Introduction

Most of the world has become acquainted with the concerns over overfishing and pollution as major threats to the commercial harvest of marine animals and the health of the seas and oceans. This review analyses a much lesser known problem in salt-water ecosystems: the decline of kelps – seaweeds which in fact are not only major harvestable resources in their own right but also serve as habitat for huge amounts of sea life. Unlike terrestrial habitats, the marine realm and especially kelp forests are largely invisible to most people, and so the alarming risks to their welfare are not evident. The chief menaces – all caused by human activities – are habitat depletion, reduction of water quality, global warming, overharvesting and elimination of predators that control kelp herbivores. As will be discussed, it is possible to sustainably manage the supply of kelps for the benefit of both people and biodiversity.

The plants

‘Algae’ (singular: alga) include unrelated groups of photosynthetic organisms, both unicellular and multicellular species. Except for the freshwater family Characeae (known as ‘stoneworts’ and ‘brittleworts’), which is apparently the ancestor of higher land plants, none of the algae is related to flowering plants. Nevertheless, traditionally almost all ‘green’ or ‘greenish’ photosynthetic species have been referred to as ‘plants’. The practice of placing all photoautotrophic organisms (i.e. those that capture the energy of sunlight) in the ‘plant kingdom’ is still very common, although it is clear that some are in fact more closely related to animals or fungi than they are to flowering plants.

The term ‘seaweed’ is also now known to refer to an assemblage of unrelated groups. Seaweeds are large photosynthetic marine species of remarkable diversity (Figure 1; Textbox 1). They are also called ‘macroalgae’ (literally ‘large algae’), because unlike numerous photosynthetic species which are microscopic or almost so (and which are usually unicellular or composed of cells associated in very small colonies) they are large, sometimes huge. The seaweeds are ‘protists’: a mixed grouping of quite unrelated species. They cannot be classified as animals, plants, or fungi, and are diverse, including amoebae, brown and red (but not green) algae, dinoflagellates, diatoms, Euglena and slime moulds. Many are unicellular and microscopic, unlike seaweeds, which always develop multicellular bodies.

Textbox 1. The evolutionary relationships of kelps

The application of new methods in molecular biology, biochemistry, ecophysiology and also ecology has drastically changed our perception of kelps. The major discovery was that kelps are very distant from higher land plants and have to be considered as protists in the broad sense: classically brown algae, along with green and red algae were regarded as plants. Among many other features they share the presence of plastids and of complex vegetative bodies, at least in their advanced groups. However, brown algae on the one hand and green and red algae on the other are fundamentally different with respect to the nature and origin of their plastids… kelps may thus be regarded as photosynthetic protists… They form a fifth independent lineage of multicellular organisms, next to animals, fungi, green algae and land plants, and red algae.

– Bartsch et al. (2008)

About 10,000 species of seaweeds have been recognised. They fall into three principal groups (often called ‘divisions’) based on their dominant pigmentation: red algae (Rhodophyta), brown algae (Phaeophyta) and green algae (Chlorophyta). Fleurence and Levine (2016) estimated that there are about 7000 species of red seaweeds, 1500 species of brown seaweeds and 900 species of green seaweeds. Kaliaperumal (2015) estimated the groups to contain 6000, 2000 and 1200 species. (Authorities differ in how green algae should be recognised, particularly
flowering plants, algae do not reproduce by flowers and seeds. The life cycle of the brown algae involves alternation of a large stage (the ‘sporophyte’) which produces spores that swim by flagellae, and a microscopic stage (the ‘gametophyte’) which produces male swimming gametes (the equivalent of sperm cells) that swim to a female gamete (the equivalent of an egg) that is stationary (attached to the sporophyte) (Luthringer et al. 2014). The combination of male and female gametes produces a new sporophyte, and the cycle repeats.

The most important brown algae are the ‘kelp’ (used both as singular and plural) or ‘kelps’ – the brown algal

Figure 1. Illustration (public domain) of seaweed biodiversity, painted by Adolphe Millot (1857–1921). Source: Pierre and Augé (1906). The 47 species are identified at https://sr.wikipedia.org/sr/%D0%94%D0%B0%D1%82%D0%BE%D1%82%D0%B5%D0%BA%D0%B0:Adolphe_Millot algues.jpg.

whether the Characeae mentioned previously should be included.) Many brown seaweeds are huge, whereas most red and green seaweeds do not exceed a metre in length. The red algae tend to dominate warm waters, while the brown algae prevail in cold waters. Of the more than 1000 genera of seaweeds recognised, only about three dozen are harvested commercially, mostly from the red and brown groups, although about 100 genera are collected for local use (West et al. 2017).

All known brown algae are multicellular, and most are marine, although a few of the 300 or so genera occur in fresh or estuarine water (Kawai and Henry 2016). Unlike flowering plants, algae do not reproduce by flowers and seeds. The life cycle of the brown algae involves alternation of a large stage (the ‘sporophyte’) which produces spores that swim by flagellae, and a microscopic stage (the ‘gametophyte’) which produces male swimming gametes (the equivalent of sperm cells) that swim to a female gamete (the equivalent of an egg) that is stationary (attached to the sporophyte) (Luthringer et al. 2014). The combination of male and female gametes produces a new sporophyte, and the cycle repeats.

The most important brown algae are the ‘kelp’ (used both as singular and plural) or ‘kelps’ – the brown algal
order Laminariales. The kelps are among the largest algae in the world, and many are huge, tough and leathery (Figure 2). The classification of several of the genera has recently been revised (Lane et al. 2006), so that some common species are known by both an older and a newer scientific name. About 112 species in 33 genera are currently recognised (Bolton 2010). While rather variable, most kelps have a root-like holdfast, a flexible stipe (stem-like portion) and large blades (flattened expansions often resembling leaves). The holdfast anchors the plant so that it will not float away, but is not like the root systems of terrestrial plants, which serve to absorb water and dissolved nutrient elements. Of course, marine algae are mostly or entirely in water, so most cells have ready access to elements in the water. Some species have gas-filled bladders near the blades to elevate them near the water surface where they will be exposed to light. There are both annual and perennial species. The most important commercial kelps are *Saccharina japonica* (formerly *Laminaria japonica*, and known by several Asian names) and *Undaria pinnatifida* (known as ‘Wakame’; Kim et al. 2017). Giant Kelp (*Macrocystis pyrifera*; Figure 2) is the most impressive of the kelps, occasionally developing weights of over 200 kg (440 lb) and lengths of 80 m (260 feet). It is one of the most important commercial genera of seaweeds (North 1987; Schiel and Foster 2015).

Another brown algal order, the Fucales, also contains seaweeds sometimes marketed for drug purposes as kelp (and also often as ‘Fucus’), although these are best referred to as fucoids. *Fucus vesiculosus* (Bladderwrack), a frequent inhabitant on the rocky coasts of the Atlantic and Pacific Oceans, and *Ascophyllum nodosum* (Knotted Wrack) of the coasts of the North Sea, the western part of the Baltic Sea, and the east coast of Canada, are the species usually encountered in commerce. The pharmacological properties of these fucoids are comparable to those of the true kelp. The most famous genus of the Fucales is *Sargassum*, which is the most common brown algal genus in the world, and includes numerous species (frequently simply called ‘Sargassum’) of the temperate and tropical oceans, including free-floating species. The Sargasso Sea in the North Atlantic Ocean was named after floating carpets of Sargassum seaweeds. Earth’s only sea not bounded by land, the region is delimited by surrounding currents, and is noted for its calm waters. The sea is falsely depicted in literature as a dangerous area where ships and planes have perished. The Sargasso Sea is a biologically rich ecosystem, and a refuge for some iconic marine animals, including eels, Leatherback Sea Turtles, Humpback Whales, Sperm Whales and Bluefin Tuna (Figure 3). One of the most interesting species associated with these seaweeds is the very curious Sargassum Fish, which is camouflaged to blend into the seaweed (Figure 4).

Currents deposit refuse into the area, especially non-biodegradable plastic wastes, and the accumulation of garbage as well as the location in international waters makes the area susceptible to degradation. An international commission was established to protect the unique area (Freestone and Bulger 2016).
Geography and ecology of kelps

Textbox 2. The role of kelps in supporting other species

As foundational species and important contributors to primary production, the large canopy-forming fucoids and laminarians provide food, habitat, nursery refugia and shelter to a wide range of intertidal species, thereby supporting complex food webs in coastal habitats. The large structural seaweeds offer protection from predation to some species while allowing refuge from desiccation at low tide and they can also be involved in reducing tidal surge and waves affecting coastline erosion and sedimentation rates, by dampening the incoming energy.

– Mac Monagail et al. (2017)

Habitat forming species or ‘engineers’, such as kelps and corals, exert control over entire communities by modifying the environment and resources available to other organisms. In particular, kelps alter light, nutrients, sediments, physical scour, and water flow conditions for proximal organisms while providing structural habitat for a wide range of flora and fauna. Within the UK alone, over 1800 species have been recorded from kelp dominated habitats.

– Smale et al. (2013)

Like most seaweeds, kelps are ‘lithophytic’ (growing attached to hard substrates, such as rocks), although a few are free-floating. The majority of kelp species occur in the North Pacific, with about 40 from the coast of North America, about 40 from Asia, and only eight in the North Atlantic (Lane et al. 2006). Kelps are common in coastal waters of cold-temperate regions from the Arctic to the Antarctic, and usually dominate the lower intertidal and upper subtidal floras. They are well-adjusted for cold waters and overcast skies, and are fast-growing. Kelps provide food and habitat for numerous species of marine organisms (Small, Druehl, and Catling 1997). They are ‘foundation species’, essential because their removal can greatly disturb the ecosystems they support (Textbox 2).

Kelp forests

Seaweeds, especially kelps, have been characterised as the ‘trees of the oceans’, an analogy that is appropriate given how they physically dominate the ecosystems in which they occur. ‘Kelp forests’ are frequently viewed as the marine equivalent of terrestrial rainforests. They are stands of large brown algae, growing on the sea edge, typically on rocky ground at levels down to 40 m (130 feet). Kelp forests are made up of continuous, dense groves, with different species dominating bands from the lower intertidal to deep subtidal zones. They constitute important marine ecosystems in temperate and polar coastal areas of much of the world. Rarely, they occur in tropical areas (Santelices 2007). Kelp forests are found in temperate

Figure 3. Illustration of a Sargassum floating mat and the varied biodiversity supported (including fish, sea turtles, birds and marine mammals). Public domain figure prepared by the U.S. National Oceanic and Atmospheric Administration.

Figure 4. Sargassum Fish (Pterophryne histrio) camouflaged to live among drifting Sargassum seaweed. (a) Painting (public domain) from Baldwin, A. H. 1905. The Bahama Islands. Geographical Society of Baltimore. 1905. Plate LV. (b) Photo of fish from the Gulf of Mexico. Public domain figure prepared by the U.S. National Oceanic and Atmospheric Administration. Credit: SEFSC Pascagoula Laboratory; Collection of Brandi Noble, NOAA/NMFS/SEFSC.
habitats in situations that are similar to those occupied by coral reefs in tropical waters. Natural stands of kelps support significant commercial and recreational fisheries, especially for indigenous groups and small operations. The oceans now receive considerable run-off of nitrogen and phosphorus from urbanisation and agriculture, and kelp forests have become an important factor in decreasing their levels in marine environments. The oceans are also being acidified by increasing carbon dioxide in the atmosphere (the water absorbs CO₂ from the air, leading to a decrease in pH), and once again kelp forests are important planetary controllers of such pollution, reducing levels of dissolved carbonic acid. There is evidence that kelp forests are being affected negatively by human-caused changes to the environment (Krumhansl et al. 2016).

Sea urchins are very significant herbivores of kelp, but their numbers are controlled through predation by lobsters, crabs and Sea Otters (Steneck et al. 2002; Filbee-Dexter and Scheibling 2014; Figures 5 and 6). Widespread destruction of kelp beds in shallow water on both the East and West Coasts of North America has been attributed to the unchecked overfishing of lobsters and crabs in the East, and the early extirpation of Sea Otters in the West to supply fur for the European market during the 1700s. Sea Otters were recently reintroduced from Alaska to north-western Vancouver Island and are extending their range along the British Columbia coast. This has led to a decline in sea urchin populations and a resulting revival in barrier kelp, which was once so extensive that it provided a safe navigation route of sheltered water between the offshore beds and the land.

Kelp forests vastly increase the surface area upon which huge numbers of invertebrates and fish can locate, thus increasing biodiversity. One of the most interesting kelp inhabitants is the Leafy Seadragon (*Phycodurus eques*; Figure 7) of southern coastal Australia. The long leaf-like protrusions from its body serve as camouflage, making it very difficult to distinguish from kelp growing in its habitats. This small fish (20–24 cm or 8–9.5 inches long) is a relative of the Sea Horse. It is the marine emblem of the state of South Australia, and has protected status.

**Harvest**

Although most seaweeds are now collected from aquacultures, they have been traditionally harvested from nature, using boats on open waters, or from shore areas (either by wading or simply by picking up material washed up on shore, as shown in Figure 8). Receding tides have often left abundant material. Coastal communities traditionally
collected seaweeds on a small scale, for food, forage, or as a fertiliser or soil conditioner. In some parts of the world, including Korea, divers (especially women) swim down to the bottom of large seaweeds and cut them off at the base. Commercial harvesting often utilises mechanical harvesters.

**Economics**

Fossil evidence suggests that humans employed seaweeds at least as far back as the Neolithic period (about 10,000–2000 BC, depending on location). Even older, seaweeds that had been cooked and partly eaten were found at a 14,000-year-old site in southern Chile (Kim et al. 2017). The first written records trace to about 1700 years ago, in China (Buschmann et al. 2017), and references in ancient Greece and in the Icelandic sagas to the use of seaweeds to feed livestock for several past millennia (Makkar et al. 2016). The earliest uses were as raw material for food, feed, fuel, and medicine. In more recent times, seaweeds have been employed predominantly as sources of industrial, medicinal and food extracts.

Seaweeds are primary producers, the foundation of coastal ecosystems, providing a harvest estimated to be worth about US$8 billion dollars annually (Hehre and Meeuwig 2016), US$10 billion annually (Rebours et al. 2014), or as much as US$16 billion (Lindsey White and Wilson 2015). Commercial harvest of seaweeds is carried out in about 35 countries, amounting to about 21 million metric tons. More than 95% of global seaweed production is farmed, about 60% in China (Figure 9), 21% in Indonesia and 9% in the Philippines (Hehre and Meeuwig 2016). In Europe and the Americas, seaweed cultivation is minor, but has the potential for considerable growth (Rebours et al. 2014). Only a small fraction of the total seaweed harvest is cut from the wild, mostly from 32 countries (Mac Monagail et al. 2017). Most seaweed harvested by Europe, Canada and Latin America is from the wild. Wild harvest amounts to about 1 million tonnes (fresh weight) annually, the top producers in decreasing order being Chile, China, Norway, Japan, France, Ireland, Iceland, South Africa and Canada (West et al. 2017). Wild kelps are of special biodiversity and economic value to Chile (Vásquez et al. 2014; Figure 10). The global fresh weight harvest of seaweed biomass is about 30,000,000 tonnes, which is dwarfed by the corresponding biomass of harvested terrestrial vegetation: 1,600,000,000,000 tonnes (Buschmann et al. 2017).
edible brown seaweeds is indigestible. Nevertheless, kelps are used directly as vegetables and condiments, principally in China and Japan. The Ainu in northern Japan collected *Saccharina japonica* for food as early as the eighth century AD, and during a later period only the privileged classes were allowed to eat this sea vegetable. Like other seaweeds, kelp are also harvested as dried fodder for terrestrial livestock in coastal areas (despite the limited digestibility), and sometimes grown as forage for cultivated aquatic animals, such as abalone. A special roe growing on kelp, greatly valued in sushi bars of Japan, has been produced in British Columbia by herring spawning in penned kelp enclosures. The industry is largely managed by indigenous people and the harvest is valued at over 20 million dollars annually.

**Hydrocolloids**

Seaweeds are commercial sources of high-value polysaccharides, especially agar, carrageenan and alginates. Chemically, these compounds are ‘hydrocolloids’, which produce viscous colloidal solutions or gels in water. They are primary cell wall structural constituents of brown and red algae. Unlike cellulose in land plants (and also in seaweeds), which results in rigidity to withstand gravity, the hydrocolloids provide seaweeds with flexibility to withstand currents and waves. About 20% of world production of seaweeds is employed for hydrocolloid production for use in the food, industrial, cosmetic, and medical sectors (West et al. 2017). ‘Phycocolloids’ are hydrocolloids obtained from seaweeds. Carrageenans and agars are important hydrocolloids commercially obtained from red algae. In fact, three of the seven most cultivated seaweeds of the world are red algae employed mainly for hydrocolloid extraction: *Euchema* species and *Kappaphycus*
Kelp tablets and powders have become popular herbal preparations in North America, and claims have been made that kelp products are useful in treating a variety of ailments. The therapeutic properties of kelp have been attributed particularly to content of trace minerals, especially iodine, which is typically 20,000 times as concentrated in the seaweed by comparison with its aquatic habitat. However, the level of iodine has been found to vary considerably among algal species and even within a species, so that commercially available products may deliver different dosages. The very high iodine content of brown algae led to their use in goitre medicines, but the variability of concentrations and the varying absorption conditions for bound and unbound iodine in the plant has made such algal therapy obsolete. Required daily intake of iodine in adults is only 150 micrograms, and the thyroid gland normally does not make use of excess iodine, and indeed very large doses of iodine can induce or intensify hyperthyroidism. Kelp are currently marketed as a weight-reducing agent, supposed to be a result of increased production of thyroid hormones that increase metabolism and so remove deposited fats. While beneficial effects on obesity have been claimed, the medical community considers such therapy as potentially dangerous and highly inadvisable. Kelps have large amounts of sodium, and so should be avoided in salt-restricted diets. Calcium and magnesium, both desirable as nutritional electrolytes, have also been found to be very high in some commercial kelp preparations.

Although kelp is thought to inhibit heavy metal absorption in humans, kelp growing in polluted waters may accumulate very high levels of heavy metals such as strontium and cadmium. Toxic levels of lead can develop. Most dangerously, kelp accumulates arsenic, although in non-polluted waters this should not pose a risk. Manufacturers of kelp products should of course ensure that toxic levels of any of these are not present.

**Other products**

Kelps and indeed other large marine algae have a diversity of uses, like many terrestrial plants. The British Columbia coastal Indians stretched kelp stipes to make fishing lines and used the hollow bulbs and stipe bases as bottles. Many brown algae have been extensively used as agricultural fertilisers, especially as a source of potash (which supplies potassium). As a soil amendment, seaweeds also tend to be rich in micronutrients and nitrogen, but are low in phosphate. They have the advantage of being free of terrestrial weeds and fungi. They are also beneficial in reducing, albeit to a very minor extent at present, the use of synthetic fertilisers, which have catastrophic effects on the environment. Just as there has developed a certain mystique about the health benefits of brown algae for humans, so too are some
conviced that algae have particular nutritional benefits for land plants. This has led to considerable research on plant growth factors in seaweeds (possibly plant hormones, particularly cytokinins), and the marketing of seaweed extracts for use as plant growth stimulants. The hope has also been expressed that alginic acid (marketed as Nomozan) may inoculate some crops against viruses.

There is interest in developing seaweeds as a source of biofuels (López-Contreras et al. 2017). There are indications that bioethanol can be produced from seaweeds in more eco-friendly ways than from terrestrial plants (Jung et al. 2017). Brown algae tend to produce more biomass per unit area than red or green algae, and so are especially suitable for production of biomass to be employed as biofuel (Song et al. 2015). The kelp species Saccharina lattissima has been evaluated as a source of bioethanol (Adams, Gallagher, and Donnison 2009). A recent development is the use of kelp as a substrate for biogas (methane) production, a technology that was developed during the OPEC crisis by General Electric of the United States. The value of this technology in reducing the high energy costs in the Canadian Arctic has been explored by Canadian companies.

**Risks and benefits of seaweed farming**

‘Aquaculture’ refers to raising of species in water for harvest of economic products. (This could include growing unicellular algae for biofuels, or even growing yeast in fermentation tanks to produce alcohol in beer and wine production.) ‘Mariculture’ is usually defined as a branch of aquaculture, dedicated to growing species in marine environments, i.e. the raising of marine plants and animals in the oceans. Most cultivated marine species are seaweeds, mollusks, crustaceans, or finfish. The degree to which the species raised are ‘free-living’ can be variable (they may be kept in enclosures, or especially if non-motile they may simply be maintained in a designated area of the ocean). Sometimes mariculture is more broadly interpreted as also including such cultivation in brackish water, or in artificial salt water created on land. Sometimes mariculture is less broadly interpreted as only referring to cultivation in natural seawater in the sea, and cultivation in artificial seawater or seawater pumped to a location on land is placed under aquaculture. Regardless of these distinctions, almost all seaweed cultivation occurs in the sea very near the shore, although attempts are underway to establish ‘offshore’ sites.

In rich Western countries (mostly in Europe and North America) nearshore aquaculture is heavily regulated, because shorelines are used for recreational (boating, fishing, swimming) and residential (waterfront homes and hotels) purposes, and because environmentalism is relatively accepted. By comparison, seaweed farms are mostly located in shallow marine habitats in developing countries with high rates of population growth, often employing poor people desperately in need of income and food. In these circumstances, pollution, siltation, overexploitation, and harmful harvesting practices cause ecological damage. Regrettably, ‘the introduction of seaweed farming does little to mitigate the effects of fisheries overexploitation, and that rather than replacing fishing it is utilised as an additional source of income’ (Hehre and Meeuwis 2016). Coral reefs and some seagrass habitats have been particularly susceptible to development of seaweed farms. Curiously, after shallow marine habitats have been significantly degraded, the subsequent establishment of seaweed farms has sometimes been found to benefit fish, particularly herbivorous species (although often further reducing species richness, abundance and biomass of fish assemblages). On the whole, cultivating seaweeds has harmful effects on marine biodiversity in parallel with how terrestrial agriculture has harmful effects on land-dwelling biodiversity, and the best that can be done is to minimise harm to natural habitats and the organisms they support.

The most significant accomplishment of seaweed farming has been to reduce the pressure on natural stands, and the uncontrolled harvesting of wild-growing algae. Seaweed farming does not significantly use fresh water or arable land, both resources that are increasingly rare and to date have been associated with terrestrial biodiversity loss, so indirectly mariculture tends to benefit land ecosystems.

**Polyculture and IMTA**

‘Polyculture’ has been variously defined, for example ‘the simultaneous cultivation or exploitation of several crops or kinds of animals.’ The simple fact that more than one crop is cultivated in a given field is often advantageous in avoiding or reducing the problems associated with monocultures (for example, uniform plantings are especially attractive to pests). A more sophisticated definition of polyculture follows: ‘Polyculture is agriculture using multiple crops in the same space, providing crop diversity in imitation of the diversity of natural ecosystems, and avoiding large stands of single crops, or monoculture… It is the raising at the same time and place of more than one species of plant or animal’ (Wikipedia). ‘Integrated Multi Trophic Aquaculture’ (IMTA) has been claimed to be distinct from polyculture (Chopin 2006), and in any event is a relatively ecologically attractive system of co-cultivated species to establish simple analogues of natural ecosystems in which a trophic (feeding) cycle is established to recirculate generated chemicals that if not removed would be pollutants. IMTA has attracted the interest of many in the seaweed industries (Chopin 2013). Typically the waste from a
marine animal fertilises a seaweed that feeds the animal(s)). Another technique is to take advantage of one partner’s output as fertiliser or feed for the other (e.g. feeding seaweed extractives to cultured animals). By carefully balancing of the chosen species, it is possible to achieve more efficient and profitable business outputs, as well as improving environmental and ecosystem health.

Conservation aspects

Textbox 3. The conservation importance of seaweeds

Macroalgae or seaweeds are one of major components of primary biomass production in coastal maritime ecosystems and play an essential ecological role as habitat and substrata for invertebrates, fish, mammals, and birds. Drastic reduction of any macroalgal community directly influences marine biodiversity, as well as reproduction, recruitment, and growth rates of marine fauna. Furthermore, macroalgae may also protect coastlines against erosion and contribute significantly to the marine carbon cycle. It is possible that overexploitation of natural seaweed resources could lead to significant ecological, economic, and social consequences at local, regional, and even global scales.

– Rebours et al. (2014)

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

– Charles Darwin (1 June 1834, Tierra del Fuego, Chile; cited by Erlandson et al. 2007)

Habitat threat

Seaweeds are critical to the welfare of coastal ecosystems (Textbox 3). The future of marine biodiversity and biore-sources is more dependent on wild kelps than on any other group of species, and hence they need to be considered in any analysis of marine conservation. Kelp forests support enormous amounts of marine creatures, and harvesting of wild kelps and the effects of pollution, nutrient overload, and coastal development on kelp distribution represent critical threats to marine biodiversity. Although most seaweed production is by cultivation, several countries produce most of their seaweed by harvesting wild resources, and over-exploitation can lead to considerable loss of biodiversity associated with kelp forests. Because seaweeds absorb considerable amounts of elements, they represent a means of decreasing pollution from adjacent land, but this only makes sense if cultivating seaweeds is carried out in ways that do not add polluting chemicals to the oceans. The canopies of seaweeds cultivated near shorelines dampen the coastal erosion effect from waves (the same applies to wild seaweeds), and this can assist in preserving coastal ecosystems (Duarte et al. 2017).

Seaweeds oxygenate water, promoting biodiversity, and this is true not only for natural stands of kelps but also for those that are cultivated (Duarte et al. 2017).

Climate change threat

Conceivably climate change could be beneficial to some species, extending their ranges. Similarly, it could be argued that increasing CO₂ concentrations in oceans is good because it increases photosynthesis of some (non-calci-fied) species, and rising sea levels is good because it increases shoreline habitats. Generally, however, climate and environmental stresses destabilise ecosystems and endanger many of their biota. Kelps are especially affected by rising water temperatures because sexual reproduction in most kelps will not occur above 20°C (68°F), and local climate warming in parts of Europe is thought to be endangering several species (Raybaud et al. 2013; West et al. 2017). Other possible ways that seaweed cultivation might reduce the harmful effects of climate change include (Duarte et al. 2017): when used for biofuels, emissions from fossil fuels are reduced; when used as fertiliser, the use of synthetic fertilisers and their associated consumption of fuels are reduced; and when included in cattle feed, methane emissions from cows are reduced.

Algae store as much as half of the world’s carbon (Chung et al. 2011). Because seaweeds absorb considerable carbon, they represent a means of decreasing (‘sequestering’) atmospheric CO₂, the chief contributor to the greenhouse effect and climate warming. Carbon sequestered in both living and non-living biomass in the ocean and coastal habitats has been termed ‘Blue Carbon’ (Chung, Sondak, and Beardall 2017) and aquaculture promoting the reduction of atmospheric CO₂ has been termed ‘Blue Carbon Farming’ (Duarte et al. 2017).

Gene threat

Many wild terrestrial plant populations are at risk of genetic alteration or even extinction because they interbreed easily with nearby cultivated or introduced plants. Considerable care is currently taken to prevent genetically engineered land crops from contaminating related wild species, but little care has been exercised in the past to prevent gene contamination of wild species from pollen of crops or introduced species. For example, in Canada the rare Red Mulberry is being exterminated by overwhelming hybridisation with the introduced, cultivated White Mulberry (Burgess et al. 2005). The major cultivated seaweeds are undergoing domestication to produce superior cultivars (Valero et al. 2017), and there is danger that the problems of gene contamination experienced by wild terrestrial
plants will also occur in wild seaweeds (Buschmann et al. 2017). Seaweed cultivars that have been selected for chemicals could alter the health of marine herbivores. Seaweed cultivars that have been selected for increased tolerance to temperatures could greatly extend their ranges, becoming significant alien weeds, and possibly also spreading parasites and diseases affecting marine species.

**Transgenic threat**

Algae, as well as many other economically important organisms, have been subjected to genetic engineering, and concern has been expressed about the associated dangers to biodiversity (Austin 2009). Where the intent is to culture transformed species in a controlled situation, such as in vats remote from salt water, it is possible to prevent escape. Kelps are too large to cultivate economically in tanks, and the possibility that transformed kelps could be released into marine environments is intimidating, since once escaped they would be virtually impossible to eliminate. Regrettable attempts are underway to transform seaweeds with no apparent concern for the possible genic contamination of wild relatives (Zeyu and Xuemei 2007; Qin, Lin, and Jiang 2012; Lin and Qin 2014).

**Biodiversity threat**

Mariculture, especially of animals, is known to be associated with biodiversity loss associated with negative impacts, such as habitat degradation, pollution, eutrophication, accidental spread of alien species and introduction of diseases (Beveridge, Ross, and Stewart 2005), and while there are economic and social benefits to farming of seaweeds, efforts need to be made to control aspects that endanger marine species. Natural seaweed stands, especially kelp forests, are astonishingly biodiverse habitats, and it should be possible to cultivate seaweeds in ways that are friendly to other species.

**Believe it or not**

- A primitive breed of sheep on North Ronaldsay Island (the most remote of the 70 Orkney Islands, north of mainland Scotland) feeds almost exclusively on seaweeds, particularly the kelp *Macrocystis* (Balasse et al. 2005; Figure 12). The tides regularly shower the beaches with uprooted seaweeds, providing a plentiful supply. However, when the tide recedes, many sheep also forage on seaweeds among the wet rocks of the shoreline (and sometimes drown when they misjudge the timing of incoming tides). The sheep show evident dietary adaptation to algae, absorbing more of minerals like copper, and when overfed with a conventional grass diet (which is rich in copper), they can suffer toxicity, even death. The Rare Breeds Survival Trust, a charity promoting the conservation of native farm animal genetic resources of the United Kingdom, lists the breed as ‘Vulnerable’.

- Seaweeds need access to sunlight. Although some corals (which are colonial marine invertebrates) trap small fish and unicellular algae, most, including those that build reefs, rely on associated photosynthetic unicellular dinoflagellates (a group of unicellular motile organisms), and so they also require sunlight. Accordingly, seaweeds and corals are natural competitors for space. Land plants are well known to compete for space by the process of ‘allelopathy’: the production of chemicals that discourage competitors. Seaweeds have also been found to produce chemicals that harm corals when they come too close (Longo and Hay 2017).

- The ‘Kelp Highway Hypothesis’, proposed by Erlandson et al. (2007, 2015), suggested that maritime explorers 16,000 years ago were aided in moving by boats from Asia to America by coastal kelp forests that extended during deglaciation from Japan to Baja California. The kelp forests would have provided relatively safe temporary mooring sites, and the fish, shellfish, and marine mammals associated with the kelp could have been used as food.

- Underwater photography has been a great tool for environmentalists to bring the beauty and importance of marine ecosystems to the attention of society. Much more challenging is underwater painting (Figure 13), a feat attempted by some members of
the Ocean Artists Society, whose mission statement is 'Using ocean art to inspire people around the world to a greater awareness of our need to preserve our natural world' (Ocean Artists Society 2014).

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Disclosure statement

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