Natural History Museum

Global Seaweed SUPERSTAR

THE STATE OF THE WORLD'S SEAWEEDS

2025

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Cover image: Alex Mustard

Suggested citation: Corrigan, S., Cottier-Cook, E.J., Lim, P.-E. & Brodie, J., 2025. *The state of the world's seaweeds.* Natural History Museum, London. doi.org/10.5519/4ln9oqk7.

DOI provided by the Natural History Museum, London.

For further information: https://globalseaweed.org/

Acknowledgements

We are very grateful to the reviewers of this document and thank them for their work: Alan Critchley, Mélanie Cueff, Aaron Eger, Angie Gall, Jason Hall-Spencer, Christine Maggs and Flower Msuya and Philippe Potin. We also thank everyone who has provided images and given us permission to use them in this document. We also thank the Global Seaweed Coalition team who have provided input throughout the creation of the report. We also thank Cyrielle Lâm (Ocean & Climate Platform) and Kristina Rodriguez (UN Climate Champions team) who have provided input in relation to the UNFCCC High Level Climate Champion 2030 Breakthrough Agenda.

Funding: We gratefully acknowledge that this work is funded as part of i) GlobalSeaweed-SUPERSTAR (grant number GCBC RGC1 G01-007211) project under the Defra-funded Global Centre on Biodiversity for Climate (GCBC) programme, and ii) GlobalSeaweed-PROTECT (grant number BBSRC APP34799) project under the UKRI-funded Sustainable and Resilient Aquaculture Systems in Southeast Asia programme.

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Preface

The oceans are experiencing extraordinary human-induced threats from global climate change, overfishing, pollution and an increase in invasive non-native species. Seaweeds create the largest vegetated marine habitats on the planet, which underpin global marine function but are threatened by the impacts of environmental change. Despite the importance of seaweeds, and the threats they face, they are afforded inadequate conservation measures, a major gap which urgently needs to be addressed.

The state of the world's seaweeds has come about as a result of this need. It provides the evidence-base which will inform a 'Seaweed Breakthrough', a potentially powerful means of protecting seaweeds and seaweed habitats through the UNFCCC High Level Climate Champion 2030 Breakthrough Agenda. Through setting global targets to halt habitat loss, protect and restore habitats and secure sustainable investment, Breakthroughs falling under the overarching goal for Marine Conservation aim to achieve significant change to reach a resilient, zero carbon future by 2030 across every sector of the global economy.

We have compiled an up-to-date overview on the state of the world's seaweeds. Through a series of chapters covering information on seaweed distribution, habitats, ecosystem services, as well as how they are threatened, protected and restored, we have identified knowledge gaps and drafted ambitious high-level targets that will form the basis of expert-led workshops to support the Seaweed Breakthrough.

This review demonstrates how important seaweeds and their habitats are in the functioning of marine ecosystems, global fisheries, food security, valuable materials for industrial and pharmaceutical uses and, therefore, livelihoods. It documents what is known. For example, we now have quantitative evidence for the severity of losses and degradation that kelp forests are suffering in many regions around the world. Less is known about most other seaweed habitats, as they have received far less attention. For example, rhodolith beds, habitats formed by free-living calcified red seaweeds, are extensive in many parts of the world and are still being discovered. However, they are threatened by pollution, habitat degradation, climate change, ocean acidification and trawling. Deep-water seaweed habitats have also only been studied in a tiny fraction of the oceans yet are likely to hold diversity that is still to be discovered.

The state of the world's seaweeds has been compiled by a team of leading scientists in seaweed and marine research. Professors Liz Cottier-Cook, Phaik Eem Lim and I have worked together over many years under the *GlobalSeaweed* initiative and have been fortunate to be joined by Dr Sophie Corrigan who brings up-to-date experience of studying the impact of seaweed farming on marine ecosystems. We see this review as a working document to be updated as knowledge gaps are filled and advances are made.

Professor Juliet Brodie, April 2025

Executive summary

The state of the world's seaweeds is an up-to-date review, prompted by an urgent need to conserve and protect the world's seaweeds in the face of devastating impacts due to human activities and the triple planetary crisis of climate change, pollution and biodiversity loss. Bringing together multiple sources of evidence on global seaweed distribution, habitats and ecosystem services, with how seaweeds are threatened, protected and restored, this document provides the evidence for a Seaweed Breakthrough conservation initiative.

Seaweeds occur on rock and other hard surfaces in coastal marine environments and can form floating habitats on the High Seas. They are integral to global marine ecosystem function andcover by far the largest estimated area of vegetated marine ecosystems (74%), compared to seagrasses (20%), coral reefs (3.4%), mangroves (1.8%) and saltmarshes (0.8%). As the feeding, breeding, spawning and nursery grounds for fish of many of the world's commercial fisheries and the foundation of the seaweed aquaculture industry, seaweeds help secure the world's food security and millions of livelihoods. Despite this, red, green and brown seaweeds and the habitats they create are barely mentioned in policy, conservation and environmental management documents.

Seaweed habitats support an immense diversity of organisms through their physical structure and the resources that they provide. A summary of common seaweeds habitats, listed here in order of highest to lowest estimated cover, included rhodolith beds, fucoid forests, kelp forests, crustose coralline algae, *Halimeda* meadows, seaweed turfs, free-living seaweeds and deepwater assemblages. Rhodolith beds, i.e., habitats created by free-living red nodule-like calcified coralline red seaweeds, covering an estimated 4.12 million m^2, continue to be discovered and considerably exceed kelp forest cover at 1.47 million m^2. Whilst useful estimates exist for seaweed habitats, the true extent of their cover remains uncertain. Deep-water seaweed habitats for example, are known from very few places across the world due primarily to their inaccessibility yet are almost certainly widespread globally.

An assessment of seaweed importance is highlighted in their contribution to all seventeen Sustainable Development Goals (SDGs). The roles seaweeds play are extensive, including supporting, regulating, provisioning and cultural services. They contribute to the maintenance of ecosystem processes and biodiversity, in regulating climate, pests and diseases, the provision of food, other materials and genetic resources, as well as cultural aspects, including recreation, education and heritage. With extensive global coastal cover and high productivity, seaweeds also play an important role in the carbon cycle. Seaweed habitats have been estimated to take up more carbon than terrestrial forests, seagrasses, mangroves and saltmarshes.

However, the fate of this carbon also needs to be properly tracked to determine the potentially large contributions of seaweed habitats towards carbon capture and climate change mitigation strategies.

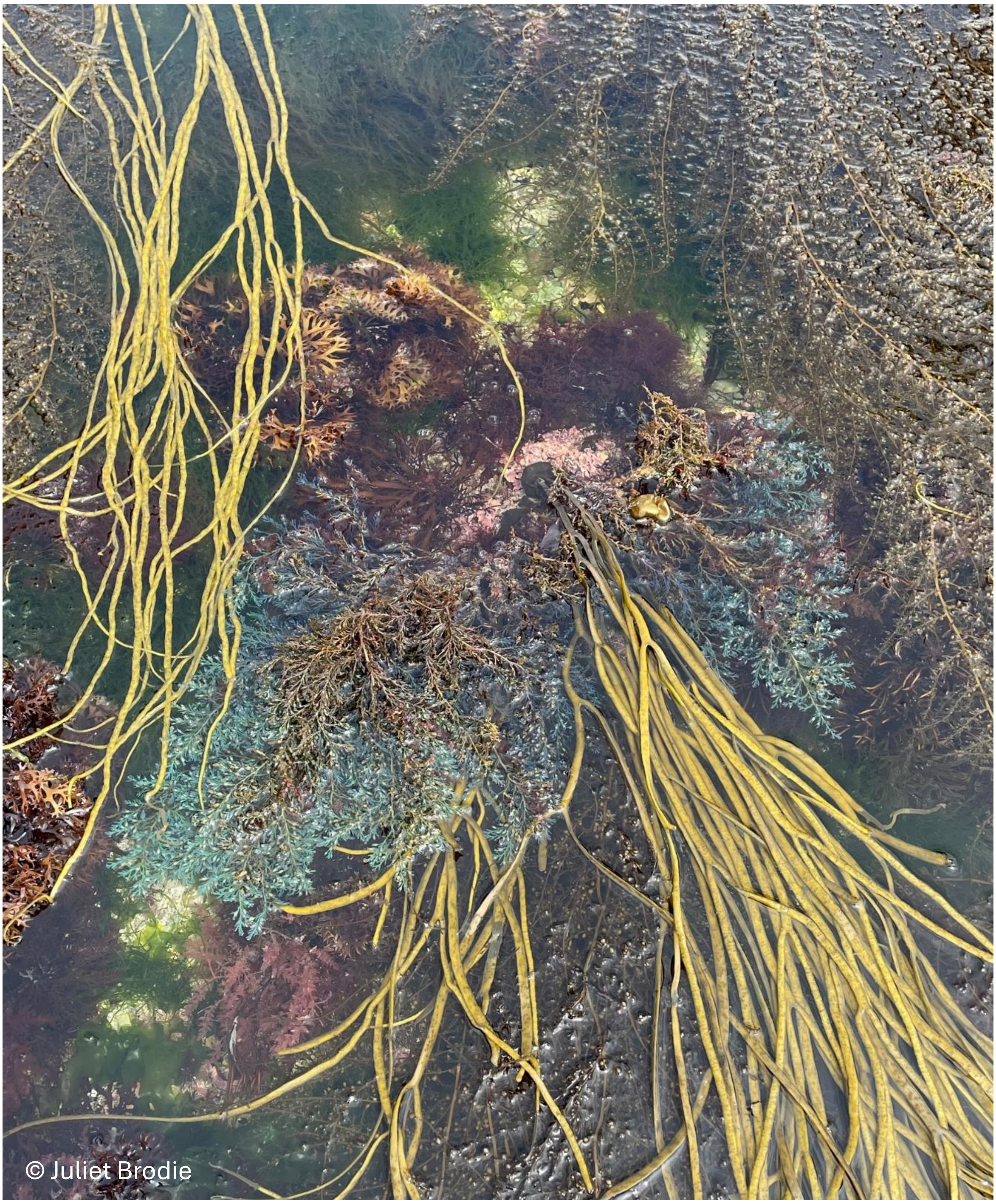
Threats to seaweeds come from multiple stressors related to both the climate crisis and human impacts including overharvesting, harmful fishing methods, pollution, coastal development, invasive species and disease. Of all the threats that face seaweeds, ocean warming has been identified as one of the main drivers to affect their overall distribution and survival. The evidence is stark. General range shifts in seaweed distribution polewards are well-documented, as well as declines and losses. Kelp forests, for example, are declining at an annual rate of twice that of coral reefs and more than four times that of rainforests. We do not know the rates of change in other seaweed groups as data are severely lacking. Future seaweed distributions are being projected under modelled climate change scenarios, which help to forecast where changes will occur, but there is a need for more data and global collaboration to accurately inform these models.

Assessing the state of seaweed conservation designations reveals protection to be patchy and potentially ineffective. This includes the extent to which Marine Protected Areas (MPAs) cover seaweed conservation in their designations and if so whether directly or indirectly. Regional, national and international policies, laws, governance and frameworks usually lack any mention of seaweeds. The IUCN and the use of Red Listing to assess the status of seaweeds also falls dramatically behind the number of assessments made for other species groups. A major hurdle in getting better protection for the seaweeds relates to a lack of knowledge about seaweed biodiversity. Although highly numerous with c. 12,277 species of seaweeds described so far, there are thousands more species that are currently undescribed. Many parts of the world are under-sampled or lacking taxonomic assessments using up-to-date techniques.

Seaweed restoration is increasingly recognised as a way to improve coastal ecosystems. However, currently, seaweed restoration is slow, challenging and expensive with mixed success, falling behind restoration initiatives for other vegetated marine ecosystems. Efforts have primarily been focused on restoring kelp forests using seeding techniques (e.g., green gravel), grazer control (e.g., removal of sea urchins), and the use of artificial reefs. This effort is being largely driven by the Kelp Forest Alliance, who have launched ambitious global targets via the Kelp Forest Challenge to protect and restore 4 million hectares of kelp forests by 2040. No such initiatives have been set for other seaweed habitats at present, and no efforts have been made to restore extremely slow growing seaweed habitats, such as cold-water coralline algal beds.

This review pinpoints major knowledge gaps that need to be addressed. There is an urgent need to bring the global seaweed community together to document and monitor seaweed biodiversity and to build capacity in identification and taxonomic skills. There needs to be confidence in estimates of the global extent of seaweed habitats and whether they are expanding or declining.

The state of the world's seaweeds culminates in an overview of the 'Seaweed Breakthrough', a potentially powerful means of protecting seaweeds through the United Nations Breakthrough Agenda. The Seaweed Breakthrough outlines four high level targets that are needed to secure a sustainable future for seaweed habitats by 2030 and a set of guiding principles with which to implement them.



1. Introduction

Seaweeds - red, green and brown marine macroalgae – are highly diverse, habitat-forming photosynthetic organisms that range from charismatic towering kelp forests to long-lived, low-lying, expanses of calcified red algae, known as rhodolith beds or maerl beds. Collectively, seaweeds form the largest vegetated marine ecosystems worldwide and are crucial for marine functioning, the ecological health and survival of the planet.

Seaweeds and their habitats provide numerous critical ecosystem functions and services for coastal biodiversity, support commercially important fisheries', and play significant roles in carbon and nutrient cycling. Natural seaweed populations are also the source of wild seaweed harvest and the basis of seaweed farming industries, both of which support food and livelihood security for millions of people worldwide. Consequently, seaweeds are recognised for their contribution to all 17 of the Sustainable Development Goals (SDGs; Box 1). The SDGs are an urgent call for action by all countries and are at the centre of the 2030 Agenda for Sustainable Development (United Nations, 2015). Investing to ensure that seaweed habitats continue to survive and thrive is, therefore, essential for tackling the triple planetary crisis of climate change, pollution and biodiversity loss and for increasing resilience in coastal communities at this pivotal moment in the Earth's history.

Seaweeds, despite their ecological and economic importance, are not recognised to the same extent as other marine habitats, such as mangroves, seagrass beds or coral reefs. As a result, seaweeds have so far received the least study, funding and protection of all vegetated marine habitats (Ross et al., 2023). The consequences of this failure are critical, particularly as some seaweed habitats are declining at an alarming rate. For instance, kelp forests are declining at an annual rate two times that of coral reefs and more than four times that of rainforests (Feehan et al., 2021; Filbee-Dexter et al., 2022b). The launch of the Kelp Forest Challenge in November 2024, sets ambitious targets for the much-needed protection and restoration of kelp forests worldwide (Eger et al., 2024a). Nevertheless, kelp forests make up less than 25% of all seaweed habitat extent (Filbee-Dexter, 2020). This leaves the rest of the seaweeds and their habitats lacking global unified conservation goals to provide protection. Losses to seaweed habitats are attributed to the climate crisis, pollution, overexploitation, and a multitude of other anthropogenic threats, with significant repercussions for both humanity and the planet.

Advancing effective management and conservation of seaweed habitats, however, is challenged by extensive knowledge gaps on the diversity, distribution and status of most seaweeds and their habitats. Efforts to study, manage and protect different seaweed habitats also tend to occur in isolation, despite their interconnectivity and reliance on each other. Urgent global action is needed now to address these gaps, halt future loss, and protect and restore the most vulnerable seaweed habitats to their full potential to secure a future for seaweeds and for the millions of livelihoods that rely on them.

This report provides a scientific overview of the state of the world's seaweeds. It covers knowledge on the diversity and distribution of seaweed species and their habitats, and highlights the ecological, economic and societal importance of these organisms. It also reports on how seaweeds are threatened, and how the impacts of these threats are affecting seaweed distribution, abundance and loss, and gives an overview the current state of seaweed conservation management and protection. By compiling this report, key knowledge gaps are identified that must be addressed to provide the evidence-base on which realistic global targets for seaweed conservation can be determined. The report also identifies the key stakeholders that need to come together to ensure the long-term protection of seaweeds.

Box 1. How seaweeds can contribute to the Sustainable Development Goals (SDGs)

1. No Poverty
Seaweed farming provides opportunities for coastal communities, where it can support livelihoods by income generation and can create jobs, thereby reducing poverty.

2. Zero Hunger
Seaweeds are sources of nutrient-dense foods that can be rich in vitamins, minerals, and proteins. They therefore play a key role in global food security and can be used to supplement diets, notably in coastal communities.

3. Good Health and Well-being
Seaweeds are used in traditional medicine and contain bioactive compounds that may contribute to disease prevention and be beneficial for health. Many seaweeds are known to have anti-inflammatory, antioxidant, and antimicrobial properties.

4. Quality Education
Seaweed farming and research offer educational opportunities in marine biology, sustainable aquaculture, and environmental sciences. Knowing about the benefits of seaweeds can promote sustainable practices with the potential to empower coastal populations.

5. Gender Equality
Seaweed farming has the potential to empower women, especially in remote rural and coastal areas, by providing them with income-generating activities and leadership roles in the aquaculture industry.

6. Clean Water and Sanitation
Seaweeds act as natural filters, improving water quality by absorbing excess nutrients and pollutants.

7. Affordable and Clean Energy
Seaweed can be used as a source of bioenergy. It can be processed into biofuels, reducing dependence on fossil fuels and contributing to cleaner energy solutions.

8. Decent Work and Economic Growth
By generating jobs in aquaculture, processing, and distribution seaweed farming can promote economic growth.

9. Industry, Innovation, and Infrastructure
Seaweed-based industries contribute to the development of new industries based, for example, around bioplastics and pharmaceuticals. They are also driving innovation in the production of sustainable materials, such as biodegradable plastics, and contributing to green infrastructure by supporting marine biodiversity and ecosystem services.

10. Reduced Inequality
Seaweed farming has the potential to reduce inequalities by creating economic opportunities for marginalized coastal communities, especially women and indigenous populations.

11. Sustainable Cities and Communities
Seaweed farming can promote the development of sustainable coastal communities, and help with natural disaster mitigation (e.g., protecting coastlines from erosion).

12. Responsible Consumption and Production
Seaweed is a renewable resource. Its farming and consumption can contribute to responsible use of marine resources and offer alternatives to land-based agricultural products.

13. Climate Action
Seaweeds take up carbon and can help mitigate climate change by absorbing CO_2 that has dissolved into seawater from the atmosphere. Kelp forests and other marine plants play a role in carbon cycling and help in reducing ocean acidification.

14. Life Below Water
Seaweed farming and wild seaweed habitats support marine biodiversity and provide essential habitats for marine life. They help maintain healthy marine environments and seaweed farms can contribute to the restoration of degraded coastal ecosystems.

15. Life on Land
Seaweed can indirectly support land-based ecosystems by promoting sustainable agricultural practices, such as using seaweed-based fertilizers, which reduce the need for chemical fertilizers.

16. Peace, Justice, and Strong Institutions
Seaweed farming can be part of inclusive governance by fostering community-based management of marine resources. It helps build social cohesion and a sense of ownership over coastal ecosystems.

17. Partnerships for the Goals
The development of seaweed-based industries requires partnerships between governments, NGOs, research institutions, and private sectors. International collaboration can foster knowledge exchange and support for sustainable seaweed farming practices.

2. The world of seaweeds

Summary: The world of seaweeds provides an overview of the red (Rhodophyta), green (Chlorophyta) and brown (Phaeophyceae) seaweeds, including their diversity, distribution and habitats. The current numbers of species described in these three seaweed groups are provided and maps of their global distribution presented. Summaries are given of the major seaweed habitats and their estimated global areas where known.

2.1 The diversity of seaweeds

Seaweeds are species of red (Rhodophyta), green (Chlorophyta) and brown (Phaeophyceae) marine macroalgae that are extremely numerous and diverse and that form a wide variety of ecologically important marine biogenic habitats (Section 2.3). The origins of red and green seaweeds are ancient. Red seaweed ancestors date back to 1.6 billion years ago and were among the first multicellular organisms on Earth (Bengtson et al., 2017). Green algae date back at least 1 billion years (Tang et al., 2020). The origin of the brown algae is estimated to be 450 million years ago (MYA), with the emergence of algal forests at c. 200 MYA and the kelps between 100 and 50 MYA (Denoeud et al., 2024). Seaweeds have therefore survived multiple dramatic climate shifts and mass extinction events, from ice ages to extreme warming, and evolved to give rise to the extraordinary diversity of seaweed species and habitats that exist around every continent on Earth today.

Over 12,000 species of seaweeds have been described (Guiry 2012; 2024) (Table. 1). The total number of seaweed species may be considerably more, and has been estimated to be up to 24,000 (Guiry 2012; 2024). There are a number of reasons why there may be many more species to describe. Seaweeds exhibit high levels of cryptic diversity, where species which look alike and cannot be distinguished using morphology but are genetically distinct based on molecular methods (Robba et al., 2006). Morphology can vary within and between species such as in the calcified red coralline algae where there may be as many as 10,000 undescribed species based on evidence from molecular data (Le Gall, personal communication). Some seaweeds are endophytes which live fully or partially inside other species including seaweeds or other organisms such as mollusc shells. There are unexplored areas of the world, particularly in the Southern Hemisphere, or species have been described from different part of the world but require re-examination based on state-of-the-art taxonomic approaches. Finally, progress is slow in describing species due to the painstaking nature of the process and a limited number of professional taxonomists working in the subject area.

To understand, protect and manage seaweed biodiversity, it is necessary to identify, describe and name species – a massive task for a small and diminishing number of specialist seaweed taxonomists, although a global initiative is underway to address this (J. Brodie, personal communication).

Table 1. Number and proportion of species described in red, green and brown seaweed groups. Source: Guiry & Guiry (2025).

Seaweed group	Number of described species	Proportion of species (%)
Red (Rhodophyta)	7677	66
Green (Chlorophyta)	1853	16
Brown (Phaeophyceae)	2147	18
Total	**12277**	**100**

Box 2. Open access databases with seaweed information

AlgaeBase (https://www.algaebase.org/) is a global algal database of taxonomic, nomenclatural and distributional information, which currently lists over 177,000 species and infraspecific names, 23,500 images, 72,000 bibliographic items and 564,000 distributional records (Guiry and Guiry, 2025).

GBIF (https://www.gbif.org/) is the Global Biodiversity Information Facility, an international network and data infrastructure funded by the world's governments and aimed at providing anyone, anywhere, open access to data about all types of life on Earth.

OBIS (https://obis.org/), Ocean Biodiversity Information System, is a global data and information clearing-house on marine biodiversity for science, conservation and sustainable development.

Globally accessible databases, such as AlgaeBase, the Global Biodiversity Information Facility (GBIF), the Ocean Biodiversity Information System (OBIS) (under the UNESCO (IOC) program) and the World Register of Marine Species (WoRMS) (Box 2) act as important online repositories for data on seaweed species and their distributions. These databases are helping to track the status of reported seaweed species and to develop tools to protect and sustainably manage them. However, the seaweed records in GBIF and OBIS need to be treated with caution. They are not suitable for distribution maps as they show where people have conducted surveys and the noise of unfiltered data entry errors.

2.2 The distribution of seaweeds

Seaweeds occur in all the world's seas and globally are estimated to form the largest vegetated marine ecosystems (Fig. 1). They occur in a wide range of environments from the poles to the tropics and over a wide depth range from the top of the shore, to the subtidal, to > 300 m deep (Littler et al., 1991; Stefanoudis et al., 2018). Seaweeds are estimated to cover 6 to 7.2 million km^2 globally, dominated by the red seaweeds (Duarte et al., 2022) (Fig. 2). Seaweeds, therefore, could cover up to 35 times the area occupied by other well-studied vegetated marine habitats, such as seagrass meadows, coral reefs and mangroves (Fig. 1). Distribution modelling is helping to improve these estimates, however there are limitations with this method, and more on-the-ground research is desperately needed to validate models and determine a more accurate global extent estimate for seaweeds. The distribution of brown and red seaweeds have been mapped with models (e.g., Duarte et al., 2022; Fragkopoulou et al., 2021), but no such distribution maps or models exist so far for green seaweeds.

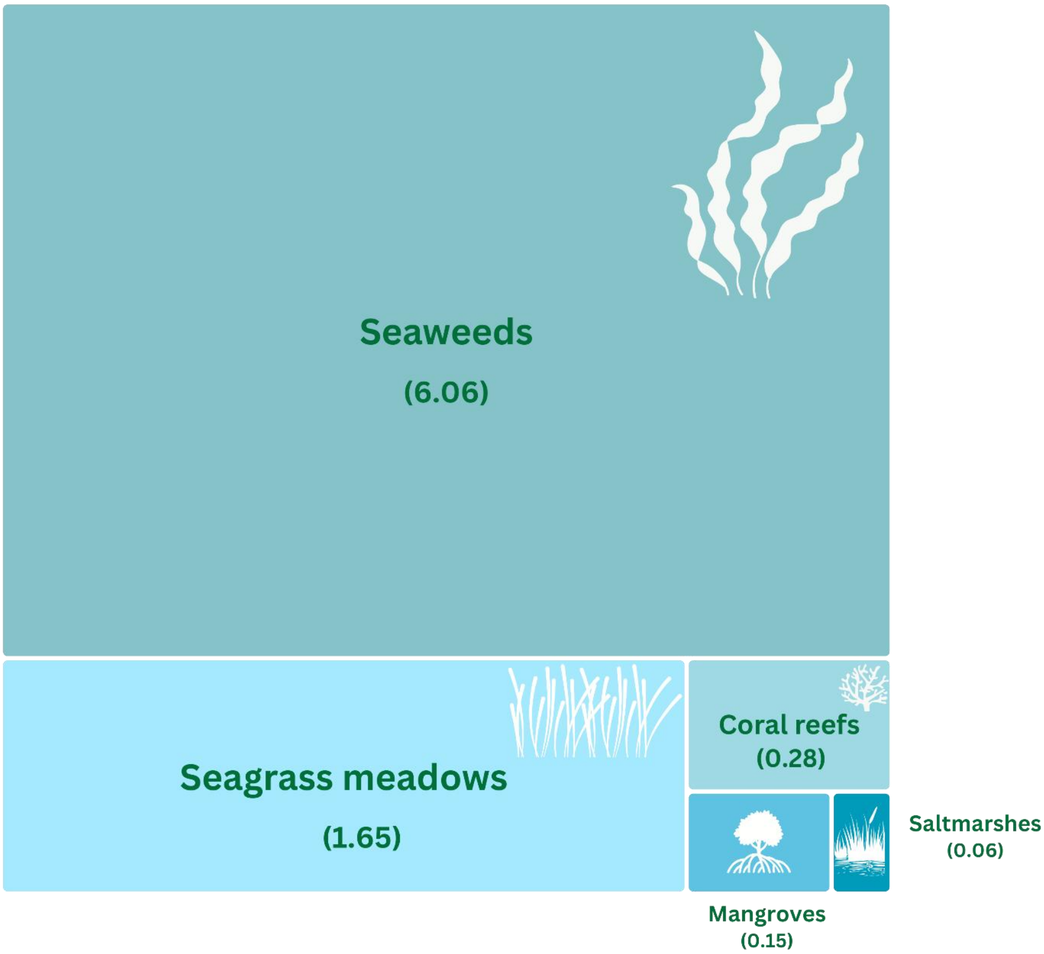


Figure 1. Proportion of estimated global coverage of major marine vegetated biomes (million km^2). The seaweed value represents the lower range estimate given by Duarte et al. (2022); data for other habitats are adapted from the United Nations Environment Programme (UNEP) World Conservation Monitoring Centre (WCMC data; UNEP 2020).

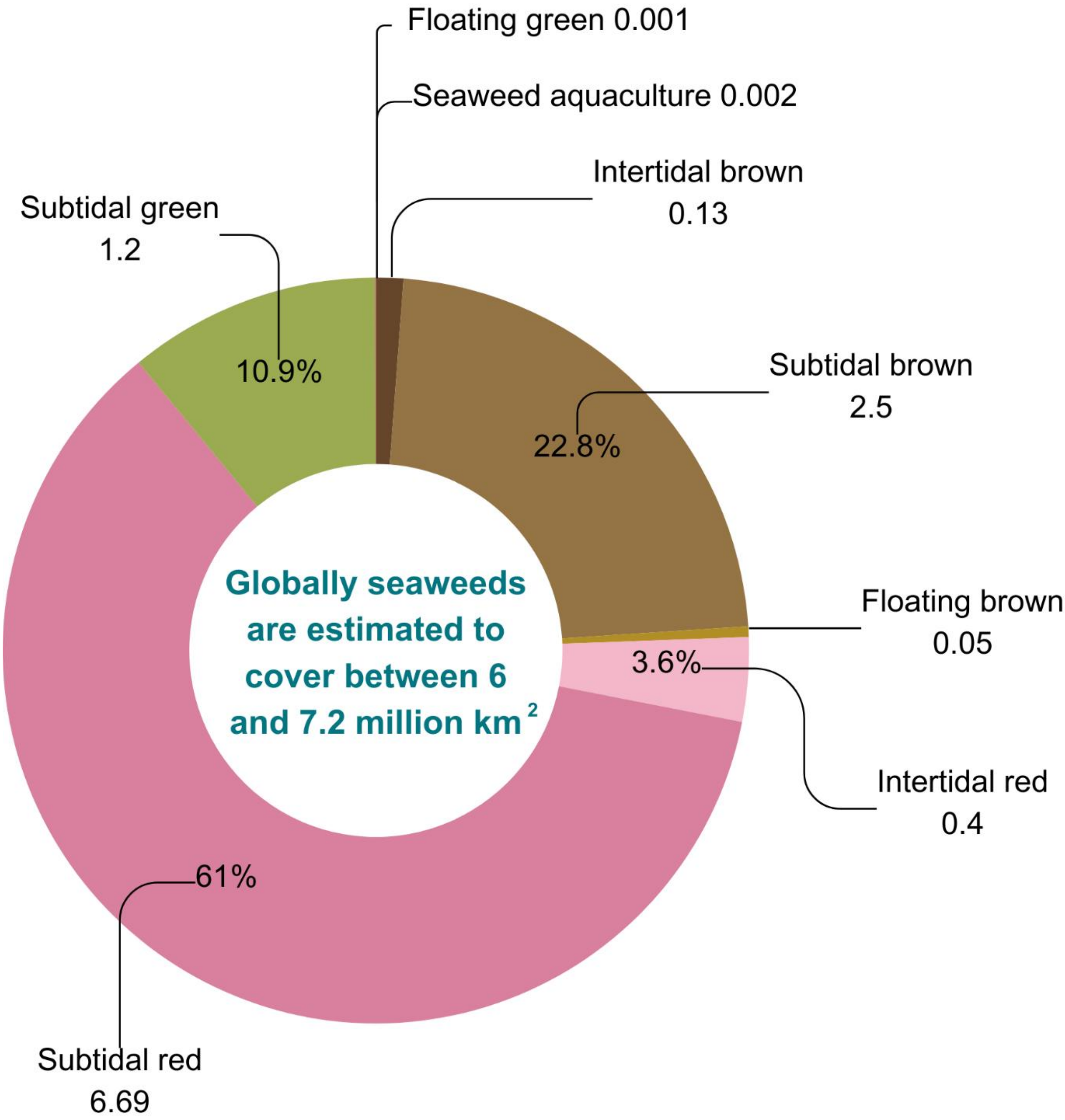


Figure 2. Estimated global area coverage (million km^2) by different seaweed groups. Figure adapted from Duarte et al. (2022). Labels show estimated area coverage by seaweed habitat (outside), and percentage contribution of each habitat to estimated total seaweed coverage (inside). Subtidal and intertidal red and brown seaweed area was estimated using a global niche modelling approach (Duarte et al., 2022). Subtidal green value is from McNeil et al. (2016). Floating green value is from Liu et al. (2013a) and Zhang et al. (2019). Floating brown seaweed value is from Wang et al. (2019), Qi et al. (2017) and Zhang et al. (2019).

2.3 Seaweed habitats

Seaweed habitats are defined by dense growths or accumulations of a few or numerous species providing physical structure and resources for an immense amount of biodiversity. Here, we outline some of the most common seaweed habitats, however, this list is not exhaustive, and the diversity of seaweed species has led to many unique seaweed habitats globally. They are presented in order of estimated global coverage (Table 2). Seaweed habitats are also not always distinct and often coexist with each other or with other vegetated marine habitats (Box 3).

Rhodolith beds

Rhodolith or maerl beds are formed of aggregations of unattached calcified red algae and frequently support other marine vegetation (Box 3). Rhodolith beds are the most expansive seaweed habitat and have been found around coastlines in tropical, temperate, and polar regions (Redina et al., 2022). The low light tolerance of rhodolith beds allows them to grow from the low intertidal zone down to ~150 m water depth (Aguilar et al., 2009; Foster et al., 2013). However, the deepest rhodolith beds recorded are c. 300 m below the ocean's surface (Littler et al., 1991; Fragkopoulou et al., 2018). It is estimated that rhodolith beds cover 4.12 million km^2 worldwide (Fragkopoulou et al., 2021). According to van der Heijden & Kamenos (2015), based on published studies, the total average cover of the seabed for coralline algae was estimated to be 45%, of which rhodoliths make up 45%, with the rest consisting of crustose coralline algae (see below).

Fucoid forests

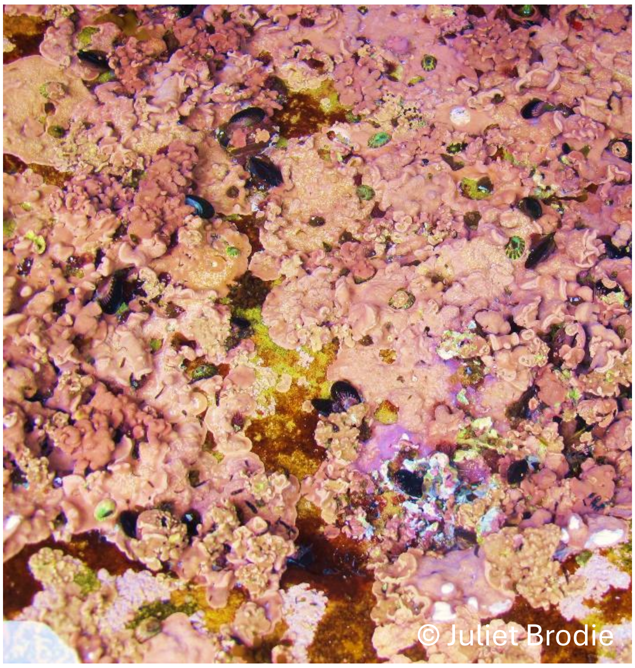
Fucoid forests occur globally on rocky shores in the intertidal zone and in the shallow subtidal, spanning the poles to the tropics (Thomsen et al., 2024). These habitats are dominated by brown seaweeds in the order Fucales, mostly fucoids or wracks, such as species of *Fucus*, *Ascophyllum*, *Pelvetia*, *Hormosira*, *Durvillaea* and *Sargassum*. They can also be rich in other seaweed diversity, including a high variety of red and green species. In the intertidal zone, the seaweed communities occur in distinct zones that reflect their ability to tolerate wave action and being uncovered and covered by the tides. They are estimated to be one of the most extensive seaweed habitats worldwide covering over 2.5 million km^2 (Fragkopoulou et al., 2022).

Kelp forests

Kelps are the largest seaweed species, primarily belonging to the order Laminariales, and form impressive underwater forests. Kelp forests are found along approximately 25% of the world's coastlines (Filbee-Dexter, 2020). Kelps are predominantly temperate and subpolar and are found in the intertidal and subtidal zones typically down to 15-25 m depth. Kelp forests are also prominent in some polar and tropical regions. In locations near the equator, they have been found in the clear, nutrient-rich water below the thermocline (>30 metres) (Graham et al., 2007). In exceptionally clear and cool nutrient-rich water, kelps can exist at 200 m depth (Žuljević et al., 2016). Kelp forests also tend to host diverse understory assemblages of other red, green and brown seaweeds, which also provide important habitat for a rich diversity of marine species (e.g., Teagle et al., 2018). Kelp forests are estimated to cover approximately 1,470,000 km^2 (Jayathilake and Costello, 2020).

Crustose coralline algae

Crustose coralline algae have hard, calcified cell walls that adhere tightly to other hard surfaces, such as rocks and coral reefs, playing an important role in coral reef formation. They can tolerate a range of light conditions, from shallow, brightly lit waters to dim, deeper regions, which has enabled them to thrive in a variety of marine environments, including coral reefs, rocky shores, and deep-water ecosystems. Crustose coralline algae are estimated to cover over 50% of the estimated 45% total cover of coralline algae of the seabed (van der Heijden & Kamenos, 2015; see rhodolith beds above).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Halimeda meadows and bioherms

Calcareous green algae (*Halimeda* spp.) form meadow-like structures and sedimentary mounds known as “bioherms” in tropical and subtropical waters, including in lagoons, seagrass beds, and coral reef flats. They grow in areas with moderate light and good water circulation and can range from a few centimetres to over a meter in height. These habitats contribute to carbonate sediment formation and coastal protection when they die. Although there is no global estimate for *Halimeda* spp. coverage, they have been found to occupy large areas, for instance bioherms cover >25% of the northern Great Barrier Reef shelf (~6000 km^2), which is larger than the adjacent coral reef system (Ritchie, 2022).


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Seaweed turfs

Seaweed turfs are dense, low-lying communities of small, filamentous red, green, and brown algae, including *Gelidium* and *Cladophora* species. Turfs typically grow where there is not enough light for kelps and are often biodiverse habitats that trap sediments. However, as they are fast growing, they can quickly overgrow disturbed habitats such as coral reefs or kelp forests, often impeding their recovery and competing for resources.


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Tropical seaweed beds

Tropical seaweed beds are a conspicuous shallow water habitat made up of a mixture of species such as canopy-forming brown *Sargassum* and *Turbinaria* species along with red eucheumatoids such as *Eucheuma* and *Kappaphycus* species, greens including *Ulva* spp. and brown *Padina* spp. They have been shown to support high numbers of gammarid amphipods and harpacticoid copepods (Tano et al. 2016) which provide an important source of food for a number of juvenile fish species (Tano et al. 2017). The extent of these tropical seaweed habitats are not known.


© Phaik Eem Lim

Deep water seaweed communities

In some deep waters of the world (e.g., off the coast of Bermuda (Stefanoudis et al., 2018, 2019) and the Gulf of Mexico (Fredericq, 2003), between depths of c. 60 m to 200 m (or more in some extreme cases), there are habitats that are made up of red, green and brown seaweeds. Species composition varies, but includes calcified *Udotea,* fleshy *Caulerpa* and spongy crusts of *Codium* in the greens, as well as fleshy (e.g., *Halymenia*) and calcified reds (e.g., *Galauxaura),* and fleshy *Lophophora* species in the browns. The extent of such habitats globally is largely unknown due to a lack of exploration, but they are almost certainly much more widespread than reported.


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Floating or free-living pelagic seaweeds

Seaweeds can form extensive floating rafts, that drift with winds and currents, such as the vast rafts of *Sargassum fluitans* and *S. natans* that occur in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea. These rafts can cover 6000 km^2 and weigh more than 20 million tons (Wang et al., 2019). Seaweeds that have been detached from the seabed by strong wave action can also form rafts, such as *Sargassum horneri* in the East China Sea. Huge rafts of green seaweed *Ulva prolifera* have also formed in the Yellow Sea, recorded weighing over 1 million tonnes and covering 400 km^2 (Liu et al., 2013b). These floating seaweeds can cause major socio-economic problems (see Section 4.2.3). For example, changing ocean currents driven by climate change can cause massive *Sargassum* strandings (‘golden tides’) (Vázquez-Delfín et al., 2023), and eutrophication coupled with global warming can lead to green algal blooms (‘green tides’).

Farmed seaweeds

Due to the rise in seaweed farming globally, new human-made seaweed habitats have been created. These are typically dense monocultures of seaweed species grown on lines that are either suspended off the bottom of the sea floor (e.g., red seaweeds grown in tropical areas) or from the surface of the water (e.g., kelps grown in temperate regions). These are not natural habitats; however, they can be extensive, covering hundreds of square kilometres, and affect local biodiversity, and so have been included due to the rapidly increasing extent of the global seaweed industry.

Table 2. Estimated global coverage of seaweed habitats.

Habitat	Estimated global coverage (million km^2)	References
Rhodolith beds	4.12	Fragkopoulou et al. (2021)
Fucoid forests	2.57	Fragkopoulou et al. (2022)
Kelp forests	1.47	Jayathilake & Costello (2020)
Halimeda meadows, *Caulerpa*, *Padina* and other algae including greens	1.2	McNeil et al. (2016); Duarte et al. (2022)
Crustose coralline algae	0.021–0.23	Moura et al. (2013); Carvalho et al. (2020)
Seaweed turfs	?	
Floating or free-living pelagic seaweeds	0.05	Duarte et al. (2022); Wang et al. (2019); Qi et al. (2017); Zhang et al. (2019); Liu et al. (2013a)
Deep water seaweed communities	?	
Tropical seaweed beds	?	
Farmed seaweeds	0.3	Duarte et al. (2022)

Box 3. Seaweed coexistence and support of other habitats

Seaweeds and their habitats are commonly interlinked with one another and may be important for each other's establishment and resilience. For example, in the Bay of Islands, New Zealand, over 100 seaweed species, representing ~30% of the known local seaweed flora at the time, were associated with rhodolith beds (Nelson et al., 2014). Similarly, in the Northeast Atlantic, 350 seaweed species were recorded on rhodolith beds, again representing ~30% of the region's seaweed flora (Peña et al., 2014). Recent studies suggest that rhodolith beds may also act as seedbanks and refuge areas following periods of environmental stress (Fredericq et al., 2019; Voerman et al., 2022).

Seaweed habitats are also vital for the establishment and ecological and genetic connectivity of many other marine habitats, including seagrass beds, mangroves, and coral reefs. For instance, corals rely on calcified red seaweeds to cement them together, which enables reef formation and the presence of certain species can even induce coral larval settlement on the reef (Jorissen et al., 2021). Crustose coralline algae (e.g., *Porolithon onkodes*) can also cover 40% of the coral reef slope (Littler & Doty, 1975; Stearn et al., 1977), 60% of the reef flat and 5% of lagoon sites (Atkinson & Grigg, 1984), with rhodoliths covering up 90% of the reef crest and seaward shallow reef slope (Sheveiko, 1981; Chisholm, 1988). Calcareous green seaweeds, *Halimeda* spp. create "bioherms" that connect and act as protective physical barriers for coral reefs (McNeil et al., 2016).

Maerl bed with seagrass (left) taken at the 2025 Maerl Conference (hosted by Natural England and Cornwall Council), kelps growing on Crustose coralline algae (right)

3. The importance of seaweeds

Summary: This chapter highlights the ecosystem services that seaweeds provide that are crucial to the functioning of the planet and humanity. These services are reviewed under four major categories: supporting, regulating, provisioning and cultural services. They cover the role of seaweeds in maintenance of ecosystem processes and biodiversity, in regulating climate, pests and diseases, the provision of food, other materials and genetic resources, as well as cultural aspect, including recreation, education and heritage.

3.1 Seaweeds and ecosystem services

A wide range of ecosystem services are provided by seaweeds and their associated habitats. Ecosystem services are defined as the direct and indirect contributions that ecosystems provide for humans by the intrinsic nature of ecosystem functionality. They

Box 4. Ecosystem services and summary of related goods provided by seaweeds and their associated habitats*.

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1. Supporting services

Ecosystem process maintenance
Life history maintenance
Biodiversity maintenance/protection
Biogeochemical cycling

2. Regulating services

Climate regulation
Natural hazards regulation
Purification of water, air and soil
Water/water flow regulation
Erosion and soil fertility regulation
Pests and disease regulation

3. Provisioning services

Food
Water
Raw materials
Fuel
Medicinal resources
Ornamental resources
Genetic resources

4. Cultural services

Recreation and tourism
Aesthetic values
Inspiration
Education and research
Spiritual and religious experience
Cultural identity and heritage
Mental well-being and health
Peace and stability

* Adapted from IUCN and Millenium Ecosystem Assessment 2005.

are typically organised into four categories: i) supporting services, ii) regulating services, iii) provisioning services, and iv) cultural services (Box 4).

Seaweed ecosystem services support coastal and marine ecosystem functioning, such as maintaining marine biodiversity and fisheries, carbon, oxygen, halide, sulphur and nutrient cycling. Seaweeds also support other marine habitats and the ecosystem services they provide, such as coral reefs (see Box 3, Section 2.3). Natural seaweed populations also form the basis of the seaweed industry, which supports global food security and the livelihoods of over 6 million people, mainly in coastal communities (Cottier-Cook et al., 2021), notably those that work in the seaweed harvesting or farming, fisheries and marine tourism industries.

3.1.1 Supporting services

Summary: This section outlines how seaweed habitats maintain and protect biodiversity, covering the extensive range of organisms that benefit. It also covers the role of seaweeds in industries, including commercial fisheries and seaweed harvesting and farming. Additionally, it outlines their important role in biogeochemical cycling.

Biodiversity: maintenance and protection

All seaweed habitats are important for supporting marine biodiversity, as they provide shelter and refuge areas, food sources and foraging grounds, breeding and spawning areas and nursery grounds for many ecologically and commercially important species. As ecosystem engineers, seaweeds create liveable spaces for other species to inhabit. For instance, the holdfasts (the attachment base) of kelps offer complex structures that can provide habitat for thousands of individuals and hundreds of species (e.g., Christie et al., 2003; Anderson et al., 2005; Teagle et al., 2018). Similarly, rhodolith beds create complex structures that can provide refuges for detritivores and nutrient recycling species, which are then a food source for many hundreds of fish species that inhabit the beds (e.g., Moore et al., 1998; Moura et al., 2021). These species in turn attract larger charismatic keystone predators to live and forage in seaweed habitats, such as seals, sea otters, octopus, sea birds, sharks and other predatory fish, thus supporting the wider marine food web. Seaweed habitats are, therefore, important biodiversity hotspots. For example, coralline algal beds can host almost double the species richness compared with many neighbouring habitat types (Steller et al., 2003). Many of the species supported by seaweed habitats are also incredibly valuable for tourism and commercial and recreational fisheries and the millions of livelihoods these industries support (see Provisioning Services 3.1.3 and Cultural Services 3.1.4).

Crucially, seaweed habitats also support many species that are endemic and/or categorised as threatened or endangered, as well as supporting the early or vulnerable life stages of ecological and/or economically important organisms (Tuya et al., 2023). For instance, 60% of organisms found living in a rhodolith bed in the Gulf of California were juveniles (Riosmena Rodriguez & Medina-López, 2010). Tropical red algal beds in Tanzania have also been found to support twice the abundance of juvenile fish than nearby seagrass meadows, particularly from commercially important species for local fisheries (Tano et al., 2017). Examples of commercially important fisheries species include the Patagonian squid (*Doryteuthis (Amerigo) gahi*), which attaches its eggs to giant kelp (*Macrocystis pyrifera*); juvenile pollack (*Pollachius virens*) which shelter from predators in kelp canopies in the North East Atlantic. In addition, rhodolith beds provide important refuges for juvenile scallops, and fishes such as Atlantic cod (*Gadus morhua*) and hake (*Melanogrammus aeglefinus*); and pelagic *Sargassum* rafts also provide important feeding grounds and shelter for fish and juvenile turtles, many of which are endangered, including loggerhead turtles (*Caretta caretta*). Large *Sargassum* rafts that wash up on beaches can, however, inundate turtle nesting habitats and may cause turtles to move from heavily impacted areas to nest (Maurer et al., 2021). Such inundations can also impede hatchling turtles returning to the sea (Schiariti & Salmon, 2022).

Some species also rely on different seaweed habitats throughout their life history, emphasising the importance of understanding the interconnectedness of seaweed habitats for conserving valuable species at all life stages. For example, in Japan the commercially important abalone (*Haliotis discus hannai*) inhabit crustose coralline algae beds as juveniles, whereas adults are abundant in kelp forests (Won et al., 2013).

The importance of seaweed habitats also extends beyond their immediate footprint. For example, drifting fronds or fragments of seaweeds that have been dislodged during storms can provide food sources for neighbouring areas and wider ecosystems, such as subsidising deep-sea communities and providing food for terrestrial species when cast ashore (Filbee-Dexter et al., 2024b).

Seaweeds host millions of microbial prokaryotic and eukaryotic taxa, forming a holobiont (Saha et al., 2023). Whilst the functions of these microbial communities are relatively unknown, they are potentially important for the function and protection of the host seaweed and for supporting other ecosystem services, such as nutrient cycling (e.g, Egan et al., 2013 and see paragraph below on biogeochemical cycling). Recent studies of seaweed microbiomes (primarily the bacterial component of the holobiont) have revealed that bacteria associated with kelp were involved in key functions, including dissolved organic matter assimilation, alginate metabolism, vitamin B12 production, and nitrogen cycling, potentially providing the host kelp with vitamins and nutrients (Weigel et al., 2022). These microbiomes also help seaweeds adapt to environmental stress, while promoting their growth and healthy development (Saha et al., 2023, and references therein).

Supporting commercial fisheries

Many of the species which seaweeds provide habitat for are fisheries species of high socioeconomic importance, including crabs, lobsters, abalones, scallops and commercial finfish species. This means that millions of livelihoods are supported by seaweeds' role in fisheries production, generating significant economic value in coastal regions. Fisheries production from seaweed habitats also directly contributes to food security globally, which is especially important in developing regions.

It is estimated that the fisheries value generated by kelp forests alone is substantial, with one hectare of kelp forest potentially producing nearly 2400 kg of fish biomass in a year, of which approximately 900 kg could be harvested with a value of $29,900 per year (Eger et al., 2023a). This figure is only based on the six main kelp genera, and the value for all seaweed habitats for fisheries globally will likely be magnitudes greater. However, no estimate for the total value of all seaweed habitats in sustaining fisheries globally has been calculated yet, as this area is greatly understudied and needs more research. Figure 3. includes some examples of the value kelp forests have to fisheries globally based on available information.

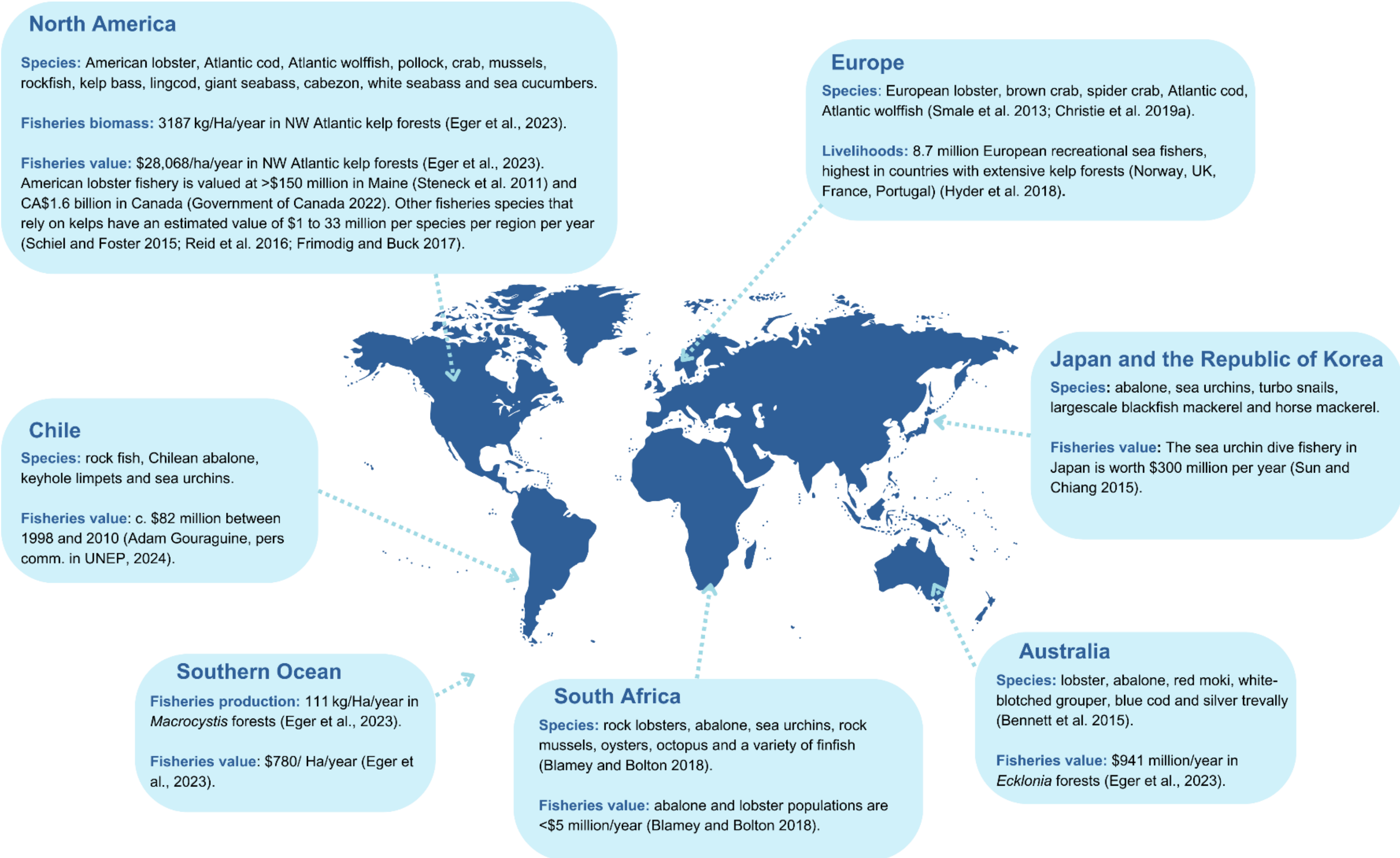


Figure 3. Summary of the value of kelp forests to supporting fisheries globally in terms of the commercial species they support and their production and value. Adapted from UNEP (2023) and Eger et al. (2023a).

Supporting the seaweed harvesting and farming industries

The health and status of wild seaweed habitats underpins the stability of the seaweed farming and harvesting industries, their significant economic value, the food and resources they provide (see Section 3.1.3), and the estimated millions of livelihoods they support worldwide. This is because these industries rely on healthy wild seaweed stocks either for directly harvesting or for providing genetically diverse source material for farming.

Biogeochemical cycling

Seaweeds play a considerable role in the world's carbon cycle (see paragraph on climate change mitigation in Section 3.1.2). They are also key players in oxygen, nitrogen, phosphorus, sulphur and iodine cycles, particularly when considering the function of their associated microbiomes. However, understanding the effects of seaweeds and their microbiomes on biogeochemical cycling is still in its infancy (Sun et al, 2023).

Nevertheless, it is expected that seaweeds make significant contributions to these ecosystem services. For instance, in a year, a hectare of kelp forest removes an average of 720 kg of carbon, 660 kg of nitrogen and 60 kg of phosphorus from the environment (Eger et al., 2023a). These services are valued between ~$36,000 and ~$115,000 per hectare annually, dependent on kelp species (Eger et al., 2023a). This value predominantly comes from nitrogen removal by kelps, which is estimated to be worth $73,800 per hectare per year (Eger et al., 2023a). Seaweed farms have also been recognised for this service, with estimates of Chinese seaweed farms removing over 70,000 tonnes of nitrogen and 8,000 tonnes of phosphorus from seawaters annually (Gao et al., 2021).

Seaweeds have also been recognised for their potential to help mitigate deoxygenation in coastal waters, with seaweed farms in China estimated to generate over 2 million tonnes of oxygen per year (Gao et al., 2021). However more research needs to be done to fully appreciate the extent of oxygen production from natural seaweed habitats.

Seaweeds also uptake and cycle sulphur and iodine, which play important roles in environmental and chemical processes, such as cloud production, atmospheric chemistry and climate control (McFiggans et al., 2004; Leblanc et al., 2006; Rondan et al., 2024). Kelp species are recognised as the most efficient iodine accumulators among all living systems, with an average content of 1.0% of dry weight in *Laminaria digitata*, representing a c. 30,000-fold accumulation of this element from seawater (Leblanc et al., 2006).

3.1.2 Regulating services

Summary: This section covers ecosystem services relating to the role seaweeds play in relation to environmental factors. It includes the relationship of seaweed productivity, carbon cycling and carbon storage with climate change mitigation. It also includes the role of seaweeds in coastal defence and eutrophication mitigation.

Climate change mitigation

The productivity (i.e., the amount of growth or biomass made over time) of seaweed habitats, coupled with the extensive areas they occupy, means they play hugely important roles in global carbon cycling and climate change mitigation. For example, seaweed habitats have extraordinarily high production rates, with a global average of over 650 and 1700 g of carbon per m^2 $year^{-1}$ in the subtidal and intertidal zones respectively (Figs 4 and 5; Pessarrodona et al., 2022). This is up to 10 times higher than coastal phytoplankton in temperate and polar seas (Pessarrodona et al., 2022) and corresponds to around 20 per cent of global coastal net primary production (NPP; the rate at which primary producers store energy as biomass) (Dunne et al., 2007). This production is the result of the conversion of inorganic carbon, such as dissolved carbon dioxide, and nutrients, including nitrogen and phosphorus, into organic biomass. Seaweeds can assimilate more carbon into their biomass for a given amount of nutrient resource than phytoplankton (Sheppard et al., 2023). When dissolved carbon dioxide in seawater is absorbed by seaweeds it is replaced by atmospheric carbon dioxide resulting in a flux of carbon dioxide from the atmosphere into the ocean. Some estimates predict that seaweeds draw an annual global carbon dioxide flux comparable to that of the Amazon rainforest (Duarte et al., 2022).

As seaweeds can absorb carbon dioxide through photosynthesis, they may reduce the pH levels of surrounding waters, creating a local refuge from ocean acidification (Hurd 2015; Gattuso et al., 2018; Gao & Beardall 2022). This effect has also been seen in seaweed farms (Xiao et al., 2021). More research is needed to understand whether all seaweeds provide this benefit and if so, at what scale (UNEP, 2023).

All seaweeds are important for carbon cycling, however there is variation between different habitat types and the degree to which they have been studied (Fig. 6; Duarte et al., 2022). For instance, kelp forests have received the most attention and their recorded productivity is much higher compared to other seaweed habitats (~540 g of organic carbon per m^2 $year^{-1}$) (Pessarodona et al., 2022) (Box 5 and Figs 6 and 7). Nevertheless, even slow-growing calcified green and red seaweeds play an important role in carbon cycling. For instance, red coralline seaweeds produce and potentially store an average of 330 g of organic carbon and 880 g of calcium carbonate per m^2 $year^{-1}$ (Van Der Heijden & Kamenos, 2015). Global estimates predict that coralline algae have organic and inorganic production rates of 0.7 and 0.2 gigatonnes of carbon per year respectively, given their high abundance and global distribution (Van Der Heijden & Kamenos, 2015). Therefore globally, coralline algae have production rates similar to mangroves, salt marshes and seagrasses and higher production rates than coastal phytoplankton, coral reefs and benthic diatoms (Van Der Heijden & Kamenos, 2015). Previously coralline algae were excluded from blue carbon assessments as the calcification process also releases carbon dioxide (Martin and Gattuso, 2009). However, recent findings suggest coralline algae efficiently recycle 40% of this carbon dioxide during photosynthesis, leading to calls from researchers to reassess their inclusion (Mao et al., 2024).

Calcareous green *Halimeda* thalli can contain >90 % calcium carbonate (Böhm, 1973; Hillis-Colinvaux, 1980) and their carbonate production ranges from 0.8 to over 17,500 g per m^2 $year^{-1}$ in the Indo-Pacific (Schubert et al., 2023). *Halimeda* meadows are, therefore, considered major contributors to carbonate and sediment production in tropical and subtropical regions (Schubert et al., 2023). Furthermore, *Halimeda* meadows can build-up extensive bioherms (a body of rock built up by or composed mainly of sedentary organisms) that have been estimated to globally accumulate approximately 0.15–0.4 gigatonnes of calcium carbonate per year (Milliman, 1993; Hillis, 1997).

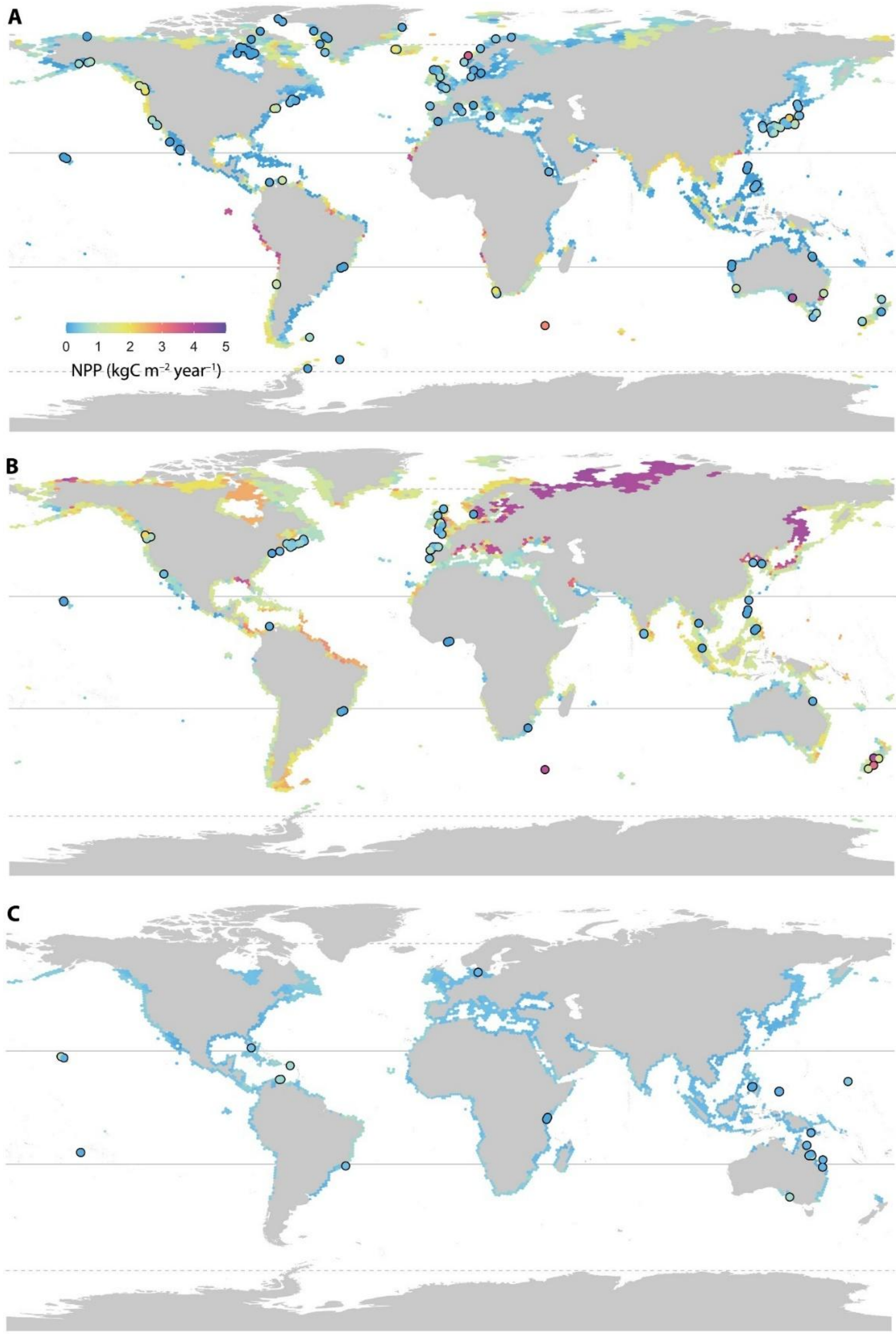


Figure 4. Globally predicted net primary productivity (NPP) of subtidal (A) and intertidal (B) seaweed forests dominated by large brown canopy-forming algae and (C) subtidal algal turfs. Points show the location of the study sites included in this database (raw NPP is indicated by the coloured dots). Lines depict the tropics (straight) and polar circles (dashed). Source: Pessarodona et al. (2022), available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

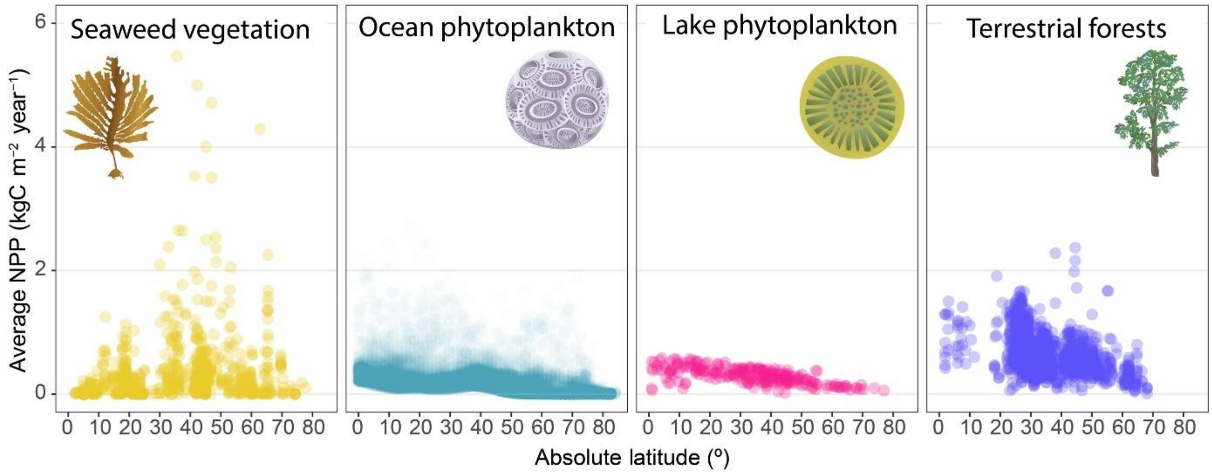


Figure 5. Relationship between latitude and net primary productivity (NPP) across Earth's major primary producers. Terrestrial forest NPP includes above and below ground productivity. Source: Pessarodona et al. (2022) available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

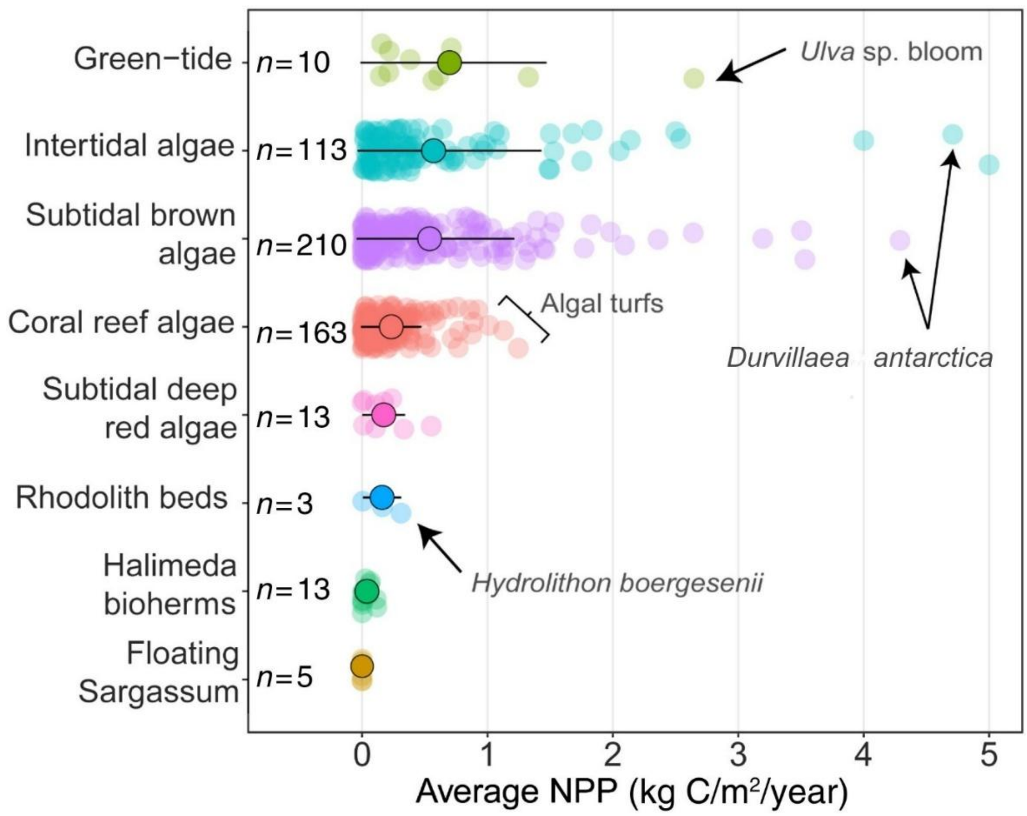


Figure 6. Annual net primary productivity (NPP) for different seaweed habitat types. Larger dots and error bars indicate the mean and standard deviation NPP of each habitat type. The number of measurements for each habitat type is indicated next to each graph. Source: Duarte et al. (2022), available under a Creative Commons Attribution-NonCommercial-NoDerivs License (CC BY-NC-ND 4.0).

Box 5. The potential role of kelp forests in climate change mitigation

Kelp forests in particular have been recognised for their role in carbon and nutrient cycling and are frequently compared to terrestrial forests for this reason.

In a year, a hectare of kelp forest removes an average of 720 kg of carbon, 660 kg of nitrogen and 60 kg of phosphorus from the environment (Eger et al., 2023a). These services are valued between ~$36,000 and ~$115,000 per hectare annually, dependent on kelp species (Eger et al., 2023a). This value predominantly comes from nitrogen removal by kelps, which is estimated to be worth $73,800 per hectare per year (Eger et al., 2023a).

Kelps are reported to sequester between an estimated 30 and 215 g of carbon per metre squared per year, which is similar to terrestrial forests, seagrasses, mangroves and saltmarshes (Fig. 7.; Eger et al., 2023a). Regional kelp forests could sequester between 4,000 and 1.48 million tons of carbon per year (Eger et al., 2023a), with forests off Australia predicted to sequester 1.3 – 2.8 megatons of carbon a year (Filbee-Dexter & Wernberg, 2020). Globally, kelp forests are estimated to sequester 4.91 megatons of carbon from the atmosphere every year (Eger et al., 2023a), which highlights their potential as blue carbon systems for climate change mitigation.

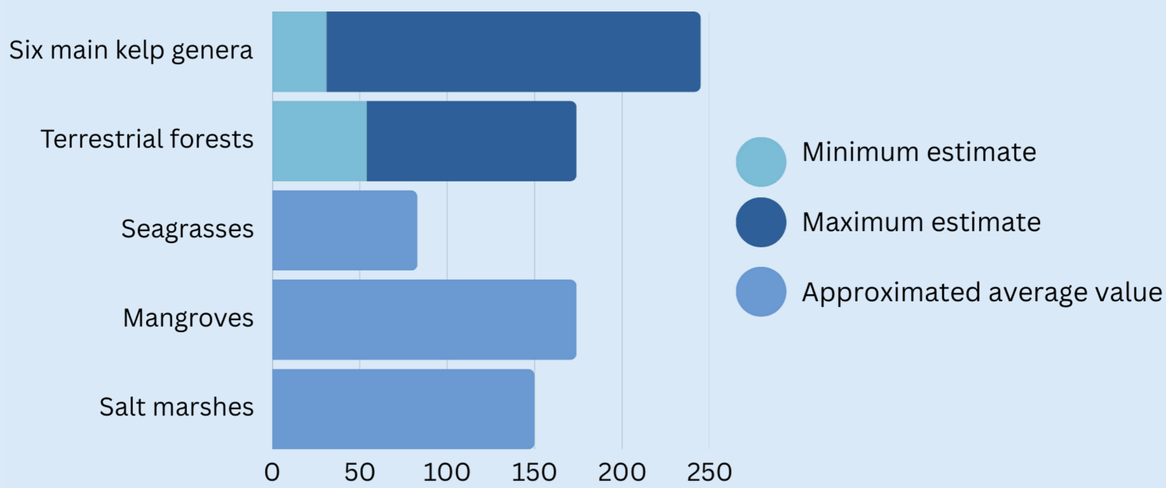


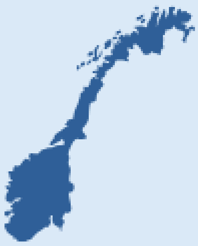
Figure 7. Estimated carbon sequestration rates (g m^{-2} $year^{-1}$) for six main kelp genera compared to other vegetated habitats. Adapted from Eger et al., 2023a. Sources: Eger et al., (2023) (kelp), Toochi et al., (2018) (terrestrial forests), Laffoley & Grimsditch (2009) (seagrasses), Alongi (2012) (mangroves and saltmarshes).

Box 5. *continued*

Examples of how kelp forests can form significant roles in national carbon accounting:

The total carbon standing stock of kelp forests in the eastern Canadian Arctic is 73 teragrams of carbon, which is equivalent to the annual greenhouse gas emissions of over 5 million Canadians (Filbee-Dexter et al., 2022). Globally, kelp forests fix as much carbon during their growth as the northern forests of Canada – nearly 1 billion tonnes a year (Pessarrodona et al., 2024).

In Australia, kelp forests have been estimated to represent a standing carbon stock of 10.3–22.7 teragrams of carbon and contribute 1.3–2.8 teragrams of carbon per year in captured production, amounting to more than 30 % of total blue carbon stored and potentially sequestered around the Australian continent (Filbee-Dexter & Wernberg 2020).



Kelp forests in Norway represent a total of 158 million tons wet weight and a standing stock of 7.1 teragrams of carbon (Frigstad et al., 2020).

While seaweeds can rapidly fix carbon and nutrients in their tissues, this does not always mean they are sequestered, or locked away, for good. Carbon sequestration (storage of carbon dioxide removed from the atmosphere for more than 100 years) varies between seaweed species and habitats, with calcified seaweeds living and storing carbon and nutrients longer term than fleshy seaweeds (Box 6). Seaweed biomass that is not sequestered is either grazed by animals, released as particulate organic carbon or dissolved organic carbon, or remineralised to carbon dioxide. In general, less than ~15 % of seaweed net primary production is estimated to be sequestered on a timescale of centuries or millennia that is meaningful for climate regulation (Duarte et al., 2022). Nevertheless, it is estimated that about 175 million tons of carbon, or 620 million tons of carbon dioxide is sequestered by seaweed habitats globally each year (Krause-Jensen and Duarte 2016). This is equivalent to approximately 10% of the annual emissions from all cars on Earth today.

It is challenging to determine how much seaweed-derived carbon is sequestered as most of it is transported away from the seaweed habitat, and it is hard to track. For instance, up to 80 % of carbon is exported out of kelp forests, up to 5000 km away (Krumhansl & Scheibling 2012; Pedersen et al., 2020). However, it is estimated that kelp-derived carbon that is transported away from kelp habitats exceeds the levels of carbon sequestered in seagrass, salt marshes, and mangroves combined (Krause-Jensen et al., 2018; Macreadie et al., 2019). Furthermore, seaweeds and microalgae have been shown to supply up to 50% of the carbon in seagrass sediments (Kennedy et al., 2010) and up to 60% of Red Sea mangrove sediments (Almahasheer et al., 2017), identifying seaweeds and microalgae as significant carbon donors (Krause-Jensen et al., 2018, Ortega et al., 2019). On average, 15 % of kelp and other brown seaweed production is estimated to be exported to the deep ocean (>200 m depth), equating to 4–44 million tonnes of seaweed-derived carbon that could be sequestered for 100 years (Filbee-Dexter et al., 2024b). This estimate does not include shelf burial or other carbon pathways, nevertheless it highlights the significant contributions seaweeds can have to natural carbon sinks.

It is important to properly quantify how much seaweed-derived carbon is effectively sequestered to understand their role in blue carbon strategies. Validation of the carbon dioxide removal potential of seaweeds will also require forensic carbon accounting and verification of air-sea carbon dioxide equilibrium before seaweed habitats and aquaculture sites can be used in carbon trading schemes (Hurd et al., 2024).

Box 6. Carbon storage by calcified seaweeds

In contrast to the large, brown seaweeds such as kelps, the calcium carbonate skeleton of coralline algae prevents them from breaking down quickly. Therefore, carbon fixed within coralline algae can be stored for hundreds to thousands of years in underlying sediments of coralline algae beds or reefs (Mao et al., 2020), far longer than carbon is stored in tropical rainforests (Hubau et al, 2020). Globally, carbon burial in coralline algae habitats has been estimated at 1.6 gigatonnes of carbon per year (Van Der Heijden & Kamenos, 2015), and regional estimates are starting to highlight where these strongholds occur. For instance, rhodolith beds in Scotland, cover over 7 km^2 and are estimated to contain nearly 450,000 tonnes of carbon, with an additional 2400-5400 tonnes sequestered annually through maerl growth and primary production (Burrows et al., 2014; Marine Gov. Scot., 2020).

Furthermore, in addition to storing their own carbon, rhodolith beds act as important depositories for storing carbon from other sources, through the burial of organic material that lands on the bed or lives within the bed. External carbon can come from seagrass and kelp fronds from coastal systems or terrestrial plants from the nearby shore (Mao, 2020). A recent study has found that of sediment organic carbon within maerl beds approximately 42% comes from marine fauna within the bed, 27% from marine plants, 23% from terrestrial plants and 8% from terrestrial soil (Mao, 2020). Preliminary studies have found that maerl beds have a similar carbon storage capacity to seagrasses (Van Der Heijden & Kamenos 2015; Mao, 2020).

More research is needed to determine the dynamics and stability of coralline algae carbon stores (Van Der Heijden & Kamenos, 2015). This is especially true under future ocean warming and acidification scenarios, which risk significantly reducing calcification and growth rates, increasing microbial respiration rates, reducing the size and distribution of calcified seaweed habitats and ultimately the large quantities of carbon they store (Kamenos et al., 2013; Burdett et al., 2018).

Coralline algae also significantly contribute to the calcium carbonate deposited in coral reef sediments and account for approximately 25 % of calcium carbonate accumulation within coastal regions (Martin et al., 2007).

Climate change adaptation

An estimated 2.15 billion people (c. 26% of the world's population) live in the near-coastal zone and 898 million in the low-elevation coastal zone globally (Reimann et al., 2023). Climate change is predicted to dramatically increase wave heights and storm frequency, causing extensive flooding, landslips, property and infrastructure damage and loss of life. Like other marine vegetated habitats, seaweeds could act as protective barriers that attenuate wave energy before it reaches shorelines, increasing coastal resilience. A study along the coast of the USA found that the number of people and the total value of residential property exposed to hazards under several projected climate scenarios could be reduced by half by preserving existing coastal habitats (Arkema et al., 2013). Importantly, maintenance of coastal habitats is also far less expensive and more environmentally sustainable than building and maintaining coastal defences like sea walls. This provides further economic incentive to conserve coastal habitats including seaweeds.

A few studies have quantified how seaweeds affect wave energy directly. However, this can vary greatly between seaweed species and the location of the habitat (Pinsky et al., 2013). For instance, kelps with robust stipes like *Laminaria hyperborea* have been found to attenuate waves by 50% in 4 m water depth, however this decreases with increasing water depth (Dubi & Tørum, 1996). Kelps with flexible stipes, such as *Ecklonia radiata*, bend under currents and do not attenuate waves (Morris et al., 2020). This highlights how wave attenuation by seaweeds can be substantial, but further research is needed to understand variation between species, the size of the seaweed habitat and environmental factors before seaweed habitats can be incorporated into effective coastal defence strategies or international frameworks for disaster risk reduction such as the Sendai Framework.

Strategically placed kelp farms may also dampen wave energy, if lines are installed appropriately for the location (e.g., perpendicular to the direction of wave energy). Models of a suspended *Saccharina latissima* farm in Maine, USA found under the correct growing conditions and with the appropriate siting of the farm, wave energy during storms could be attenuated by over 30% (Zhu et al., 2021). Furthermore, wave attenuation by offshore, suspended longline seaweed farms will not be affected by sea level rise, whereas natural kelp forests that are attached to the seabed will become less effective at dissipating wave energy during large storm-tides (Zhu et al., 2021).

On the other hand, the rise in extreme storms also severely threatens both seaweed habitats and the seaweed industry (see Section 4.1.1). Despite seaweeds being able to tolerate high wave energy, there comes a point when entire stands of kelps can be ripped from the seabed, and whole farms have been washed away by storms in southeast Asia and east Africa (e.g., De Bettignies et al., 2013; Filbee-Dexter & Scheibling, 2012; Earp et al., 2024).

Seaweed habitats, particularly rhodolith beds and *Halimeda* meadows may also contribute to reducing coastal erosion by trapping suspended particles and increasing sedimentation over large areas of soft seabed. However, increasing sediment loads in coastal waters is one of the main threats facing rhodolith habitats (see Section 4.1.5), as too much sediment can smother beds, so there is a delicate balance that needs to be better understood.

Additionally, dead and stranded rhodoliths and other calcified seaweeds can also make up a large proportion of beach sediments, contributing to coastal deposition and protection (Harvey et al., 2018; Rebelo et al., 2022). Well-known examples are the so-called "Popcorn Beaches" in the Canary Islands, where some beaches can be composed of up to 5000 stranded rhodoliths per m^2 and have important economic values for attracting tourists (Rebelo et al., 2022). Similarly, some tropical sand beaches are composed of up to 90% of green calcareous *Halimeda* seaweed fragments (Wiman & McKendree, 1975).

Eutrophication mitigation

Seaweeds may also help to mitigate eutrophication, which is now a major stressor facing coastal ecosystems worldwide. Eutrophication is caused by highly elevated nutrient concentration levels from agricultural runoff, sewage dumping, coastal development and fin-fish aquaculture entering waterways and the coastal zone (Duarte, 2009). These elevated nutrient levels trigger the proliferation of algal blooms that block light from benthic habitats and consume oxygen from the water, in extreme cases, creating toxic hypoxic or dead zones, leading to mass mortalities of fish and other species. By drawing excess nutrients out of the water, seaweeds may help to prevent eutrophication, thus providing a valuable ecosystem service. Conversely, eutrophication can also lead to nuisance seaweed blooms, which cause severe ecological and economic damages (see Section 4.2.3).

Growing and using seaweed could provide a circular economy solution (Seghetta et al., 2016, Ali et al., 2021). For example, seaweed-based fertilisers and biostimulants can help mitigate eutrophication by offering a natural, sustainable alternative to chemical fertilisers, reducing nutrient runoff, while also improving soil health and water quality.

Seaweed farming has also been proposed as a way to mitigate eutrophication by absorbing excess nutrients, particularly from land run-off if farms are placed in strategic locations (Chopin et al., 2001; Neori et al., 2004). Large-scale seaweed farms in China have reduced nutrient concentrations and harmful algal blooms that threaten shellfish farms and human lives (Yang et al., 2015). However, a small-scale seaweed farm in the UK had no effect on nutrient concentrations or plankton assemblages downstream (Walker et al., 2023). Further research is, therefore, needed to understand which factors influence the potential for seaweed farms to mitigate eutrophication before it can be used as an effective nature-based solution.

Wastewater treatment

Seaweeds have been identified as a means to improve waste-water treatment and reduce environmental pollution as they can remove pollutants including excess nitrogen, phosphorous and phenolic compounds, heavy metals, and dyes from the fashion, textile and paper printing industries (Arumugam et al., 2018). Whilst such an approach has been identified as a potential low-cost solution, this is questionable in relation to treatment and biomass disposal costs (A. Critchley, personal communication). Research has also found that some seaweeds may bioaccumulate PFAs (Per and polyfluoroalkyl substances), which wastewater treatment plants are not efficient at removing (Ford & Ginley, 2024). Integrating seaweeds as a nature-based solution into water and sanitation systems could be a particularly promising solution in coastal developing countries, where the cost for desalination for clean fresh water is high, and suitable seaweed species are readily available. Further information on the use of seaweeds in relation to treating wastewater amongst other uses are reviewed in Farghli et al. (2022).

3.1.3 Provisioning services

Summary: Here, ecosystem services are covered that provide materials which humans depend on for a wide range of uses. Starting with the earliest written records of seaweed use as food and raw materials, it includes a brief section on present day seaweed industry. It also includes summaries of seaweed uses in a wide range of industries from fertilisers and biostimulants, through pharmaceuticals to alternative materials such as bioplastics.

Provisioning of food and raw materials for humans

Seaweeds have supported coastal communities for thousands of years, with written records detailing the provisioning services of seaweeds 1,700 years ago (Erlandson et al., 2015). Archaeological evidence from Chile extends back even further, revealing that seaweeds were used for food and/or medicine by humans approximately 14,000 years ago and may have provided a key resource along the Pacific coastal migratory routes in the early settlement of South America (Dillehay et al., 2008). A study on the dental plaque from 8000-year-old human remains across Europe found that seaweed was probably an important component of diets before farming was established (Buckley et al., 2023).

Today, humans use seaweeds for much the same reasons as our ancestors did, including human and animal food and fertilisers. Now, the range of uses is increasing such as in pharmaceuticals, cosmetics, green chemicals (e.g. surfactants), bioplastics, construction materials and textiles (Table 3). Research and development are leading to more applications for seaweed-derived products in a range of economic sectors (UNCTAD, 2024). This increase in seaweed applications is helping to drive the dramatic growth and diversification of the seaweed industry, which is the fastest growing aquaculture sector, employing millions of people worldwide.

The global seaweed market is currently estimated at $17 billion (UNCTAD, 2024), with new and emerging seaweed applications having the greatest market opportunities outside the established sectors. By 2030, the World Bank estimates that the seaweed industry could be worth as much as US$11.8 billion. Other estimates predict that the seaweed industry's market value will increase seven-fold, to $85 billion by as soon as 2026 (GMI, 2021 in UNCTAD, 2024). Markets for biostimulants, animal feed, pet foods, and methane-reducing additives alone are projected to reach $4.4 billion by 2030, while markets for nutritional supplements, alternative proteins, biomaterials, bioplastics, and fabrics could reach a potential value of $6 billion by 2030 (World Bank, 2023).

Table 3. Summary of the uses of brown, red and green seaweeds. Adapted from UNCTAD, 2024, based on Sultana et al. (2023); Cai et al. (2021); Lomartire et al. (2021); Buschmann et al. (2017); Andersen (2017); Sugumaran et al. (2022).

	Seaweed group		
Use	**Brown**	**Red**	**Green**
Human food	✓	✓	✓
Animal food	✓	✓	✓
Fertilisers	✓	✓	✓
Biofuels	✓		
Construction materials	✓		
Biochemicals, bioplastics and plastic alternatives	✓	✓	
Textiles and fashion	✓	✓	
Medicines, nutraceuticals and cosmetics	✓	✓	✓

The industry is primarily led by seaweed farming (97 %), with the remaining 3 % made up of seaweed harvesting (Fig. 8). The growing demand for seaweed products has led to a boom in the global seaweed industry over the last two decades (UNCTAD, 2024), with seaweed farming in particular, tripling its production volumes from 12 million tonnes in 2000 to 37.8 million tonnes in 2022 (Fig. 9; FAO, 2024). Seaweeds accounted for over 50% of the total global marine and coastal (mariculture) farming production between 2015 and 2020 (Fig. 8; FAO 2020, 2024).

Approximately 700 seaweed species have been documented as edible, including around 195 brown, 345 red and 125 green species (Pereira, 2016). 40% of current seaweed production is used for food, which has the potential to create more sustainable food systems and increase food security, particularly in developing regions. Seaweeds have been part of the daily diets of various countries, particularly in East Asia, for centuries, and have significant cultural importance in terms of culinary traditions (FAO, 2024). In Japan, one-fifth of daily meals incorporate seaweed in some form (Leandro et al., 2020). Seaweeds are used in food products such as sushi, soups, stews and salads as well as food additives and supplements, including as thickening agents in ice-creams and smoothies. As well as being highly versatile, seaweeds are highly nutritious, being rich in vitamins (including A, B1, B2, B9, B12, C, D, E, and K), minerals (including calcium, iron, iodine magnesium and potassium), omega-3, essential amino acids, proteins, carbohydrates and fibre, while being low in calories (Lomartire et al., 2021). This highlights how some seaweeds could be a promising solution for tackling malnutrition as well as hunger globally, particularly in low and middle-income countries where nutrient deficiencies for iodine, vitamins A and B12 and omega-3s are rife, especially for children and pregnant women (UNCTAD, 2024). Some concerns have been raised over safety, however, as seaweeds can contain heavy metals, including arsenic and mercury, which are poisonous to humans, and harbour high levels of PFAs (Per and polyfluoroalkyl substances) which can lead to other health problems (Suther, 2024). More research is urgently needed to determine these levels and rule out any adverse effects of eating seaweeds, particularly for women and children (WHO, 2021).

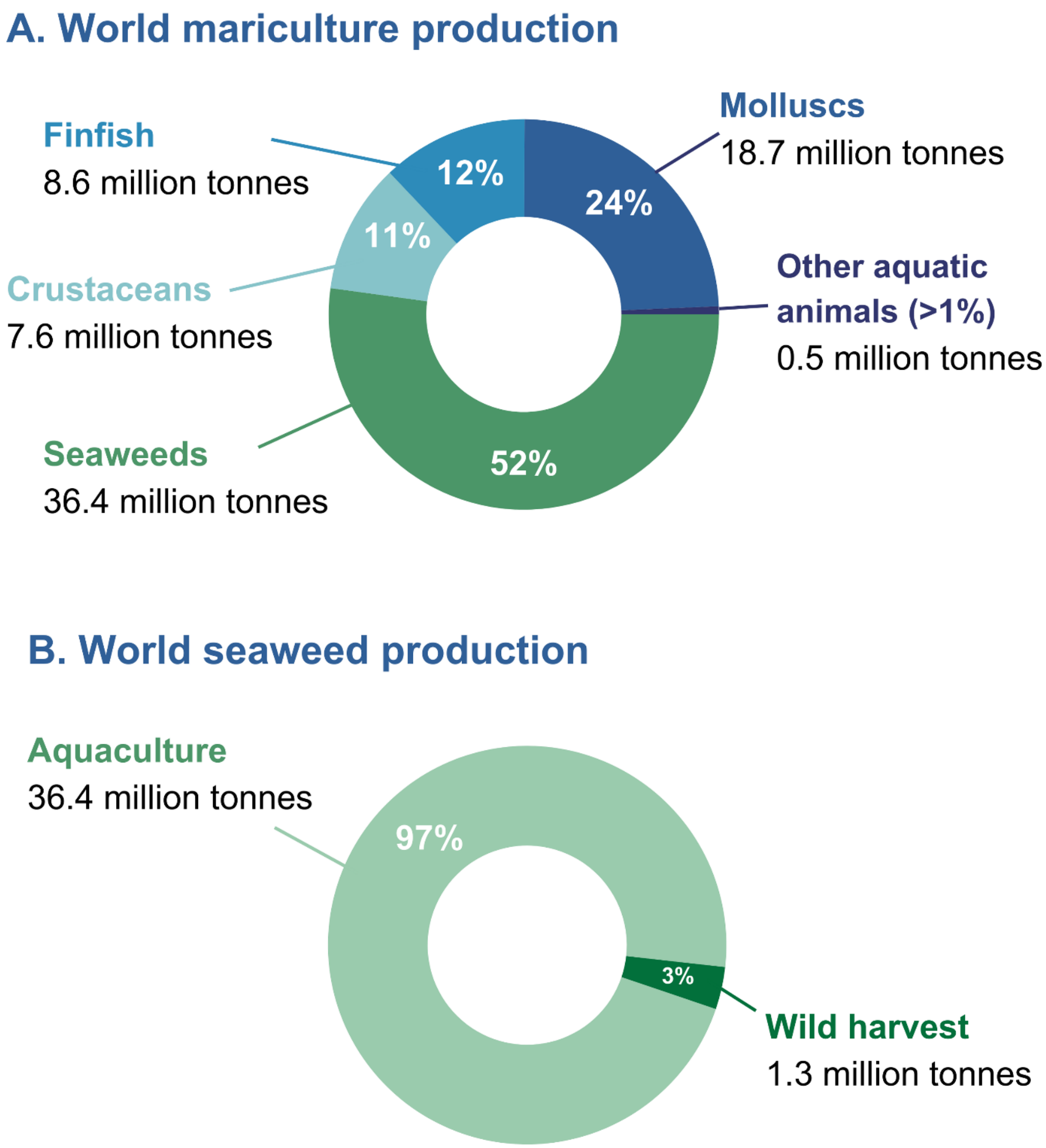


Figure 8. A. World mariculture production by species group 2022; B. World seaweed production by either aquaculture or wild harvest 2022. Adapted from FAO (2024).

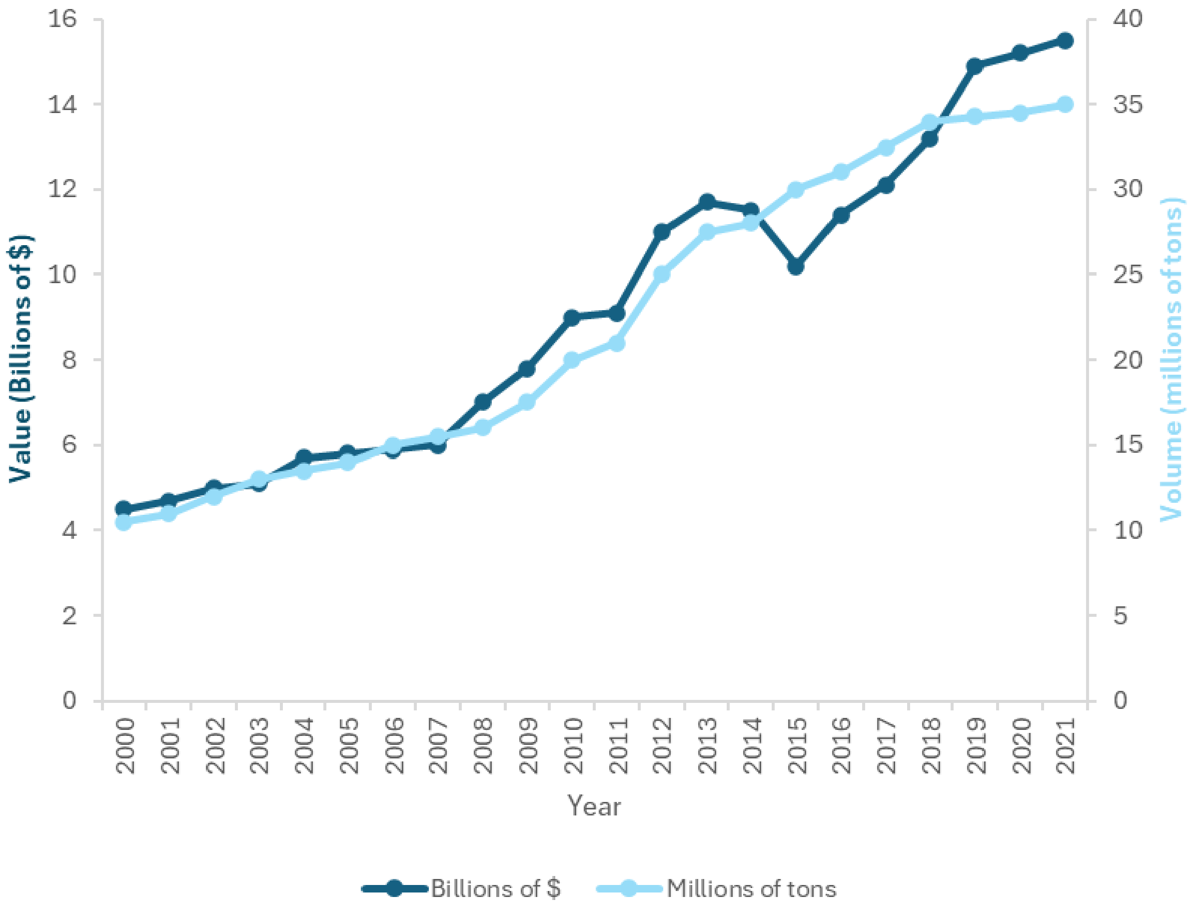


Figure 9. Growth in the seaweed farming industry in both value and volume. Adapted from UNCTAD (2024) based on UNCTADStat data.

Animal feed

Seaweeds have been fed to livestock throughout history but are increasingly recognised as an economic and environmentally friendly alternative to other feeds, such as soybean and fishmeal for terrestrially farmed and fed aquaculture species. Additionally, adding seaweed supplements to feed has been shown to yield significant improvements in animal nutrition, immunity, and health of animals, particularly for pigs, cows, sheep, poultry, and fish (Rajauria, 2015).

Extracts from red seaweeds (principally *Asparagopsis taxiformis*) and some kelp and fucoid species may also be added to the diets of ruminants to improve health, milk and meat production, or reduce their methane emissions, which is a potent greenhouse gas. Sheep produced 80% less methane when they were fed a 3% diet of *A. taxiformis* seaweed over 72 days (Li et al., 2016), while beef cattle fed a diet of 0.2% *A. taxiformis* seaweed over three months produced up to 98% less methane (Kinley et al., 2020). These findings are promising, however, more research is needed to confirm these results and test for any long-term effects on ruminants. Furthermore, with nearly 1.5

billion cattle worldwide, sustainably growing and harvesting enough seaweed to feed them all would be a serious challenge (Slater, 2021). Scientists, therefore, caution the effectiveness of methane reduction from seaweed additives given the need to produce the seaweed under certain environmental conditions and transport it great distances and urge impacts across the entire value chain to be considered before this is scaled up (Abbott et al., 2020; Slater, 2021).

Fertilisers

As many seaweeds are rich in nutrients, including nitrogen and phosphorus, they make ideal natural fertilisers, and seaweeds have been used as soil additives in the form of soil conditioners, biochar and biostimulants for hundreds of years. Using seaweeds as fertilisers can also have the benefits of improving soil health, e.g., through enhancing the effectiveness of the nitrogen cycle, improving the soil microbial community (which in turn will decrease crop losses due to disease and insects), and increasing crop yields (Ali et al., 2021). Seaweed-based fertilisers also provide a more sustainable alternative to artificial fertilisers, which are more heavily reliant on fossil fuels to produce and can cause extensive environmental damage through water quality leaching and eutrophication, air pollution and climate change through ammonia and nitrous oxide emissions (Barnett & Wentworth, 2024).

Medicines, nutraceuticals and cosmetics

Seaweeds are also commonly used in higher value products in the health and wellness industries. For instance, seaweeds are a common ingredient in medicines, cosmetics, toothpastes, soaps and bath salts. In China, seaweed extracts were used over 2,000 years ago to treat diseases including gout and tumours, oedemas and inflammations, and as aphrodisiacs. Today, seaweeds are still used in medicines such as cancer and malaria treatments, antiviral, antimicrobial and antilarval agents, bone implants and treatments for rheumatism, osteoporosis, diabetes and psoriasis (Pérez-Lloréns et al., 2023).

Seaweeds are also being investigated in the development of new drugs to treat neglected tropical diseases (NTDs), a group of diseases that are predominant in the poorest parts of the world affecting 1.4 billion people, such as insect-borne infections, leishmaniasis, Chagas' disease and Dengue fever (Freile-Pelegrín & Tasdemir, 2019). Given the extensive diversity of seaweed species, which have largely been understudied, there is a huge potential for seaweeds to help in the development of more medicines and treatments for even more diseases in future.

Due to their nutritional value, seaweeds are also frequently used in food supplements and antioxidants. Seaweeds are rich in vitamins and minerals including magnesium, iron, and iodine. Seaweeds are being used to reduce cholesterol and improve dietary health in several ways. For example, an extract of *Laminaria digitata* has been clinically approved in Europe as an appetite suppressant to help people lose weight (Lange et al., 2015).

Seaweeds are often used in cosmetics as a thickening agent, preservative or as an active ingredient with antioxidant, anti-aging, anti-inflammatory and moisturising properties. For instance, seaweed-derived products are often used to treat skin problems including hyperpigmentation, premature skin aging, and acne (Jesumani et al., 2019).

Biochemicals, bioplastics and plastic alternatives

Hydrocolloids such as alginate, carrageenan and agar from seaweeds, are used in hundreds of foods and commercial products. Commonly they are used as gels, thickening agents or preservatives in foods. These have high export value, for instance in 2021, global agar and alginate exports reached $260 million and $161 million respectively (UN Comtrade, 2023, in UNCTAD, 2024). It is harder to estimate the value of carrageenan exports as they are included with other thickening agents, with a combined export value of $1.5 billion in 2021 (UNCTAD, 2024).

More recently, with increasing attention on the plastic pollution crisis, seaweeds have been recognised as a potential plastic or bioplastic alternative. An estimated 6.3 billion tonnes of plastic waste currently litter our streets and fill our seas, and it is predicted that by 2050, there could be more plastics than fish in the sea if the current production trends continue. Plastic production also contributes to global warming, generating 1.8 billion tons of greenhouse gas emissions in 2019, equivalent to 3.4 % of global emissions (United Nations, 2024).

Seaweeds can be used to develop non-plastic substitutes and plastic alternatives that can be used for a range of applications. Unlike many other bioplastics, seaweed alternatives can be fully biodegradable and compostable. Several start-ups have created packaging materials made from seaweed to replace single-use plastics, including Notpla (winner of the 2022 Earthshot prize, Box 7), Evoware, Algeon Materials, Sway, and FlexSea (Sugumaran et al., 2022; UNCTAD, 2023; UNCTAD 2024).

Box 7. Notpla

London-based start-up Notpla, founded by Pierre Paslier and Rodrigo Garcia Gonzalez, is on a mission to replace plastics with fully degradable and compostable bioplastic made from plants and seaweeds. At the London Marathon in 2019, 36,000 Notpla-made “Oohos”, filled with Lucozade, were handed to runners. In 2023, Notpla replaced 4.4m units of plastic with biodegradable or compostable alternatives in 2023, doubling the total they achieved in 2022 and displacing 8.5 tonnes of plastic waste and avoiding 250 tonnes of CO_2 emissions. The company has recently partnered with Just Eat Takeaway.com where they have made 1 million takeaway food boxes, with the potential to replace over 100 million plastic coated containers in Europe in the future.

Notpla’s packaging is the first and only material worldwide to have been recognised as being plastic-free under the European Single Use Plastics Directive and the company is continuing to research and develop new formats and solutions, with flexible films and rigid materials in the pipeline.

Construction materials

Seaweeds can be used as resistant green construction materials. For instance, ash from *Sargassum* species has successfully been used as a mineral addition to partially replace fine aggregates in Portland cement mortar, reducing the environmental impacts of production (Lyra et al., 2024). In Mexico, Sargablock, set up by Omar de Jesús Vazquez Sánchez, turns *Sargassum* that washes up on Caribbean beaches, into low-cost bricks for affordable housing for families (Miranda et al., 2021). Interest has spread from Mexico to countries around the Caribbean and beyond.

Sargassum inundation events cause huge economic costs for the tourism industry. For example, in Mexico harvesting one m^3 of *Sargassum* was reported to cost from US$19-85, with an annual cleanup cost per km of beach between US$: 0.3–1.5 million (Rodríguez-Martínez et al., 2023). *Sargassum* inundation events also threaten coastal biodiversity and livelihoods (see Section 4.2.3), so repurposing the biomass in this way helps alleviate the problem, while generating livelihoods, income and low-cost houses.

Textiles and fashion

Seaweeds can be used to produce fibres, materials, coagulants and inks in the textile industry, including the production of flame-retardant fabrics. These products can have a lower environmental footprint than traditional products such as cotton or leather which are hugely damaging and require large amounts of freshwater and harmful chemicals that are often leached into the environment. Many companies are turning to seaweeds to provide sustainable solutions. For example, OCEANIUM is a UK company that has made “the world’s first sustainable and fully biodegradable, water-based ink derived from sustainably sourced seaweed". This offers a sustainable, non-toxic, vegan certified, alternative to solvent-based plastisol inks that are environmentally damaging.

The fashion industry is not only damaging to the environment but has also caused huge socio-economic problems and is frequently linked to child labour, modern slavery and poverty. Runa Ray is a Fashion Environmentalist who set up the non-profit *Fashioning Social and Environmental Justice* that works with local communities impacted by climate change, fast fashion and war to create high fashion from sustainable materials including seaweeds. Runa makes materials such as seaweed leather and uses ancient traditional techniques of floating inks with seaweed coagulants to help mitigate water wastage and pollution caused by dyeing and printing. Runa relies on using seaweeds collected by women in coastal communities in South India, acting as a leading example of empowerment and social justice in the fashion industry.

Biofuels

Since the 1970s, there has been interest in using seaweeds as a source of biofuels due to their advantages over other biofuel crops, including their high productivity and minimal freshwater and land use requirements. In general, microalgae are recognised to be more promising sources of biofuels, given their high lipid content and reliable growth (Wang et al., 2024). However, seaweeds, and particularly kelps, are rich in polysaccharides, and biomass can be converted (e.g., via anaerobic digestion) into ethanol which is a key component in biofuels. The European Commission financed various projects that focused on the production of biofuels from seaweeds in the North Sea to contribute to the European Green Deal and the Recovery Plan for Europe (UNEP, 2023). However, there have been no further EU-funded projects on seaweed biofuels since the end of 2019, although projects have continued relating to microalgae.

Conversion efficiency currently varies significantly between seaweed species, processing techniques and digester conditions. For the industry to be economically viable and scalable, it must focus on a few fast-growing, high-yielding local seaweed species (Twigg et al., 2024). Other challenges must be addressed to ensure wider adoption and economic viability, including optimising biomass production to create a consistent feedstock with high sugar content and favourable carbon-to-nitrogen ratios while minimising inhibitory factors like halogenated metabolites, sulphur, and heavy metals (Twigg et al., 2024). Additionally, improving conversion rates through co-digestion, pre-treatments, and scalable technology, as well as developing microbial communities that can efficiently process the diverse polysaccharides in seaweed under saline conditions, are crucial. Overcoming these challenges will significantly advance the development of a bio-energy industry based on the anaerobic digestion of cultivated seaweeds (Twigg et al., 2024). In the long term, the cost of seaweed cultivation should come down and yields go up, allowing the economic viability of biofuels from seaweeds.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3.1.4 Cultural services

Summary: This section covers how humans gain directly and/or non-directly non-material benefits from seaweeds and their biodiversity. It provides and overview of how humans connect with seaweeds through work or recreational activities and the sociocultural and Indigenous uses of seaweeds with reference to identity, gender equality, livelihoods and spirituality.

Supporting identify and connecting with nature

Seaweeds and their habitats allow humans to develop a sense of place and connectedness with nature and support the identities and livelihoods of many coastal communities and Indigenous Peoples around the world (UNEP, 2023). Harvesting of seaweed or fishing within seaweed habitats are often intrinsically linked to the cultural identity of coastal communities (Mac Monagail et al., 2017), such as the harvesting of pāua (abalone, *Haliotis iris*) by Māori Peoples in New Zealand. Seaweeds are also used in traditional foods, medicines, shelter, clothing, knowledge systems, art and ceremonial activities by numerous Indigenous communities (Thurstan et al., 2018; UNEP, 2023). For instance, seaweed is often gifted or eaten in wedding ceremonies in Japan and Korea.

Living in harmony

Many Indigenous Peoples and coastal communities have co-existed with seaweeds for thousands of years, practising sustainable use and acting as custodians of seaweed habitats. For example, in Australia, kelp forests have played an important role for Aboriginal Peoples over the past 65,000 years, where an estimated 46 Indigenous nations border the Great Southern Reef (Thurstan et al., 2018; UNEP, 2023). Much traditional knowledge on seaweeds and their habitats has been lost due to colonial atrocities committed against Indigenous Peoples, yet some uses and practices have been recorded, which are vital to recognise, preserve and restore where possible.

The future of many Indigenous and coastal communities depends on the health of seaweed habitats and the ecosystem services they provide. Similarly, the health of seaweed habitats also depends on using traditional knowledge and enabling appropriate custodianship through customary laws (see Box 8 and Section 5.1.4).

Box 8. Combining traditional knowledge and modern science for seaweed conservation

First Nations People along the coasts of Canada and Alaska use feather boa kelp *Egregia* (y̓ák̓a) in ceremonies, trading and gift-giving practices, highlighting its cultural value. Heiltsuk People have occupied their traditional territory for more than 14,000 years and have been sustainably managing the harvest of *Egregia* through ancestral laws and practices of resource management (Ǧvi̓ḷás). These traditional Indigenous knowledge systems have been passed down through generations (Kobluk et al., 2021).

Today, Heiltsuk knowledge keepers are working with scientists from Simon Fraser University (SFU) in British Columbia to investigate the ecological resilience of y̓ák̓a in relation to climate change and its potential for sustainable harvest for a small-scale kelp fishery. Here scientists worked closely with the Heiltsuk to tailor the research to the community's needs (Gilpin, 2021).

This work highlights the importance of combining traditional knowledge with science to safeguard the future of seaweed habitats and their sociocultural importance in light of the climate crisis and an expanding seaweed industry.

Gender equality

Despite the impressive scale of the seaweed industry (Fig. 10), approximately 80% of the global seaweed crop still comes from smallholders in developing countries, as the nature of seaweed production is better suited to hands-on small-scale production, like coffee, rice and cocoa (Waycott, 2024). Seaweed production is less resource and capital intensive than agriculture, fishing or other aquaculture alternatives, which makes the sector more accessible to women and lower income families (see Box 9). As a consequence, it has been highlighted as a key driver of women's, youth, and Indigenous Peoples' empowerment in coastal communities of developing countries, in line with SDGs 5 and 10 (UNCTAD, 2024; FAO, 2024).

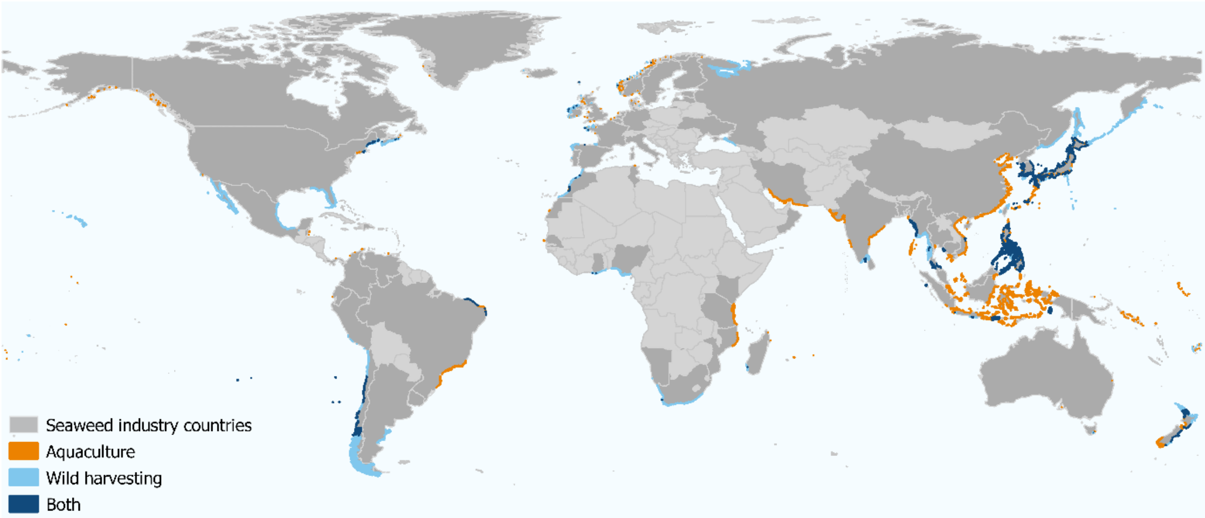

Figure 10. Spatial distribution of the global seaweed industry. Source: Brodie et al., in review.

Box 9. Women in the seaweed industry

The seaweed industry contributes to the empowerment of women in coastal communities, particularly in developing countries, including those from marginalised groups, such as divorced or widowed women (UNCTAD, 2024; Msuya, 2006). It provides significant employment opportunities in harvesting, cultivation and throughout the value chain (e.g., marketing, research, and decision-making). Seaweed farming and harvesting have low entry capital and technological requirements, which allows women to engage in income-generating activities while managing household responsibilities due to their flexible nature (Sultana et al., 2023).

Women make up 28% of the workforce in aquaculture, whereas in fisheries, they comprise just 18% (FAO, 2022). Although there is limited data to disaggregate between aquaculture types, seaweed farming is believed to have one of the highest proportions of women working on the taskforce globally. In Asia, women make up approximately half of seaweed farmers, while in Africa, seaweed cultivation is predominantly carried out by women (Msuya & Hurtado, 2017). For instance, two thirds of seaweed farmers in Kenya are women (UNCTAD, 2024).

Examples of women in seaweed farming

Zanzibar, Tanzania: Over 90% of seaweed farmers in some regions (e.g., Unguja) are women, who have dominated seaweed farming since its initiation in 1989, while men continue to work in fishing or tourism (Msuya & Hurtado, 2017). Today, women in Zanzibar produce and sell seaweed-based products like soaps, skincare items, food, and sanitation products. This has led to social and cultural benefits, with women socialising, sharing knowledge, and improving family health outcomes by integrating seaweed into their diets (Msuya, 2006; UNCTAD, 2024).

India: 50% of people employed in the seaweed sector are women (Immanuel & Sathiadhas, 2004).

Indonesia: Seaweed farming had the most significant percentage of female involvement out of all types of aquacultures (Sultana et al., 2023). Women's involvement in it resulted in work satisfaction and social recognition, which is also observed in Malaysia and the Philippines (Msuya & Hurtado, 2017).

Maine, USA: Women's participation in seaweed farming has increased gender equity in fisheries, with 37% of women involved in seaweed farming compared to 4% in wild-caught fisheries, such as lobsters (McClenachan & Moulton, 2022).


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Recreation and tourism

Seaweed habitats create visually impressive underwater worlds that support many cultural ecosystem services. These include providing aesthetic values, creative inspiration, a sense of place, physical and mental well-being and spiritual and religious experiences. Most of these relate to the intrinsic value of seaweeds, which cannot be quantified in monetary terms, but instead offer invaluable importance to humans globally. Some of this importance is, however, reflected in the socioeconomic benefits seaweeds have for coastal communities in terms of recreation and tourism, yet this is still difficult to quantify and is understudied in general.

Recreation and tourism activities, such as snorkelling, diving, swimming, surfing and recreational fishing rely on healthy seaweed habitats and many of the other ecosystem services they provide, such as supporting biodiversity and fisheries (see Section 3.1.1). Snorkelling and diving in seaweed habitats, represents a major industry and employs dive operators and tour guides. Millions of people also enjoy recreational fishing globally, which is worth millions of dollars to local and state economies annually from costs of licences and gear. These activities also provide benefits to local economies through the associated travel, food and accommodation costs (UNEP, 2023).

In Australia, ~70% of the population live within 50 km of a kelp forest, and millions of Australians and tourists directly and indirectly engage with seaweed habitats for recreation and tourism (Bennett et al., 2015a). For Australian states adjacent to the Great Southern Reef, where most kelp diving takes place, diving tourism generates around AUD 1.25 billion per year (Beaver & Keily 2015). ~15% of Australia's population takes part in recreational fishing each year and kelp forests are inhabited by many of the target species, including Red moki (*Cheilodactylus spectabilis*), white-blotched grouper (*Epinephelus multinotatus*), blue cod (*Parapercis colias*) and silver trevally (*Pseudocaranx georgianus*) (Bennett et al., 2015a).

Furthermore, given the role calcified seaweeds play in coral reef formation and maintenance (see Box 3), it could be argued that a significant proportion of the >$5 billion dollars generated from tourism and recreation on the Great Barrier reef could also be attributed to seaweeds.

In South Africa, ecotourism associated with the kelp-dominated coastline of the Western Cape is estimated to be around $113 million per year (Blamey & Bolton, 2018). It is also estimated that over $80 million is generated from the sale of permits for collecting West Coast rock lobster and by the recreational line fishery each year in South Africa, which are dependent on kelp forests (Blamey and Bolton, 2018).

Nevertheless, seaweeds can negatively affect recreation and tourism. For example, an increase in nuisance blooms washing ashore can threaten human health and cost millions of dollars in cleanup fees for tourism businesses (see Section 4.2.3).

3.2 Economic value of seaweed ecosystem services

With the exception of kelp forests, few economic assessments have been made on the ecosystem services provided by seaweeds, due to knowledge gaps surrounding their extent and value. Kelp forests are estimated to contribute over $1 million per kilometre of coastline they cover (Filbee-Dexter & Wernberg, 2018). Regional economic valuations of kelp forests, which have incorporated various ecosystem services (e.g., harvest, fisheries, and tourism) have been estimated to be worth between $290 million (e.g., *Ecklonia* and *Laminaria* forests in South Africa) (Blamey & Bolton, 2018) and $540 million per year (e.g., *Lessonia* and *Macrocystis* forests in Central-Northern Chile) (Vásquez et al., 2014; Eger et al., 2023a) (Fig. 12).

Collectively, kelp forests are estimated to generate a mean value of $500 billion per year in ecosystem services worldwide, primarily through fisheries production (see Section 3.1.1), nitrogen removal and carbon sequestration (see Section 3.1.2). This means that over the next 20 years, kelp forests will have an estimated Net Present Value of $7.44 trillion (Eger et al, 2023).

The full economic value of seaweed habitats is likely to be orders of magnitude higher if all species, habitats and ecosystem services are fully considered. Furthermore, the true value of seaweeds and their associated habitats extends much further than their economic benefits. For instance, it is impossible to put a price on the intrinsic value seaweeds have to many Indigenous communities (see Section 3.1.4).

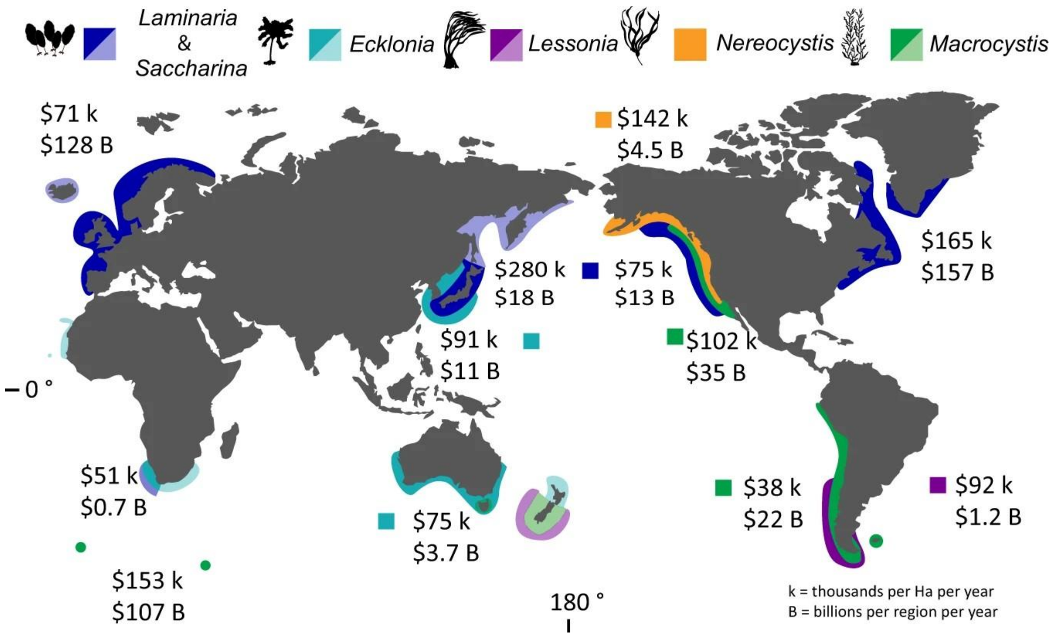

Figure 11. Global kelp distribution, total economic value per m^2 year^{-1} (k), regional value (B). Lighter shade colours: regions where distribution estimates were not F and, therefore, these values were not included in the regional value calculation. Source: Eger et al., 2023a, available under a Creative Commons BY license (CC BY 4.0); no changes have been made. Image credit from original authors: Tim Carruthers, Integration and Application Network (ian.umces.edu/media-library) for the *Ecklonia*, *Laminaria, Lessonia, Macrocystis, Nereocystis* images and map provided by FreeVectorMaps.com.


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4. Threats to seaweed distribution and diversity

Summary: This chapter outlines the current understanding of threats to seaweeds from multiple stressors. This covers the climate crisis as well as anthropogenic threats including overharvesting, harmful fishing methods, pollution, invasive species and disease. Changes in seaweed distribution, including range shifts, declines and losses, and future projections under modelled climate change scenarios are also documented.

4.1 Threats to seaweeds

Seaweeds and their associated habitats face an increasing number of threats, most of which are driven or compounded by the climate crisis. The majority of threats facing seaweeds are human induced, which means that we have the potential to reduce their impact, but only if action is taken now.

4.1.1 The climate crisis

The climate crisis is the main threat to seaweeds. Rising seawater temperatures and increasing frequency of marine heatwaves and other extreme weather events (e.g., storms and hurricanes), ocean acidification, melting ice sheets and glaciers, increased rainfall and coastal erosion are all the result of climate change and are all affecting seaweeds and their habitats. Negative impacts from the climate crisis also threaten the seaweed industries (e.g., farming, harvesting, tourism and fisheries), upon which millions of livelihoods depend globally, particularly in many developing countries which are disproportionately affected by the climate crisis. During El Niño events, the impacts of climate change are magnified and can have severe consequences for livelihoods, food security and seaweed exports (FAO, 2024).

Ocean warming

Rising ocean temperatures are a consequence of the oceans absorbing excess heat trapped by greenhouse gas emissions. Ocean warming is causing declines in the abundance, diversity and distribution of seaweed habitats globally, and reducing the areas suitable for seaweed farming. The consequences of this warming can be seen in reduced growth rates, tissue damage, decreased resilience to disturbance (e.g., storms), increased susceptibility to grazers, disease, invasive species, reduced reproduction and survivability of juveniles, and ultimately death. Scientists are urgently trying to determine the thermal tolerances of different seaweed species and populations to understand the risks these seaweeds face under projected warming scenarios (see Section 4.3.2), especially in combination with other increasing anthropogenic stressors (Wear et al., 2023).

The overall trend reported for many seaweeds in response to ocean warming is for a general shift poleward with their abundance tending to increase at their poleward edges and declining towards the equatorial edges (e.g., Straub et al., 2019; see also Section 4.3.2). However, species with restricted distributions or endemics may already be declining due to thermal stress, with nowhere else to go in terms of range expansion to cooler waters. For example, *Lessonia corrugata*, a kelp considered to be endemic to southern Australia and Tasmania is currently being pushed above its thermal limits in Tasmania due to ocean warming (James et al., 2024). Climate projections suggest that the thermal limit of *L. corrugata* will be regularly exceeded by 2050, as southeastern Australia is a global ocean-warming hotspot (James et al., 2024).

Seaweed farmers are also having to move to new areas and further offshore to cooler waters to cultivate their crops (Makame et al., 2021). For example, in Tanzania, there has been an increase in maximum seawater surface temperatures from 31°C to 38°C since the early 1990s (Mysuya et al., 2022). As a consequence, some seaweed farmers have had to move their farms into deeper, cooler waters requiring a boat to reach these sites which may be unaffordable for resource-poor producers.

Marine heatwaves (MHW)

At the same time as there is persistent ocean warming, there are increasing frequent discrete periods of extreme regional ocean warming or marine heatwaves (MHWs) (Smale et al., 2019). A marine heatwave is defined as a "prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution, and spatial event" (Hobday et al., 2016). Oliver et al. (2018) reported that such anomalously warm temperature events had increased in frequency by 34% and in duration by 17% from 1925 to 2016.

The impacts of MHWs on seaweeds are damaging across a range of biological processes with the potential to restructure entire ecosystems and upset the provision of ecological goods and services for the long term (Smale et al., 2019). For kelp, it has been demonstrated that its biomass is negatively correlated with the number of MHW days recorded over the previous year (Smale et al., 2019).

The direct effects of ocean warming and marine heatwaves on local seaweed habitats, however, will depend on the speed and intensity of the temperature rise, species-specific responses, and the thermal history and optimum temperature of the seaweed habitat (e.g., Venegas et al., 2023). For instance, seaweed species that are living in areas below their thermal optimum may benefit from ocean warming, whereas for species living at or above their thermal optimum, ocean warming or marine heatwaves can have devastating effects (Straub et al., 2019, 2022; Smale, 2020; Smith et al., 2023).

Ocean acidification

Decreases in ocean pH, linked to increasing levels of dissolved carbon dioxide, can positively impact seaweed photosynthesis but only when it is not limited by other factors such as light (Briggs et al., 2019). Ocean acidification can, however, also negatively impact growth rates, productivity and reproductive success in many groups of seaweeds. Calcified red and green seaweeds are particularly susceptible to ocean acidification, as their calcification and growth rates are reduced and their structural integrity weakened (Tuya et al., 2023; Schubert et al., 2023; Melbourne et al., 2023). Responses to ocean acidification can be complex and vary between species and locations with implications for changes in habitat complexity and shifts in species distribution (Melbourne et al., 2023). For example, *Corallina* species have been shown to be highly tolerant of environmental stress and well-adapted to intertidal habitats (Williamson et al., 2017 and references therein). Increased acidification may help *Corallina* species to grow in winter months, when there is less light, although it is predicted that at night the acidification may cause them to dissolve more easily (Williamson et al., 2014, 2017).

Ocean acidification can also reduce the ability to produce compounds to defend against competitors and herbivores (Schubert et al., 2023). Increasing ocean acidification may also shift calcified seaweed habitats, like rhodolith beds or *Halimeda* meadows, from a state of net carbonate production to net dissolution, triggering a positive feedback loop and threatening the large stores of carbon trapped within these beds (Fig. 12; Burdett et al., 2018; Schubert et al., 2023).

The impact of ocean acidification on non-calcified seaweeds is far less studied than calcified species. There is evidence that ocean acidification may indirectly increase the virulence of diseases (Qiu et al., 2019) and the competitive strength of filamentous turf algae over kelp forests (Connell et al., 2013). There is also evidence from a recent study from Sweden on the impact of ocean acidification on *Fucus vesiculosus*, that thallus strength will be reduced which will increase its risk of physical damage and detachment (Kinnby et al., 2023). *F. vesiculosus* is an important foundation species in the intertidal of rocky shores in the North Atlantic, so these results have implications for changes in community composition if the impact is severe.

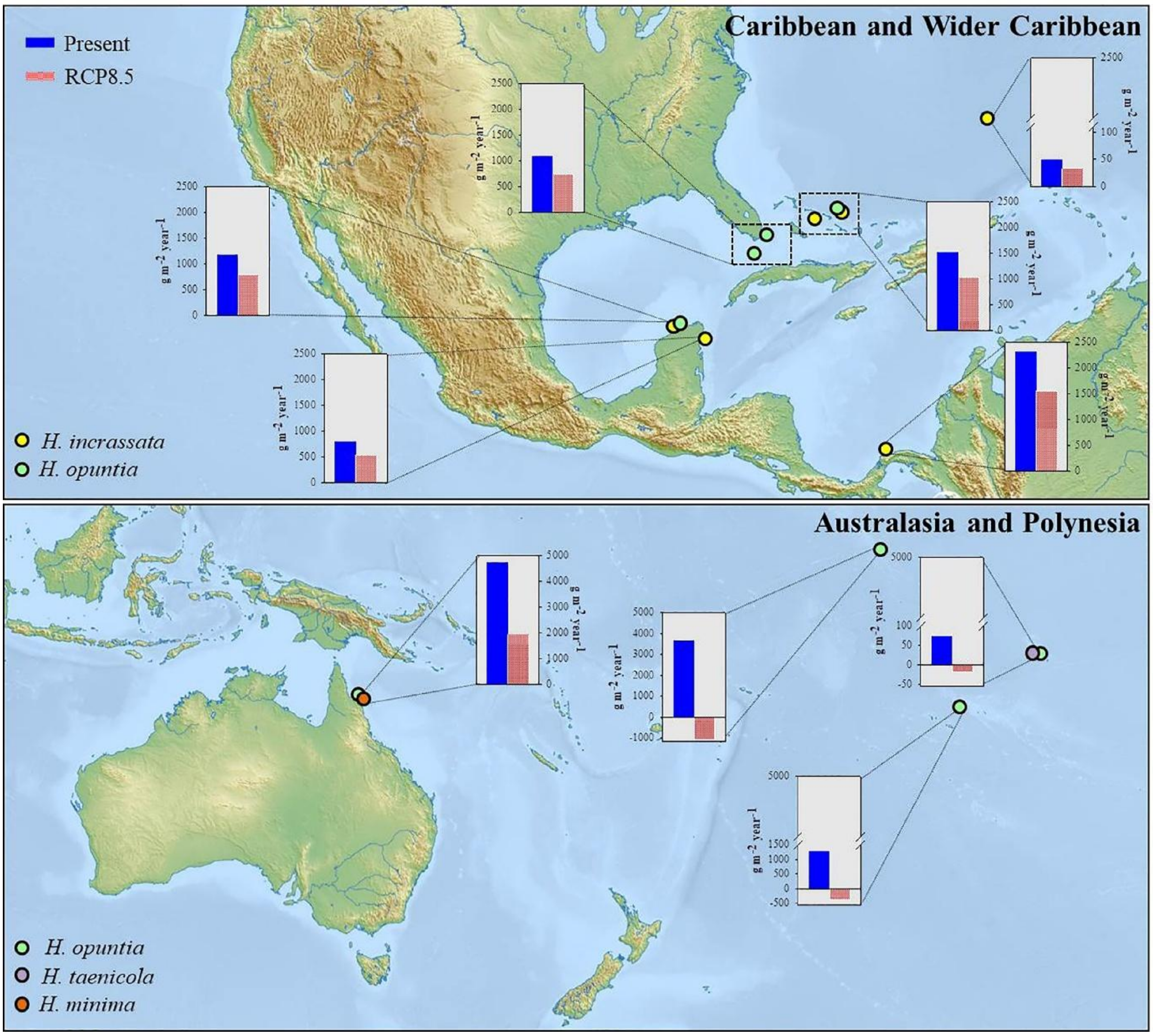


Figure 12. Carbonate production (g m^{-2} year^{-1}) in *Halimeda* spp. reported for different locations and species in the Caribbean and Wider Caribbean (upper panel) and in Australasia and Polynesia (lower panel) currently (blue), and the potential future changes (RCP8.5 by 2100) (pink), based on experimental species- and region-specific ocean acidification effects on net carbonate production. Source: Schubert et al. (2023), available under a Creative Commons Attribution-NonCommercial-NoDerivs License (CC BY-NC-ND 4.0). Maps were originally downloaded from Mapswire (https://mapswire.com/).

Storms and waves

Despite some seaweeds being able to tolerate high wave energy (see Section 3.1.2), increases in wave height and extreme storm frequency due to the climate crisis are also threatening both wild and farmed seaweeds. Whole stands of kelps have been ripped from the seabed in Europe and farms have been washed away by storms in southeast Asia and east Africa (e.g., De Bettignies et al., 2013; Filbee-Dexter & Scheibling, 2012; Earp et al., 2024). Storm damage is typically worse though during El Niño Southern Oscillation Events, where severe storms are combined with warmer water, which can degrade the health of seaweeds leaving them susceptible to damage from strong wave energy.

Water quality

Changes in salinity, turbidity and sediment loading from melting ice sheets and glaciers, increased rainfall and coastal erosion all affect the photosynthetic ability of seaweeds and are linked to the climate crisis. For example, greater freshwater run-off from heavier rainfall or increased meltwater can increase turbidity in coastal waters and cause reductions in seaweed growth and the success of microscopic life stages (Traiger & Konar, 2017).

4.1.2 Overharvesting

The impacts of seaweed harvesting depend on the method and intensity of harvesting and the recovery time of the seaweed species. Harvesting effects on kelps for example, can be negligible when only parts of the seaweed are removed (Levitt et al., 2002; Borras-Chávez et al., 2012; Krumhansl et al., 2016). For example, in South Africa, cropping the floating canopy of *Ecklonia maxima* above its point of growth, allowed it to regrow within a year, with minimal effects on the associated flora and fauna communities (Levitt et al., 2002).

However, when whole individuals are removed, particularly with industrial-scale methods and machinery, overharvesting can lead to altered population dynamics and, in extreme cases, loss of the entire seaweed habitat. For example, in parts of Chile, intensive harvesting and the use of specialised harvesting equipment have resulted in increased kelp density, but reduced kelp size and age. Areas have also been reported where kelps have not recovered after several years following intensive harvesting or have been replaced with urchin barrens (Gouraguine et al., 2021). Similarly in Norway, intensive trawling of *Laminaria hyperborea* has reduced the ecological function and biodiversity associated with these kelp forests, which can take at least six years to recover (Steen et al., 2016; Steen, Norderhaug & Moy 2020). Recovery after harvest may be slower if other environmental stressors are also present.

Overharvesting at the population edges of seaweeds, where genetic diversity is naturally reduced can also lead to population depletion. For example, *Gigartina skottsbergii* (now *Sarcopeltis skottsbergii*) was heavily harvested at the northern limit of its range in Chile for over a decade in the late 1990s/early 2000s, until landings virtually ceased (Faugeron et al., 2004). This led to severe reductions in population size and concerns over conservation of genetic stock.

The harvest of slow-growing seaweeds, such as rhodolith beds, has serious consequences for the long-term health of the habitat. Extraction of rhodoliths causes a loss of habitat complexity and associated biodiversity, and physical disturbances including massive sediment dislodgement that triggers further death of rhodoliths nearby (Villas-Boas et al., 2014; Figueiredo et al., 2015; Osterloff et al., 2016). The slow growth rates of rhodoliths means their recovery time from harvesting can span centuries to millennia, leading to their classification as a non-renewable resource (Hall-Spencer & Moore, 2000; Barbera et al., 2003). Harvesting, therefore, seriously threatens rhodoliths and other calcified seaweeds, which is exacerbated by the lack of protection of these habitats (Berchez et al., 2022; Paiva et al., 2023).

4.1.3 Fishing and boating

Damaging fishing methods, such as bottom-trawling or dredging, as well as boat moorings and anchoring can severely harm seaweed habitats. Damaging fishing methods and boating cause reduced habitat complexity, or habitat destruction and the creation of large sediment clouds that can smother seaweeds.

Slow growing rhodoliths are particularly susceptible as disturbances result in crushing, fragmentation, and movement of rhodoliths, which reduces habitat complexity and biodiversity (Fig. 13; Tompkins & Steller, 2016; Gabara et al., 2018), and negatively affects their physiological performance (Dolinar et al., 2020).

Globally, nearly 700,000 km^2 of rhodolith suitable habitats are currently being trawled at an overall estimated intensity of ~140,000 days per year (Fig. 14; Fragkopoulou et al., 2021). If management and conservation efforts are not implemented, bottom trawling poses a direct threat to the survival of these rhodolith beds. This is particularly concerning because the majority of trawling activity (60–78%) currently occurs on rhodolith beds that have been identified as climate refugia, primarily in the temperate Northern Atlantic, covering an area of ~ 630,000 km^2 (Fragkopoulou et al., 2021). Future range expansions of rhodolith beds under climate change scenarios (see Section 4.3), will also increase the risk of them moving into heavily trawled regions (Fragkopoulou et al., 2021).

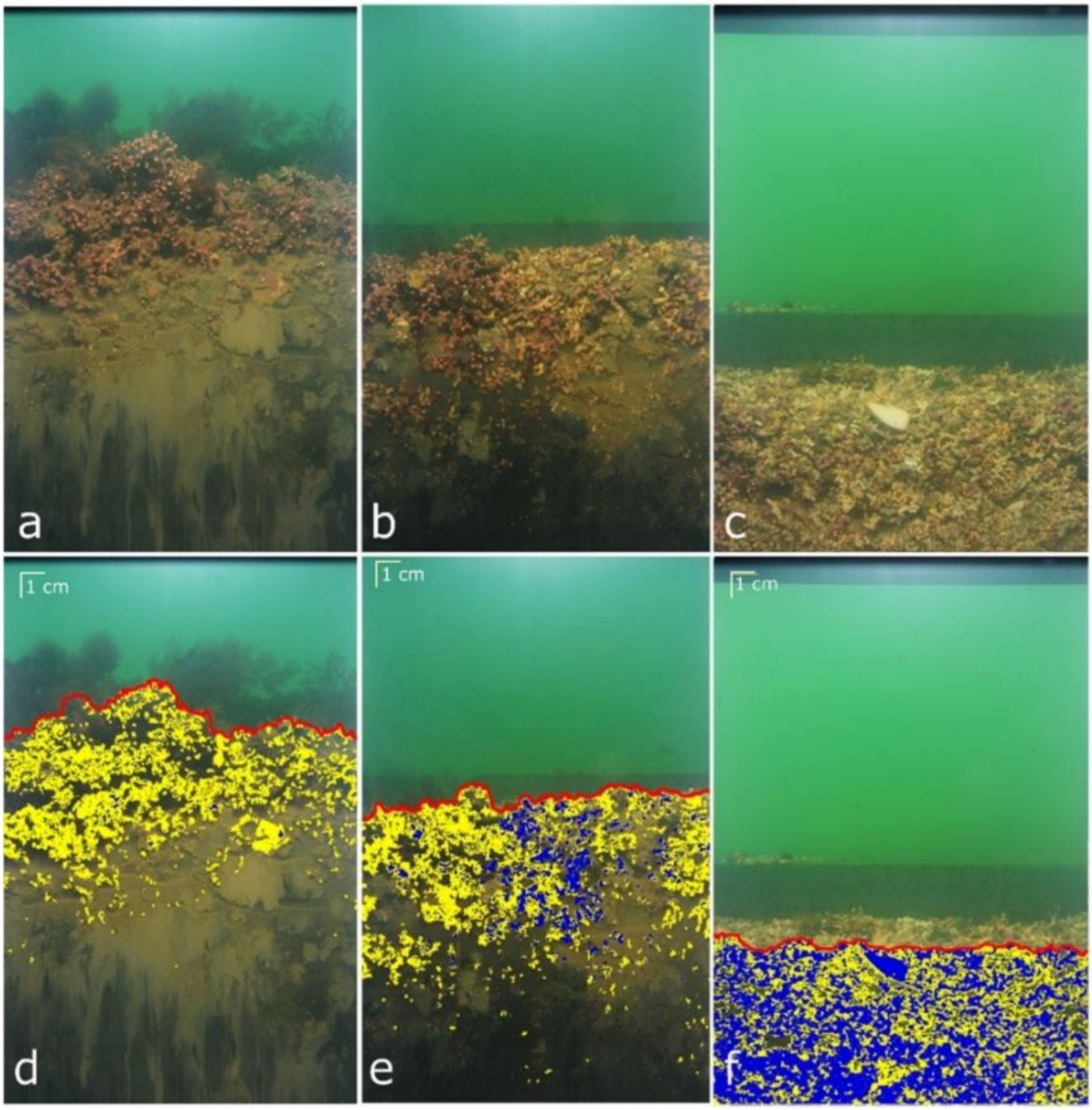


Figure 13. Examples of cross-section photographs of maerl beds under control (**a** and **d**), moderate (**b** and **e**) and high (**c** and **f**) dredging intensity. Red lines in images **d-f** refer to the water-maerl interface, yellow and blue overlays to live and dead maerl, respectively. Source: Bernard et al. (2019), available under a Creative Commons Attribution License 4.0 (CC BY 4.0), no changes have been made.

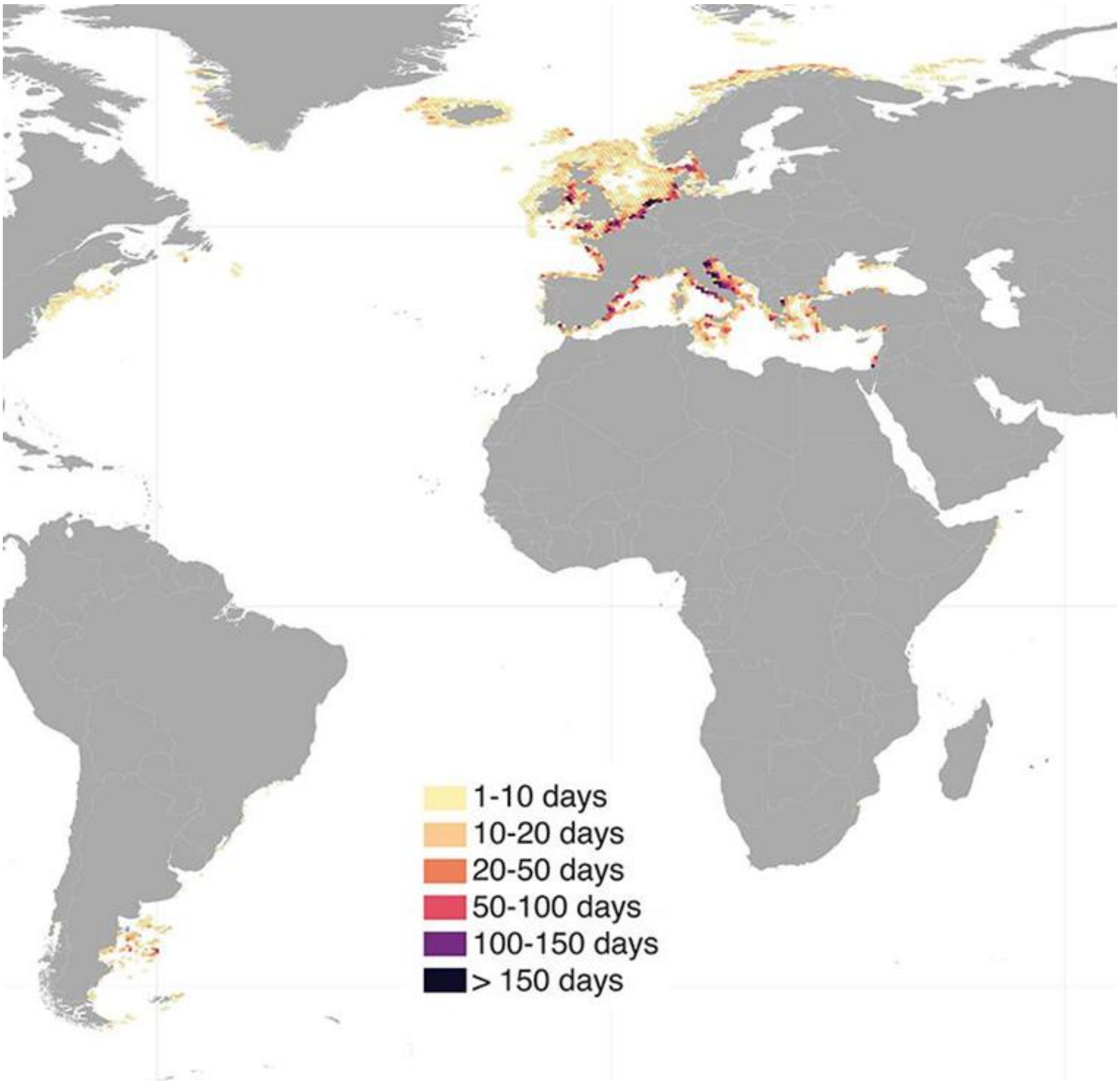


Figure 14. Bottom trawling intensity (days per year) overlaying areas of suitable rhodolith habitat. Adapted from Fragkopoulou et al. (2021), available under a Creative Commons BY license (CC BY 4.0); original has been cropped to focus on impacted areas.

4.1.4 Overfishing and overgrazing

An increase in herbivores that directly consume seaweeds (e.g., urchins, snails, and fish) can leave seaweed habitats overgrazed and even completely destroyed. Increases in herbivory can be due to removal of predators that would naturally control herbivore numbers. For example, hunting and overfishing of sea urchin predators including many commercially important species such as sea otters, cod and lobsters has led to extensive deforestation of kelp forests and the creation of urchin barrens around the world (e.g., North American Pacific (Estes and Palmisano, 1974), Northern Europe, (Norderhaug et al., 2021) and Australia, (Ling et al., 2009a)). Urchin barrens can persist for decades in some regions and can be difficult to recover from even if the initial causes of increased urchin densities are addressed (Filbee-Dexter & Scheibling 2014; Ling et al., 2015).

Increases in herbivory can also be due to introductions of non-native grazing species to an area or climate-driven range expansions of warm-water herbivores (Vergés et al., 2014a; UNEP, 2023). For instance, in Australia, grazing tropical fish and sea urchins have moved south, causing 60-100% loss of kelp canopies or urchin barrens in some areas (Ling et al., 2009a, 2009b; Bennett et al., 2015b; Vergés et al., 2016). Similar trends are seen in Japan and the Mediterranean (Haraguchi et al. 2009; Nakamura et al. 2013; Vergés et al., 2014b). Overgrazing impacts are compounded by climate change, which can weaken seaweeds, making them more susceptible to damage. Additionally, herbivores graze faster at higher temperatures (Simonson et al., 2015).

4.1.5 Pollution, coastal development and ocean sprawl

Seaweeds are threatened by pollution from multiple sources, which are linked with increasing coastal development and ocean sprawl (the proliferation of coastal and offshore artificial structures). Land-based sources of pollution include nutrient and fertiliser run-off from farming, untreated sewage, oils and heavy metals from industry, and sediment washed from coastal developments and logging (Campbell et al., 2017; Tuya et al., 2023; UNEP; 2023). Ocean-based pollution includes discharges from offshore finfish and shellfish farming, mining, oil and gas exploitation and oil spills (Tuya et al., 2023; UNEP; 2023). These can all cause issues like reductions in water clarity (e.g., through sediment resuspension) that inhibits photosynthesis of seaweeds, or eutrophication, which results in ocean darkening from phytoplankton proliferation and the formation of coastal dead zones (Tuya et al., 2023; UNEP; 2023).

Pollution can also cause organic enrichment, smothering or overgrowth of turf algae that can outcompete other seaweed species and prevent settlement and recruitment of juveniles. Epiphytic growth may also be more severe due to eutrophication, where other seaweeds may grow on host plants such as kelp, increasing drag and reducing photosynthesis and nutrient uptake (Andersen et al., 2011).

The loss of kelps in the northern Mediterranean Sea, Sweden, Denmark, Norway, and South Australia and Russia has been linked to rising coastal nutrient levels, sewage and urban pollution and increased sediment deposition (Filbee-Dexter and Wernberg, 2018). Studies from thirty years ago reported that kelp forests may be able to recover relatively quickly from acute eutrophication and sedimentation (Shaffer & Parks 1994; Tegner et al., 1995) but increasing seawater temperatures may make this less certain (Brodie, J., personal observation). However, if conditions persist, such as in heavily urbanised areas of coastal development, kelp forests will continue to be lost globally, as has been reported in California (Foster & Schiel 2010), Norway (Moy & Christie 2012), Australia (Coleman et al., 2008; Connell et al., 2008) and Brazil (Gorman et al., 2020).

Rhodolith beds are particularly vulnerable to pollution due to their slow growth and regeneration times (Rendina et al., 2022; Tuya et al., 2023). They have been subject to several mass pollution events, such as the 2015 collapse of the Doce River mining dam in Southeast Brazil, the 2010 BP Deepwater Horizon oil spill in the northwest Gulf of Mexico, and the 2019–2020 Brazil oil spill disaster (detailed in Tuya et al., 2023 and the references therein). Studies between 2010 and 2013 reported a dramatic die-off of seaweeds following the Macondo Deepwater Horizon Blowout (Felder et al., 2014), however, dredged dead rhodolith rubble taken to laboratory microcosms appeared to act as seedbanks becoming covered by epi- and endolithic algae.

Increases in coastal development and ocean sprawl are also replacing natural substrates and habitats (e.g. seaweed habitats) directly with hard artificial structures (e.g., ports and harbours, energy infrastructure, aquaculture, coastal defences) (Firth et al., 2016). This is homogenising marine biodiversity and introducing invasive non-native species into new areas (see below) (Firth et al., 2016).

4.1.6 Pests and diseases

An increasing prevalence of pests and diseases in red, green and brown seaweeds, particularly in relation to the seaweed industry, is driving the need for a better understanding of seaweed diseases, including quantitative baseline data on disease identification and progression within seaweeds (Krueger-Hadfield et al., in press). Whilst the focus has been on pests and diseases in farmed seaweeds (e.g., Ward et al., 2020, 2022), there has been less emphasis on wild seaweed populations (Brodie, 2024; Murúa et al, 2024). There is also the need to distinguish what has been assumed to be a pathogen (Murúa et al., 2023) and what is part of the holobiont (Saha et al., 2024) or part of the natural life history of a seaweed species in the wild (Brodie, 2024). The increasing demand for seaweed products coupled with an increase in pests such as epiphytic filamentous algae (EFA) and diseases such as “ice-ice” disease (IID) is exacerbating problems which are already compounded by a range of environmental factors (Faisan et al., 2021, 2024; see also Chapter 4).

Pathogens, such as bacteria, viruses, fungi and water moulds (oomycetes) are typically introduced unintentionally through natural pathways (e.g., currents, hitch-hiking on rafting species) or poor biosecurity practices and can lead to tissue decay, reduced growth rates, and mortality. This can be devastating for wild populations and seaweed farms alike and increasing climate change effects and pollution are likely to increase pathogen virulence in the future (Campbell et al., 2012; Qiu et al., 2019). For example, the *Porphyra/Pyropia* (nori) industry that is worth US$1.5 billion globally has been estimated to lose on average 10% of annual production due primarily to oomycete pathogens *Olpidiopsis* spp. and *Pythium* spp. in Japan and Korea (Gachon et al., 2010 and references therein).

Year-on-year declines in global eucheumatoid seaweed production volumes have been reported since 2015 (Hatch, 2024). In the 3 years between 2018 and 2021, eucheumatoid production dropped from 12 million tonnes to 9 million tonnes globally (Figure 15, FAO 2022). A survey by Hatch Innovation Services in 2022 revealed that farmers across seven major eucheumatoid producing regions repeatedly reported harvesting only half of their previous yields (Hatch, 2024). In the United Republic of Tanzania, where most of Africa’s eucheumatoid seaweed farming is based, production fell dramatically from 180 thousand tons in 2015 to 80 thousand tons in 2021 (UNCTAD, 2024). This drop in production is mainly due to disease and pest outbreaks, low biosecurity standards, and the low prices paid to farmers, which remain major constraints on the development of this industry in the region (Word Bank, 2023; UNCTAD, 2024).

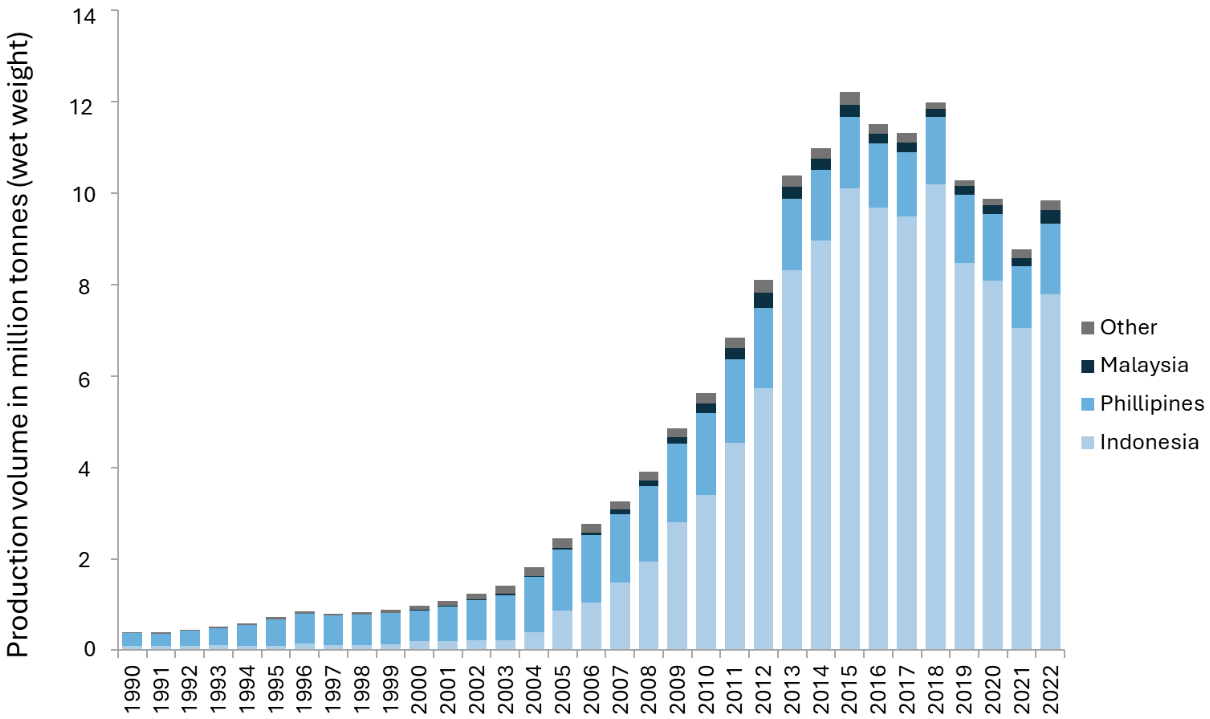


Figure 15. Global production volumes for eucheumatoids 1990-2022 based on 2022 figures provided by FAO Fisheries and Aquaculture (volume in tonnes wet weight) Source data: FAO 2024, FishStat: Global aquaculture production 1950-2022 in: FishStatJ. Available at www.fao.org/fishery/en/statistics/software/fishstatj (accessed 14/02/25) under a Creative Commons licence (CC BY 4.0).

The IID in tropical red *Kappaphycus* and *Eucheuma* species, which results in the whitening and hardening of tissues, has had a particularly severe impact on seaweed health (Ward et al., 2022) across Southeast Asia. In this region, seaweed farms have been completely shut down due to outbreaks of this disease, with the production of eucheumatoid seaweeds in Malaysia declining from 330 to 170 thousand tonnes (wet weight) between 2012 to 2018 (DOFM 2020, FAO 2020). Biosecurity measures, including regular monitoring and cleaning can be used to control outbreaks of IID and pests in farms (e.g., Kambey et al., 2021). Minimising the multiple environmental stressors, however, including fluctuations in temperature, salinity and nutrient concentrations that trigger IID, will be key to avoid further losses in the future.

Although major disease outbreaks are less common in wild seaweeds, they are an increasing threat, with viral infections of golden kelp (*E. radiata*) causing die-offs in New Zealand (Cole & Babcock 1996; Easton et al., 1997; Beattie et al., 2018). In Europe, wild kelp populations have suffered severe reductions in kelp growth and survivorship attributed to oomycete (water moulds) infections (Eggert et al., 2010), although a wide range of endophytes (a plant or fungus that lives inside another plant) are found in large brown algae (e.g. Bjorbækmoet al., 2023) which makes it difficult to distinguish correlation from causation. Coralline seaweeds have also experienced disease outbreaks, for example in the 1990s coralline lethal orange disease (CLOD) infected Pacific coral regions with potentially severe knock-on effects on coral reef ecology and reef-building processes (Littler & Littler, 1995).

4.1.7 Invasive non-native species

Non-native species are those that are introduced intentionally or unintentionally by anthropogenic means and established outside their native range (Blackburn et al., 2011). Some of these introduced species are invasive and known as invasive non-native species (INNS). The rate at which introductions of non-native algae and the spread of INNS are increasing around the world (e.g., Brodie et al., 2014). For example, at the country level, in 2016, c. 5% of the seaweeds were non-native in Britain (Brodie et al., 2016). By 2022, the number had increased to c. 6% (Brodie et al., 2023). In the Northeast Atlantic, Mediterranean and Macaronesia, 140 non-indigenous seaweed species have been recorded (van der Loos et al., 2023), although not all of these are invasive species. The numbers of invasive seaweed species in the more remote parts of the world are difficult to determine given the challenges of accessing these places and high levels of cryptic species in the seaweeds, requiring the use of molecular methods to determine species. The discovery in South Georgia of the green seaweed *Ulva fenestrata*, was the first record of a non-native, potentially invasive seaweed from this remote island in the Southern Ocean (Mrowicki & Brodie, 2023). Introductions of INNS can be devastating, causing severe social, economic, cultural, and environmental impacts that affect livelihoods, biodiversity, and ecosystem services (Blackburn et al., 2019; Linders et al., 2020; Pyšek et al., 2020).

In relation to threats to native seaweeds, a number of invasive invertebrates have been shown to overgraze seaweed habitats or affect growth and survivability. For example, in France, the invasive gastropod *Crepidula fornicata*, has been shown to smother and kill rhodoliths (Grall & Hall-Spencer, 2003). Similarly, in the North-West Atlantic, the introduction of the invasive bryozoan *Membranipora membranacea* has covered kelp blades, decreasing their growth, reproductive output and increasing mortality rates (Saunders et al., 2010).

Invasive non-native seaweed species, *Sargassum muticum* and *Undaria pinnatifida*, have also had a significant negative impact on natural kelp forests in Europe through their rapid growth and recruitment rates (Stæhr et al., 2000; Cosson, 1999; Epstein, Foggo & Smale 2019). Likewise, kelp forests in North America are threatened by expanding populations of invasive turf algae (Dijkstra et al., 2017) and the invasive non-native filamentous red algae *Womersleyella setacea* and *Acrothamnion preissii* have also smothered rhodolith beds in the Mediterranean (Ferrer et al., 1994; Sciberras & Schembri, 2007).

4.2 Changes to seaweed distribution patterns

Seaweed habitats are facing dramatic changes in their distribution and diversity globally, but these changes vary regionally depending on seaweed species and their ability to adapt. This has resulted in range shifts, with some species moving poleward, or local extinctions, where species cannot adapt or relocate to other suitable areas. Range expansions have also occurred, as in the case of the nuisance blooming or rafting species. The distribution of kelp species is generally the best understood compared with other seaweed species, due to an emerging global effort to determine their distribution and health status, although large knowledge gaps remain in this respect (Eger et al., 2024c).

4.2.1 Kelp forests

Kelp forests are amongst the fastest declining coastal ecosystems on the planet (Fig. 16) (Krumhansl et al., 2016; Feehan et al., 2021). Over 10,000 km^2 of kelp forests are currently considered to be in a degraded state, and millions of hectares of kelp forests have been lost globally (Rogers-Bennett & Catton, 2019; Filbee-Dexter et al., 2022b; UNEP, 2023). Global kelp abundance has been estimated to decline by ~2% per year (Wernberg et al., 2019; Krumhansl et al., 2016; UNEP, 2023), however more recent data and updated estimates are needed to determine if this rate is changing.

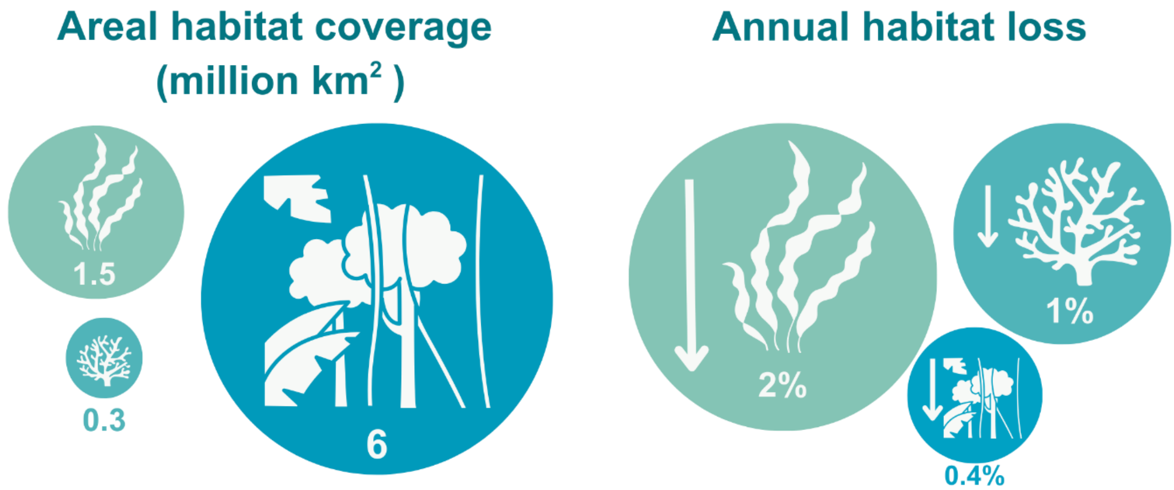


Figure 16. Global areal habitat coverage and annual habitat loss of kelp forests compared to the Amazon rainforest and coral reefs. Kelp forests cover an ocean area five times greater than all coral reefs and a quarter the size of the Amazon rainforest, however they are declining at an annual rate two times that of coral reefs and more than four times that of rainforests. Adapted from Feehan et al. (2021) and Filbee-Dexter et al. (2022b).

Over the past 50 years, kelp forests have declined in 38% of the regions for which there are sufficient data for analysis, compared to increases in 27% of regions, with the remaining regions showing no detectable change (Figs 17 and 18; Krumhansl et al., 2016). However, 66% of the bioregions which feature kelp forests have no time series data, so it is not possible to track their status (Mieszkowska et al., 2006; Krumhansl et al., 2016).

Some regions though are facing particularly drastic declines (e.g., Box 10 - on California). For example, in 2011, a severe marine heatwave hit Western Australia causing over 40% of kelp forests to be lost, with a range contraction of ~100 km, which has yet to recover over 10 years later (Smale & Wernberg 2013; Wernberg et al., 2016; Wernberg 2021). In contrast, other regions have remained relatively stable or even increased their distribution (Figs 17 and 18; Smale, 2020; Smith et al., 2023), such as cooler areas where kelp forests have remained largely unimpacted (Wernberg et al., 2013, 2016). Long term declines in kelp forests, however, have been seen in Nova Scotia, the Gulf of Maine, North-Central California, Norway, Ireland, and South Australia, where some of the longest available time series data of kelp forests exist (Wernberg et al., 2019). Losses are mostly linked to climate change, particularly ocean warming and marine heatwaves (see Section 4.1.1).

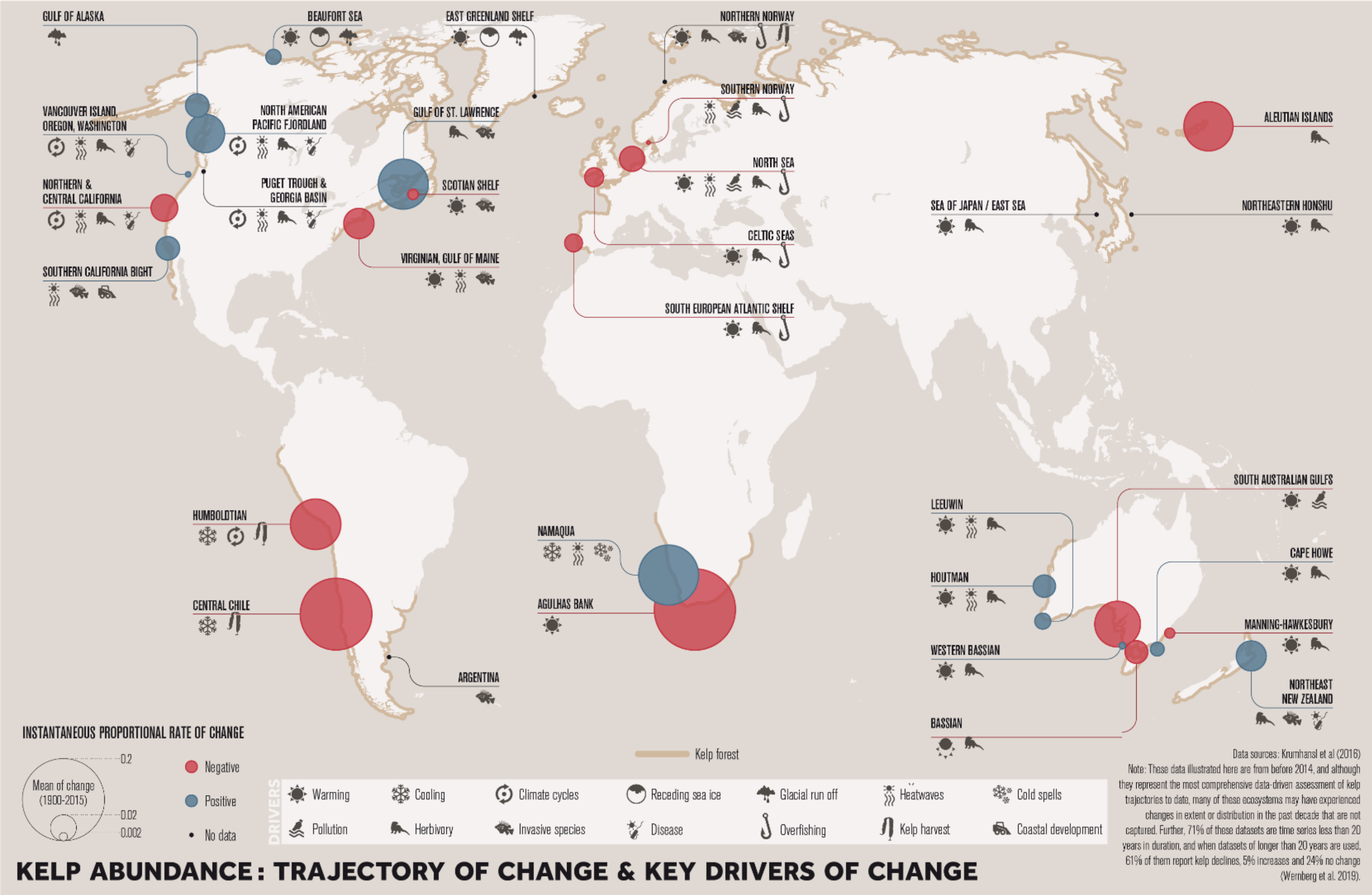


Figure 17. Trajectory of change in kelp abundance and key drivers of change, by ecoregion globally. Source: Grid Arendal for UNEP (2024) adapted from Wernberg et al. (2019). Data sources: Krumhansl et al., 2016. Note, these data illustrated here are from before 2014, and although the represent the most comprehensive data-driven assessment of kelp trajectories to date, many of these ecosystems may have experienced changes in extent or distribution in the past decade that are not captured. Further, 71% of these datasets are time series less than 20 years in duration, and when datasets of longer than 20 years are used, 61% of them report kelp declines, 5% increases and 24% no change (Wernberg et al., 2019). To view a larger version of this figure, please visit: https://www.grida.no/resources/15763.

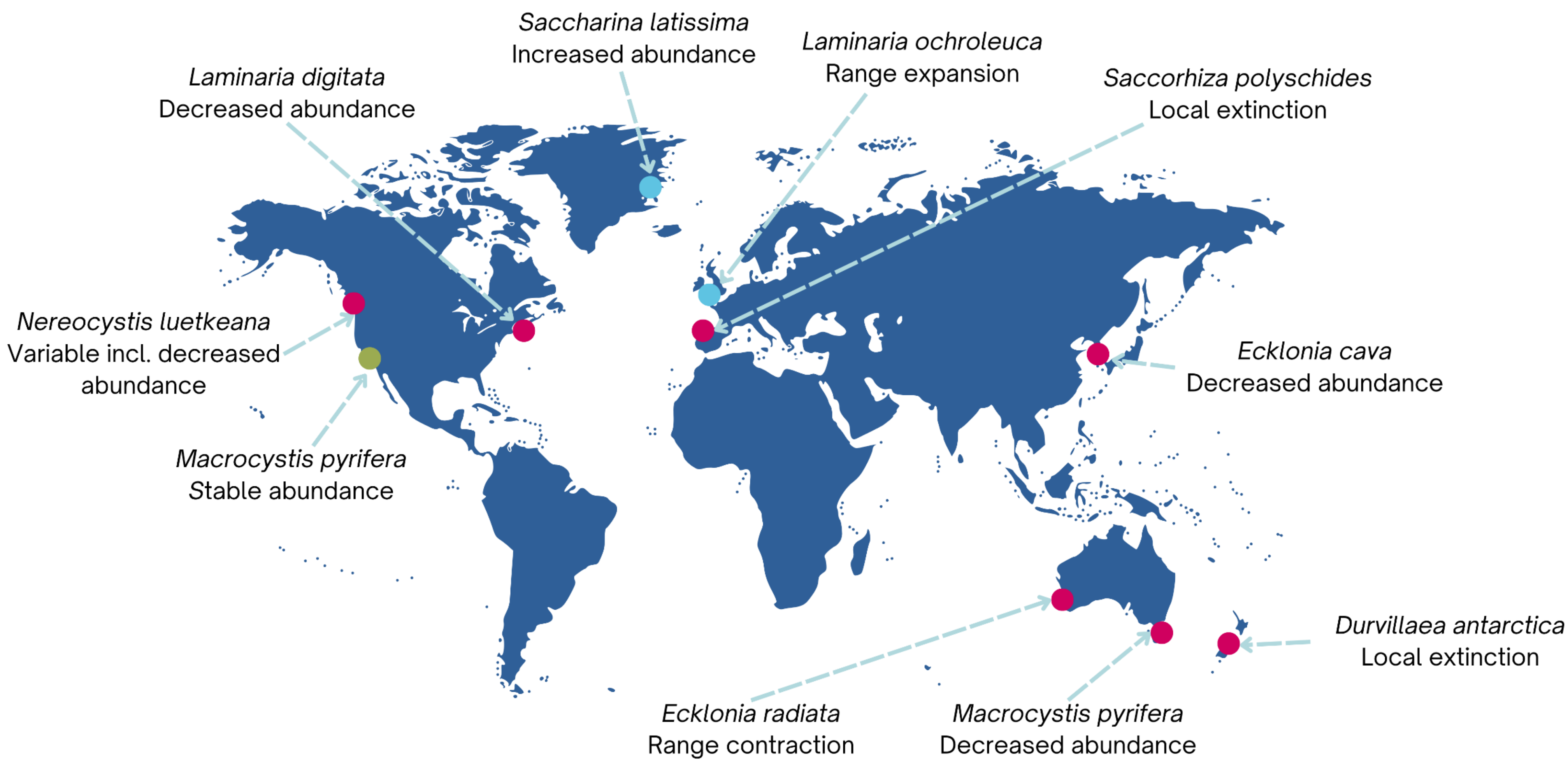


Figure18. Recent examples of responses of kelp populations and ecosystems to ocean warming. Examples represent a range of species, responses and regions, not a comprehensive analysis of recent responses. Adapted from Smale (2020).

Box 10. Marine heatwaves cause substantial socioeconomic losses of kelps in California

The most dramatic decline in seaweed habitat coverage due to a marine heatwave called 'the Blob', occurred in Northern California in 2014-2016. This marine heatwave, along with other stressors, such as overgrazing by urchins, resulted in reductions of bull kelp canopy of over 90% along more than 350 km of coastline (Rogers-Bennett & Catton, 2019; McPherson et al., 2019). This decline severely impacted many ecosystem services, including reductions in commercial kelp harvesting and alginate production and declines in recreation and tourism, including the closure of a recreational abalone fishery valued at US$44 and the collapse of the north coast commercial red sea urchin fishery worth US$3M. The impact of the marine heatwave was made worse by increased herbivory from urchin population booms, that resulted from the mass mortality of sea stars from wasting disease, which is also linked to warming (Rogers-Bennett & Catton, 2019).

Kelp forests further south in Baja California are also suffering massive declines as rising temperatures are exceeding the thermal optimum of the kelps (Arafeh-Dalmau et al., 2019; Edwards, 2019).

Figure 19. Satellite images show the dramatic reduction from 2008 to 2019 in the area covered by kelp forests (gold) off the coast of Mendocino and Sonoma Counties in Northern California. Source: Stephens,2021 (https://news.ucsc.edu/2021/03/kelp-forests-norcal.html, accessed 24/05/25) original images by Meredith McPherson.

Some kelp forests have shown signs of recovery, however, following the removal of the threat(s). For example, after restrictions were placed on hunting sea otters in Alaska, kelp began to recover due to increased predation on urchins, which had been left to overgraze hundreds of kilometres of kelp forests (Estes & Palmisano, 1974; Watson & Estes, 2011). This persistence and recovery indicate the resilience of some kelp species, and in some cases the consequence of effective ecosystem management where recovery is taking place (Wernberg et al., 2019). However, recovery is not always possible, if surviving populations become too small to successfully repopulate an area or if the area has "shifted to a new state" with different seaweed species (See Box 11). Gains of kelps in some areas may also be linked to range shifts of seaweeds moving into new areas (Wernberg et al., 2019; see Section 4.3.1).

Box 11. Shifts to new states

Over the past few decades, kelps and other large brown seaweeds in many regions have been replaced by urchin barrens, turf algae and/or encrusting coralline algae following stress events. These shifts can cover tens to hundreds of kilometres of coastlines and reduce habitat complexity and ecosystem services in these areas (Wernberg et al., 2019). For instance, in Norway, between 2002 and 2011, sugar kelp (*Saccharina latissima*) forests were lost or severely reduced at nearly 60% of monitored sites and replaced by turf algae with limited habitat complexity and this was attributed to eutrophication and climate change (Moy & Christie, 2012).

4.2.2 Green and red seaweeds

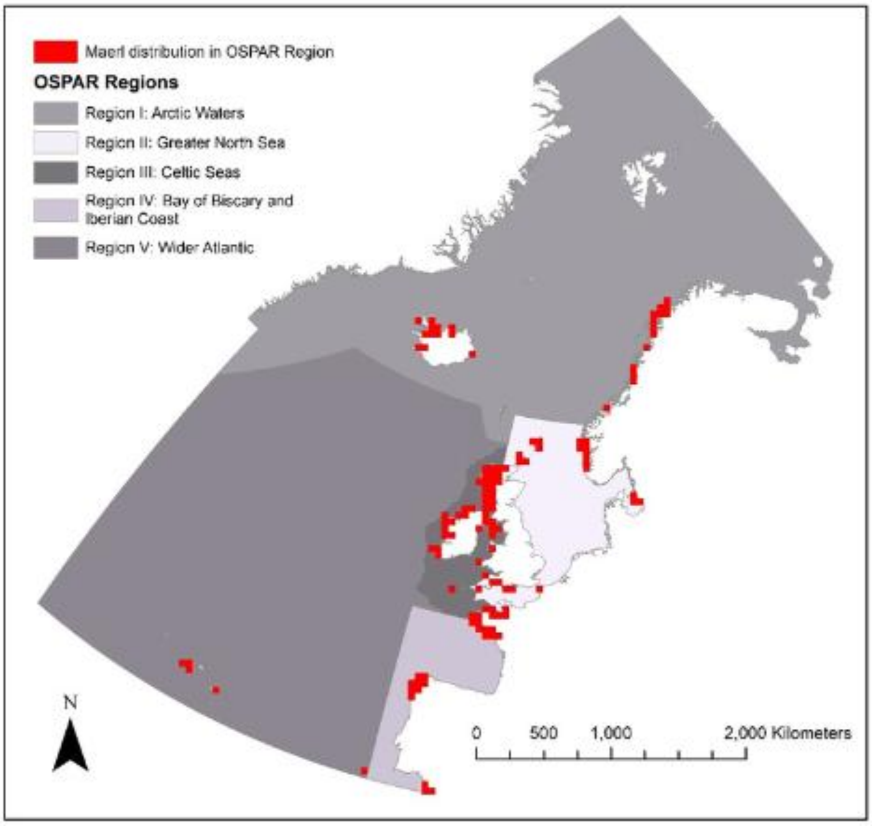
With limited estimates of the global coverage or very few long-term monitoring projects existing for green and red seaweeds, it is challenging to quantify global changes or declines in these groups. For instance, no comprehensive global assessments of rhodolith beds have been carried out to date, despite their recognised importance and susceptibility to threats (Tuya et al., 2023), although some regional assessments have been conducted (Box 12). Similarly, no baseline assessments on the status of tropical red species have been carried out, despite their vital importance in supporting the seaweed industry in many developing countries (Cottier-Cook et al., 2023).

However, changes and losses due to anthropogenic pressures and changing environmental conditions have been documented in several seaweed habitats worldwide, including local extinctions. For example, the green calcareous seaweed *Halimeda tuna*, has completely disappeared from areas of the Mediterranean, where it was commonly found in the 1970s and 1990s, most probably as a consequence of stressors related to climate change (Rilov et al., 2020).

Box 12. Rhodolith beds in the OSPAR region

Rhodolith or maerl beds were added to the OSPAR List in 2004, however their full extent in this region is still unknown. Declines in condition, distribution and extent of rhodolith beds have occurred in the Celtic Seas region (where they are listed as threatened) and in parts of the Greater North Sea and the Bay of Biscay and Iberian Coast regions (Fig. 20). While the extent of rhodolith beds in Ireland has remained the same, the quality of the beds has declined (Fig. 20).

Rhodolith bed condition is currently assessed as good in the Norwegian part of Arctic Waters, but its extent is thought to have decreased by < 20% over 50 years (1968-2018) (Gundersen et al., 2018). It is not possible to determine the trends in condition and extent of these beds since their last status assessment in 2010, however, their condition is predicted to decrease by a further < 20% over the next 50 years (2018-2068) due to degradation by biotic factors (Gundersen et al., 2018). See more on future projections below (Section 4.3.2).



Maerl Beds Status		Distribution		Extent		Condition		Assessment of Status
Region*	I	?	4	?	4	?	4	Unknown
	II	?	4	?	4	↓	4	Poor
	III	?	3	↓	3	↓	3	Poor
	IV	⟷	4	↓	4	↓	4	Poor
	V							N/A

Evidence of Current Status*
red - poor
green - good
? - status unknown.
NA - Not Applicable
Trends in status (since the assessmen in the background document)
↓ decreasing trend or deterioration of the criterion assessed
↑ increasing trend or improvement in the criterion assessed
⟷ decline or deterioration of the criterion has been halted

Figure 20. Distribution of 50 km squares containing maerl beds in the OSPAR maritime area, based on OSPAR T&D database (2018) and Article 17 data on *Lithothamnion corallioides* and *Phymatolithon calcareum* distribution from Spain. Source: OSPAR Commission (sheet reference: POSH2019/Maerl_Beds_OSPAR) available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

4.2.3 Nuisance species

Nuisance seaweed species are defined as those that form usually large scale, ephemeral events, often involving monospecific blooms or rafts of indigenous species that grow rapidly (Joniver et al., 2021, and references therein). Green (Chlorophyta), red (Rhodophyta) and brown (Phaeophyceae) taxa are all known to form extensive blooms or rafts, the former often referred to as green, red or golden tides due to their colour and nature of arrival and departure.

In some areas of the world, due to changes in ocean currents and increases in nutrient loads and ocean temperatures, certain nuisance seaweed species are becoming more prevalent and hazardous. Green tides and extensive *Sargassum* rafts are plaguing coastlines around the world, causing significant damage to local economies and the environment. For instance, since 2011, *Sargassum* inundation events have been increasingly wreaking havoc on the shorelines and tourist industries of the tropical Atlantic, Caribbean, and Gulf of Mexico with over 20 million tons of biomass beached in a year (US EPA, 2023). This has led to substantial revenue losses for businesses and local governments as cleanup and remediation efforts can cost up to US$25,000 a day (George, 2022). In 2018, the Caribbean faced an estimated US$120 million cleanup cost, while annually in Miami-Dade County, Florida, removal and disposal of *Sargassum* costs US$35 million. In 2022, the U.S. Virgin Islands declared a state of emergency as excessive accumulation of *Sargassum* obstructed the water intake of a desalination plant, which subsequently struggled to produce sufficient water to meet the demands of the area during a prevailing drought (US EPA, 2023).

Rotting seaweeds cast on the beach can also be an unsightly nuisance that attracts sand flies, produces foul smells, and poses danger to lives through harbouring dangerous pathogens (e.g., *Vibrio* bacteria) and producing noxious gases (e.g., hydrogen sulphide) as seaweeds decompose. In Brittany, France, previous tourist destinations have become overwhelmed with decomposing tides of green seaweeds that are linked to excessive agricultural runoff and pose serious threats to human and animal health, including death (Schreyers et al., 2021).

These extensive blooms can be tracked using satellites from space (Wang et al., 2019; Schreyers et al., 2021). For instance, scientists from NASA Earth Observatory and the University of South Florida have been using satellites over the past decade to track the *Sargassum* rafts and better understand the factors that contribute to their formation (Fig. 21; Wang et al., 2019). This informs predictions on the size and trajectory of this huge volume of *Sargassum*.

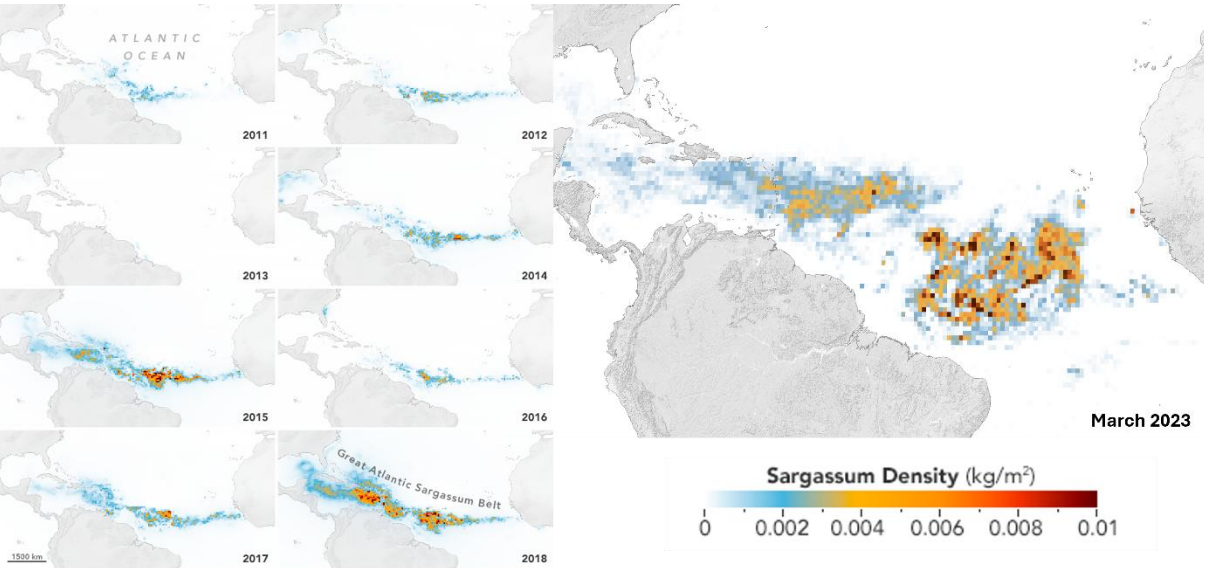


Figure 21. NASA Earth Observatory images of the "Great Atlantic *Sargassum* Belt" each year from 2011 to 2023 by Lauren Dauphin and Joshua Stevens, using MODIS satellite data courtesy of Brian Barnes at the University of South Florida (USF), Optical Oceanography Lab and Wang et al. (2019). Source: NASA, Available: https://earthobservatory.nasa.gov/images/151188/a-massive-seaweed-bloom-in-the-atlantic

4.3 Range shifts and future projections

The majority of seaweeds are predicted to experience a high degree of local extinction and poleward expansions by the end of the century, with overall global declines in coverage and diversity. Given the foundational role of seaweed habitats in marine ecosystems, the projected declines will have severe effects on associated biodiversity, ecosystem functioning and the ecosystem services they provide. However, range shifts will vary between species and populations depending on their adaptability.

4.3.1 Range shifts

The climate crisis is causing species redistribution globally. Ocean warming is driving some seaweed species poleward, dependent on the existence of suitable coastlines and environmental factors like salinity, productivity, light, water quality, and local stressors.

These shifts are changing seaweed community composition and diversity, with losses in tropical regions where species are near their thermal limits and gains to some species in cooler polar regions as reduced sea-ice cover creates new habitats (see Box 13) or as they capitalise on increasing anthropogenically-induced eutrophication in some coastal areas. However, even as seaweeds expand toward the poles, they remain vulnerable to marine heatwaves and other anthropogenic threats, and not all Arctic species are expected to survive (Box 13; Fig. 22). Moreover, this redistribution will alter patterns of biodiversity, disrupt important ecosystem services and cause a separation between humans that rely on seaweeds and their future distributions. For example, seaweed harvesters or farmers may no longer be able to harvest or cultivate seaweeds in their local regions if temperatures become too high.

Range shifts are also species- and population-dependent. For example, poleward shifts have already been recorded around the world for kelp species, which typically have relatively short generation time and widespread dispersal (Smale, 2020). In contrast, minimal shifts in calcified red coralline algae species are expected due to their slow growth rates and limited dispersal abilities (Brodie et al., 2014). Within species, some populations may be more adaptable than others to the increasing threats they face.

Some calcified red coralline algae may have a limited potential for adaptation to changing conditions, but there is little evidence on their population dynamics and sexual reproduction to inform whether this will be quick enough given the rate of climate change (Pardo et al., 2019; Simon-Nutbrown et al., 2020). In tropical waters, coralline algae with a short generation time (6 to 8 weeks) can develop resistance to ocean acidification over multiple generations (Cornwall et al., 2020). However, Arctic species, with their longer generation time, likely lack the time or capacity to acclimatise, risking their possible disappearance this century (IPCC, 2007; Büdenbender et al., 2011;

Lebrun et al., 2022). Similarly, rhodoliths have experienced a variable response to marine heatwaves, with negative effects reported in subtropical and temperate regions (Schubert et al., 2019, 2021), whereas subarctic rhodoliths are seemingly resilient to changes in sea temperature over a relatively broad thermal range (Bélanger and Gagnon, 2021). Identifying population strongholds or areas of climate refugia, therefore, should be a priority for increasing the effectiveness of protected areas under future climate change scenarios (see Section 4.3.2).

Box 13. Severe shifts in Arctic seaweeds (adapted from Lebrun et al., 2022)

The Arctic is warming at over twice the global average rate, with projections suggesting that sea surface temperatures could increase by up to 5°C by 2100 (Kwiatkowski et al., 2020). Combined with sea ice loss, increased precipitation, freshwater discharge, ocean acidification, and changes in underwater light, this is drastically altering seaweed habitats' distribution in the Arctic (Lebrun et al. 2022).

Brown seaweeds are expanding into the Arctic, with predictions that kelp and fucoid biomass could double in less than 30 years in Arctic regions (Lebrun et al., 2022; Filbee-Dexter et al., 2019). In Svalbard, the cover and biomass of brown intertidal seaweeds (e.g., *Fucus distichus* and *Laminaria digitata*) have already increased 2-4 times in the past few decades (Weslawski et al., 2010; Hop et al., 2012; Bartsch et al., 2016). Species such as *Saccharina latissima* are likely to thrive due to their genetic diversity and adaptability (Bartsch et al., 2008; Guzinski et al., 2016).

Increases in brown seaweeds will cause shifts in species composition and community structure, reducing sessile invertebrates and suspension feeders and potentially leading to extinctions (Lebrun et al., 2022). For example, in Kongsfjorden, Svalbard, once dominant sea anemones, have decreased by 80% and been replaced by filamentous brown algae (Kortsch et al., 2012). Additionally, some endemic species, such as the kelp *Laminaria solidungula*, are threatened by increasing temperatures, hyposalinity, reductions in light due to glacial melt and turbidity and may be outcompeted by other seaweeds (Müller et al., 2009).

Projections indicate a potential disappearance of coralline algae in the Arctic within 10 to 30 years due to warming and increased ocean acidification, which is intensified in polar regions (IPCC, 2007; Büdenbender et al., 2011). Changes in sediment dynamics and increased sediment resuspension due to decreased ice cover are also reducing the distribution of rhodolith beds, as currently seen in Svalbard (Teichert et al., 2014) and increased competition for space with kelps will also further their declines.

Overall, the changes in seaweed communities in the Arctic are having severe implications for biodiversity, ecosystem functions and Arctic marine health.

Box 13. ***Continued***

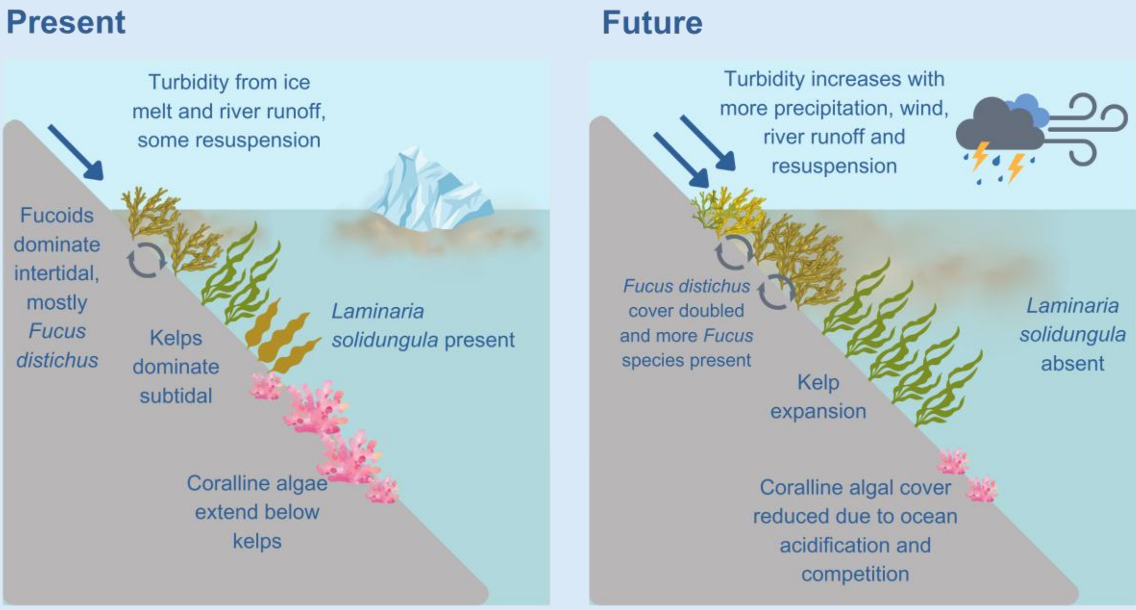


Figure 22. Schematic of the present and expected future Arctic coastal macroalgae communities due to predicted changing environmental conditions. Adapted from Lebrun et al. (2022).

4.3.2 Future projections

In contrast to predictions for many terrestrial or other marine species, there are no comprehensive, global-scale models of the future distribution of all seaweed habitats under different climate change scenarios. Several studies have recently projected the distributions of certain seaweed habitats under future scenarios however, with significant declines in the global diversity and distribution of seaweeds predicted by the end of the century, these vary significantly with latitude and region.

Brown seaweeds

Under both intermediate and worst-case emissions scenarios, it is estimated that there will be an 80% decline globally in the availability of highly suitable habitat for brown seaweeds, including kelps by the end of the century (Manca et al., 2024). Brown seaweeds, including kelps are, therefore, expected to lose a large proportion of their present extent (6-11%) and species diversity (6%) by 2100, which will be barely compensated by expansions into new, suitable areas like the Arctic (Manca et al., 2024). Losses in coverage and diversity will vary regionally according to differences in suitable remaining habitat and the disproportional effects of climate change in some locations (Figs 23, 24).

In Australia, kelp forests are predicted to lose over 70% of their current distribution by 2100 (under the IPCC Representative Concentration Pathway (RCP) 6.0 carbon dioxide emission scenario), with major poleward shifts predicted for 13 of the 15 kelp species (Martínez et al., 2018). Local extinctions of *Macrocystis pyrifera* are also expected in Australia (Martínez et al., 2018). This could be worsened due to additional threats from overharvesting, outbreaks of pests and diseases and other climate-driven impacts.

Similar losses are predicted in Japan, where grazing pressure is modelled to intensify under even the lowest emission scenario (RCP 2.6), and previously suitable habitats are expected to become uninhabitable for *Ecklonia cava* by 2090 under RCP 8.5, causing range contractions of 85% due to intensified warming and grazing (Takao et al., 2015).

In the North Atlantic, eight kelp species are projected to lose 50% of their distribution in regions at their warm range margins by 2100 (under RCP 2.6), with several local extinctions expected under more severe scenarios (RCP 8.5) (Assis et al., 2018). At the same time, range expansions for three of the eight kelp species are predicted at their cool margins, including *S. latissima* expanding into the Arctic and *L. ochroleuca* expanding into southern Europe (Assis et al., 2018).

Models also project an expansion of suitable brown seaweed habitat in the sub-Arctic and Arctic from approximately 3 to 8% by 2100 (Manca et al., 2024), corresponding to pole-wards range shifts (see above). Conversely, models did not predict expansions of seaweed habitat in Antarctica or the Southern Ocean, due to their geographic isolation.

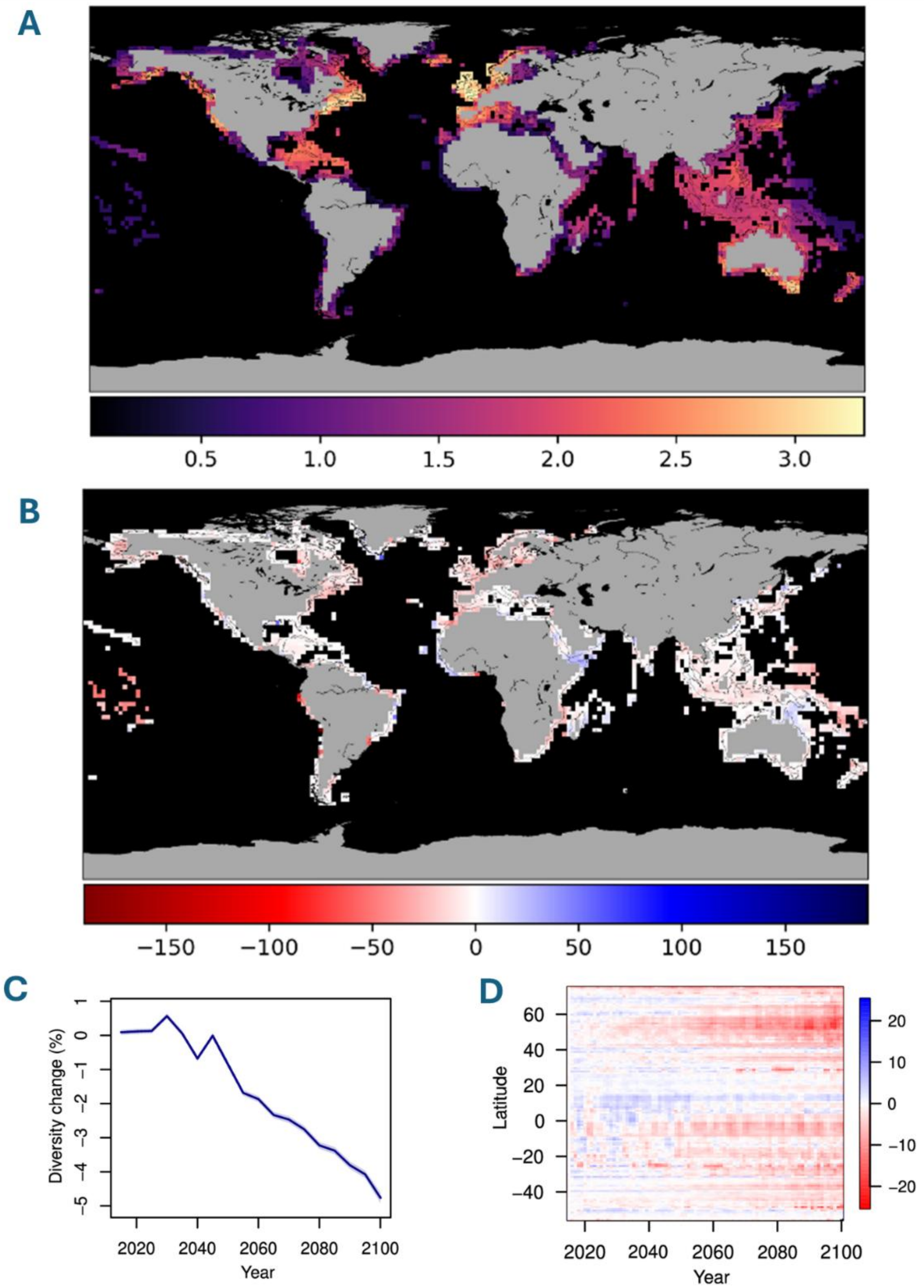


Figure 23. A. Present distribution. **B.** projected end-of-century changes in global brown macroalgal species diversity under an intermediate emissions scenario (SSP3-7.0). **C.** Mean trajectories in local brown macroalgal diversity (i.e., number of macrophyte species in every 0.5° × 0.5° latitude/longitude grid cell) relative to 2015 (data were aggregated at 5-year intervals). **D.** Expected future changes in diversity as loge percentage change relative to 2015 diversity averaged across latitudes (0.5° × 0.5° latitude/longitude resolution). B and D: species diversity gains = blue, losses = red. Adapted from Manca et al., 2024, available under a Creative Commons Attribution License 4.0 (CC BY 4.0), no changes were made to the figures, however they have been compiled into one panel.

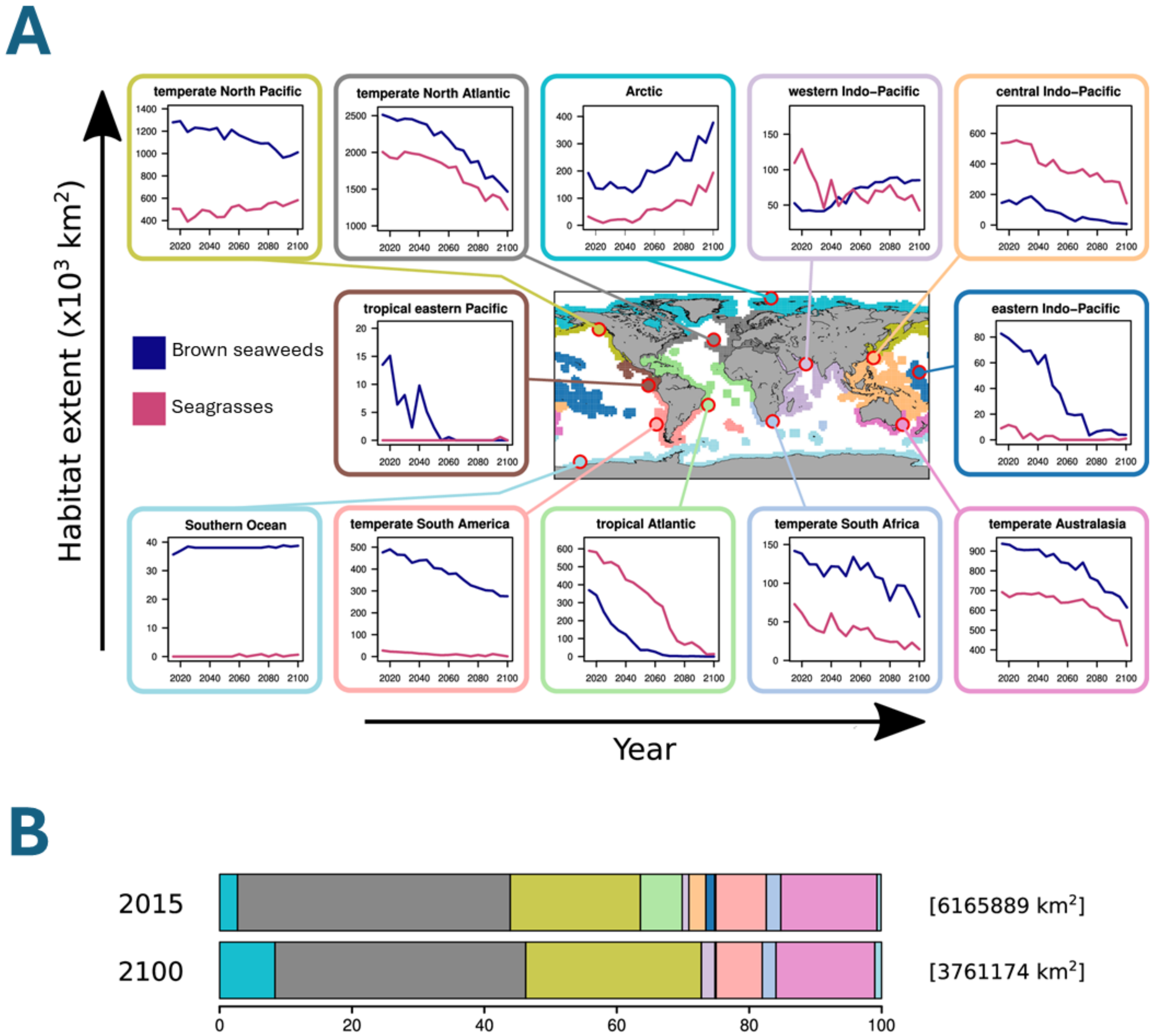


Figure 24. Variation in the extent of suitable brown seaweed and seagrass habitat across marine regions for the IPCC's shared socioeconomic pathways (SSP) emissions scenario SSP3-7.0 for the period 2015–2100. **A.** Variation in habitat extent (km^2) for brown seaweeds (purple) and seagrasses (pink) within each marine region, aggregated every 5 years. **B.** Comparison of the percentage of global suitable habitat in each marine region between 2015 and 2100 for brown seaweeds. Colours refer to marine regions as shown in (a). Square brackets show the total global suitable habitat extent. Adapted from Manca et al. (2024), available under a Creative Commons Attribution License 4.0 (CC BY 4.0), no changes were made to the figures, although the image has been cropped to focus on brown seaweeds. To view a larger version of this figure, please visit: https://www.nature.com/articles/s41467-024-48273-6/figures/4.

Coralline red algae

Models for future coralline red algae distribution, including rhodolith beds, estimate declines in their global area of 26–44% by 2100 depending on the warming scenario (Fig. 25; Fragkopoulou et al., 2021). Declines will be experienced mainly in shallower and tropical regions, including the Eastern and Western Indo-Pacific, which are predicted to lose up to 80% of the suitable habitat for rhodolith beds (Fragkopoulou et al., 2021). Shifts to boreal and deeper areas were estimated to cause ~20–50% range expansion, mostly in the Temperate Northern Pacific (e.g., Japan, Okhotsk and Bering Seas) and the Arctic (e.g., Labrador, Greenland and Norwegian Seas) (Fragkopoulou et al., 2021). Understanding future distributions of rhodolith beds allows future strongholds or climate refugia to be identified, which currently represent up to 75% of the present distribution, mostly located in the temperate regions of Northern Atlantic (~1.1–1.4 million km^2), South America (~350,000 km^2) and Australasia (~220,000–500,000 km^2). Understanding where these refuge areas are located can be used to guide effective protection (Fragkopoulou et al., 2021).

In certain coralline strongholds, such as Scotland, models predict declines in suitable habitat area of up to 84% for rhodolith beds by 2100, with large scale declines in coralline algal distribution observed under all IPCC RCPs and total loss of coralline algae in some areas even under intermediate scenarios (Fig. 27; Simon-Nutbrown et al., 2020). This model could not include any changes due to increased ocean acidification, as datasets do not exist, however given the sensitivity of calcified seaweeds to low pH, this will likely worsen the predicted declines significantly. No habitat that was previously unsuitable for rhodolith beds (present day) became suitable under any of the RCP scenarios (Fig. 26; Simon-Nutbrown et al., 2020). However, refuge populations that persisted under future change were identified (e.g., around the northwest mainland coast of Scotland, the Northern Islands and areas around the inner Moray Firth) (Fig. 27), which should inform priority areas for future conservation efforts to maximise the long-term survival of this globally important ecosystem.

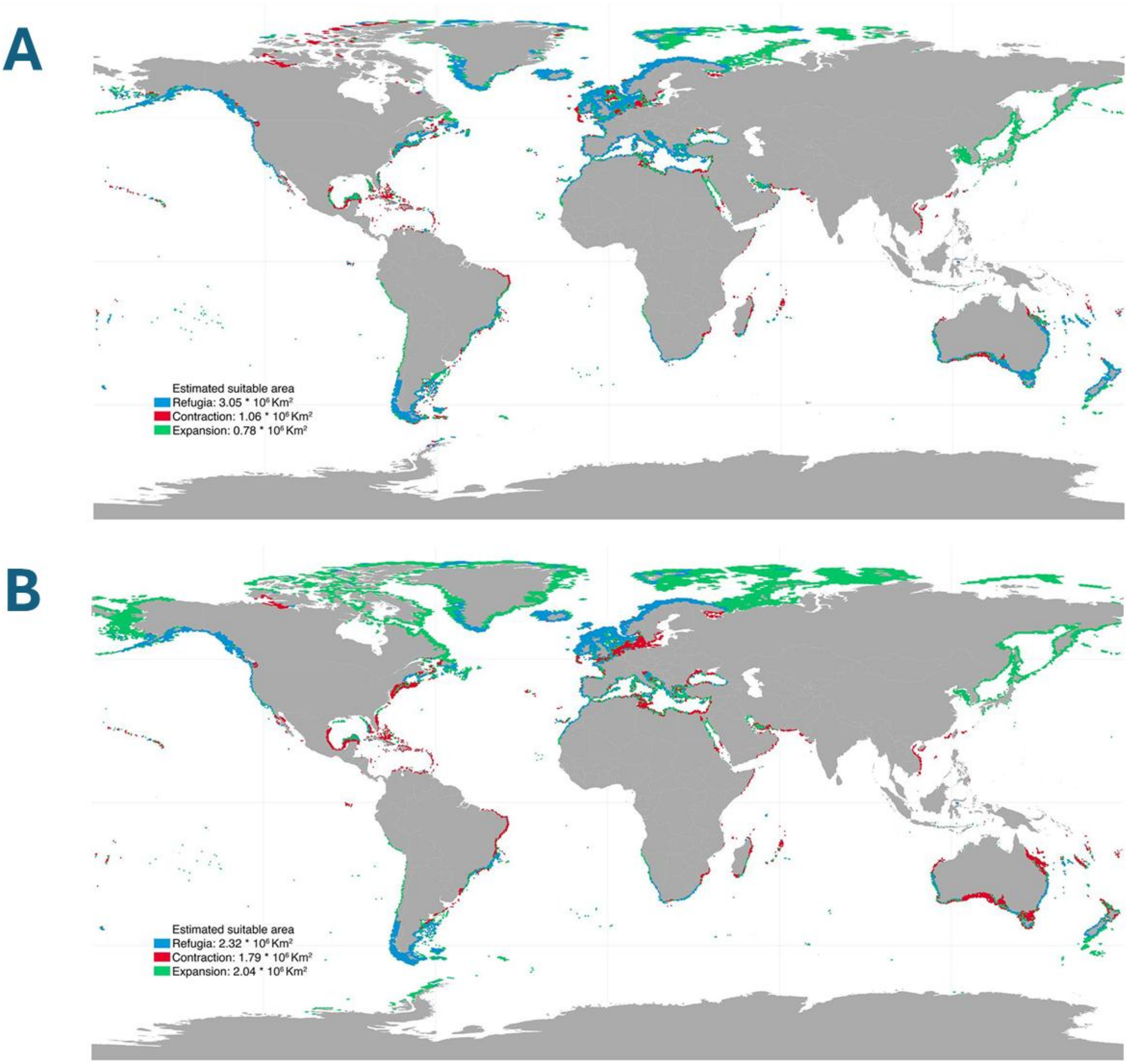


Figure 25. Global projected future distribution for rhodoliths under the IPCC Representative Concentration Pathway (RCP) emission scenarios. **A.** Under RCP 2.6 scenario. **B.** Under RCP 8.5 scenario. Blue, red, and green colours depict regions of refugia, range contraction and range expansion, respectively. Adapted from Fragkopoulou et al. (2021), available under a Creative Commons BY license (CC BY 4.0), no changes made to original maps, although they have been compiled into one panel.

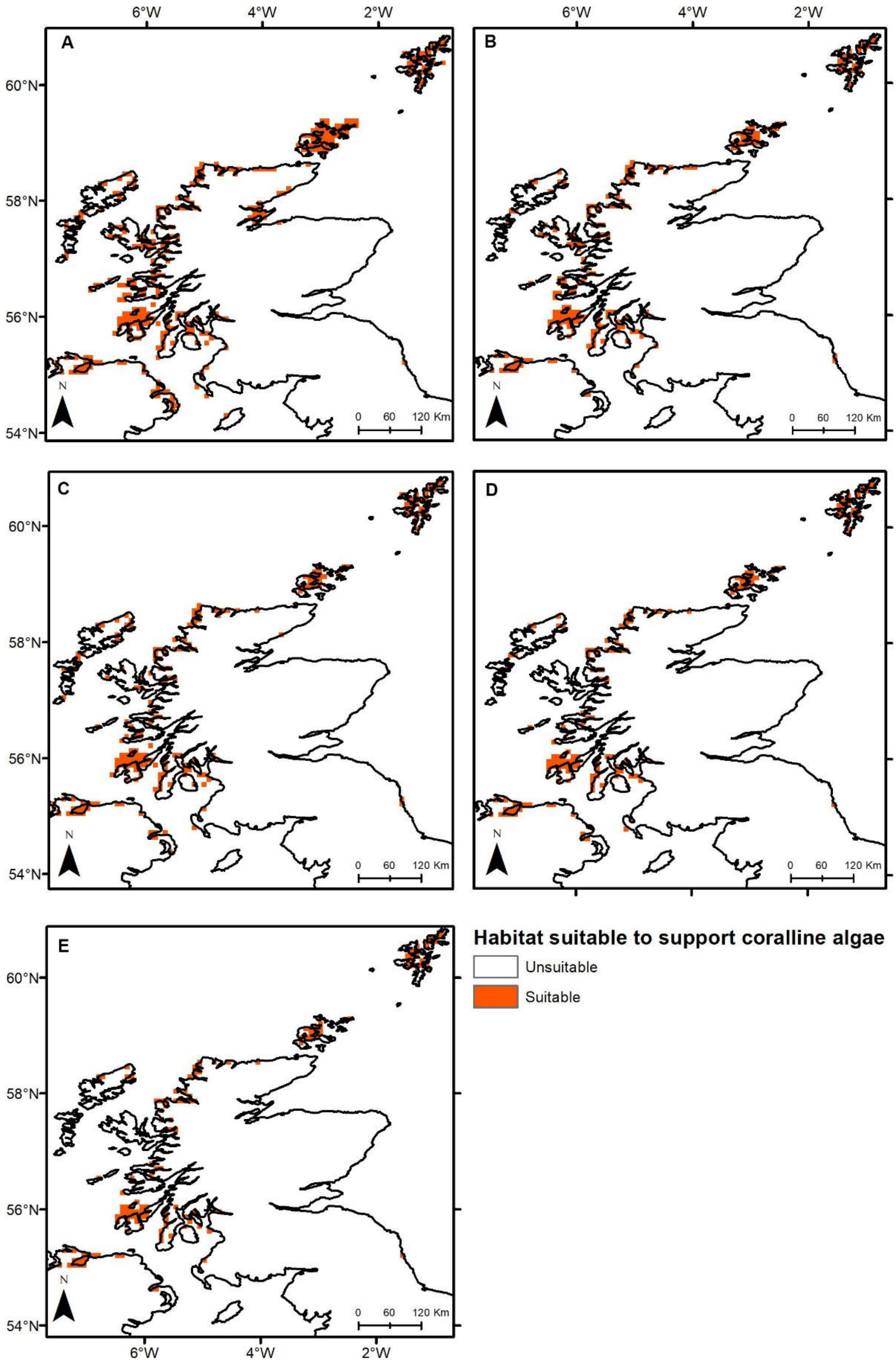


Figure 26. Threshold maps of coralline algal beds distribution around Scotland in the present-day (A) and by 2100 under the IPCC Representative Concentration Pathway (RCP) emission scenarios. (B) RCP 2.6, (C) RCP 4.5, (D) RCP 6.0, and (E) RCP 8.5. Orange indicates predicted presence of coralline algal beds. Source: Simon-Nutbrown et al. (2020), available under a Creative Commons BY license (CC BY 4.0), no changes made.

5. The current state of seaweed protection

Summary: This chapter, which reviews the state of protection of seaweeds and their associated habitats, reveals the patchiness and potential ineffectiveness of protection designations. This includes the extent to which Marine Protected Areas (MPAs) cover seaweed conservation and whether seaweeds are included directly or indirectly, the role of the IUCN and Red Listing, as well as the lack of mention of seaweeds in regional, national and international policies, laws, governance and framework. It also considers how financial incentives in relation to ecosystem services might be a way of building long-term security for the seaweeds.

5.1 Protecting seaweeds

Seaweeds and their associated habitats lack adequate protection in comparison to other marine species and habitats, despite the increasing recognition of their importance (Section 3) and vulnerability to increasing threats (Section 4) globally. This section outlines how seaweeds are currently protected and highlights how they are generally excluded from many protection strategies.

5.1.1 Marine Protected Areas (MPAs)

One of the commonest ways to protect marine species and biodiversity is through the establishment of MPAs that are managed through legal or other effective means. MPAs are typically designed to protect biodiversity, cultural resources, and ecosystem services from different drivers of loss, through prevention of stressors, increasing resistance to stressors or aiding recovery following stressors. However currently, there are almost no MPAs (or equivalent protected areas) designated specifically for protecting seaweeds or their associated habitats, compared to other vegetated marine ecosystems, leaving them less protected (Table 4).

It is estimated that only 16% of kelp forests are found within some form of protected area worldwide, with only 1.6% in highly protected areas (Eger et al., 2024c). There is currently no global figure for the percentage of other seaweed habitats, however, that fall within MPAs (Table 4). A recent meta-analysis of the seaweed industry, however, has found that 50% of seaweed farms and harvesting areas are close to or within protected areas (Brodie et al., in review). A lack of accurate global distribution data for the majority of seaweeds unfortunately limits our ability to calculate a global figure (see Section 2.2). Nevertheless, even when seaweed habitats fall within designated MPA boundaries, they are rarely specifically mentioned or prioritised for protection (Cottier-Cook et al., 2023). Seaweeds are, therefore, mostly indirectly protected due to their proximity to other protected species or local features. For example, rhodolith beds may be protected due to their proximity to other habitats, such as seagrass meadows or coral reefs that do have specific protection. This lack of explicit mention of seaweeds, however, leaves them vulnerable to the specific threats they may face (e.g., overharvesting, trawling) and this fails to incentivise monitoring of their status in MPAs, and other similar protected areas, compared with other species or features that are mentioned explicitly.

Table 4. Coastal and marine ecosystems within marine protected areas (MPAs). Estimated global coverages are based on coarse habitat models. Adapted from UNEP, 2023.

Habitat	Estimated global coverage (million km^2)	Percentage within marine protected areas	References
Seaweed habitat:			
Fucoid forests	2.57	?	Fragkopoulou et al. (2022)
Rhodolith beds	4.12	?	Fragkopoulou et al. (2021)
Kelp forests	1.47	16	Jayathilake & Costello (2020); Eger et al (2024c)
Halimeda meadows, *Caulerpa*, *Padina* and other algae including greens	1.2	?	McNeil et al. (2016); Duarte et al. (2022)
Rhodoliths	0.021–0.23	?	Minimum: Moura et al. (2013) ; maximum: Carvalho et al. (2020)
Seaweed turfs	?	?	
Floating or free-living pelagic seaweeds	0.05	?	Duarte et al. (2022); Wang et al. (2019); Qi et al. (2017); Zhang et al. (2019); Liu et al. (2013a)
Deep water seaweed communities	?	?	
Other vegetated marine habitats:			
Seagrasses	0.32	26	Adapted from United Nations Environment Programme (UNEP) World Conservation Monitoring Centre (WCMC) data: UNEP (2020)
Mangroves	0.15	43	
Saltmarshes	0.05	42	
Cold-water corals	0.02	32	
Warm-water corals	0.15	40	

Furthermore, MPAs may be ineffective to protect seaweed habitats in the first place, if they are unable to address the specific reasons for seaweed decline, lack appropriate enforcement, or prevent seaweed recovery by prohibiting restoration activities from taking place due to strict management strategies (Eger et al., 2022a; Filbee-Dexter et al., 2024a). In a recent perspective from global kelp conservation experts, the authors question whether strengthened global protection in MPAs will create meaningful conservation outcomes for kelp forests, particularly in a changing ocean (Filbee-Dexter et al., 2024a). The effectiveness of MPAs for mitigating the different drivers of loss for kelp forests is summarised in Fig. 27 showing that very limited evidence exists to support the benefit of MPAs to kelp forests due to a lack of long-term monitoring (Filbee-Dexter et al., 2024a). For example, MPAs may be beneficial for addressing local stressors, such as overharvesting and overfishing (if they are enforced as no-take zones). They are unlikely, however, to provide much protection from ocean warming, marine heatwaves, coastal darkening, and pollution, which are major threats to all seaweed habitats that are set to increase in future (see Section 4) (Filbee-Dexter et al., 2024a). MPAs may, however, promote resilience of kelp forests to marine heatwaves by preserving trophic cascades (Kumagai et al., 2024), so it is recommended that MPAs should still be designated to protect seaweed habitats from local stressors, where possible. Nevertheless, additional measures to tackle threats directly and actively promote recovery may be required to ensure degraded seaweed habitats can recover and become more resilient (see Section 6).

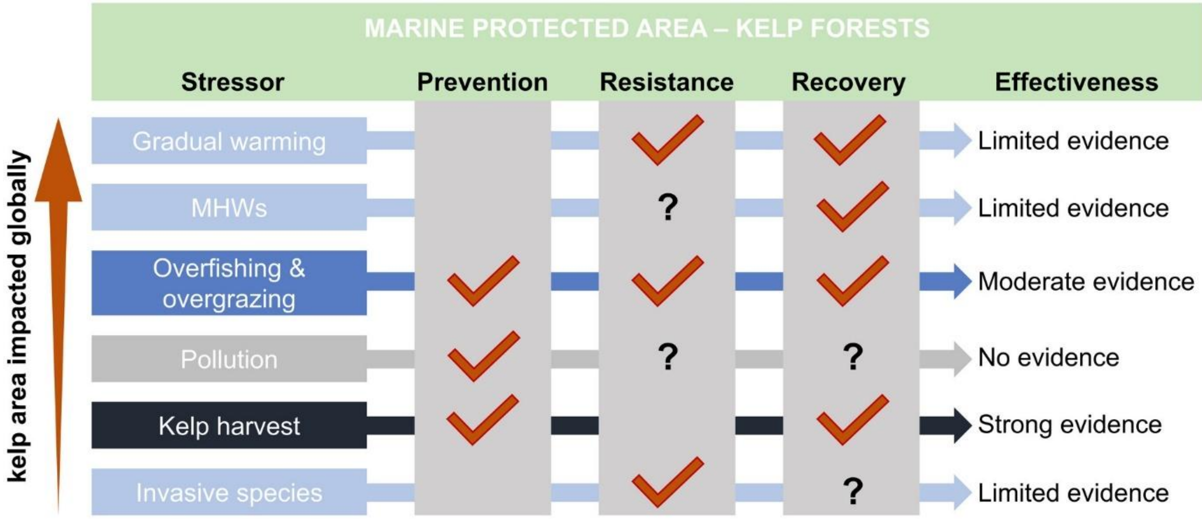
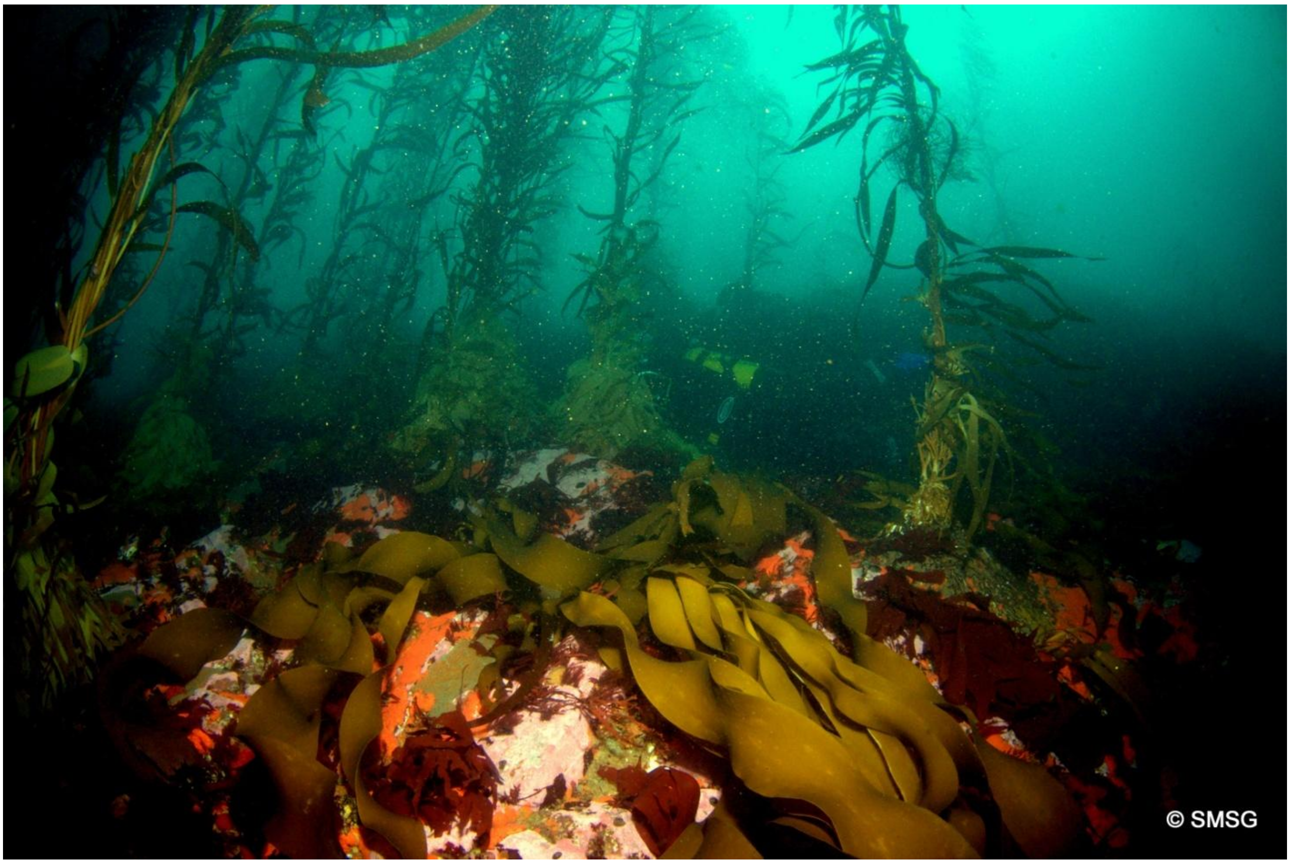


Figure 27. Summary of the effectiveness of Marine Protected Areas for mitigating different drivers of stress in kelp forests in terms of improving prevention, resistance and recovery for kelps. Ticks and designations of effectiveness are based on studies of kelp forests within MPAs, and do not include theoretical or modelled scenarios. The scale of kelp area impacted is approximate and based on global estimates of lost kelp areas and associated drivers summarized in Filbee-Dexter et al. (2022b). Source: Filbee-Dexter et al. (2024a), available under a Creative Commons Attribution-NonCommercial-NoDerivs License (CC BY-NC-ND 4.0).

In addition, to ensure the long-term effectiveness of MPAs, they should be designed to accommodate future projected changes in distributions/polewards shifts of seaweed habitats. For instance, projected climate models (see Section 4.3) will be key in identifying future strongholds of seaweed populations and/or habitats that should be prioritised for protection against threats that might compromise their resilience (see Box 14). Natural seaweed losses will continue to occur with normal climatic and seasonal fluctuations which cannot be prevented. However, under these circumstances, seaweeds should be enabled to recover naturally, for instance, by expanding into new areas without human-induced barriers. “Climate-smart” MPAs that “promote connectivity and gene exchange among populations, incorporate adjustments to MPA boundaries to reflect changing climatic conditions, target protection of blue carbon habitats that enhance CO_2 drawdown, and integrate knowledge of climate refugia that might enhance recovery potential” are beginning to emerge (Filbee-Dexter et al., 2024a and references therein).



Box 14. Ensuring effective long-term protection by using climate forecasts and identifying strongholds: a Scottish case study

Scotland is a European stronghold for rhodolith beds. The majority of these beds fall within the Scottish MPA and Special Area of Conservation (SAC) network. However, only 10 out of over 200 protected areas are specifically designated for their protection (Simon-Nutbrown et al., 2020) and even in these protected areas, some activities that may harm rhodolith beds are permitted (e.g., licensed fishing), which questions the effectiveness of their protection (Scottish Natural Heritage, 2019).

Also, it is predicted that only 20% of the rhodolith beds that have been identified as potential refuge populations under future climate change scenarios will be covered under current protected areas (Figure 28; Simon-Nutbrown et al., 2020). This suggests the long-term distribution of rhodolith beds is at risk around Scotland. Although MPAs do not protect against changing environmental conditions caused by the climate crisis, they do lessen the impact of other pressures, which may help to ensure the resilience of strongholds and enhance the potential for climate change-related mitigation and/or adaptation (Roberts et al., 2017). Therefore, models of future climate change scenarios that identify strongholds in seaweed habitats and populations should be used to plan MPAs that prioritise these areas to ensure effective long-term protection.

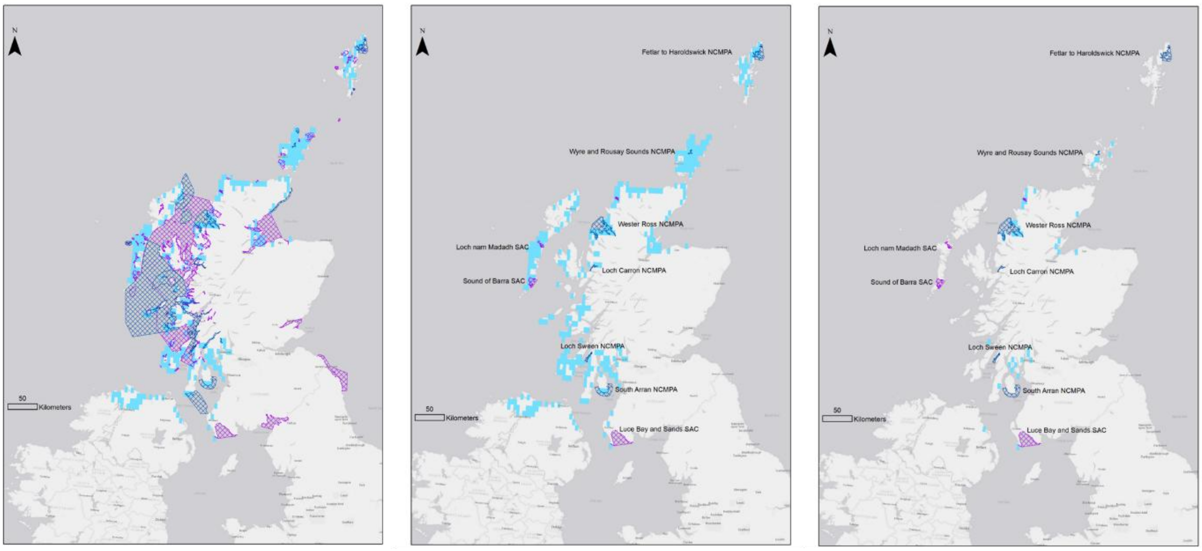


Figure 28. Left: Present day predicted coralline algae bed distribution and all marine protected areas around Scotland. **Middle:** Present day predicted coralline algae bed distribution and marine protected areas where coralline algal beds are specifically protected. **Right:** Predicted coralline algae bed distribution for 2100 under IPCC emissions scenario RCP 8.5 and present day marine protected areas where coralline algal beds are specifically protected. Purple= Special Area of Conservation (SAC), Blue= Nature Conservation Marine Protected Area (NCMPA), Light Blue= habitat suitable to support coralline algal beds. Source: Simon-Nutbrown et al. (2020).

5.1.2 IUCN Red List of Threatened Species

The International Union for the Conservation of Nature (IUCN) Red List of Threatened Species is widely recognised as the most comprehensive, objective, global approach for evaluating the risk of extinction for plant and animal species. As such, the Red List is a powerful tool in biodiversity conservation and the world's main source of global information about the status of biodiversity. However, seaweed species have received little attention from the IUCN Red List and particular challenges are found in applying the Red List criteria to seaweeds (Brodie et al., 2023).

Less than 1% of seaweed species described to date have been documented with Red List criteria on the National IUCN Red List database and nearly 76% of the 99 seaweed entries are data deficient. Even in areas with relatively well-studied seaweed populations, such as Britain, 55% of nearly 620 seaweed species assessed using Red List criteria were described as Data Deficient (Brodie et al., 2023). This lack of complete Red List assessments for seaweeds creates major challenges in reporting on risk status and potential declines of seaweed populations. As well as focusing on species assessments, the IUCN also focuses on habitats. For instance, all coralline algal beds are listed as “Vulnerable” or “Endangered” on the European IUCN Red List of habitats (Gubbay et al., 2016).

It is important to note, however, that the presence of a species or habitat on the Red List does not infer protection. However, due to the Red List's wide global acceptance and objective approach, it remains a powerful tool to incentivise protection of vulnerable species and/or habitats. The recent creation of the IUCN Seaweed Specialist Group (Arafeh-Dalmau et al., 2024) is a promising step in helping to increase the number of assessments of seaweed species globally. Nevertheless, the long-term monitoring and accurate species identification tools needed to carry out these IUCN assessments are often lacking (Brodie et al., 2023). Key knowledge gaps in seaweed taxonomy and distribution also need to be addressed before many assessments on seaweed species or habitats can be made (see Sections 2.1 and 2.2).

5.1.3 Legal frameworks

Seaweeds are typically poorly covered in international, national and regional legislation and policies compared to other marine habitats. This has been raised specifically for kelp forests, which, despite their ecological and cultural value and the strength of evidence of their decline, have been largely invisible in international governance (Fig. 29 Valckenaere et al., 2023). All seaweeds in general lack such international governance; there are no global laws or policies that purposely protect seaweeds and/or their associated habitats (Beattie et al., 2025). Nevertheless, increased recognition of the importance and vulnerability of some seaweeds and their associated habitats has led to a few instances of their specific protection, particularly at national and regional levels (see Box 15).

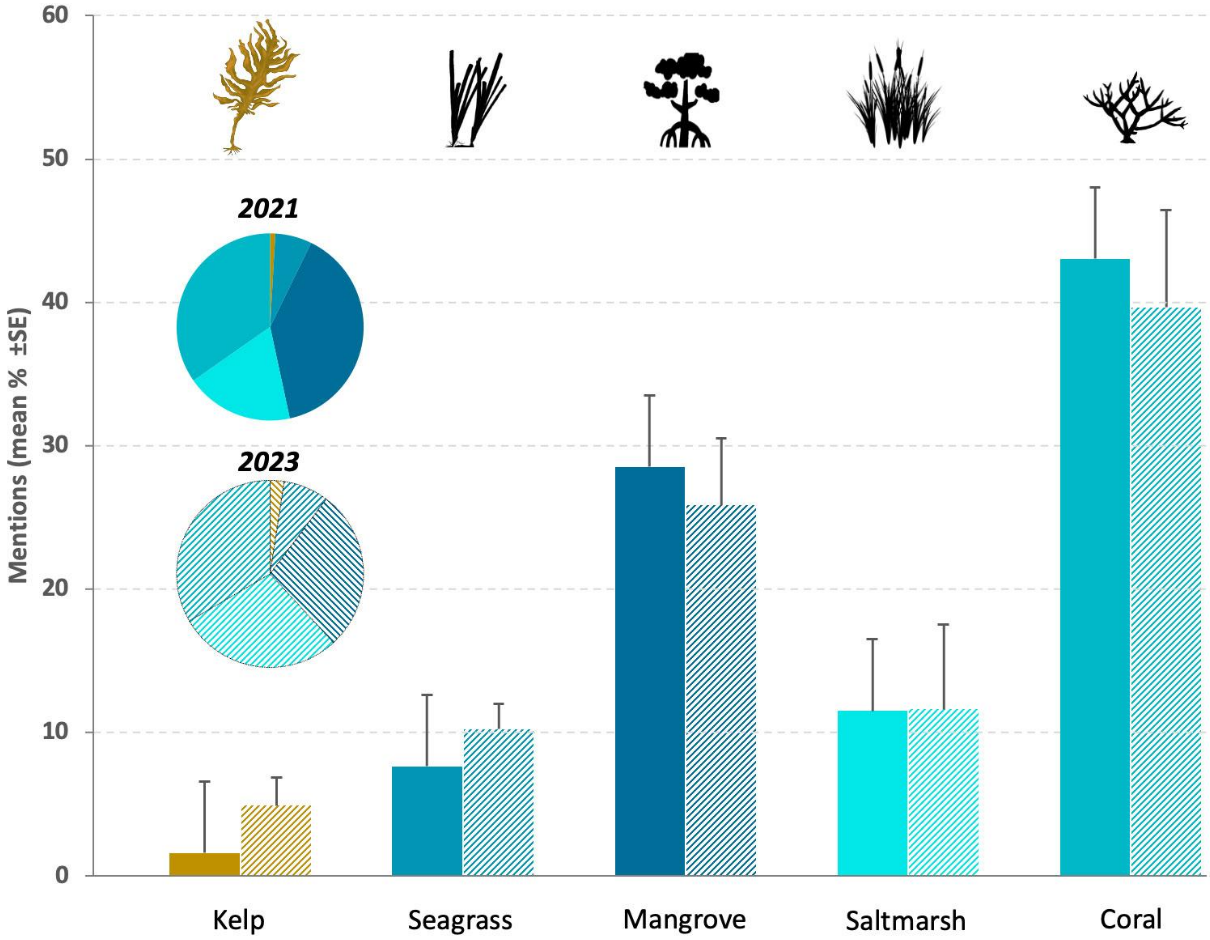


Figure 29. The number of times each dominant marine biogenic ecosystem (kelp forests, seagrass meadows, mangrove forests, salt marches, and coral reefs) was referred to across all major relevant governance regimes and institutions between 2021 and 2023, displayed as a percentage of total mentions across all ecosystems. Total recorded mentions for all five ecosystems: 2021 = 15,931; 2023 = 7,722. Note: This study did not assess other seaweed habitats, but it was assumed that if assessed their mentions would have been fewer than kelp. Source: Valckenaere et al. (2023), available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

Box 15. Examples of national or regional protection policies for seaweeds

Australia: *Macrocystis pyrifera* forests of south-east Australia have been protected by a species-based approach at the national level through the Environment Protection and Biodiversity Conservation Act 1999.

US: An Executive Order released in 2021 on tackling climate change, specifically highlighted the need to protect and restore kelp forests.

Europe: In 2004, rhodolith beds were protected under the EU Habitats Directive and the OSPAR Commission in the North-East Atlantic as ‘Threatened and/or Declining habitats’ and are an important feature of Natura 2000 sites – a network of protected areas covering Europe's most valuable and threatened species and habitats (Hall-Spencer et al., 2008; European Commission, 2018). Two rhodolith species (*Lithothamnion corallioides* and *Phymatolithon calcareum*) are also listed as species whose exploitation requires management in the Annex V of European Community Habitats Directive 1992.

Mediterranean: At a regional scale, rhodolith beds are included in the Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona Convention), in an Action plan for the ‘Protection of the Coralligenous and other Calcareous Bio-concretions in the Mediterranean and within the framework of the United Nations Environment Programme Mediterranean Action Plan (UNEP-MAP; UNEP/MAP, 2017).

Mediterranean: The kelps *Laminaria rodriguezii* and *L. ochroleuca* are protected through the Bern Convention (Convention on the Conservation of European Wildlife and Natural Habitats), which also leads to the indirect protection of the rhodolith beds they inhabit.

Scotland: Maerl beds are considered ‘Priority Marine Features’ (Scottish Government, 2018).

New Zealand: Rhodolith beds have been recognised as sensitive marine habitats by the Ministry for the Environment (MacDiarmid et al., 2013) and are incorporated in regional coastal plans.

There are also policies that indirectly reduce the threats to seaweed habitats (see Section 5.1.5) and may also help to protect and restore seaweed habitats. These include policies which control pollution, greenhouse gas emissions, overfishing or harmful fishing methods that contribute to seaweed habitat decline. For instance, a ban on trapping sea otters restored their role as sea urchin predators, which helped kelp forests recover off the coasts of Alaska (Gorra et al., 2022). Similarly, a ban on bottom trawling in waters < 50 m deep for Mediterranean countries in 1994 has indirectly protected rhodolith beds, and as a consequence almost 30 % of the known rhodolith beds are now protected in northwest Atlantic Spain (Peña & Bárbara, 2009).

National laws and policies for the sustainable harvesting, protection, management and restoration of seaweed habitats differ considerably between nations, driven by national interests and local contexts (UNEP, 2023). Currently regulating the harvesting of seaweeds is still considered the most developed form of seaweed management (UNEP, 2023). Even within nations, though there is a divide between environmental (protection and restoration) and natural resource management (utilisation, including harvesting) laws and policies, which hampers integrated approaches to the protection and sustainable utilisation of seaweed habitats (UNEP, 2023).

Customary laws, however, in some countries do play a role in protecting seaweeds where they are important to the traditions, customs or norms of a local or Indigenous community (see Section 3.1.4). For instance, in New Zealand/ Aotearoa, seaweeds that are valued by Māori, such as rimurapa or bull kelp (*Durvillaea* spp.), receive some protection due to their historical and cultural significance (UNEP, 2023). Under the Fisheries Act 1996, taiāpure and mātaitai reserves were also introduced (Bess, 2001; Jackson; 2013), which allow the local management of fisheries, including restrictions on harvesting certain kelp species and any activities that may affect the rimurapa populations require consultations with Māori beforehand. Similarly, in Canada, First Nations people have been conserving and utilising kelp for thousands of years. For example, herring lay their eggs (roe) on kelp and the Heiltsuk people collect the roe as a delicacy and this has been recognised legally as a traditional (Aboriginal) right (Gauvreau et al., 2017).

5.1.4 International policy frameworks

Seaweeds may be directly or indirectly protected under several global policy frameworks (Table 5). These include, the Paris Agreement, the Kunming-Montreal Global Biodiversity Framework 30 x 30 targets, and both the UN Decades on Ecosystem Restoration and Ocean Science for Sustainable Development (2021–2030). These international frameworks do not have legally binding commitments but can form “soft laws” and act as powerful tools to incentivise nations, NGOs, and the public by setting binding obligations, standards, priorities, and targets, and providing technical reports, guidelines, and forums for collaboration. They are also important tools for generating crucial knowledge to underpin policy development and for raising awareness about seaweed habitats, their potential to be used as nature-based solutions and their threats at an international level. There have already been strong levels of engagement from private sector actors engaged in kelp-related activities and the Kelp Forest Challenge (See Box 15), which has been recognised as part of the UN Decade of Ocean Science for Sustainable Development's endorsed actions.

It is important, however, to ensure seaweeds are explicitly included in these frameworks, as previous non-binding commitments have excluded seaweeds completely despite their relevance. For example, at the United Nations Ocean Conference in 2017, stakeholders from governments, civil society, the scientific community, and other areas, were requested to make voluntary commitments to initiatives that support the implementation of Sustainable Development Goal 14 – Life Below Water. By January 2022, over 1,600 voluntary commitments had been submitted, approximately 30 of which relate to mangroves, three to seagrass and none to kelp forests or other seaweed habitats (Source: United Nations Department of Economic and Social Affairs, no date in UNEP, 2023). As of 2022, only one country, Namibia, had explicitly referenced seaweeds (kelps) in their national climate change commitments to the Paris Agreement (Republic of Namibia, 2021, via UNEP, 2023).

Additionally, many of these targets lack clarity, which may impact the efficacy of protection and restoration. For example, under the UN Decade on Ecosystem Restoration the Kunming-Montreal Global Biodiversity Framework, countries pledge to "ensure that by 2030 at least 30% of areas of degraded terrestrial, inland water, and marine and coastal ecosystems are under effective restoration…". Narrow definitions of terms like "degraded" and "effective", however, could be interpreted in different ways, which would reduce the effectiveness of restoration (Bell-James et al., 2024).

Table 5. Frameworks that currently are, or could be used to protect seaweed habitats adapted from Valckenaere et al., 2023; UNEP, 2023.

Frameworks	Examples
Those that protect habitats and areas	The World Heritage Convention, the Ramsar Convention on Wetlands
Those that seek to conserve and manage biodiversity	The Convention on Biological Diversity and the Kunming-Montreal Global Biodiversity Framework
Those that focus on climate change	The UN Framework Convention on Climate Change, the Paris Agreement, the Intergovernmental Panel on Climate Change
Those that seek to uphold the law of the sea	The United Nations Convention on the Law of the Sea
Key global inter-governmental and non-governmental institutions that seek to provide assessment, guidance, and scientific evidence on global environmental challenges	The Food and Agriculture Organisation, the UN Educational, Scientific and Cultural Organisation, the Intergovernmental Oceanographic Commission, The United Nations Environment Programme, and the International Union for Conservation of Nature

5.1.5 Financial incentives for the protection of ecosystem services

A number of financial mechanisms are also becoming more widely used that may help to build the long-term security of seaweed habitats. Payments or credit schemes are being provided to governments or communities in return for capturing carbon, or delivering some of the other ecosystem services that seaweeds and their associated habitats can provide. This may incentivise the protection or restoration of seaweed habitats, however, credit schemes have been heavily criticised by scientists for “greenwashing” and failing to recognise the more intrinsic benefits of seaweeds that are invaluable, such as their cultural importance (Section 3.1.4). Recognising seaweed habitats for their contributions to helping nations achieve biodiversity and climate targets however could be beneficial. For instance, parties should recognise the importance of their seaweed habitats as nature-based solutions when setting national targets under the Paris Agreement or the Kunming-Montreal Global Biodiversity Framework, which sets out an ambitious set of goals to reach by 2050 and targets to meet by 2030, including protecting 30% of land and sea by 2030. National governments and financial markets could also potentially call upon the global seaweed industry to assist with seaweed protection (Box 16).

Box 16. Can the seaweed industry provide protection for wild seaweeds?

Analysis of the seaweed industry's global distribution in relationship to Marine Protected Areas (MPAs) revealed nearly 50% of aquaculture and wild harvesting sites were within 1 km of a conservation area (Brodie et al., in review) (Fig. 30). This presents an opportunity for farmers and harvesters to help protect wild stocks, through possible payment via a government payment or credit scheme, whilst securing the genetic diversity that will provide them with climate resilient crops in the future. This inter-dependency presents a possible way of protecting wild seaweeds, through active engagement with the industry.

Furthermore, the development of the seaweed farming industry could be strategically used to protect coastal habitats from other more damaging marine industries, such as bottom-towed fisheries, through the creation of de facto MPAs, or as a form of Other Effective area-based Conservation Measures (OECMs) as seen in other aquaculture types (Le Gouvello et al. 2017, 2023, Brown et al. 2020, Mascorda-Cabre et al. 2021, 2023; Corrigan et al., unpublished). OECMs are geographically defined areas, which are governed and managed in ways that achieve positive and sustained long-term outcomes for the *in-situ* protection of biodiversity, with associated ecosystem services (Laffoley et al. 2017). In OECMs, protection is often a secondary benefit and not the designated purpose of the area (Laffoley et al. 2017). So, for example, for seaweed farming, the primary purpose would be the production of seaweed biomass for economic benefits and the secondary benefit the protection of benthic habitats and provision of new suspended habitat, which in turn could contribute to the secondary production of commercial fisheries species (Corrigan et al., 2024). Using seaweed farming as a nature-based solution could, therefore, contribute towards governments' net-zero or biodiversity targets, although more research is needed to ensure the benefits outweigh any wider ecosystem impacts (Corrigan et al., 2022).

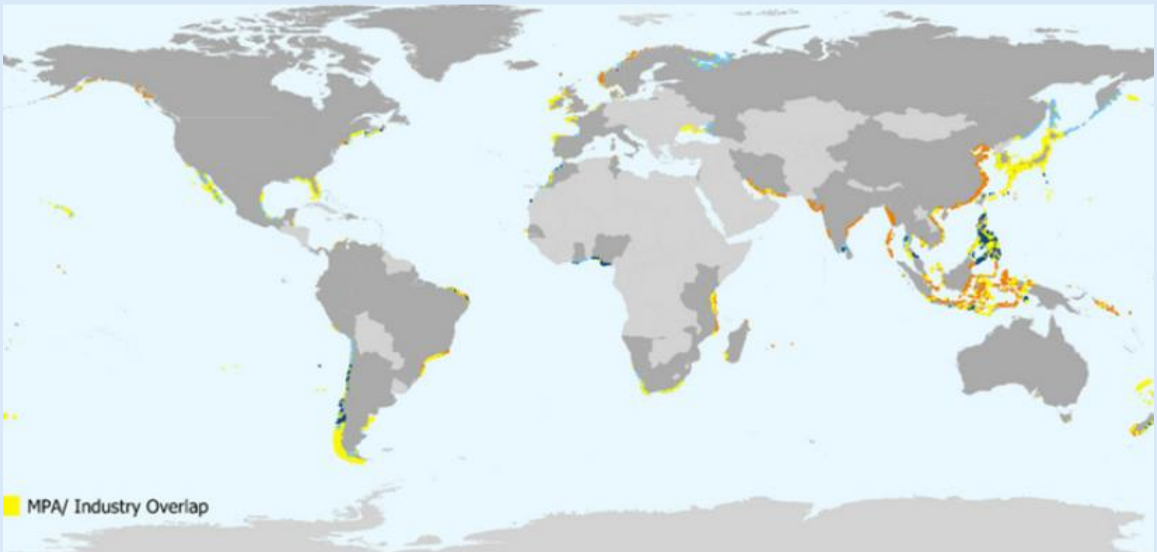


Figure. 30. Spatial distribution of areas where Marine Protected Areas and the seaweed farming industry (orange) and harvesting industry (light blue) or both (dark blue) overlap, as marked in yellow. Source: Cottier-Cook et al. 2023.

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5.2 Identifying impediments and solutions to seaweed protection

5.2.1 Naming seaweeds

It is estimated that less than half of all seaweed species are currently described (Guiry, 2012 and see Section 2.1), which represents a huge gap in seaweed taxonomic knowledge and a major gap for the discovery and development of new commercially valuable products. Seaweed species identity is fundamental if they are to be protected and used commercially, particularly when provenance and safety of the product is now expected by many consumers. Seaweed checklists (i.e., a list of all the seaweed that have been recorded in a given area), may exist, but many areas in the world do not have even a basic list. Furthermore, many of these checklists are based on outdated information, including a lack of awareness of high levels of cryptic diversity in the seaweeds. In addition, some seaweed groups are notoriously difficult to distinguish based on morphology alone and require molecular techniques to provide an accurate identification (Saunders & Kucera 2010; Tran et al., 2022). Seaweed taxonomists routinely use molecular approaches in their work, such as DNA barcoding for species identification. Molecular techniques are becoming increasingly advanced, including use of Next Generation Sequencing techniques to generate whole genomes which can be used for the reconstruction of phylogenies to resolve taxonomic and understand evolutionary relationships. Molecular-assisted taxonomy is used in tandem with extensive historical records held in museums and herbaria, to describe new species more rapidly and efficiently, including for seaweeds used in the aquaculture industry. However, progress remains slow even for commercially important species (e.g., Lim et al., 2017).

The role of taxonomy should never be under-estimated in seaweed conservation (Brodie et al., 2009). The task of identifying the remaining seaweed species, however, is immense and will require co-operation on a global scale. There is a need to train more taxonomists with the appropriate skills, both to document diversity and to overcome taxonomic uncertainties in the seaweed industry if it is going to reach its full potential (Cottier-Cook et al., 2023; Brodie et al., in review). It is also crucial that herbaria and natural history collections (NHC) continue to be recognised as they are critical to the practice of taxonomy, serving as sources of data for biodiversity and conservation (Nelson et al., 2013). There is a need to capacity building at the local level to enable stakeholders to produce their own seaweed checklists at any scale (local, regional, national, international), develop herbaria, and to discover new, potentially commercially valuable, species.

5.2.2 Mapping seaweed distribution

The area that seaweeds are thought to cover i.e., up to 35 times the area occupied by other well-studied coastal habitats (see Section 2.2) is still considered to be a rough estimate, given that it is based on coarse habitat models and the extent of most seaweed distributions are poorly known. Mapping the distribution of seaweed habitats is, therefore, vital in understanding their global extent, value and status. Unlike terrestrial forests, however, mapping seaweed habitats is challenging as they mostly occur below the ocean's surface, sometimes at depths of up to 300 m. Seaweed habitats can also be difficult to survey even in shallow waters, as many occur in inaccessible, remote, cold, turbid, and/or wave-exposed environments. Mapping techniques typically rely on field observations, including underwater surveys conducted by divers or from drop-down camera imagery from boats. In deeper waters, side-scan sonar, drop-down cameras and autonomous underwater vehicles can be used to survey depths that divers cannot reach. However, all these survey techniques are expensive, laborious, time-consuming and remain difficult at depth.

Modern advances in remote-sensing techniques offer new possibilities for mapping large areas with higher accuracy and efficiency (Bennion et al., 2019). Satellites can be used to spot seaweeds that form floating rafts or surface canopies at a broad scale. The Landsat series of satellites provides a record of floating seaweeds back to 1983 at 30 m resolution (Cavanaugh et al., 2011; Nijland et al., 2019) with more recent satellites providing higher resolution. Even more detailed maps can be generated using images taken from light aircraft and drones. However, canopy-forming kelps on low-contrast bottoms or in deeper or turbid water can be difficult to see from the air, and canopies can vary in visibility with tides. Kelps can also only be detected to a depth of 6 m (Uhl et al., 2016). This depth only covers a portion of their depth range and satellite imagery has limited effectiveness for the many areas without surface or shallow kelp, let alone other smaller seaweed species. Furthermore, as with remote sensing generally, ground-truthing is still often needed to determine the full extent of the kelp beds.

Field survey methods though can be especially effective when combined with artificial intelligence (AI) (Box 17) and machine learning algorithms to create spatial distribution models. These models can generate predictions of seaweed distributions based on the overlap of known tolerances of seaweed species with known environmental variables, such as climate and depth. This can provide an important starting point for understanding where certain seaweed species are likely to occur, especially on long and remote coastlines. These modelled predictions can then be validated with real-life observations. Distribution models can also help us to estimate the historical extent and standing stock of different species to understand recent losses in distribution.

Box 17. Using AI to map remaining kelp forests

Only 5% of giant kelps remain off Tasmania's coast after dramatic losses due to climate change, and remaining kelps continue to be at risk from rising sea temperatures (Layton and Johnson, 2021). Identifying and monitoring these remaining kelps is challenging and time-consuming. Artificial Intelligence (AI) is being used to rapidly identify where the remaining giant kelps are in order to protect them. This is through a new partnership between Google and Australian researchers from the Commonwealth Scientific and Industrial Research Organisation, the Institute for Marine and Antarctic Studies, The Nature Conservancy, the Great Southern Reef Foundation and the Kelp Forest Alliance (Riddle et al, 2024). Here (Fig. 31) satellite images from Google Earth Engine are being rapidly analysed with Google Cloud's AI platform Vertex AI to locate and analyse kelp forests in an area of 7,000 km squared (Riddle et al, 2024). AI is also being used to analyse the specific heat-tolerant genes of the 5% of giant kelp that have survived in order to grow more of these resilient kelp strains to repopulate and restore lost forests (Riddle et al., 2024). This is an example of how AI can be used responsibly to create efficient, long-term monitoring strategies and restoration methods. These AI research tools are available open-source to help the restoration of other giant kelp forests (Riddle et al., 2024).

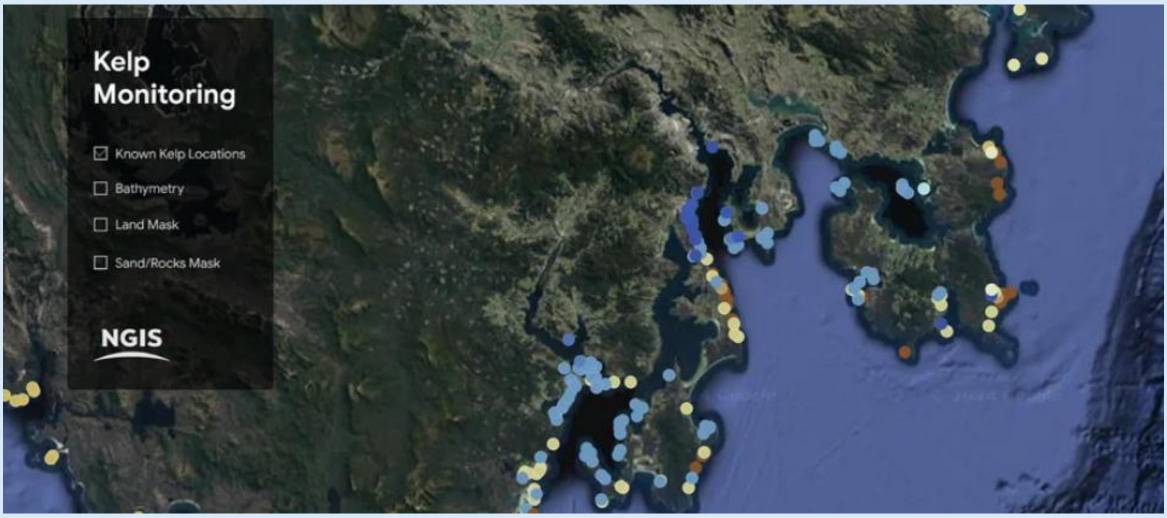


Figure 31. Example of the Google Earth Engine map showing known Giant Kelp locations in Tasmania. Source: Riddle, 2014 (https://blog.google/intl/en-au/company-news/technology/ai-giant-kelp/, accessed: 24/05/25).

5.2.3 Monitoring changes in seaweed health and distribution

After mapping, continued long-term monitoring of seaweed habitats is essential to track changes in their distribution, composition and coverage in response to increasing threats or mitigation measures and inform management decisions. Scientific monitoring of seaweed habitats began relatively recently, with only a few records before the widespread use of SCUBA diving in the 1980s. Momentum, however, is growing and approximately 70 long-term monitoring programs currently exist (Duffy et al., 2019). Nevertheless, the coverage of these programs is patchy compared to the global extent of seaweed habitats and they focus primarily on kelp forests in temperate regions, with few if any existing for other seaweed habitat types, particularly in tropical and polar regions. For example, few, if any, long-term monitoring programmes exist for rhodolith beds, which means no comprehensive global assessment of their status exists. Additionally, the seaweed industry is now at risk due to a lack of baseline species checklists and long-term routine monitoring of wild stocks (Cottier-Cook et al., 2023).

Monitoring programs also tend to operate in isolation and, therefore, vary widely in scale and methodologies used, with differences in sampling designs, replication, taxonomic resolution and frequency (Duffy et al., 2019). This makes inter-regional comparisons difficult and limits our perception of how seaweed ecosystems respond to anthropogenic threats on the scales necessary for informing effective national and international management and policy (Duffy et al., 2019). Additionally, short-term funding cycles that typically only last a few years tend to restrict the growth and momentum of programmes.

It is critical, therefore, to standardise seaweed habitat monitoring by building on existing networks, sharing best practices and identifying key priorities and metrics for survey design, data management and capacity building (Duffy et al., 2019). The Kelp Forest Alliance have produced a comprehensive guidebook for kelp forest monitoring which aims to equip the global community with practical knowledge to contribute to the protection and restoration of kelp forests around the world (Eger et al., 2024b).

Sustaining coordinated monitoring networks requires close engagement of stakeholders, including local communities and Indigenous Peoples. It also requires focus on the long-term maintenance of local capacity, particularly in developing countries (Duffy et al., 2019), and the support of local custodianship of the seaweed habitats, e.g. by seaweed farmers, to encourage their protection and sustainable use (Brodie et al., in review).

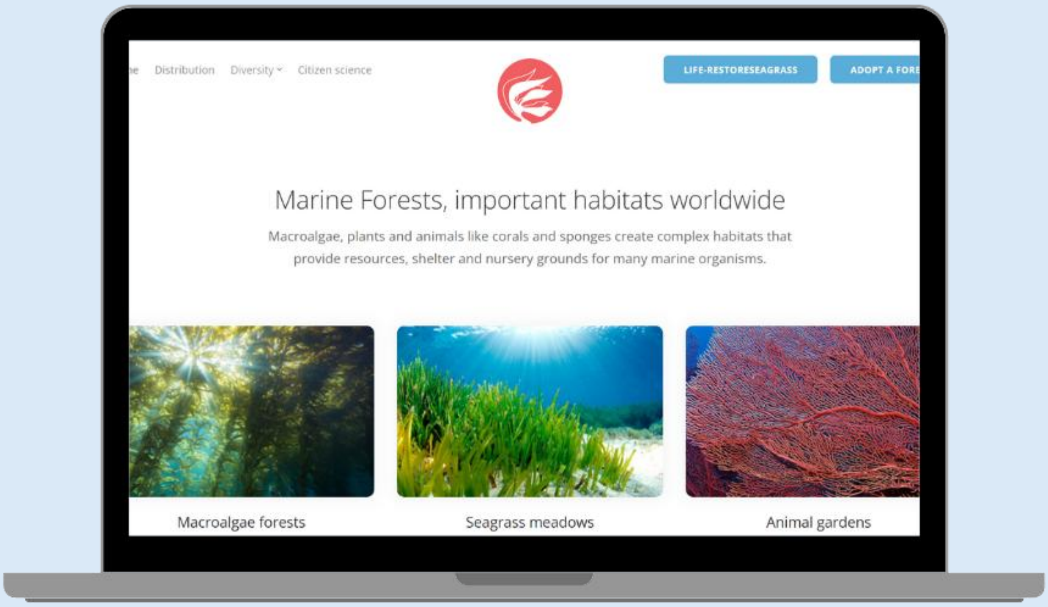
5.2.4 Increasing awareness and building capacity

Many people are still unaware of the numerous benefits seaweed habitats provide for people and the planet. Global networks, such as the Global Seaweed Coalition and the Kelp Forest Alliance have vastly increased seaweed awareness at local, national and international levels, highlighting best practices to support seaweed management and conservation and the safe and sustainable scaling of the seaweed industry. However, awareness could be developed further, with wider global coverage, especially for lesser-known seaweed habitat types.

Citizen science can be an important, low-cost source of mapping and monitoring information, especially when systematic scientific resources are scarce. Volunteer programs can be useful for covering large areas regionally or worldwide and for analysing or taking images for presence/absence of seaweed species (e.g., Box 18 and 19). Citizen science projects are not only important scientific tools, but they can also help to engage the public on the importance of seaweeds and the threats they face, while empowering them through their contributions. These programs still rely on resources to be coordinated and scientific expertise to check the reliability of data collected by citizens, however increasingly new technologies and AI are being developed to help streamline this process.

Box 18. The Marine Forests database

Nearly 14,000 citizens have produced over 700,000 records of over 4,000 species of seaweed, seagrass, corals, and other forest-forming species on the Marine Forests website (Centre of Marine Science, 2025) where anyone can participate as long as they have access to the internet and can provide a photograph date and location of species recorded.



Box 19. The Big Seaweed Search

In the UK, citizen scientists are invited to help monitor the effects of environmental change on Britain's seaweeds via the Big Seaweed Search. Since 2009 the partnership between the Natural History Museum and the Marine Conservation Society has used data gathered by thousands of participants in hundreds of surveys that evaluated the impact of sea temperature rise, non-native species and ocean acidification on seaweeds, along the British coastline (Brodie et al., 2023).

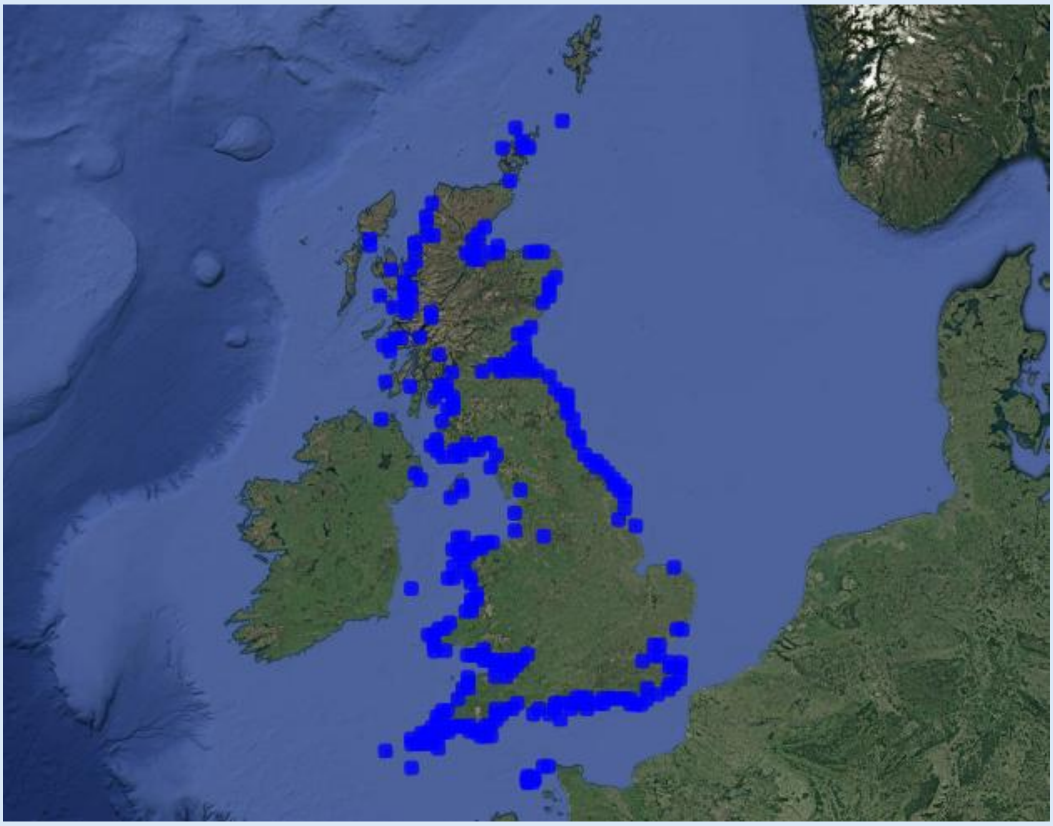


Figure 32. Map of survey locations around the UK used in the Big Seaweed Search. Source: Big Seaweed Search (Accessed: 13/02/25).

6. The current state of seaweed restoration

Summary: Restoration attempts are mostly focused on restoring kelp forests, where ambitious global targets are currently set by the Kelp Forest Alliance and the Kelp Forest Challenge. Seaweed restoration is currently challenging, expensive and for some seaweed species restoration is not possible due to their extremely slow growth rates. However, new innovations, best practice techniques and global partnerships are being established which offer hopeful solutions. Nevertheless, conservation measures need to be urgently targeted and prioritised to protect the most vulnerable species.

6.1 Seaweed restoration

Ecosystem restoration is a nature-based solution defined as a means of assisting intact, degraded or destroyed ecosystems (SER, 2004). Protecting remaining seaweed habitats and preventing losses from occurring in the first place should always be the key priority. This is because restoration projects are challenging, expensive and may take many years to restore seaweed habitats and the ecosystem services they provide back to their original state. Nevertheless, given the significant declines that many seaweed habitats have already experienced worldwide and the values that they would provide to ecosystem services and the environment if restored, restoration is highly important and logical in many instances. For example, the restoration of seaweed habitats should be recognised as an important nature-based solution to mitigate climate change and increase coastal resilience at international and national levels.

6.2 Kelp restoration

Nearly all seaweed restoration efforts have been focused on kelp forests, with the first kelp restoration attempt made over 300 years ago (Eger et al., 2022a). There have been nearly 260 documented kelp forest restoration attempts between 1957-2020 in 16 countries (mostly in Japan and the USA), with mixed success (Fig. 33; Eger et al., 2022a).

Like research and conservation efforts, the scale and number of kelp habitat restoration projects over the past few decades have fallen significantly behind those for other vegetated marine ecosystems (Saunders et al., 2020). Global restoration of kelp habitats has so far been slow, small scale and with a lack of sharing of knowledge and resources between isolated restoration attempts. In line, however, with the UN Decade on Ecosystem Restoration (2021–2030), the Kunming-Montreal Agreement and the 30 x 30 targets, multiple initiatives are now emerging. For example, the Kelp Forest Alliance (KFA) (Box 20) is connecting kelp restoration projects globally and have produced the

"Kelp Restoration Guidebook" (Eger et al., 2022b). This guidebook includes lessons learnt and best practices and includes examples of effective restoration success stories for kelp forests worldwide.

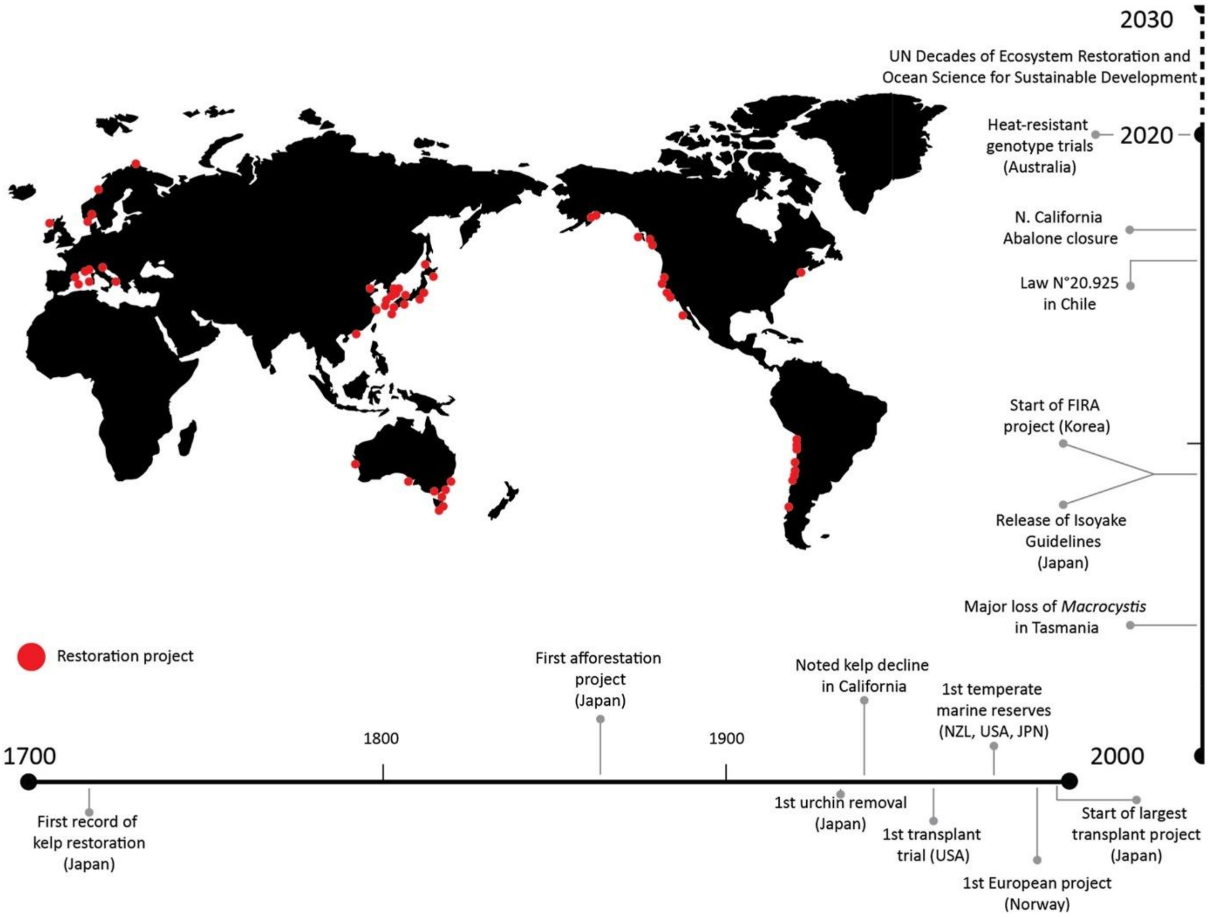


Figure 33. Location and timeline of important global kelp restoration-related events. Source: Eger et al. (2022), available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

6.2.1 Current kelp restoration efforts

Most kelp forest restoration projects to date have been small scale (<100 m^2), short in duration (<2 years) and academically driven (Eger et al., 2020, 2022a). To date, approximately 15,000 hectares of kelp have been restored, most of which is in South Korea (Box 21; FIRA, 2019). Due to a combined global effort, however, and the formation of the Kelp Forest Alliance (KFA) (see Box 20), there is a far better understanding of the decline in kelp forests and what is needed to restore them successfully.

Box 20. The Kelp Forest Alliance (KFA) and its main initiatives

KFA (Kelpforestalliance.com): This is a pioneering initiative, that brings together people and organisations working on kelp forest ecosystems. It aims to enhance the protection and restoration of these valuable ecosystems, whilst increasing inclusivity and strengthening collaborations between countries and their citizens. The Alliance works to produce and facilitate global knowledge exchange on kelp forest management across languages and professional sectors internationally. It also works to raise the profile of kelp forests and advocate for stronger protection of these ecosystems. Since its initiation in 2021, the KFA has brought together 570 people and over 200 organisations from nearly 30 countries around the world, as well as 15,000 web users.

Kelp Forest Challenge: This was recently launched the by the KFA (Eger et al., 2024a). It is an ambitious and inspiring mission to protect and restore four million hectares of kelp forests by 2040 in line with the Kunming-Montreal agreement. To achieve this target, the KFA have designed a roadmap, which provides a detailed strategy for how businesses, governments, communities, universities, content creators, and anyone else with an interest can help (Eger et al., 2023b). The roadmap outlines the substantial investment, collaboration, and innovation that is needed across different sectors, countries, and philosophies (Eger et al., 2023b). The KFA also actively tracks the progress of the Kelp Forest Challenge and quantifies the value of achieving its targets in terms of the ecosystem services kelp forests provide.

Kelp Restoration Guidebook: The KFA, with the Nature Conservancy in California have successfully produced a this guidebook to bring together lessons learnt from 50 expert contributors representing 45 institutions from every kelp growing region of the world. The guidebook details the steps needed to conduct kelp restoration, highlights the success stories, and provides an important knowledge base for future restoration efforts.

KFA project database: To track kelp forest restoration projects and their success, the KFA have created a database that provides a standardised display of previous restoration projects and allows users to upload new information about their own work. The database centralises the storage of project information, lets users learn from previous projects and helps track kelp restoration into the future. Tracking and recording restoration efforts in this way is also crucial for motivating momentum in restoration projects and makes it easier to notice and learn from mistakes, identify factors driving success, and monitor progress made towards global conservation targets. The KFA are now working to produce a set of monitoring guidelines for recording the outcomes of restoration projects to get a better understanding of the factors involved in successful kelp forest restoration.

The KFA website: This platform promotes the value of kelp forest ecosystems, hosts the project database, restoration guidebook, and houses the network of members. It provides a standardised data entry portal for restoration projects and tracks projects across the world. It also provides a forum for members to collaborate and discuss matters related to kelp forest restoration.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Box 21. Kelp forest restoration in Korea

The Korean Fisheries Resources Agency has been running a nationwide kelp restoration program since 2009, where almost 15,000 ha of kelp have been successfully restored. The release of their kelp restoration manual in 2019 "The Process for the Marine Forest Project" (FIRA, 2019) details valuable lessons learnt over a decade, including how the FIRA Seaforest program is run, sites are selected, restoration is conducted and monitored afterwards. Although this guide is written specifically for kelp restoration in Korea, it contains valuable information for other seaweed restoration projects globally.

6.2.2 Kelp restoration methods

Kelp restoration currently takes many forms, from removing a specific threat (e.g., grazers, such as sea urchins) and leaving the seaweed habitat to recover naturally, to more active interventions, such as replanting in areas where the seaweeds have been heavily degraded or lost completely. The overarching aim being to return the seaweed habitat to as close to its original condition as possible.

A variety of methods have been used to restore kelp habitats. Best practices have been detailed thoroughly in the KFA's Kelp Restoration Guidebook (Eger et al., 2022b), although many of these methods can also be applied to other seaweed species. These include measures to halt the loss of seaweeds, such as grazer removal, and ways to actively restore them, for example, by transplanting individuals from healthy populations or seeding new individuals into the area (Fig. 34; Eger et al., 2022a). Seeding is often favoured over transplantation due to its reduced costs and scalability, and consequently the Green Gravel Action Group (Box 22) has been set up to connect projects working with this method. Currently, best practice recommendations suggest restoration projects are most successful when a combination of methods are used and adequately supported financially, socially and institutionally (Eger et al., 2022a,b). Seaweed restoration, however, is currently still limited by inadequate financing, governance hurdles, and a lack of institutional support, which are needed to restore seaweeds at the desired scales (Eger et al., 2022a).

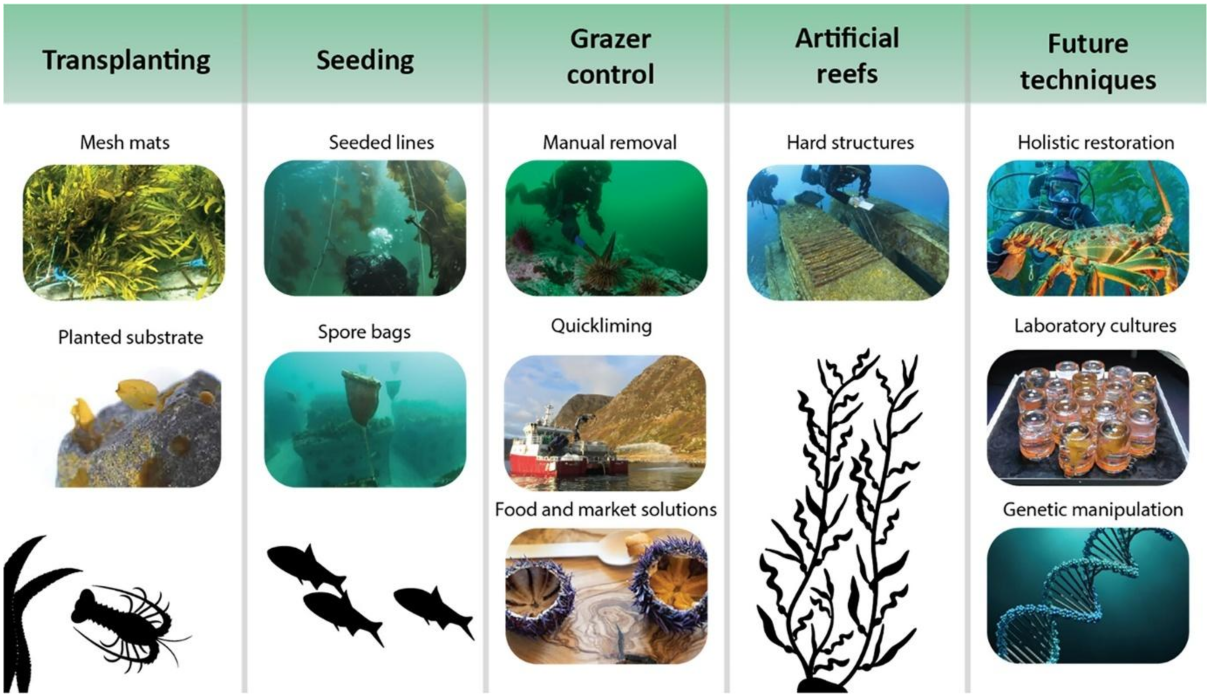

Figure 34. Methods used in kelp forest restoration (photograph credits, left to right, top to bottom: Operation Crayweed, FIRA, Ryan Miller, FIRA, NOAA, Green Gravel, FIRA, NIVA, University of Tasmania, Urchinomics, Pixabay). Source: Eger et al., 2022a, available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

Box 22. The Green Gravel Action Group (GGAG)

The Green Gravel Action Group (GGAG) is a global network of nearly 70 members (Fig. 35; Wood et al., 2024) that are working to restore a diverse range of macroalgal forests using the 'green gravel' method of seeding rocks with seaweed propagules. The network aims to facilitate knowledge exchange between restoration projects to fast-track innovation and implementation of out-planting approaches worldwide (Wood et al., 2024).

Currently, the mean total area that projects are working across is 30 km^2, although physical out-planting activities were only being conducted within a much smaller subset of this, from 4 to 8,000 m^2 (Wood et al., 2024). Currently, almost 90% of projects are mostly experimental and focused primarily on research and method development, which is an important step to ensure restoration is scaled up effectively using the appropriate techniques. Over 70% of projects also participate in community outreach, including media releases, educational workshops or community plantings.

The group meets twice a year to discuss key questions, activities, challenges, solutions and project outcomes, some of which are summarised below (Table 6) and available in more detail in Wood et al. (2024). Restoration success across the GGAG has been highly site- and context- dependent, highlighting the need to understand the complex biotic and abiotic drivers of out-planting (and more broadly, restoration) effectiveness on both local and regional scales (Wood et al., 2024).

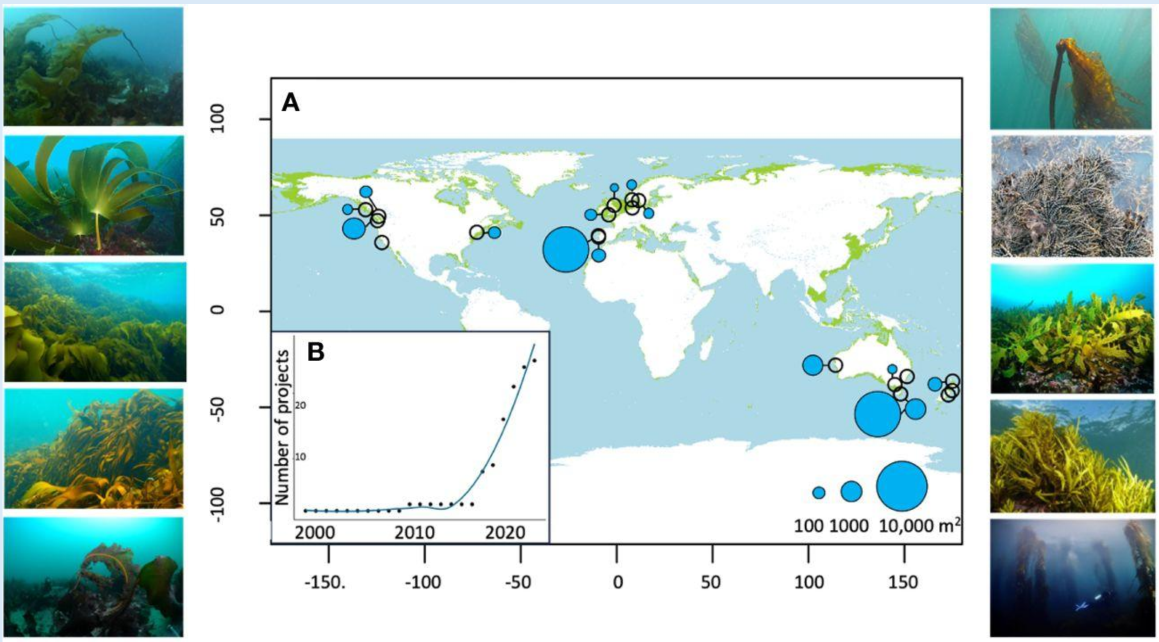

Figure 35. Green Gravel Action Group (GGAG) projects. (A) Map of GGAG project locations; open circles = projects in planning and scoping stages; blue circles = location where field-based restoration projects have been initiated. Blue circle size indicates the area over which the project is actively out-planting macroalgae. (B) Cumulative number of projects starting each year for the period of 2000-2023. Side panels: study species being worked on in the GGAG (in clockwise order from the top left): *Saccharina latissima, Nereocystis luetkeana, Hormosira banksii, Ecklonia radiata, Phyllospora comosa, Macrocystis pyrifera, Alaria marginata, Laminaria digitata, L. hyperborea and L. ochroleuca* (photos: Karen Filbee-Dexter, Kathy Burnham, Paige Bentley, John Turnbull, Scott Ling, Robert Scheibling and João Franco). Source: Wood et al. (2024), available under a Creative Commons Attribution License 4.0 (CC BY 4.0).

Table 6. Key challenges and recommendations in Green Gravel projects. Adapted from Wood et al. (2024).

Challenge	Recommendation
Funding and capacity limitations	Explore new funding strategies and skills development
Dealing with sources of environmental stress at restoration sites	Account for changing ecosystem states
Technical barriers and narrow focus	Embrace commercial partnerships and embed experiments as projects scale
Hurdles at the restoration-policy interface	Engagement with local authorities and rights-holders from the outset

6.3 Restoration for seaweeds in general

Despite the majority of seaweed restoration projects being focused on kelp forests, restoration methods are currently being explored for other seaweed species. For instance, in Korea, attempts are being made to restore the ecologically and commercially important brown seaweed *Silvetia siliquosa* (Gao et al., 2017). In addition, researchers in Malaysia are looking at new methods to restore the commercially important eucheumatoid species, such as *Kappaphycus* spp. and *Eucheuma* spp., as part of the Global Seaweed SUPERSTAR project (www.globalseaweed.org).

6.3.1 Guidance for other seaweed habitats

Other seaweed habitats that can be restored will also benefit from the KFA initiative, with guidance on project design, monitoring, engaging with communities and partners and utilising Indigenous knowledge all being relevant. Furthermore, the launch of the "Kelp Forest Challenge" by the KFA can be used as a gold-standard initiative for setting ambitious, but science and stakeholder-based goals and targets, and should be scaled for seaweed habitats more widely. Other seaweed habitats, however, will face different challenges and possibilities for restoration compared to kelps, such as the rhodolith beds, where restoration may not be feasible at all, since they can take centuries to millennia to recover from disturbance (Hall-Spencer & Moore, 2000). Therefore, specific initiatives will need to be developed to protect and restore different seaweed types effectively based on scientific understanding of each habitat type.

6.4 Future-proofing restoration

Similarly to future proofing the protection of seaweed habitats under projected climate change scenarios, methods have been proposed to increase longevity of restoration projects (Eger et al., 2022a). These include, selecting more temperature resilient genotypes for restoration through selective breeding, direct genetic manipulation (Coleman et al., 2020), or by using material from seaweed populations that are adapted to warmer temperatures or have survived extreme events (Coleman & Wernberg, 2020).

Another area of research explores the potential of seaweed epigenetics (changes in organisms caused by modification of gene expression rather than alteration of the genetic code itself) to prime kelp seeding material to increase their tolerance to temperature stress for use in restoration projects (Jueterbock et al., 2021). However, caution should be taken to avoid any negative consequences of introducing different genetic material or possible invasive non-native species, pest and/or diseases into the restoration area. Biosecurity protocols are, therefore, vital in preventing the unintentional introduction of non-target species into the restoration site (Kambey et al. 2021). Gene and/or seed banks are also essential in understanding genetic resources and ensuring important genetic material is collected and preserved, especially in populations that are threatened and/or declining (Box 23).

Understanding the role of the seaweed microbiome in relation to optimising growth conditions, including maximising settlement and survival in the early growth stages has also been proposed for seaweed restoration where ex-situ cultures could benefit by the application of probiotic mixtures (e.g. Malfatti et al., 2003; Savonitto et al., 2021). Commercial seaweed extracts also show promise as biostimulants in relation to restoration (and in seaweed farming) by reducing epiphyte attachment (e.g. Hurtado & Critchley 2020).

Box 23. Genetic resources and gene banks

Maintaining genetically diverse wild seaweed populations is crucial to ensuring the recovery and restoration of degraded sites, in light of the increasing challenges and threats they are facing. Having diverse genetic resources will also give seaweeds a better chance to adapt to climate-induced changes, such as increasing seawater temperatures. It will be important to ensure there is increased available information on the role of genetic diversity in relation to building sustainable livelihoods and achieving biodiversity targets, and on the status and trends in their protection, sustainable use and development to guide effective management of these resources.

However, unlike the work carried out by the Global Crop Trust on terrestrial genetic resources and gene banks, the preservation of seaweed biodiversity relies on subsidies without long-term investment. This leads to a loss of knowledge and insufficient preservation of seaweed biodiversity. Additional challenges include conserving seaweed species in seawater, which is very costly in terms of manpower and space. Despite the emergence of cryopreservation, very few seaweed species that have been tested are viable function under cryopreservation, requiring investment in research.

Together with FAO, The Global Seaweed Coalition and seaweed genetics experts are aiming to compile a seaweed AquaGRIS platform, a global information system for aquatic genetic resources launched in September 2024. This database will include seaweed species that are currently used in the seaweed industry and may link seaweed gene banks to the associated seaweed species. In a second phase of this project, the registration of wild seaweed species for conservation purposes could be executed.

This work will help to:

- obtain an understanding of the current state of seaweed biodiversity for industrialised species
- identify gaps between preserved seaweed strains currently in banks and strains used in the seaweed industry
- facilitate exchanges in gene bank material
- enhance biobanking initiatives where needed
- allow for better ocean governance: species and gene banks being recognized at a national level through validation of national focal points

6.4.1 Ensuring equity during restoration

As with the protection of seaweed habitats, restoration measures must align with the needs of Indigenous People and Local Communities (IPLCs), including the seaweed farmers, as they are paramount to the successful protection of the wild seaweed stocks (Cottier-Cook et al., 2023). It is not always a formal requirement to gain permission and/or involvement from IPLCs before embarking on restoration projects, although it is frequently advised and beneficial to do so (IPBES, 2019; Eger et al., 2022b). There are also many shared benefits from partnering with and ensuring equity between IPLCs, including shared knowledge and increased stakeholder support, which are likely to make restoration projects more successful. For instance, engaging Māori communities with Green Gravel projects in New Zealand has been seen as a positive way to place the responsibility for nurturing the environment on the community, in keeping with the Māori world view (Wood et al., 2024).

6.4.2 Financing restoration

Many of the benefits from protecting and restoring seaweed habitats can be further underpinned by strong financial arguments, particularly in terms of the ecosystem services they provide. However, one of the main constraints on restoring seaweed habitats currently is a lack of sustainable long-term funding. Most restoration efforts for subtidal programmes range between thousands to millions of dollars per hectare (Bayraktarov et al., 2016). Previous large-scale kelp forest restoration projects' budgets have ranged between $5 to $267 million USD (2010), depending on the size, scale and longevity of the project and the restoration methods required (Eger et al., 2020, 2022). These examples are exception in terms of costs but kelp restoration can cost substantially more than restoration in other marine ecosystems (coral ~$196000, seagrass ~$126000, mangroves ~$11000, saltmarsh ~$80000 per ha, USD, 2020; Bayraktarov et al., 2016) However, restoration methods for kelp forests vary in price, with sea urchin control having the lowest costs (~$1500 - 67800 per ha (USD 2020)) and other methods including transplanting, seeding, and building artificial reefs, range between $526000 - $707000 per ha (Eger et al., 2022a)., There are also examples of kelp restoration projects in Japan and Korea costing far less at between $8000 – 10000 per ha (A. Eger, personal communication). It is, therefore anticipated that costs should reduce in future as restoration methods are refined and new technologies developed (Eger et al., 2022a).

Best estimates of the costs required to meet the Kelp Forest Challenge's target of restoring 1 million ha of kelp forest will require an initial investment of ~$11 billion (A. Eger, personal communication). However, it is predicted that this will produce in return, tens of billions of dollars each year through a coastal restoration industry comprised of fisheries, blue carbon and tourism (Kelp Forest Alliance, 2025; United Nations Decade

On Restoration). These benefits would potentially offset the costs of restoration within 1–12 years, depending on the restoration methods used (Eger et al., 2022a).

Since we have little information on the restoration potential of other seaweeds or their associated habitats, there is currently no global estimate of how much it will cost to restore all the seaweed habitats worldwide, however it would likely be an order of magnitude higher than the estimates for kelp forests alone. Generating long-term and sustainable funding for seaweed restoration, however, is crucial and could come from a range of sources (detailed in Eger et al., 2022a). These sources could include government investments, philanthropists and the private sector, including the seaweed industry. Investments and businesses could benefit restoration activities directly or indirectly, for example, the company Urchinomics helps restore kelp forests while generating income from sea urchin sales (Box 24).

Partnering with the seaweed industry (or wider aquaculture industry) offers an opportunity to connect seaweed and other stakeholders, share resources and reduce the costs of restoration, whilst increasing its scalability. For instance, resources and techniques used for growing seaweed at scale for commercial use, could be applied to restoration projects (e.g., seaweed farming hatcheries could be used for growing juvenile seaweeds on substrates to be deployed in restoration areas, like Green Gravel projects). This collaboration may also help to tackle challenges faced by both the seaweed farming industry and wild seaweed habitats, such as identifying and cultivating thermally tolerant seaweeds for future-proofing farming and restoration (e.g., Layton & Johnson, 2021). The creation of more gene banks at regional and international levels will also benefit both seaweed conservation and the industry, by conserving genetic diversity (see Box 23).

Box 24. Urchinomics: combining restoration with business

Urchinomics (https://www.urchinomics.com) is a business that combines kelp restoration with sea urchin aquaculture to enable sustainable use of kelp forests. The company pays commercial divers to harvest overgrazing sea urchins and turn them into premium seafood through aquaculture. So far, urchin populations have been reduced, and the kelp forests have begun to recover. Urchinomics have also secured the world's first voluntary blue carbon credit in 2022 for their ecologically restorative operations in Japan (Hermans, 2022; United Nations Ocean Decade, 2022). Here, scientist Dr. Teruhisa Komatsu, formerly of University of Tokyo used Urchinomics data to estimate that over 1400 kg of overgrazing sea urchins needed to be removed to restore 1 ha of kelp forest, which in turn would generate approximately 1.5 tonnes of verifiable blue carbon credits, valued at over JPY 78,000 per tonne in 2022 (Urchinomics, 2024).


SAVE OUR
SEAWEEDS
NATURE
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7. Securing a sustainable future for seaweeds

Summary: This section draws attention to recent advances in science and collaborative global efforts in protection that are now getting seaweeds on the political agenda and demonstrating their immense ecological and economic value. It also recognises the need both to urgently address the gaps identified in this document and to work together. This section also covers the Seaweed Breakthrough concept, provides draft high level Breakthrough targets and Guiding Principles to implement the Breakthrough in a fair and ethical way.

7.1 Understanding the importance of seaweeds – key knowledge gaps

The *State of the world's seaweeds* demonstrates unequivocally the vital importance of seaweeds to the health and survival of the planet and consequently millions of livelihoods worldwide, whilst documenting the urgent need for conservation measures to ensure their protection and survival. Amongst the biggest challenges in incentivising the effective global protection of seaweeds globally are the major knowledge gaps in relation to their identification, distribution and contributions to biodiversity, livelihoods and climate change mitigation, which are required to understand and fully appreciate the scale of their importance to the planet. This lack of knowledge has been a contributory factor to a lack of investment in their protection and restoration at the national and international level. Addressing these knowledge gaps will help to incentivise and inform the appropriate level of protection and restoration efforts globally.

7.2 Seaweeds for long term food security

With traditional agriculture now recognised as one of the leading causes of biodiversity loss, and wild capture fisheries operating at or above maximum sustainable yield, it is an urgent priority to secure food for the world's growing population without costing the planet. The seaweed industry already supports millions of farmers worldwide, the majority in developing countries and can produce a sustainable, fast growing and nutrient rich food source, whilst not relying on land, freshwater or pesticides. They also provide other indirect benefits to food production such as fertilisers, plant biostimulants or raw materials.

In contrast to land-farming which relies heavily on the use of inorganic fertilisers, commercial production of seaweeds has been reliant on naturally occurring inorganic nutrients in the sea. However, in some parts of the world, such as Southern Philippines there is a disturbing trend where inorganic fertilisers are being used in seaweed farming supposedly to boost production, leading to poorer carrageenan yield, loss of organic status and ecological disaster due to indiscriminate use and disposal of the inorganic fertilisers (Roleda et al., 2025).

More positively, seaweeds are also relatively resilient crops under future climate scenarios and may be an important farming option in arid coastal states where land-based agriculture may no longer be viable. Furthermore, seaweeds have been identified by the European Commission (2022) as ‘having the potential’ to meet an estimated 100 million tonnes more biomass requirement for human food over the next two decades.

Currently however, the potential for seaweeds to improve food and nutrition security is overlooked by many countries that do not have a history of using this product, and food security policies and programmes are lacking due to insufficient data on their composition and lack of awareness of their value compared to terrestrially sourced foods (FAO, 2024). The majority of the regulatory frameworks for seaweed farming and harvesting are also limited in their effectiveness (Brakel et al., 2021; Beattie et al. 2025), and need urgent improvement given the size and scale of global seaweed production in many countries in south-east Asia (FAO, 2024). These include a lack of regulations and standards for seaweed production and processing, which hinders the successful scale up of the sector (UNCTAD, 2024).Declines in eucheumatoid seaweed production, for example over the last two decades, have also highlighted the critical need for climate-resilient, tropical seaweed varieties, and the urgent need for farmers to access high-quality seed stocks, specifically strains or cultivars that are resilient to climate change, resistant to diseases, and consistently remain high yielding. The poor knowledge of the genetic diversity of seaweeds, inconsistencies in the naming of the commercial varieties and a lack of investments in breeding programmes, however, are severely hindering this industry, particularly for tropical seaweed farms, where the same cultivars (e.g., *Eucheuma* spp. or *Kappaphycus* spp.) have been grown and propagated for decades. This means there is limited genetic diversity in farms, which makes them more susceptible to diseases, pests and the other associated impacts of the climate crisis (Cottier-Cook et al., 2023). As the cultivars have been domesticated and exchanged between farms over many years, it can also be difficult to distinguish which strains are being grown. This can lead to inconsistencies in the quality of the product, uncertain provenance and value, which can be a major constraint and risk in the industry (Cottier-Cook et al., 2023). Combining traditional knowledge from farmers with genetic information could, therefore, help to identify the species that are being grown and those that are the best candidates for genetic improvement programmes and for adaptation to specific conditions (Dumilag et al., 2023; FAO, 2024).

7.3 Working together

To protect the most vulnerable seaweeds and their habitats, a coordinated global response is needed (see Box 25). As seen with other habitats, protection and restoration are most effective when stakeholders work together to share knowledge, resources and best practices. Stakeholders relevant to protecting seaweeds are diverse, including such groups as local communities and Indigenous Peoples, scientists, academics, conservationists, the seaweed industry (including harvesters, farmers, processors, buyers, sellers, investors), national and international governmental agencies and non-governmental organisations (NGOs) amongst others.

Organisations currently exist with the purpose of bringing together seaweed stakeholders either regionally or internationally. These are primarily focused either on protecting or restoring seaweed habitats or developing the seaweed industry and providing sustainable livelihoods. Prominent international organisations include the Global Seaweed Coalition, the Kelp Forest Alliance and the International Seaweed Association. The IUCN established a Seaweed Specialist Group in 2023 and the GlobalSeaweed-SUPERSTAR team has been working for almost a decade in this research area funded by UK International Development. Each have their own missions to protect seaweed populations and/or achieve the safe and sustainable expansion of the global seaweed industry. This is in addition to many other NGOs, community groups, research centres and governmental agencies that have been working globally to protect seaweeds and their associated habitats. As a result, seaweeds now have a far greater recognition on the world stage However, more effort is needed for the less well-known and non-commercially valuable seaweeds.

As with alliances for mangroves and coral reefs, a united seaweed front could foster broader partnerships and secure the participation and commitment of more stakeholders and therefore leverage more support for seaweeds.

Box 25. Working together will:

- Address knowledge gaps in the status and importance of seaweeds
- Increase inclusivity and strengthen collaborations
- Increase global awareness of the ecological and economic value of seaweeds
- Ensure integration of seaweeds in conservation, climate and development policy
- Drive scaled-up conservation and restoration efforts on the ground
- Promote and leverage investments in seaweed habitats and the seaweed industry
- Promote the sustainable use of seaweeds for resilient coastal livelihoods

7.4 The Seaweed Breakthrough

The state of the world's seaweeds report demonstrates emphatically that red, green and brown seaweeds and their habitats are crucially important for the functioning of marine environments and consequently for life on Earth. Multiple sources of evidence show that species and habitats are declining or disappearing at an alarming rate before they can be discovered or described, yet protection of seaweeds remains inadequate or non-existent.

About the UNFCCC 2030 Breakthroughs Agenda

A potentially powerful means of protecting seaweed habitats is through the 2030 Breakthroughs. Developed in partnership by the UN High-Level Climate Champions and the Marrakech Partnership, the 2030 Breakthroughs are rooted in the theory of change responding to the question: "What must we achieve by 2030 to transform the way these sectors operate?". They support global campaigns led by the UN High-Level Climate Champions, namely the Race to Resilience and Race to Zero, and their respective action agendas: the Sharm-El-Sheikh Adaptation Agenda and the 2030 Climate Solutions Agenda.

In 2023, the ocean community, united under the Marrakech Partnership on Ocean and Coastal Zones, with the support of the UN High Level Climate Champions, specifically identified the Ocean Breakthroughs: a set of targets to achieve by 2030 in five key sectors - marine conservation, shipping, ocean renewable energy, aquatic food systems and coastal tourism - to deliver for Climate, People and Nature. Indeed, accelerated action and investments in each of these sectors will help unlock the potential of the ocean as a source of solutions to the pressing challenges posed by climate change and biodiversity loss. While developed by Non-State actors, the Ocean Breakthroughs must be understood as a compass for all, including governments. Indeed, they are rooted in the "Blue Ambition Loop" - the positive feedback loop in which bold government policies and non-state actor leadership reinforce each other, and take ocean-based climate action to the next level.

The Seaweed Breakthrough initiative

In 2023, a Seaweed Breakthrough was proposed as part of the broader Ocean Breakthroughs (Fig. 36). Its potential inclusion under the overarching 'Marine Conservation' Breakthrough is under discussion, on the basis that this would cover conservation of marine function in general and food, being the basis of many of the world's fisheries and wild and farmed seaweeds. Putting the Seaweed Breakthrough in this category would elevate seaweed habitats at the same level as other critical marine habitats, e.g., mangroves, corals and seagrasses.

The Seaweed Breakthrough initiative aims to catalyse global action to conserve, restore, and sustainably manage seaweed ecosystems. The Breakthrough has begun with the development of the first-ever State of the World's Seaweed Report, which was launched at the 25th International Seaweed Symposium, in Victoria, Canada, May 2025.

Aligned with key global commitments, including the Kunming-Montreal Global Biodiversity Framework, the Paris Agreement, and the UN Decades on Ecosystem Restoration and Ocean Science, the Seaweed Breakthrough will serve as a stepping stone toward broader climate and biodiversity goals.

By aligning with Breakthroughs for other blue carbon ecosystems and aquatic food systems, such as kelp, seagrass and mangroves, the initiative aims to create a cohesive framework for protecting and restoring coastal ecosystems globally. This integrated approach will enhance resilience to climate change, safeguard biodiversity, and unlock the full potential of nature-based solutions to address pressing environmental challenges.

Setting the Seaweed Breakthrough targets

The Seaweed Breakthrough team is currently drafting a set of high-level ambitious Seaweed Breakthrough targets to halt the loss of seaweeds and their habitats, protect and restore them and secure financial investment by 2030 (Fig. 37). These draft Seaweed Breakthrough targets will form the basis of expert-led workshops to refine them and ensure they use informed decision making and best practice recommendations, are globally representative, inclusive and equitable. Implementation of the Seaweed Breakthrough targets will be undertaken following the Guiding Principles.

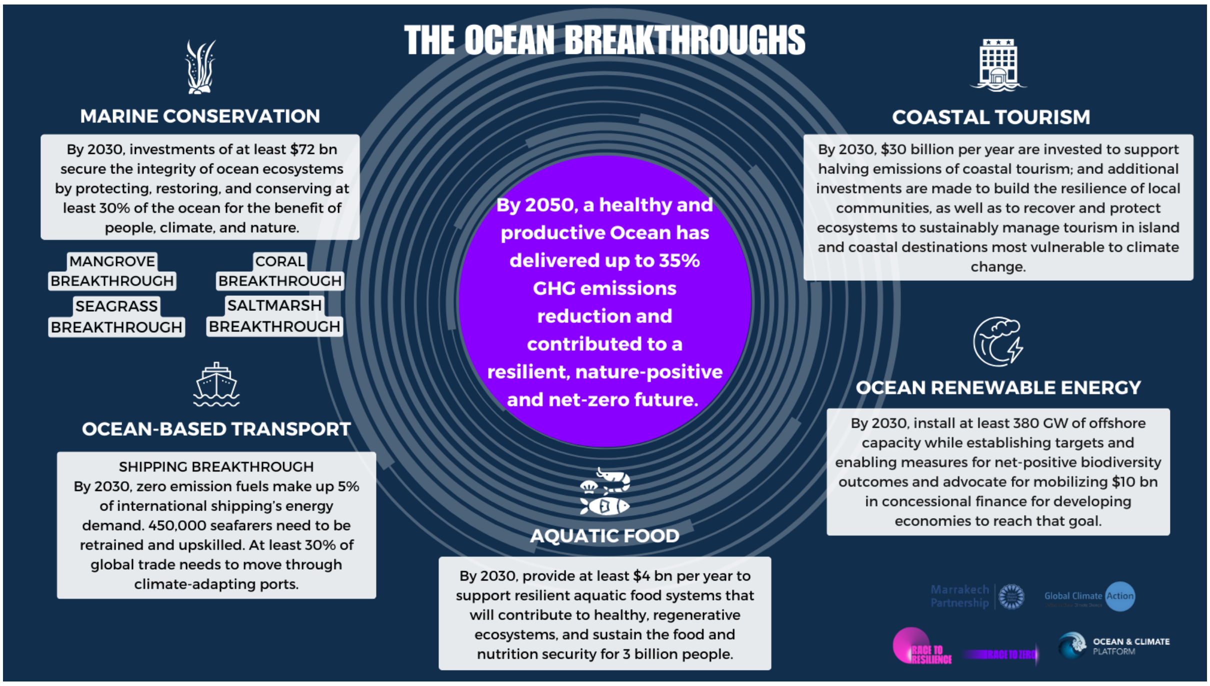

Figure 36. The UN Ocean Breakthrough categories, with the Seaweed Breakthrough proposed to fit in the Marine Conservation category.

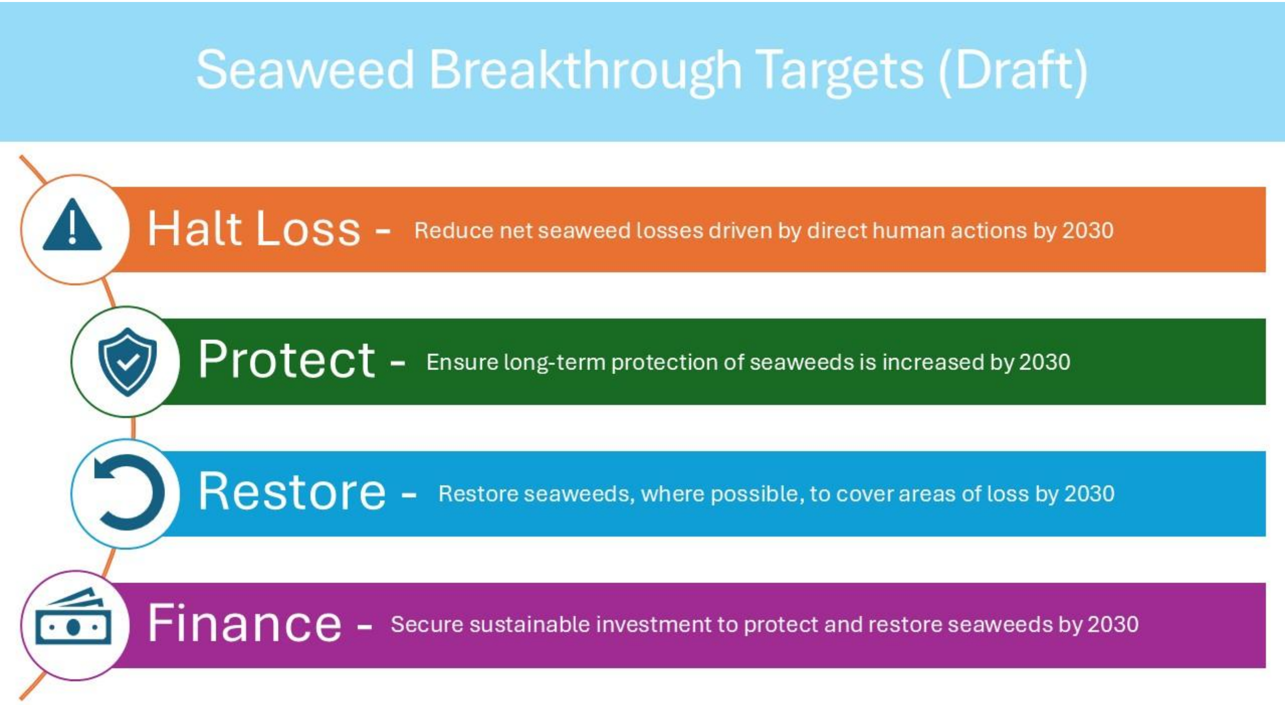

Figure 37. Draft Seaweed Breakthrough Targets.

Seaweed Breakthrough 2025: Guiding Principles

The guiding principles for implementing the Seaweed Breakthrough are aimed at protecting seaweeds and their wider habitats in an ethical way. The guiding principles provide a Code of Conduct for all parties, including civil society organizations, governments, Indigenous Peoples, local communities and the private sector who commit to endorsing the Breakthrough, and to reaching the targets in a fair and equitable way in line with the following principles:

1. Safeguarding nature and ecosystem function – all actions contributing to the Seaweed Breakthrough must align with protecting seaweeds and their habitats.

2. Employ science-based best practices in decision making – the most up-to-date scientific knowledge base and evidence-based understanding, including local knowledge and Indigenous knowledge, must be used to inform principles and practices for the Seaweed Breakthrough.

3. Inclusion, equity and justice – all conservation, restoration, monitoring and finance activities relating to the Seaweed Breakthrough must be undertaken with the explicit support, engagement, social inclusion, prioritisation of human and environmental rights and leadership of local communities, including Indigenous Peoples and marginalised communities, who depend upon or live alongside seaweed habitats. All actions must also ensure a just and equitable access to and clear benefit from efforts to conserve, protect and restore seaweeds for local communities, including the data and information generated from any such actions.

4. Empowerment and capacity building – all activities must include some form of capacity building as necessary to empower through the development and strengthening of skills, abilities and resources of organisations and communities who rely on seaweeds, taking into account gender and social equity.

5. Transparency and accountability – all activities relating to the Seaweed Breakthrough must be conducted in a transparent and accountable way.

6. Monitoring, Compliance, and Enforcement – all impacts (positive and negative) related to the activities of the Seaweed Breakthrough must be tracked at local, regional and global levels against Global Biodiversity Framework indicators to show progress on the delivery, review performance and highlight the legacy of the Breakthrough targets.

7. Policy Coherence – all actions, as appropriate, related to the Seaweed Breakthrough must work towards harmonising policies across various sectors and local legal frameworks to create a unified approach that supports and promotes the effective management of both the conservation of seaweed ecosystems and the livelihoods of communities dependent on these resources.

8. Design for sustainability, resilience and adaptability - all activities contributing to the Seaweed Breakthrough should be designed to be sustainable, resilient and adaptable using climate-smart approaches beyond 2030, to ensure flexibility given the climate crisis.

9. Sustainable financing – all stakeholders must ensure that financing for the Seaweed Breakthrough is ethical and includes diverse sources of funding through sustainable and long-term financing and investment methods; consideration of natural capital accounting and development of nature-positive economies should be included.

10. Platform for innovation – all activities relating to the Seaweed Breakthrough should enable stakeholders to pioneer new innovative solutions, whenever possible.

7.5 Closing remarks – a call to action

The state of the world's seaweeds, through bringing together a wealth of evidence from across the globe, recognises both the immense challenges seaweeds face but also provides hope in the power of science and innovation through research for new applications and conservation strategies. It also highlights the determined efforts already being made at local, national and international scales by individuals and organisations to safeguard the future of seaweeds. For this to succeed, engagement is needed across all levels of society and there needs to be a call to action on the global stage to accelerate protection and restoration of seaweed habitats, as well as securing sustainable investment.

Seaweeds are extraordinary. A world without seaweeds means devastation to the functioning and food security of the Earth as we know it. A world with seaweeds that are healthy and thriving offers hope of a better future for the planet. **[J. Brodie]**

Glossary

Algae: A collective, informal term for unicellular and multicellular photosynthetic organisms from across the tree of life that are not land plants.

Biofuels: Liquid or gaseous fuels, such as biodiesel and bioethanol, made from biomass.

Biogenenic: Produced or brought about by living organisms.

Biogeochemical cycles: The movement of nutrients and other chemicals between biotic and abiotic factors. Examples: carbon cycle, nitrogen cycle, sulfur cycle.

Biome: An area classified to the species that live in that location; e.g. rainforest, kelp forest.

Biostimulants: Resources that, when applied in small quantities, enhance plant physiological processes resulting in improved crop nutrition, stress tolerance, yield or quality without causing damage to, or possibly improving, the surrounding environment.

Calcareous: Containing calcium carbonate.

Carbon sequestration: The secure storage of carbon-containing molecules for 45 >100 years. In the context of carbon dioxide removal for climate mitigation, the origin of this CO_2 is from the atmosphere.

Circular economy: A model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible.

Citizen Science: The involvement of volunteers in scientific projects where they contribute to expanding our knowledge of the natural world through the systematic collection, analysis or interpretation of environmental observations. Also referred to as Community Science.

Connectivity: The degree to which gene flow affects evolutionary processes within populations (genetic connectivity), and the relative contribution of dispersal to population dynamics (demographic connectivity); relevant for management and conservation purposes.

Crustose coralline algae: Non-geniculate coralline algae attached to substrate (see Jardim et al. 2025).

Cryptic species: Organisms that are morphologically indistinguishable but genetically distinct enough to be considered separate species.

Cultivar: A variety that has been selected, modified or improved artificially by humans.

Deep water seaweed communities: Red, green and brown seaweeds that form habitats between depths of c. 60 m to 200 m or more (c. 300 maximum recorded).

Ecosystem restoration: A nature-based means of assisting intact, degraded or destroyed ecosystems.

Ecosystem services: The direct and indirect contributions that ecosystems provide for humans by the intrinsic nature of ecosystem functionality.

El Niño: A global climate phenomenon that emerges from variation in winds and sea surface temperatures over the tropical Pacific Ocean.

Endophyte: Living within the tissues or sheath of a plant or alga; e.g. an algal that lives inside another alga can be referred to as endophytic.

Eutrophication: An ecological process in which a water body becomes increasingly enriched with essential nutrients.

Farmed seaweeds Human made, typically monoculture of seaweed species grown on lines that are typically on the surface of the water or suspended in the water above the sea floor.

Floating or free-living pelagic seaweeds: Floating rafts, often extensive that drift with winds and ocean currents.

Fucoid forests: Intertidal and shallow subtidal habitats dominated by brown seaweeds; mostly fucoids or wracks in the order Fucales.

Green gravel: A restoration technique developed for kelp forests where small rocks are seeded with kelp spores in the laboratory, incubated for a few weeks and then scattered onto reefs to continue to grow.

***Halimeda* meadows:** Calcareous green algae that form meadow-like structures and sedimentary mounds in tropical and subtropical regions that contribute to carbonate formation and coastal protection.

Hydrocolloids: A group of water-soluble naturally occurring polymers of long polysaccharide chains found abundantly in nature; e.g. carrageenan, agar, alginate.

Invasive, non-native species (INNS): Those non-native species that have established and spread outside their native ranges some of which cause severe social, economic, cultural, and environmental impacts, affecting human livelihoods, biodiversity, and ecosystem services.

International Union for Conservation of Nature (IUCN) Red List of Threatened Species: An inventory of the global conservation status and extinction risk of biological species. Also known as the IUCN Red List or Red Data Book and founded in 1964.

Kelp forests: Underwater forests dominated by kelps mostly in the order Laminariales.

Kunming-Montreal Global Biodiversity Framework (GBF): A framework adopted in 2015 (Paris agreement) at the 15th meeting of the Conference of the Parties (COP15) which sets out a pathway to reach the global vision of a world living in harmony with nature by 2050. Key elements are 4 goals for 2050 and 23 targets for 2030 and it supports the achievement of the Sustainable Development Goals (SDGs).

Marine conservation: The protection and preservation of marine life. Sometimes referred to as ocean conservation.

Marine macroalgae: A term used to refer to the red (Rhodophyta), green (Chlorophyta) and brown (Phaeophyceae) seaweeds found in marine environments. They are macroscopic, typically multicellular, eukaryotic organisms, although some green species, e.g. *Codium*, are one giant cell (coenocytic). A few unicellular red seaweeds are included in seaweed lists, e.g. *Porphyridium*.

Marine protected area: Defined by the International Union for Conservation of Nature (IUCN) as: A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.

Morphology: Form or shape of an organism.

Nature-based solutions: Actions to address societal challenges through the protection, sustainable management and restoration of ecosystems.

Non-native species: A species introduced intentionally or unintentionally and established outside its native range. Sometimes referred as non-indigenous.

Nuisance algae: Species that form usually large scale, ephemeral events (e.g. algal blooms or green tides composed of *Ulva*; golden tides composed of *Sargassum*); often composed of just one species that grows rapidly.

Ocean acidification: Decreases in ocean pH linked to increasing levels of dissolved carbon dioxide in the water.

Ocean sprawl: Proliferation of coastal and offshore artificial structures.

Per- and polyfluoroalkyl substances (PFAS): A large, complex group of synthetic chemicals used in consumer products around the world since about the 1950s and are slow to degrade in the environment.

Productivity: The amount of growth or biomass that is made by a plant over a given time period. Gross primary productivity - energy used from sunlight via photosynthesis to turn inorganic compounds such as carbon dioxide into organic material. Net primary productivity is that left after energy is used in respiration. Think of this as net productivity.

Rhodolith beds: Aggregations of unattached calcified red algae; also known as maerl beds (see Jardim et al. 2025).

Seaweed health: The state of being physiological able to grow and reproduce to its potential, survive and adapt to biotic (e.g. grazing) and environmental stresses (e.g. excessively high temperatures), unbleached, and resistant to pests and diseases.

Seaweed microbime: The microbial communities of seaweeds consisting of an abundant, diverse assembly of organisms (including archaea, bacteria, fungi, microalgae, protozoa and viruses) on their surface and tissues.

Seaweed turfs: Dense low-lying aggregations of filamentous red, green and brown algae.

Seaweeds: Red (Rhodophyta), green (Chlorophyta) and brown (Phaeophyceae) marine macroalgae.

Strain: a known cultivar that differs in some way from the natural vegetative characteristics of the original cultivar.

Sustainable Development Goals (SDGs): A universal call to action comprised of 17 integrated goals to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity. They were adopted by the United Nations in 2015 and recognize that action in one area will affect outcomes in others, and that development must balance social, economic and environmental sustainability.

Taxonomy: The science of naming, describing and classifying organisms and includes all plants, animals and microorganisms of the world.

Triple Planetary Crisis: The three main interlinked challenges - climate change, pollution and biodiversity loss - that humanity currently faces.

Tropical seaweed beds: Shallow water habitat composed of a mixture of red (notably *Kappaphycus* and *Eucheuma* - eucheumatoids), green and brown (notably *Sargassum* and *Turbinaria*.

Vegetated marine habitat: A photosynthetic benthic marine habitat. Sometimes referred to as a biogenic habitat. It includes seaweeds, seagrass (eelgrass) meadows/beds, coral reefs (algal component), mangroves, saltmarshes.


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