

Section 4

Subchapter 4I

Macroalgae, not including phytoplankton

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Key points

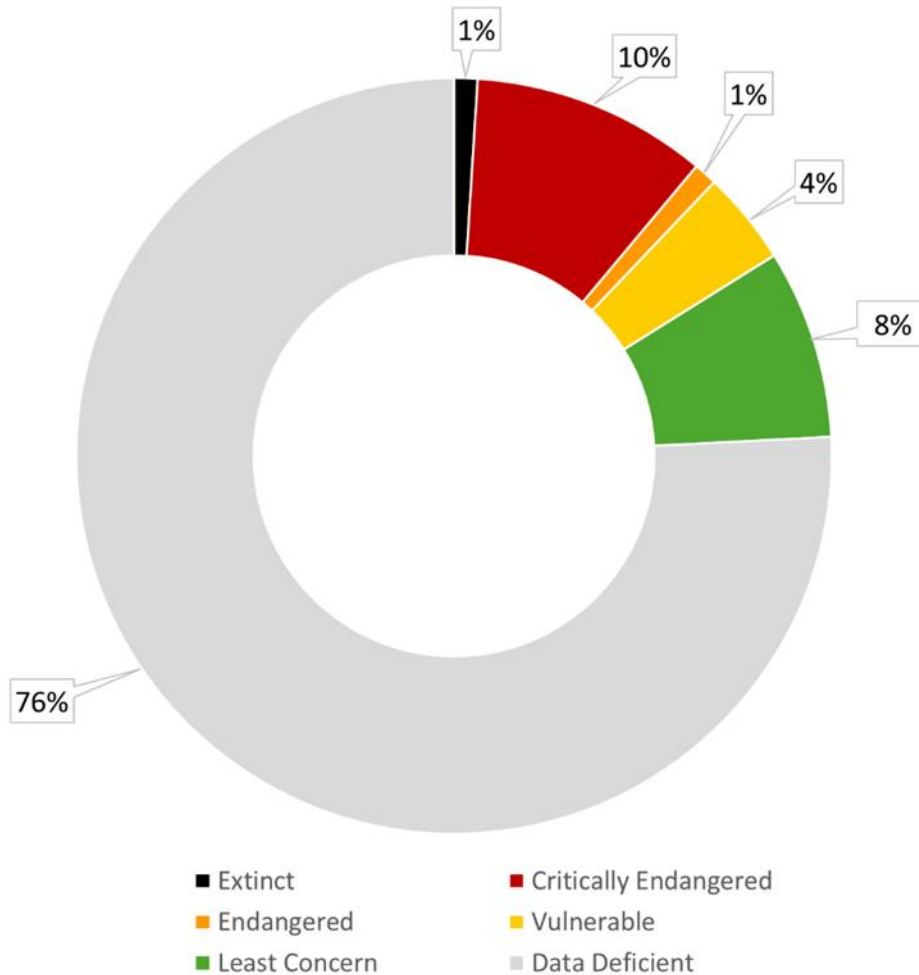
- Rapidly warming oceans, combined with anthropogenic stressors, will lead to further significant losses of certain macroalgal species and changes in the distribution patterns of others.
- The distribution of temperate and warmer water species is likely to shift poleward into temperate boreal and deeper waters, conditional on dispersal capacity and substrate availability.
- The incidence of invasive macroalgal blooms and turfs is likely to increase, leading to changes in ecosystem function.
- Less than 1% of macroalgal species described to date have been evaluated for their extinction risk using the International Union for Conservation of Nature (IUCN) Red List of Threatened Species assessment, and nearly 76% of the 99 macroalgal entries on the List are Data Deficient. This significant gap poses substantial challenges for assessing risk status.
- Significant gaps in taxonomic and distribution knowledge for many macroalgae is impeding progress in the effective monitoring of changes in population size and geographical range.

1. Introduction

The present subchapter contains a presentation of the overall status of red, green and brown macroalgae (commonly known as seaweed) and changes in the period 2018–2024. Here, the macroalgae are considered in their own subchapter, having been considered as a food source and as an ecosystem in the first *World Ocean Assessment* and included with marine plants in the second *World Ocean Assessment*. Up to 2024, only 99 macroalgae, from a total of over 11,400 species described (Guiry, 2024) are included in the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2024), and 76% of these are categorized as Data Deficient (figure I). Recognizing macroalgae in the third *World Ocean Assessment* is, therefore, timely and critically important, given that the maximum potential area of ocean that seaweeds can occupy is an estimated 6 million to 7 million km² (Duarte and others, 2022). Seaweeds also play a crucial role in marine ecosystem functioning, and many species are being significantly affected by climate change and other anthropogenic stressors (Cottier-Cook and others, 2023).

Figure I

Categorization of 99 macroalgal species on the International Union for Conservation of Nature Red List, reported from the Pacific North-West, the Pacific South-East and the Pacific South-West



Source: Prepared by the writing team.

Note: No macroalgal species in other marine regions have been categorized on the IUCN Red List.

2. Environmental change since the second *World Ocean Assessment*

Changes in overall status

Red macroalgae

Red macroalgae (Rhodophyta) occur from the poles to the tropics and from the intertidal zone to 290 m deep (Littler and others, 1991). Most red macroalgae are marine (97%) (Sutherland and others, 2011); they are habitat-forming (e.g. rhodolith beds; see figure II) and are integral components of other habitats (e.g. coral reefs and temperate and arctic rocky reefs) (see sect. 4, subchap. 5D). Red macroalgae provide ecosystem services, including by serving as breeding, spawning and nursery grounds for ecologically and commercially important marine species (Rendina and others, 2022). They are also harvested and/or

farmed, primarily in South-East Asia for their gelling and emulsifying colloidal agents and in East Asia for food and aquaculture feed (Cottier-Cook and others, 2021) (see subsect. 5A, subchap. 1D). The maximum potential area for red macroalgae globally is estimated as 6.69 million km² (Duarte and others, 2022), including 4.12 million km² of rhodolith beds (Fragkopoulou and others, 2021).

Currently (as of 2024), 7,698 red macroalgal species have been described (Guiry, 2024), although high levels of (pseudo-) cryptic diversity mean that many still need to be described and that new species are continually being discovered (Leliaert and others, 2018). Since the publication of the second *World Ocean Assessment*, two new orders have been established, Corallinapetrales (Jeong and others, 2021) and Inkyuleeales (Díaz-Tapia and others, 2019). Many larger genera (e.g. *Pyropia*) have been split into smaller units to better reflect their evolutionary relationships (Yang and others, 2020) and many species have been moved between genera on the basis of recent research (Hughey and others, 2020).

The role of coralline red algae in carbon sequestration remains contested, as the calcification process also releases CO₂. New research suggests that coralline macroalgae recycle 40% of the carbon from calcification into photosynthesis (Mao and others, 2024). Given the longevity of coralline macroalgae and the extent of rhodolith beds, globally they could represent an important store of carbon (400 to 38,000 tons of carbonate deposits) (Schubert and others, 2024) (see subsect. 5B, chap. 1).

Figure II

Rhodolith (maerl) bed, Ireland



Source: Peter Tinsley.

Green macroalgae

Green macroalgae, most of which belong to the class Ulvophyceae (Chlorophyta), consist of 1,900 species and are distributed worldwide (El-Manaway and Rashedy, 2022). They are typically found in shallow waters, although species have been recorded at depths greater than 210 m (Littler and others, 1985). They provide a wide variety of ecosystem services, including an important food source for marine

grazers, nutrient cycling and reef building (e.g. *Halimeda* spp.). Although the total coverage of green macroalgae has not been estimated, the global coverage associated with soft or sandy and coral habitats is estimated at 1.2 million km² (McNeil and others, 2016). *Halimeda* species produce reef-like habitats (bioherms) and their carbonate production ranges from 0.8 to over 17,500 g per m² per year in the Indo-Pacific (Schubert and others, 2023). These habitats are now considered to be major contributors to carbonate production in tropical and subtropical regions (Schubert and others, 2023).

A few opportunistic *Ulva* species can form extensive blooms (known as “green tides”), which have increased in frequency and can cause biodiversity loss, health risks and a reduction in ecosystem services in the affected area (Smetacek and Zingone, 2013; Joniver and others, 2021). The introduced *Halimeda incrustata* has also spread rapidly in shallow subtidal habitats of the western Mediterranean Sea (Vergruggen and Ballesteros, 2024).

Progress in resolving evolutionary relationships in green macroalgae is continuing. Since the publication of the second *World Ocean Assessment*, studies have indicated that not all green macroalgae of the class Ulvophyceae may descend from a common evolutionary ancestor (Del Cortona and others, 2020; Hou and others, 2022). Bryopsidales is likely to be more closely related to Chlorophyceae, a class of predominantly freshwater green microalgae, than to the remaining Ulvophyceae.

Several studies focused on local diversity of green macroalgae have highlighted the discovery of many undescribed taxa (Lagourgue and others, 2022; Tran and others, 2022), particularly in tropical regions. The sequencing of *Ulva* types has resulted in several name changes (Hughey and others, 2020; Hughey and others, 2021, Gabrielson and others, 2024), with *U. fenestrata* being the correct name of the temperate species often reported as *U. lactuca*, and *U. lactuca* being the correct name for the pan-tropical *U. fasciata* (Hughey and others, 2019).

Brown macroalgae

The brown macroalgae or Phaeophyceae (Ochrophyta) provide several ecosystem services, including food and habitat provision, nutrient cycling and carbon fixation, with an estimated value of approximately 500 billion dollars globally (Eger and others, 2023). The number of brown macroalgal species has been estimated at 1,800 (Guiry, 2024), with the vast majority inhabiting the marine environment. Their distribution is global, although they are mainly temperate and polar species, except for *Sargassum* and species from the order Dictyotales, which are often abundant in the tropics. They occur from the intertidal zone to a depth of 30 to 40 m, although they can extend down to depths greater than 200 m (Žuljević and others, 2016). The overall estimate of the total potential area for brown macroalgae based on distribution models is 2.68 million km², including 0.13 million km² for the intertidal zone (Duarte and others, 2022), 2.5 million km² for subtidal zone (Gattuso and others, 2006), and a maximum of 6,000 km² for floating *Sargassum* species (Wang and others, 2019, Zhang and others, 2019). The latter includes more than 20 million tons of floating *Sargassum* extending from West Africa to the Gulf of Mexico (Wang and others, 2019).

Since the publication of the second *World Ocean Assessment*, a novel brown macroalgal genus and species, *Setoutiphycus delamareoides* (Ectocarpales), has been described in Japan (Kawai and Hanyuda, 2021). Numerous other new species have also been described, including 15 new *Lobophora* species (Sun and others, 2021, Vieira and others, 2021, Jurejan and others, 2024) and two new species of *Dictyota* (Win and others, 2024).

Eger and others (2023) recently estimated that six major forest-forming kelps (*Ecklonia*, *Laminaria*, *Lessonia*, *Macrocystis*, *Nereocystis* and *Saccharina*) sequester 4.9 million tons of carbon from the atmosphere annually. Increased understanding of the role of brown macroalgae in the carbon cycle has also yielded new global estimates for seaweed-derived particulate carbon export below a depth of 200 m, which total 3% to 4% of the ocean carbon sink capacity and correspond to the sequestration of 4.4 to 48.5 million tons of seaweed-derived carbon annually for 100 years (Filbee-Dexter and others, 2024).

Major threats

Changes in climate and the rapidly warming ocean (Intergovernmental Panel on Climate Change (IPCC), 2023), together with anthropogenic stressors such as overharvesting, eutrophication, ocean acidification and pollution, are predicted to lead to an unprecedented decline in many macroalgae species. Conversely, the incidence of certain macroalgal bloom-forming species and turfs is likely to increase (Filbee-Dexter and Wernberg, 2018; Bermejo and others, 2023; Feng and others, 2023) (figure III). Since the publication of the second *World Ocean Assessment*, reports have warned, however, that ocean warming, thermohaline and circulation change, and marine heat waves, combined with other anthropogenic stressors, have resulted in the loss of more than 90% of certain kelp species in regions of Australia, the United States of America and Mexico, with significant implications for associated biodiversity and local economies (Dalmau and others, 2024). By the year 2100, depending on the warming scenario, brown seaweeds are predicted to lose 6 to 11% of their present estimated global coverage (Manca and others, 2024), and calcified red algal distribution is estimated to decline by 26 to 44% (Fragkopoulou and others, 2021), the latter being more susceptible to threats such as ocean acidification than the brown seaweeds (Cornwall and others, 2021). Furthermore, due to their extremely slow growth rates (around 1 mm per year), rhodolith beds may take centuries to millennia to recover from damage and are consequently described as a non-renewable resource (Barbera and others, 2003).

Seaweed loss is also predicted to increase in tropical regions (e.g. tropical red algae in South-East Asia) due to the effects of climate change and the associated pest, disease and invasive species outbreaks (Brakel and others, 2021) (see sect. 4, chap. 6), increased incidence of typhoons, ocean acidification (Page and others, 2022) and overharvesting (Mac Monagail and others, 2017). Ranges are also likely to shift further into Arctic, temperate boreal and deeper waters (Lebrun and others, 2022; La Guardia and others, 2023).

Figure III

***Ulva* species bloom in Songosongo, United Republic of Tanzania**



Source: Flower Msuya.

3. Region-specific changes

Arctic Ocean

Arctic macroalgae are experiencing significant changes due to rapid warming, declining sea ice, and increased habitat availability. Many species, particularly brown and red macroalgae, are predicted to expand their distributional ranges northward from more temperate regions, with a predicted loss of existing high-latitude macroalgae occupying similar habitats (Bringloe, and others, 2022). It is also likely that the potential calcified algal coverage will decline in the region as increasing temperatures and lower pH levels reduce the ability of these algae to calcify (Chan and others, 2020).

North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Marine heat waves in this region have led to a marked range shift or population-level change in a number of kelp species, such as *Laminaria digitata*, which is predicted to undergo a poleward range contraction and experience declines in growth performance (Leathers and others, 2024). Declines in the fucoid *Fucus vesiculosus* and increases in the filamentous turfing algae *Pylaiella littoralis* and *Ectocarpus siliculosus* have been attributed to increased eutrophication in the Baltic Sea (Hall and others, 2024). In the Mediterranean Sea, *Fucus virsoides* has seen a significant decline (Descourvières and others, 2024), and species that favour warmer waters (i.e. invasive species from tropical and subtropical regions, e.g. *Rugulopteryx okamurae*) have increased and spread (Falace and others, 2024; Wesselmann and others, 2024) (see sect. 4, chap. 6).

South Atlantic Ocean and wider Caribbean

Increases in macroalgal cover on hard coral reefs have been reported in the Mexican Caribbean (Contreras-Silva and others, 2020) and in floating, invasive, “pelagic” *Sargassum* species, which have extended beyond the Sargasso Sea (see subchap. 5Q) (Wang and others 2019) and proliferated in the tropical Atlantic between West Africa, Brazilian oceanic islands (Pellizzari and others 2020) and South America (Robledo and others, 2021; Sissini and others 2017) (see sect. 4, chap. 6).

Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

As in the Caribbean, more temperature-tolerant macroalgae are becoming increasingly dominant on coral reefs following incidences of coral bleaching (Gonzalez and others, 2024).

North Pacific Ocean

Twenty red macroalgal species are reported on the IUCN Red List for this region and all are endemic to the Republic of Korea (North-West Pacific). Of these species, 4 are categorized as Least Concern and 16 are categorized as Data Deficient (IUCN, 2024). The green macroalga *Codium spinulosum* (Bryopsidales) and three species of brown macroalgae are also endemic to the Republic of Korea (Yim and Won, 2023) and are categorized as Data Deficient (IUCN, 2024).

South Pacific Ocean

The IUCN Red List contains 58 red macroalgal species found in the South Pacific Ocean. They include one Extinct species from the South-West Pacific and 57 species from the South-East Pacific, categorized as Critically Endangered (6), Vulnerable (3), Least Concern (4) and Data Deficient (44) (IUCN, 2024). The brown macroalga *Nereia lophocladia* is endemic to New South Wales, Australia (Mamo and others, 2021), in the South-West Pacific, and two green macroalgal species, *Rhizoclonium robustum* (Cladophorales) and *Entocladia thivyae*, are both endemic to the Galapagos Islands in the South-East Pacific (Ruiz and Ziemmeck, 2013). All three species are categorized as Data Deficient (IUCN, 2024). Fifteen species of brown macroalgae from the South-East Pacific are thought to be endemic to the Galapagos and are categorized as Endangered (1), Critically Endangered (4), Vulnerable (1) and Data Deficient (9) in the IUCN Red List (IUCN, 2024).

Southern Ocean

Records have recently been compiled for this region, which include 151 macroalgal species (85 Rhodophyta, 34 Ochrophyta and 32 Chlorophyta) in Antarctica, in the South Shetland Islands (Pellizzari and others 2023; Oliveira and others, 2020), King George Island and Adelaide Island (Nelson and others, 2022). Distributional shifts and a reduction in the endemism rate have been reported in this region (Pellizzari and others, 2017), and, according to a recent modelling study, there is a high potential for macroalgal expansion into this region as a consequence of climate change (Manca and others, 2024).

4. Key remaining knowledge gaps

Despite the substantial evidence showing that macroalgal species and their habitats are declining, significant numbers of species remain undescribed, undiscovered (Guiry, 2024) and/or inadequately protected or conserved. The lack of a sound taxonomic framework for identifying and monitoring species hampers efforts to determine their distribution, threats and changes to status (Brodie and others, 2023), as

well as efforts to implement effective conservation, protection and restoration strategies. It also presents significant challenges for assessing species for the IUCN Red List, which can raise awareness and assist in the global conservation of a species, as clearly shown by the fact that less than 1% of macroalgae known are listed from a very limited number of regions globally. The contribution of many seaweeds (e.g. rhodolith beds and kelp forests) to larger-scale processes such as carbon sequestration (Schubert and others, 2024) also requires further investigation (Intergovernmental Oceanographic Commission (IOC-UNESCO), 2024). There is urgent need, therefore, to (a) strengthen data-driven conservation efforts to ensure that losses in macroalgal diversity are halted and habitats restored whenever possible; (b) ensure that range shifts are reported and vulnerable species protected; (c) identify undescribed species using the latest molecular approaches; and (d) ensure that the role of macroalgae in large-scale ocean processes is more widely understood.

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