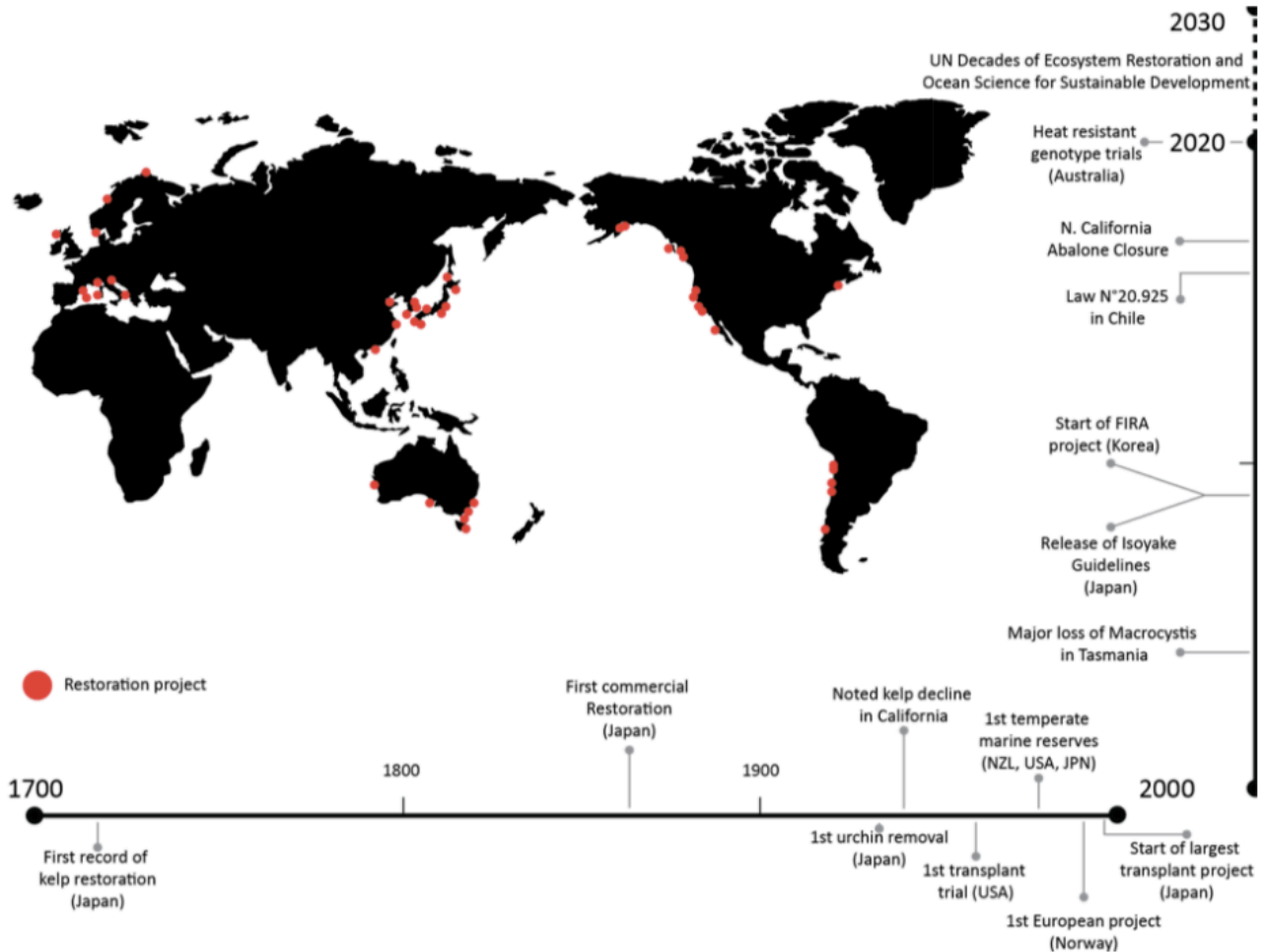


Figure 6. Worldwide locations and timeline of kelp restoration projects (Source: Eger et al. 2022).

Wheeler North Reef, Southern California, United States

The discharge of cooling water from the San Onofre nuclear power plant in southern California caused extensive losses of 73 ha of giant kelp forest, *Macrocystis pyrifera* (Reed et al. 2006). The State of California mandated the utility company Edison to offset the damage by constructing an artificial reef to replace the lost kelp forest and associated reef fish. Edison started building the “Wheeler North Reef” in the 1990s, resulting in 156 ha of boulder reefs that are now extending along 7 km of coastline.

The reef was constructed using a barge and crane to drop quarry rocks into the shallow coastal areas with the aim of being colonised by a minimum of 60 ha of

giant kelp forest that supports at least 28 tons of associated reef fish to offset historic losses.



Barge deploying quarry boulders to create an artificial reef to recover a local giant kelp forest. Photo: San Clemente Times

Urchin culling, Northern Norway

The loss of urchin predators led to a population explosion of the green sea urchin, *Strongylocentrotus droebachiensis*, causing the largest overgrazing events ever observed in the NE Atlantic along the Norwegian coastline and further into Russia around the early 1970s (Norderhaug and Christie, 2009, Norderhaug et al. 2021). Highly productive kelp forests were transformed into desert-like urchin barrens across an estimated 8400 km² (Gundersen et al. 2011) and have persisted for many decades, especially in northern parts of Norway.

In 2011, a collaboration between local authorities, research institutions and industry tested the use of quicklime (CaO) to cull urchins and thereby recover local kelp forests. Quicklime is a strong alkali that reacts with and immediately destroys the tissue of echinoderms, such as starfish and sea urchins, but is considerably less harmful to other marine species (if any) that may be found on barren grounds. Sea urchin densities were successfully reduced to levels that allowed for rapid kelp recovery within less than 1 year after treatment. The method was then scaled up in Porsanger in year 2 (~30 ha) and replicated in nearby Hammerfest over approximately 80 ha of urchin barrens in 2017 (Strand et al. 2020). These restoration efforts resulted in the return of kelps (*Saccharina latissima* & *Alaria esculenta*) and increased faunal diversity.



A vessel spraying quicklime over urchin barrens in Norway to restore kelp forests. Photo: Justnes et al. (2020)

Marine Restoration Programme, Korea

The east coast of Korea has experienced declines of kelp forests, primarily driven by urchin grazing. On the south coast and off the island of Jeju, urchins are absent and the decline of *Sargassum* spp., *Undaria pinnatifida*, and *Saccharina* spp. were caused by coastal development and habitat loss. In the 1990s, these deforested areas increased rapidly triggering the implementation of

restoration actions in 2002. In 2009, the government established a national research fund for kelp restoration. A collaboration between fisheries authorities and universities aims to restore 54,000 ha of kelp forests by 2030 to enhance the productivity of Korea's fisheries (Lee, 2019). The project deploys artificial concrete reefs, combined with kelp transplants, seeding and urchin removal. By 2019, reefs were established across more than 20,000 ha (Park et al. 2019, Hwang et al. 2020). New methods are currently being developed to deploy transplants on natural reefs, removing the need for artificial structures.



Restoration of kelp forests in Korea using concrete structures and seeding techniques. © FIRA

Transplants, Shizuoka Prefecture, Japan

Between 1985 and 2000, populations of the kelps *Ecklonia cava* and *Eisenia nipponica* suffered severe declines of 8,000 ha in Hainan, Japan due to reduced water clarity and intense grazing by herbivores (Hasegawa, 2010). Consequently, authorities were forced to close the local *Eisenia* and abalone fisheries and started investigating solutions to renew these resources (Unnno et al. 2010). The Shizuoka Prefectural Government started its restoration efforts by transplanting small concrete blocks into nearby *Ecklonia* beds to allow for natural recruitment onto the substrate before relocating them to the restoration site in Hainan.

Initial results seemed promising, but within three years, herbivorous fish (e.g. *Siganus fuscescens* – a species of rabbit fish) grazed down the transplants. A second, larger attempt mass cultured *Ecklonia* sporophytes using a deep-sea water circulation system on more than 2000 concrete blocks that were then transplanted onto the degraded reef. To reduce the impact of herbivorous fish, the governing bodies paid local fishermen to harvest them, supported by the local fishery

cooperative, the municipal, prefectural and national governments that provided logistical and financial support. As of 2018, the project has restored around 870 ha of kelp habitat and fisheries cooperatives are now considering to re-open the local abalone fishery.

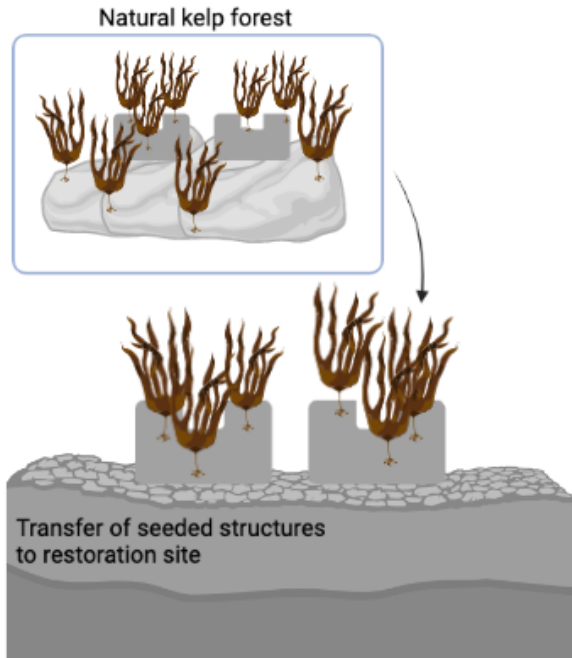


Illustration of the restoration approach in Japan using concrete structures seeded in natural kelp forest for transfer to restoration sites.

Operation Crayweed, Australia

Operation Crayweed focuses on the restoration of underwater forests that disappeared from the coast of Sydney four decades ago. The target species *Phyllospora comosa*, also known as ‘Crayweed’ because of its use as habitat by ‘crayfish’ and rock lobster (Young et al. 2016), was lost from around 70 km of Sydney’s Metropolitan coastline in the 1980s. Sydney used to have major sewage pollution issues in the past that coincided with the timing of Crayweed disappearance.

Operation Crayweed is a collaborative project that combines basic discovery research, solution-focused science, large-scale restoration, community engagement and art to restore seaweed forests (Verges et al. 2020). The project has evolved from initial small scientific experiments to trial reinstatement of Crayweed over larger areas. The project transplants Crayweed individuals from nearby populations to the restoration sites where they are secured with cable ties to a plastic mesh that is bolted to the seafloor. Once

reproductive, these parent plants seed the adjacent area with new offspring (the ‘craybies’) that grow into reproductive adults and continue the natural expansion of the restored area without further need for ongoing maintenance. In Long Bay, adult Crayweed re-established across ~4,000 m² of reef along 500 m of coastline in 6 years. Today, Operation Crayweed has expanded to over 12 sites along Sydney’s coastline.



Phyllospora comosa being transplanted onto degraded reefs along the Sydney coastline. © Operation Crayweed

Further Resources

The Nature Conservancy 

Kelp Restoration Guidebook

Eger, A. M., Layton, C., McHugh, T.A., Gleason, M. and Eddy, N. (2022): *Kelp Restoration Guidebook: Lessons Learned from Kelp Projects Around the World*, The Nature Conservancy, Sacramento, CA, USA.



<https://kelpforestalliance.com/>

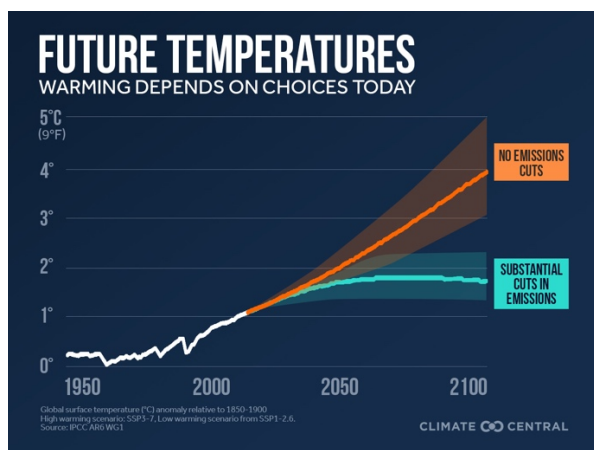


<https://www.greengravel.org/>

The future of kelp forests

The world's population is growing rapidly and will reach approximately 9.2 billion by 2050. At the same time, the impact on our coastal oceans intensifies to feed the growing demand for food, living space and our modern commodities. Combined with a changing climate and rising ocean temperatures, kelp forest loss is expected to continue and likely accelerate in the future, while being replaced by low-productivity ecosystems that are of little value to local communities and ocean-related economies. Considering a global annual loss of 2%, we may lose half of the remaining kelp forests within the next 35 years if we do not take immediate actions to reduce our impact on the ocean.

Scientists have been modelling projected changes in kelp distribution by the end of the century, according to different emission scenarios and associated global temperature rise based on figures from the Intergovernmental Panel on Climate Change (IPCC). Under a "business as usual" high emissions scenario (RCP8.5) in which greenhouse gas (GHG) emissions continue to grow unmitigated, we may experience a mean global temperature increase of more than 4°C by 2100. The RCP2.6 scenario describes a situation in which we cap our GHG emission and become carbon neutral to limit global temperature rise to below 2°C by the end of the century.



In Australia, projections have painted a dire picture for kelp ecosystems in which kelps and other canopy forming seaweeds will lose an average of 62% of their current distribution even under the low emission RCP2.6 scenario (Martinez et al. 2018). Under the "business as usual" scenario giant kelp forests (*Macrocystis pyrifera*) are projected to go extinct and

the smaller kelp *Ecklonia radiata* to lose 71% of its current abundance and become limited to the south coast.

For the North Atlantic, similar declines have been forecasted where kelps are projected to lose 50% of their distribution, under the RCP2.6 scenario, in regions where they already exist at their temperature limits, while under "business as usual" several local extinctions are expected (Assis et al. 2018). At the same time, some species such as *Saccharina latissima* are forecasted to expand into the Arctic due to the loss of sea ice and *Laminaria ochroleuca* expanding into southern Europe where they replace *Laminaria hyperborea* (Assis et al. 2018; Smale et al. 2015).

In Japan, the kelp *Ecklonia cava* is expected to cope with rising temperatures under the RCP2.6 scenario but may be impacted by range expansions of herbivores such as sea urchins (Takao et al. 2015). If we do not mitigate GHG emissions, kelps will be highly impacted by these drastic temperature changes and may lose 85% of their current distribution.

Many regions across the world will likely experience similar degrees of kelp loss. Even if we significantly reduce our GHG emissions and become carbon neutral, we cannot stop the warming of our planet that is already underway. But there is reason for hope! We can help our kelp forests to become more resilient to future environmental changes by reducing local impacts now, such as pollution and intensive harvesting, to allow them to regain their natural resilience. We can reseed kelp forests across degraded reefs and even implement effective management solutions to recover sea urchin predator populations and thereby allow kelps to recolonise previously urchin-dominated seascapes. But perhaps the most effective solutions to safeguard kelp ecosystems into the future is to help them adapt to a changing climate. We can assist certain species to migrate to regions with more favourable conditions, selectively breed resilient genetic strains or even use cutting edge genomics. But regardless of what we do now, it seems almost certain that many kelp forests a few decades from now will differ substantially from what they are today.

Support Our Ocean Forests

Centuries of ecosystem damage from human activities have left our natural environment in a dire state. We are losing biodiversity at a rate only rivalled by historic mass extinctions, and if we continue on our current path, we will face the collapse of our natural world, and with it our sources of food, clean air and everything that we depend on. We are now at a crossroad and the actions we take today will determine the future for us all. The UN has rightfully declared 2021 to 2030 as the Decade on Ecosystem Restoration as there has never been a more urgent need to restore nature than now.

Kelp forests and their alarming disappearance still lack the needed public attention as well as adequate financial support to restore these productive underwater habitats. This is why SeaForester has made it its mission to restore these forgotten ocean forests by raising public awareness and developing efficient seaforestation techniques. Our vision is to reforest the world's coastlines by supporting coastal communities in becoming the guardians of their blue front yards to seize the vast potential of seaweeds in supporting local livelihoods and ocean health.

What we do at SeaForester

Since 2016 SeaForester has been driving innovation in seaweed restoration through optimising seaforestation techniques and creating awareness about the forgotten forests in our ocean. After successful demonstrations in Portugal and our involvement in a research project in Australia, SeaForester decided to further develop and implement the “green gravel” approach as its main seaforestation tool. All that is needed are four natural ingredients: Seeds – Stones – Seawater – Sunlight. After raising a new generation of young kelps in our land-based nursery and releasing them into the ocean, nature does the rest.

Our trials in Portugal showed highly promising results for this technique. We seeded small stones with the golden kelp, *Laminaria ochroleuca*, and after several months at sea, the kelps were well developed with reproductive structures forming on the blades and holdfasts firmly attached to the seabed. Encouraged by this great success, we ramped up our infrastructure and production capacity and are now able to expand green

gravel to a scale, bigger than anything ever tested in the world. At the same time, we are testing additional seaforestation techniques to enable seaweed restoration where our seeded stones are less efficient due to local conditions.



Replanting golden kelp with green gravel in Portugal.
© João Nuno Franco (MARE-IPL / SeaForester)

Grow your own ocean forest

SeaForester invites clients in the private and public sector to directly engage in seaforestation actions by financing specific projects around the world. As we scale up our activities, SeaForester will continuously improve its techniques and deliver a practical, efficient, scalable and low-cost solution to restore seaweed ecosystems worldwide. New partnerships are needed to progress our efforts in restoring our ocean forests with all their biodiversity and benefits to nature and human society.



Green gravel ready for deployment. © SeaForester

For more information, visit <https://seeforester.org/>

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