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A seaweed aquaculture imperative to meet global sustainability targets

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Seaweed aquaculture accounts for 51.3% of global mariculture production and grows at 6.2% yr^{-1} (2000–2018). It delivers a broad range of ecosystem services, providing a source of food and natural products across a range of industries. It also offers a versatile, nature-based solution for climate change mitigation and adaptation and for counteracting eutrophication and biodiversity crisis. Here we offer the perspective that scaling up seaweed aquaculture as an emission capture and utilization technology, one supporting a circular bioeconomy, is an imperative to accommodate more than 9 billion people in 2050 while advancing across many of the United Nations Sustainable Development Goals.

Achieving the United Nations (UN) Sustainable Development Goals (SDGs), including environment, biodiversity and climate targets (https://www.un.org/sustainabledevelopment/) requires reduced resource consumption. At the same time, the growing human population, expected to approach 9.7 billion by 2050 (https://population.un.org/wpp/), raises demands of healthy food, clean energy and products. Solving this conundrum requires new solutions to deliver the required resources while meeting the UN SDGs. Here we identify seaweed farming as a unique, scalable and sustainable solution to this conundrum, and submit that delivering the full potential of this option is an imperative for a sustainable future.

The capacity of agriculture to meet future food demands is forecasted to become limited by arable land and freshwater availability[1]. Likewise, reducing greenhouse gas emissions to meet the targets of the Paris Agreement while supporting increasing energy and food demands remains challenging[2,3]. Our capacity to achieve the goals of the Convention on Biological Diversity is jeopardized by losses of ecosystems and species on land and in oceans, with these losses further aggravated by climate change. Achieving a healthy environment is also fundamental to meet the UN SDGs, encompassing poverty eradication, improved health and provision of good jobs, while reducing economic and gender inequality.

Meeting the UN SDGs on time and at scale while the human population continues to grow requires novel, potentially disruptive strategies to deliver the required transformational change. Specifically, there is a need to identify novel bioresources that can: be grown sustainably, with minimal requirements of arable land, water and energy; support a net production of healthy food for humans and animals grown on land and at sea, and sustainable and cost-effective energy; and provide sustainable materials harmless to the environment, all while delivering positive, rather than negative, impacts on biodiversity and the environment. The search for bioresources with such a broad slate of positive contributions is rapidly converging into seaweed aquaculture as a scalable, sustainable solution to many of these challenges[1,4,5]. Indeed, whereas we developed vegetable crops on land over 10,000 years ago, the domestication of seaweed for industrial aquaculture is a relatively recent and still ongoing phenomenon[6].

We anticipate rising demands for seaweed products driving production to be increased orders of magnitude above present levels, and examine the capacity of seaweed aquaculture to supply those benefits while avoiding negative impacts. We do so by first addressing the requirements and potential to expand seaweed aquaculture, and the environmental bottlenecks and risks involved. We then discuss how seaweed aquaculture can help achieve the UN SDGs, including the multiple products and services seaweed aquaculture may deliver.

Seaweed aquaculture production

Marine aquaculture is the fastest-growing component of food production (>7% yr^{-1})[1], far exceeding the growth rates of agriculture (2% yr^{-1}), livestock production (2.6% yr^{-1}) and wild fisheries (0.1% yr^{-1})[1]. Sustaining the high growth rate of aquaculture has been proposed to play a critical role in developing the capacity to feed the 9.7 billion people populating Earth by 2050, as the growth rate of agriculture will become limited by arable land and freshwater supply, and that of fisheries by the need to lower catches to maintain healthy wild fish stocks[1,7].

Seaweed aquaculture globally produced 31.8 million tons (Mt) in 2018, comprising 51.3% of global mariculture production, with a market value of more than US$11.3 billion (ref. [8]). Almost all of the production (99.9%) is derived from Asia, with China and Indonesia accounting for about half and a third of global seaweed production, respectively (Fig. 1), and a growing contribution from Africa[8].

Seaweed farms have reached large sizes in Asia, but their global extent, calculated as the ratio between the global production of 31.8 Mt of fresh weight[8] (MtFW; about 10 times the dry weight (DW)) and assuming a yield of 16 tDW ha^{-1} yr^{-1} (ref. [9]), is limited to approximately 1,983 km^2. This is about 250,000 times smaller than the global area occupied by agriculture and pastures[10], and 0.04% of the estimated areal extent of wild seaweed[11].

Following decades of growth in seaweed aquaculture production, the global production became stagnant from 2015 (Fig. 1)[8]. This is entirely due to a decline in production in tropical nations, particularly Indonesia (Fig. 1), in part owing to spreading of diseases, heat waves and general loss of strain vigour[12], as well as perturbations in the global carrageenan market. Indeed, a decline in production from

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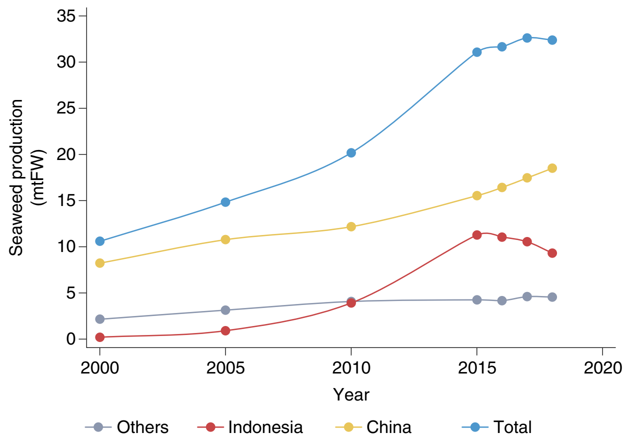


Fig. 1 | Seaweed production. Total seaweed aquaculture production for 2000–2018, along with the contributions of the main nations (China and Indonesia) and other nations[8].

2017 was apparent in other carrageenophyte-producing nations besides Indonesia, such as Malaysia, Tanzania, the Philippines and Madagascar, which emphasizes that global biosecurity strategies are pivotal for the resilience of the seaweed aquaculture industry. The recent decline in production in Indonesia and other nations may also be partially due to improved national reporting to the Food and Agriculture Organization.

At the long-term (2000–2018) growth rate of about 6.2% yr^{-1}, seaweed aquaculture would reach a global production of 252 MtFW by 2050, extending over an area of about 15,733 km^2 (Fig. 2). This is 6.6-fold higher than the current production, but not far greater than the increase needed if the global demand for seaweed as food was to approach Japanese standards (5.3 gDW per person per day[13]), which, at a global population approaching 9.7 billion by 2050, would require a global production of 187 MtFW yr^{-1} (Table 1). A hypothetical upper limit to seaweed aquaculture, modelled on the basis of adequate nutrients and temperature as the only constraints, and without considering possible adverse effects on marine ecosystems, has been estimated at 48 million km^2, equivalent to about 700,000 MtFW yr^{-1} (ref. [14]). At the current growth rate of 6.2% yr^{-1}, it would take two centuries to reach that ceiling, which is 18,373-fold above current production. The maximum area is about 10-fold greater than the area estimated for wild macroalgal forests[11], suggesting major competition for space and nutrients with native ecosystems should this limit be achieved. The ceiling therefore needs to be much further constrained to levels that do not exert negative effects on native ecosystems, probably to areas below those of wild macroalgal forests[11]. Even if a much smaller precautionary upper limit is adopted to avoid negative impacts, there is ample scope for seaweed aquaculture to accelerate in response to increasing demands for seaweed products. Doubling the current growth rate to reach 12% yr^{-1} would lead to an estimated yield of 1,195 MtFW and an area of 74,524 km^2 by 2050, while a maximum, but highly unlikely, potential growth rate of 20% yr^{-1} would lead to an estimated production of 10,869 MtFW, needing an area of 677,832 km^2 by 2050 (Fig. 2 and Table 1). These estimates are conservative, as the average yield of seaweed aquaculture of about 16 tDW ha^{-1} used is nearly 10-fold lower than the maximum productivity reached under intensified farming conditions[15].

These calculations illustrate that the future growth of seaweed aquaculture is likely to represent the largest component of the industrialization of the oceans yet seen. The biophysical limits to global seaweed aquaculture will not be met by 2050, nor possibly at any point before well into the twenty-second century. However, biophysical limits may be met at national scales for nations with limited suitable areas or those that, as is the case for China, already have a mature seaweed aquaculture industry and may meet their biophysical limits, imposed by nutrient availability in this case, within the twenty-first century[9].

Whether the future growth rate of global seaweed aquaculture will conform to a 'business as usual' 6.2% yr^{-1}, slow down to half of that or accelerate to triple that rate will be imposed by the regulatory environment and market demand, as well as technical development. The regulatory environment needs to be prepared for the rising demand for seaweed products, to provide concessions to accommodate the growing demand for seaweed farms. Whereas systems are in place in Asian and African nations with a mature seaweed industry, the regulatory environment in Western nations remains unprepared to accommodate seaweed farming. Marine spatial planning that identifies suitable areas to be set aside for seaweed farming, identifies local biophysical limits and seeks positive synergies while avoiding negative impacts is required. Positive synergies may derive from pairing seaweed farms with locations and activities that increase nutrient inputs, including areas supporting animal aquaculture. Avoiding negative impacts requires closing areas that act as sources of toxic pollutants, which may compromise the safety of seaweed products (unless these are used for biofuel or other non-consumptive uses), or areas that harbour vulnerable habitats, such as benthic macrophytes (for example, seagrass, coral reefs or wild seaweed forests) that may be negatively impacted if shaded by overlying seaweed farms. Market demand for seaweed products is constantly expanding, and can be propelled further by generating incentives or tax deductions that compensate the farmers for the environmental benefits that seaweed farming may bring about, such as nutrient and carbon removal.

As the targets for marine protected areas (MPAs) raise in ambition, from the current 7.6% of ocean space to 30% being proposed for 2030[16], and even more space is set aside for MPAs in the future, seaweed farming provides an activity that, adapted in scale and practice to local conservation targets, may contribute to the goals of MPAs while providing jobs and revenue to local communities[17], which may be otherwise at risk of being excluded from operating in the MPAs.

Seaweed aquaculture contributions to UN SDGs

Catalysed by mushrooming applications and demands for seaweed products, seaweed aquaculture is poised to become globally relevant

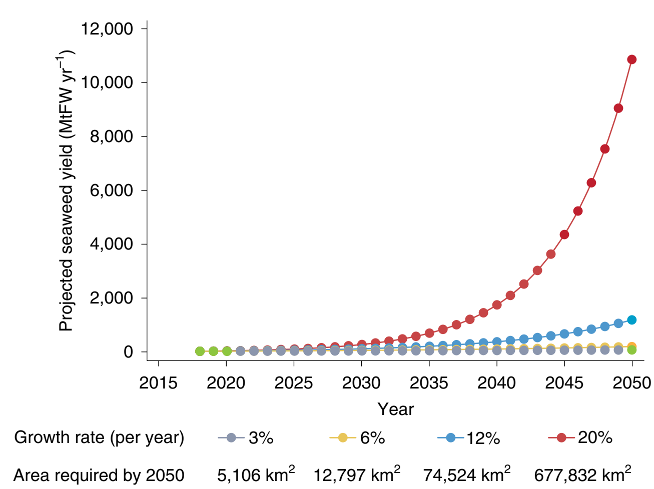


Fig. 2 | Projected seaweed yield. Projected seaweed aquaculture production at annual growth rates of 3%, 6%, 12% and 20% yr^{-1} from current levels[8] along with the corresponding area required by 2050 assuming conservative production of 1,604 tDW km^{-2}.

Table 1 | Summary of projected growth in seaweed production by 2050 and products and associated requirements

Component	2050 projection	Constraints and enablers
Production (MtFW yr^{-1})	81.8 (3% yr^{-1})	None at 3% yr^{-1}
	252 (6.2% yr^{-1})	Growth in demand at 20% yr^{-1}
	200,968 (20% yr^{-1})	
Area (thousand km^2)	5.1 (3% yr^{-1})	None at 3% yr^{-1}
	15.7 (6.2% yr^{-1})	Growth in demand and, locally, nutrient inputs and available space at 20% yr^{-1}
	677.8 (20% yr^{-1})	
Nutrient requirements and removal (MtN or MtP)	Nitrogen	None at 3% yr^{-1}
	0.31 (3% yr^{-1})	Growth in demand and, locally, nutrient inputs and available space at 20% yr^{-1}
	0.94 (6.2% yr^{-1})	
	40.8 (20% yr^{-1})	
	Phosphorus	
	0.048 (3% yr^{-1})	
	0.12 (6.2% yr^{-1})	
	5.15 (20% yr^{-1})	
Carbon sequestration ($TgCO_2$ yr^{-1})	1.8 (3% yr^{-1})	None
	5.5 (6.2% yr^{-1})	Growth in demand and, locally, nutrient inputs and available space at 20% yr^{-1}
	239 (20% yr^{-1})	
Demands for food production (MtFW yr^{-1})	187 (upper limit)	Human population matching Japan's intake of 5.3 gDW per person per day (ref. [15])
Demands for animal feed production (MtFW yr^{-1})	160	Meeting projected animal demand at 1% of feed DW contributed by seaweed

The estimates are bracketed using a low-growth scenario, 3% yr^{-1} (half of the realized long-term growth); a high-growth scenario, 20% yr^{-1}; and a 'business as usual' scenario of the recent, decadal growth rate of 6.2% yr^{-1}. The values are calculated considering conservative current yield (16 tDW a^{-1} yr^{-1} (ref. [8])), nutrient uptake (60.3 tN and 7.6 tP km^{-2} (ref. [8])) and CO_2 sequestration (0.00035 $TgCO_2$ km^{-2} yr^{-1}) estimates.

as a source of jobs and the economy. There is, therefore, an opportunity to manage the growth of seaweed aquaculture to realize the full potential of how it could serve as an emission capture and utilization (ECU) technology while simultaneously contributing to advance human development along several UN SDGs. Indeed, seaweed aquaculture generates multiple ecosystem services that lead to direct benefits in advancing a number of SDGs (SDGs 2, 3, 7, 13 and 14), which, in turn, provide integrative benefits contributing to additional SDGs (SDGs 1, 4, 5, 8–12 and 15; Fig. 3).

Zero Hunger (SDG 2) and Good Health and Well-Being (SDG 3). Most cultivated seaweeds are currently used for human consumption (90% of production), directly or as additives (Fig. 3), the latter being predominantly hydrocolloids including agar, alginates and carrageenans, used as viscosity-modifying agents in the food and pharmaceutical industries[18].

Seaweeds are healthy components of human diets, providing macro- and micro-nutritional elements, antioxidants, fibres and healthy fatty acids contributing to mitigate the risks of various diseases[19]. Increasing the consumption of seaweeds by the global population to match the current consumption by the Japanese population (5.3 gDW d^{-1})[13] would require seaweed production for food alone of 150 MtFW at present and 187 MtFW in 2050 (human population at 7.8 and 9.7 billion, respectively). A more likely target would be to reach half of the per capita Japanese intake globally[20], which will require a maximum of 93.5 MtFW in 2050 (Table 1). This is about three times the current production (Fig. 1), and would generate a substantial market pull for expanding the seaweed aquaculture for food supply. Future demands for seaweed products would be even higher when including seaweed hydrocolloids used in the food industry, which currently account for a minimum of 54% of global seaweed production[8], but that are recommended against among some consumer groups. Seaweeds may accumulate harmful elements from the environment; thus, regular monitoring of harmful elements in seaweeds is required (http://extwprlegs1.fao.org/docs/pdf/eri42405.pdf)—a practice required for all food products, not just seaweed.

Seaweed provides an opportunity to produce sustainable feed for aquaculture animals beyond herbivores (Fig. 3). The replacement of fish oil and meal in animal feed by seaweed aquaculture products has been argued to be an imperative to develop sustainable animal aquaculture at the scale required to sustainably feed a growing human population[1]. Use of some seaweed in fish feed has positive effects on fish growth and immune systems. However, the formulation of fish feed from seaweed (directly, or indirectly by using seaweed to feed small invertebrates, which are then used as feed) has not been implemented at any scale and remains a future opportunity. Realizing this opportunity will require substantial research and development (R&D) efforts to optimize seaweed as an alternative to fish meal and fish oil in the aquaculture industry[21]. Seaweeds have also been used traditionally as supplements for livestock feed in coastal regions[22], a practice that is currently getting renewed focus. Inclusion of seaweeds in animal feed may contribute to the protein and energy requirements of livestock and provide beneficial bioactive compounds that may improve the production and health status of both monogastric and ruminant livestock[22], while also contributing to greatly reduce methane emission from ruminants[23]. As for humans, the content of harmful elements in seaweed intended for animal feed needs to be monitored to avoid negative health impacts. The global amount of animal feed for ruminants, poultry, pigs and fish is currently about 1 Gt (ref. [24]), and is forecasted to increase by 60% by 2050[24]. Assuming a potential contribution of seaweed of 1% of feed DW, the total potential demand at present would be 100 MtFW (that is, 3-fold the current total seaweed aquaculture production[8]), and 160 MtFW by 2050 (Table 1).

Seaweed washed onto shorelines has been used for centuries to amend agricultural soils and promote plant growth[25]. Seaweed extracts stimulate seed germination and root development; enhance frost, drought and salinity resistance; increase nutrient uptake; and control phytopathogenic fungi, insects and other pests[25]. Seaweed amendments also provide nutrients, including nitrogen and phosphorus, absorbed from coastal waters where excess nutrients deriving from land may threaten ecosystem health[9]. Phosphorus is an increasingly limited mineral resource, and production of nitrogen fertilizer is a highly energy-demanding process[5]. Adding seaweed to agricultural soils as biofertilizer returns these valuable nutrients to the bioeconomic system on land, helping turn a linear flow of nutrients from watersheds to the ocean into a circular economy of nutrients (Fig. 4). As for their use as food and feed, the elemental composition of seaweed needs to be monitored before application to agricultural soils to ensure that amendment of soils with seaweed leads to pollutant levels kept within safe limits, as defined by the World Health Organization.

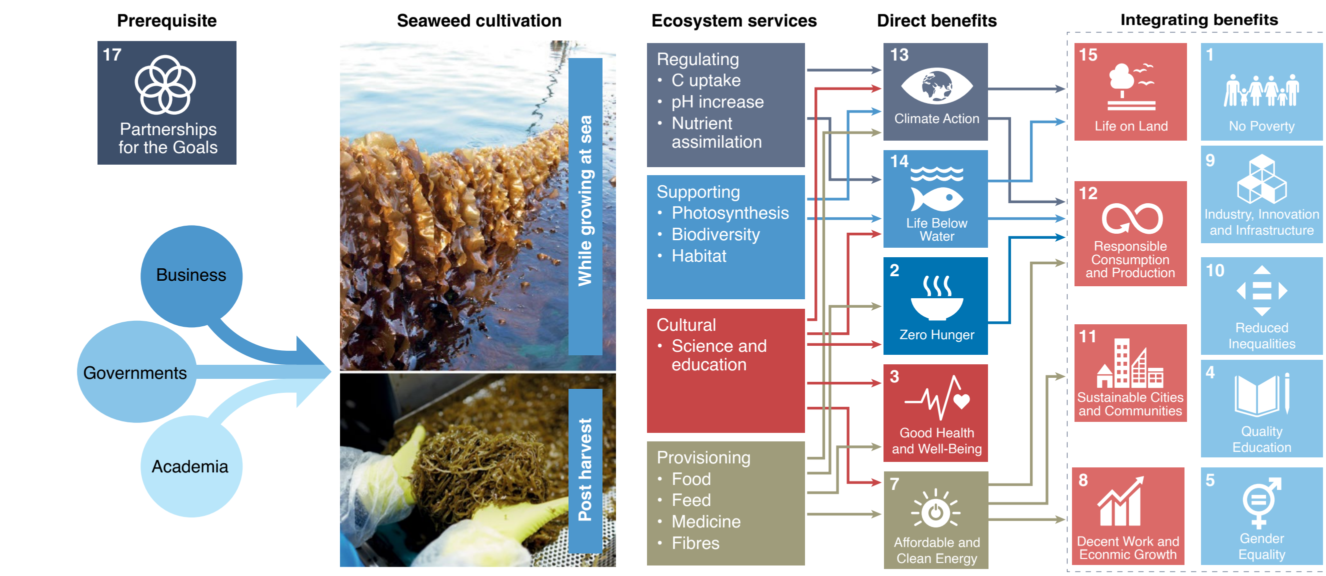


Fig. 3 | Seaweed production and utilization contributes to advancing a number of UN SDGs, which provide integrative benefits contributing to additional SDGs. Credit: Teis Boderskov (top photo) and Colourbox (bottom photo). Logos reproduced from https://www.un.org/sustainabledevelopment/news/communications-material/.

Affordable and Clean Energy (SDG 7). Seaweed biomass can be used to produce ethanol, butanol, biogas, biodiesel, bio-oil or hydrogen through a number of processes including fermentation, hydrogen release, transesterification, pyrolysis, liquefaction and gasification[26]. Demands for seaweed-based biofuels, currently using about 1% of seaweed production[18], are likely to rise, driven by demands from the transportation sector. Both the aviation and shipping industries are expected to grow at about 6% annually, and are committed to cap emissions from fossil fuels at present, or lower, levels. The search for zero-carbon, energy-dense fuels to supply the energy required by these sectors has identified seaweed as a promising source, as provision of green hydrogen at scale remains a distant goal.

Seaweed aquaculture can yield a net life-cycle integrated benefit in terms of CO_2 capture[27], in contrast to microalgae, which yield marginal net CO_2 capture at a high cost[28]. The removal of CO_2 from the atmosphere has been calculated at 961 kgCO_2 per tDW of seaweed, or about 84% of the carbon yield, reduced to 68% of the gross biofuel production when considering life-cycle energy requirements[26]. While use of seaweed biofuel will release CO_2 back to the atmosphere, it still carries the benefit of reducing emissions by displacing use of fossil fuels. However, if coupled with carbon capture technology, seaweed bioenergy with carbon capture and storage has the potential for becoming a negative emission technology[28]. Yet, life-cycle assessments indicate that current technologies and cost structures may deliver only marginal negative emission benefits[29], so more advanced technologies and system reconfigurations will be required for seaweed to support economically feasible bioenergy with carbon capture and storage (Fig. 4).

Whereas research on bioethanol and biogas production from macroalgae is growing rapidly[18], current processes do not yet lead to an economically viable model. 'Blue' biofuels are, therefore, not yet available as a consumer option, but will be a far more sustainable option than land biofuels, which have increased food prices by diverting food crops to the production of fuel, and represent a main driver of deforestation in the tropics[30]. The integration of seaweed biofuels in a cascading biorefinery, also producing molecules of interest, such as proteins[31], offers a path to increase the energy return on energy invested required to render seaweed biofuels profitable[32] (Fig. 4). The future of 'blue' seaweed biofuels remains uncertain and would depend on balancing economic and social enablers, such as increasing the price of CO_2 while avoiding high prices that would reduce the availability of seaweed as food.

Industry Innovation and Infrastructure (SDG 9). Seaweed can be used as a source of sustainable and durable biomolecules for a number of industries, including high-value molecules and seaweed biopolymers to be used in cosmetics, drugs and nutraceuticals, or materials for construction, packaging or textiles (Box 1). If produced free of hazardous chemicals, these materials can be recycled and reused in a circular economy and/or disposed of at burial sites to contribute to climate change mitigation at end of use (Fig. 4).

Climate Action (SDG 13). Seaweed farming can contribute to climate change adaptation by, for instance, locally buffering ocean acidification and ocean deoxygenation[5] (Fig. 3). The intense photosynthetic activity of seaweeds is able to raise seawater pH by up to 1 unit during the daytime, with pH values up to 9.2 for aerated cultures[33], thereby potentially enhancing conditions for biocalcification and offering refugia to calcifiers vulnerable to ocean acidification[5,34]. Likewise, their photosynthetic oxygen release may provide local refugia from coastal deoxygenation[5], as demonstrated recently both for elevated pH and oxygen, for seaweed farms in China[34].

Seaweed farming can also contribute to mitigating greenhouse gas emissions by sequestering carbon and/or reducing emissions as an ECU technology (Figs. 3 and 4). The footprint of seaweed farms on CO_2 uptake can be regionally relevant in areas with large farms, such as the coastal area of Lidao (China), where the sea surface partial pressure of carbon dioxide was reported to be, on average, 21 µatm lower than in reference areas far away from seaweed farms, enhancing annual CO_2 uptake by 1.7 tCO_2 ha^{-1} (10 mmol m^{-2} d^{-1}) relative to reference areas[35]. Moreover, depending on stocking density, the yield of seaweed production is likely to increase with increasing atmospheric CO_2 in the future, as seaweed in dense cultures is often CO_2 limited[33], further increasing their future scope as CO_2 sinks.

Growing seaweeds release a considerable fraction of their production into the environment as dissolved organic carbon and particulate organic carbon, some of which is sequestered in coastal sediments or the deep sea (Fig. 4)[10]. The few available estimates from seaweed farms suggest that farmed kelp may release as much carbon in the environment as that harvested[36], comparable to wild algal forests[11]. Assuming the fraction of exported farmed seaweed carbon that is sequestered over climatically relevant periods is similar to that of wild seaweed stocks (11% (ref. [11])), global seaweed aquaculture may have sequestered about 0.7 $TgCO_2$ in 2018. At a maximum sustained growth rate of 20% yr^{-1}, seaweed aquaculture could sequester about 421 $TgCO_2\,yr^{-1}$ in coastal sediments by 2050 (Table 1), reaching 112 $PgCO_2\,yr^{-1}$ if the reported upper ceiling to seaweed farming[14] was reached.

The climate mitigation benefits of seaweed aquaculture as an ECU technology can be expanded much further after harvest. Seaweed feed additives reducing ruminant methane emissions would contribute directly to emission reduction, and so would seaweed biofuel substitutes and seaweed plastic substitutes for fossil carbon sources. Any seaweed product substituting a product with a higher CO_2 footprint or being sequestered after use would also contribute to emission reductions. The global macroalgal production of 31.8 MtFW (ref. [8]) implies (provided an average carbon content of 24.8% of seaweed DW and a DW content of 10% of FW (ref. [5])) that 0.79 $TgC\,yr^{-1}$ is harvested globally, therefore pointing at a capture potential of 2.89 $TgCO_2\,yr^{-1}$ if all seaweed production was to be used for applications directly or indirectly substituting use of fossil carbon, or if seaweed products were permanently sequestered after use (Fig. 4). Reducing the carbon footprint of seaweed production, by identifying alternatives to energy-intensive processes and materials through life-cycle analysis, will further contribute to increasing the potential contribution of seaweed aquaculture to climate action.

Evidence from laboratory fermenters suggesting that the addition of the red seaweed *Asparagopsis taxiformis* to the feed of ruminants can greatly reduce their methane emissions has recently been confirmed at the farm scale[23]. The addition of 0.1–0.2% dried algae to cow feed led to 98% methane emission reduction, benefits in feed conversion rates and animal growth rates, and no negative impacts on dairy or meat production or quality[23]. As livestock methane emissions account for 44% of greenhouse gas emissions from agriculture, the use of seaweed as a feed supplement for ruminants holds great promise to mitigate climate change and supply more climate-friendly meat and dairy products.

Macroalgae produce short-lived halocarbons, at rates varying hugely within and among species, that destroy ozone when emitted to the atmosphere, potentially increasing ultraviolet flux to the Earth's surface[37]. Even if the growth rate of seaweed aquaculture doubled to reach an area of 100,000 km^2 by 2050 (that is, 50 times the current area), seaweed farming would increase the total seaweed emission of short-lived halocarbons by only 1%, assuming that farmed and wild seaweed support similar emissions per unit area. Moreover, wild seaweeds are believed to be a much smaller source of short-lived halocarbons than phytoplankton[38,39]. Accordingly, we argue that the contribution of seaweed aquaculture to global short-lived halocarbon emissions will remain undetectable and, therefore, of minor concern.

Life Below Water (SDG 14). Seaweeds, particularly kelps that make up more than 40% of seaweed aquaculture production, act as ecosystem engineers that stimulate biodiversity by developing complex habitats and modifying biogeochemical and physical properties of the environment while also serving as a food source[40]. In particular, seaweed communities play an important role as nurseries for juvenile fish and invertebrates[40]. Seaweed aquaculture may similarly provide complex habitats that can aid the restoration of ecologically deteriorated coastal areas, and it has been shown to enhance the abundance and species richness of macrofauna[41] (Fig. 3). In addition, seaweed farming can help displace harvest of wild seaweed, which can harm natural kelp forests and other seaweed habitats in many areas of the ocean.

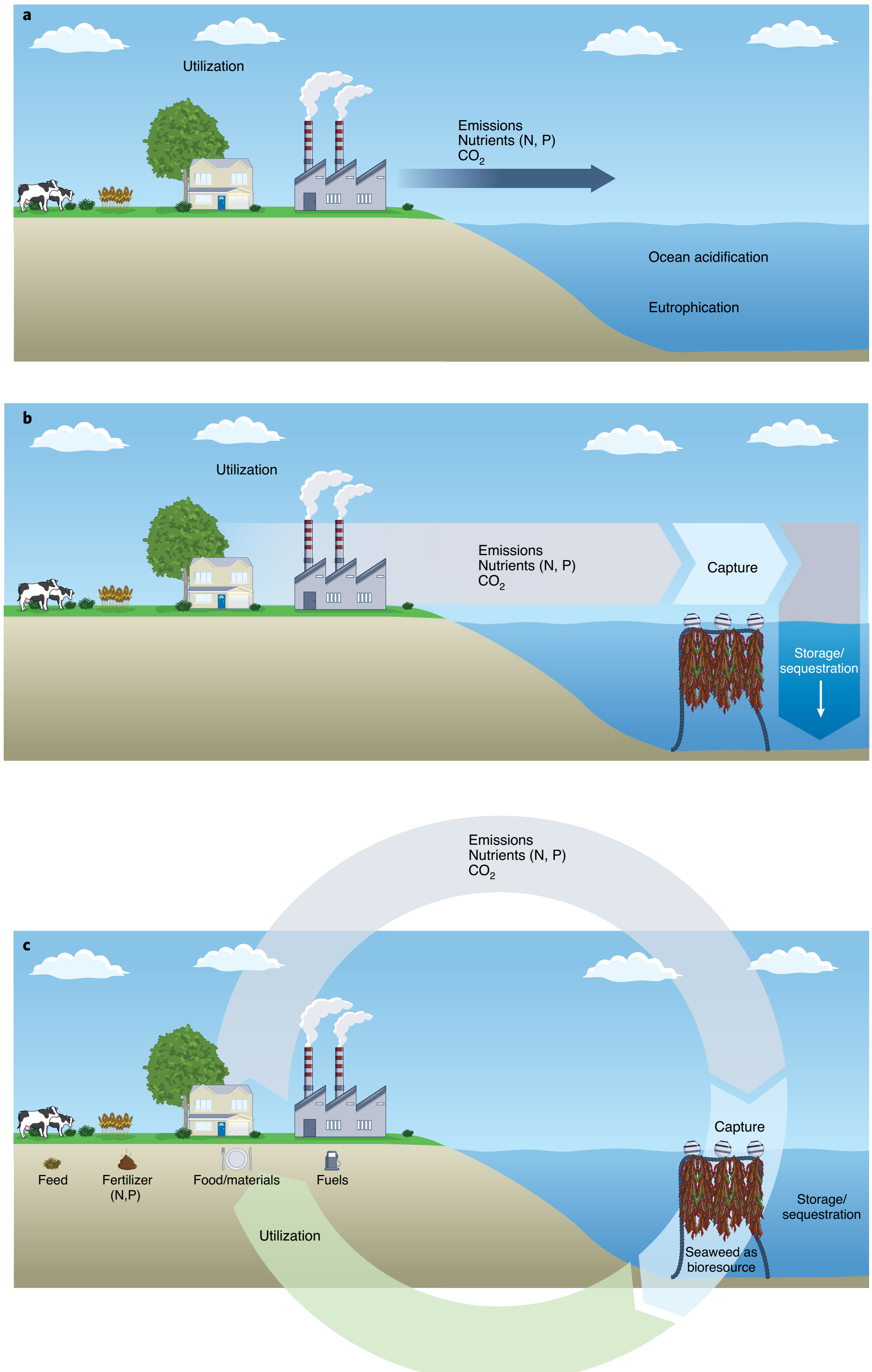
Fertilizer application to increase the yield of land crops, and subsequent emissions of excess nutrients to coastal waters, is the main driver of coastal eutrophication and hypoxia, with profound negative impacts on coastal ecosystems[42]. Seaweed aquaculture acts in the opposite direction, as nutrients are removed from coastal waters with harvest[43,44] and can be returned to the land bioeconomic system[43] (Fig. 4). Seaweed aquaculture took up about 60.3 tN and 7.6 tP per km^2 of farm in 2014 in China[9], removing 5.5% and 39.6% of N and P inputs to Chinese coastal waters, respectively[9]. Seaweed growing in integrated multi-trophic aquaculture reduces nutrient emissions from fish aquaculture by up to 60% for N and 90% for P (ref. [44]), while also providing a net input of oxygen to coastal waters[34] (Fig. 3). Seaweed farms contribute a higher net oxygen input to seawater than wild seaweed stands, which partially decompose in the environment (about 37.3% of their net production, on average[11]), thereby consuming oxygen, whereas the seaweed crop is removed from coastal waters with harvest.

The development of sustainable seaweed aquaculture must also consider the possible negative impacts on ecosystems[45,46]. These include the materials used, often including plastics and ropes of synthetic materials, which may contribute to littering marine areas around seaweed farms. There is an opportunity, once prices become competitive, to replace synthetic plastics used at seaweed farms with materials based on seaweed polymers (Box 1). Seaweed aquaculture may compete with native ecosystems for resources, including light and nutrients, and should not be placed over benthic primary producers, such as seagrass, corals or native seaweed, which may be impacted by shading and physical damage[45,47]. Seaweed farms in Indonesia are, for example, often set above seagrass meadows in reef lagoons, as their sediment offers better anchoring for supporting structures. As a consequence, seagrass meadows, which are critical habitats contributing to biodiversity and carbon sequestration, are impacted by both shading and trampling by farmers[47]. Whereas removal of excess nutrients by seaweed farms can improve water quality[9], further removal supported by background nutrient pools would lead to competition with native ecosystems for nutrients, with potential adverse effects on primary production and food webs[45]. Calculations of the ceilings to seaweed aquaculture imposed by anthropogenic nutrient inputs in China[9] can be extended to other coastal areas. Artificial upwelling has been proposed, and tested, as a possible solution to overcome this limitation[9], but the cost and associated CO_2 emissions may reduce the environmental and economic benefits of seaweed aquaculture.

Whereas seaweed farming should preferably use native species and strains, non-native species or strains are widely used, such as *Saccharina japonica* originally from Japan, now farmed in China and Korea[48]. Seaweed aquaculture has also been suggested as a possible source of explosive proliferations of opportunistic green macroalgae, known as green tides[49]. However, attribution of green-tide events in Qingdao, China, to seaweed aquaculture[50] was subsequently

Fig. 4 | Resource flow for different scenarios. a, Linear resource flow from land to sea with emissions accumulation in the atmosphere and the marine environment. **b**, Linear resource flow from land to sea, with seaweed farming supporting carbon capture and storage, with emissions accumulating in the marine environment, maintaining use and loss of fossil and mineral resources. **c**, A seaweed-based circular bioeconomy supported through ECU, where use of seaweed biomass enables reuse of carbon and nutrients in the bioeconomic system on land, and substitution of products with a higher CO_2 footprint (land-based food/feed, fossil fuels/plastics, imported soy, minerals produced through mining or Haber–Bosch process), thus generating further climate change mitigation and marine ecosystem resilience, while supporting a diverse sustainable economy.

challenged by studies that identified crustacean aquaculture pond systems in Jiangsu as the most likely 'seeds' for the bloom[51]. Further research has broadened the scope of the possible drivers of the green tide, still including the hypothesis of seaweed aquaculture[52] as a source of 'seeds' for green tides in the Sea of Japan[53]. Recent analyses suggest that adaptive management practices can reduce the risks of seaweed



Box 1 | Seaweed as a source of materials

Seaweed biopolymers. Biopolymers derived from seaweed polysaccharides are renewable, biodegradable, biocompatible and environment friendly[67]. In particular, alginate from brown seaweed can be used as a starting material for bioplastic film, with a yield of about 30% by weight for *Sargassum siliquosum*[68]. Seaweed polymers are already in use to replace synthetic polymers for a number of applications, including replacement of single-use plastics (for example, straws and cups for drinks, and plastic films; see https://www.loliware.com), synthetic fibres in textiles and plastics in shoes (for example, flip-flops; https://www.algenesismaterials.com). Bioplastics from seaweeds are reported to be more resistant to microwave radiation, less brittle and more durable compared with bioplastics from other sources, and therefore have a great scope for growth in demand.

High-value molecules. This category includes cosmetics, drugs and nutraceuticals (also contributing to UN SDG 3 Good Health and Well-Being). The unique variety of seaweed secondary metabolites combined with synergies between the bioactive and technical properties of the polysaccharides renders macroalgae biomolecules valuable in multiple biomedical applications spanning from anti-cancer to anti-obesity and gut health effects, as well as novel applications in targeted drug delivery, wound healing and tissue engineering[69]. In cosmetics and skincare, the antioxidant and antimicrobial properties are also exploited in combination with the gelling properties, optimizing at the same time the beneficial effects on mitigating skin problems such as hyperpigmentation, premature ageing and acne[69], while improving product texture and shelf life.

Durable materials. Dried or processed seaweed material is also useful for insolation, fire-resistant material, furniture or as additives or binders in composite materials based on wood or waste fibres, therefore meeting the growing demand for natural, durable and biodegradable materials.

Other materials. Alginates are commonly applied as stabilizers for the preparation of emulsions and suspensions in the production of paint, construction materials, glue and paper, as well as in oil, and in the photo and textile industries.

farming seeding green tides[54]. Global biosecurity strategies are pivotal for mitigating introduction of non-native and opportunistic species, diseases and pests, as well as for protecting local genetic resources[48].

Life on Land (SDG 15). The expansion of land-based production systems has already transformed 50 million km^2, or 46.6%, of non-frozen land into agricultural, pastoral and farmland, and remains the main driver of tropical deforestation[55], with a broad array of negative effects ranging from alteration of biogeochemical cycles to biodiversity decline and desertification[56]. Seaweed farming does not require arable land or freshwater, thereby reducing the footprint of food production on water appropriations. Likewise, neither herbicides nor pesticides are applied in seaweed aquaculture. Hence, supplementing vegetable production on land with seaweed production limits degradation of terrestrial ecosystems.

No Poverty (SDG 1). Seaweed aquaculture has been named a technology for the poor, as the capital cost required to establish a farm is modest (for example, <US\$15,000 ha^{-1} in Mexico[57]), because acquisition of heavy machinery and land is not required, possibly with the exception of post-harvest processing facilities on land and offshore kelp cultivation. It is a valuable source of income and employment, particularly in developing nations, where seaweed aquaculture often provides additional income to artisanal fisher households[4,57].

Evidence of the environmental and social benefits of seaweed aquaculture should lead to public policies and management systems that provide payments or tax benefits for ecosystem services to farmers[5]. Examples of such policies may involve providing incentives to develop seaweed aquaculture in eutrophied coastal areas, incentives to develop integrated seaweed/animal aquaculture[44], and payments for carbon and nutrient credits. The drive towards large-scale, advanced farms needs be balanced with attention to local, small-scale farms that deliver benefits to vulnerable communities. Seaweed farmers are also in need of expert advice to mitigate risks by selecting species suited for the target environments, diversify products and markets, build resistance to climate change and disease, and develop crop insurance schemes.

Gender Equality (SDG 5). In many developing nations, women take care of seaweed farms while men work as fishermen[4]. The role of women as seaweed farmers, who are organized in communities in Africa and Indonesia, has empowered them in their communities and raised their status by contributing to the household economy[58].

Partnerships for the Goals (SDG 17). Developing the full potential of seaweed aquaculture to contribute to the UN SDGs requires current barriers to be addressed. These include technical challenges in offshore cultivation, negative perceptions of marine aquaculture in general that neglect the environmental benefits of seaweed aquaculture, hurdles to obtain concessions for seaweed farms, a disconnect between production and research and innovation across regions, limited markets for the growing slate of seaweed products, and lack of monetary compensations for the ecosystem benefits seaweed farming delivers. Overcoming these barriers requires broad partnerships involving academia, industry, market operators and entrepreneurs, communicators, authorities and decision-makers (Fig. 3).

The reported impacts of some forms of marine aquaculture on the marine environment lead to negative social perceptions reflected in negative quality expectations of aquaculture compared with wild products[59], and eventually translate into adverse regulatory environments limiting the spread of marine aquaculture in many countries[60,61]. However, perceptions of aquaculture as a source of impacts to the environment overlook efforts to increase its sustainability as well as its potential benefits[1], which are many in the case of seaweed aquaculture (Fig. 3). Developing a more balanced public awareness of the role of aquaculture in the environment and addressing public misconceptions on the contribution of seaweed farming towards the sustainable use of coastal ecosystems is an imperative for the future growth of this industry. Reversing biased, negative perceptions with accurate, factual information may also facilitate the regulation for concessions, which in some nations is so demanding as to effectively prevent the development of a seaweed industry[61].

Planning for space allocations for seaweed aquaculture requires marine spatial planning[62]. This demands, in turn, the development of site selection tools that identify suitable sites from simple metrics, and hydrodynamic and ecological models that help maximize positive environmental impacts of seaweed aquaculture and avoid negative ones. Deploying seaweed farms also requires an understanding of risks as well as robust sustainability guidelines in operating the farms[46], which are available for Europe[63] and the globe from the Aquaculture Stewardship Council standard on seaweed aquaculture (https://www.asc-aqua.org/what-we-do/our-standards/seaweed-standard/). Sustainability standards need to consider biosecurity risks from exotic species, risks to consumers from heavy metals and pollutants, diseases[46,64] and potential impacts to ecosystems, such as shading of seagrass beds below ill-placed farms[47], and co-opting of nutrients required for the normal function of neighbouring ecosystems[46]. Developing a comprehensive certification system that recognizes seaweed products as compliant with sustainability standards will greatly help deliver on the potential for positive environmental impact as seaweed production expands.

Future contributions of seaweed aquaculture to climate change mitigation and adaptation will be propelled by introducing market mechanisms to compensate the farmer for climate services, which is present only on the price system of biofuels, a small fraction of the total climate change mitigation potential of seaweed aquaculture[5]. Seaweed CO_2 capture could be commercialized as certified emission reductions or voluntary carbon offsets, but the required certification systems are yet to be developed along with the robust scientific evidence for the magnitude, additionality, accountability and permanence of seaweed-based carbon sequestration in the environment. More broadly, compensation to the farmer for ecosystem services[65] and compliance with sustainability guidelines will help expand sustainable seaweed farming practices in areas, such as much of the Western world, where this industry is still at its infancy.

Global expansion of seaweed aquaculture requires the development of technological solutions for large-scale automated offshore cultivation[66], harvest and processing, and best practice cultivation guidelines or best available technology, including biosecurity programmes securing safe management of biodiversity[46,63,64]. Reducing the economic risk to farmers, particularly small, household-scale farmers that contribute much of the production in Southeast Asia and East Africa, requires implementing processes inspired by social arrangements and private–private and public–private partnerships that have provided security to small-scale farmers on land. These include securing fair and obligating trade agreements, unionization of smaller-scale growers, centralizing of specialized key processes, such as breeding and hatchery processes, and the development of crop insurance schemes to protect the growers against losses from extreme events, such as cyclones and heat waves.

The growth of seaweed aquaculture is driven by scientific development and innovation. The high rate of growth in patents using seaweed, around 12% yr^{-1} between 2000 and 2009[18], nearly doubled the growth of production, propelling a diversifying range of applications, including environmental, energy, food, cosmetic and pharmaceutical industries[18], leading to the emergence of a phyco-economy (see https://phyconomy.net; Box 1). The rate of innovation is enhanced when research efforts are coupled with a productive seaweed aquaculture industry[18], although the value-add to the economy from the intellectual property developed through the synergy between seaweed production and research has not been quantified. R&D in seaweed aquaculture technologies, largely concentrated in the Western world, is spatially dissociated from production, concentrated in Asia, Southeast Asia and Africa[18]. Developing partnerships that bring R&D providers and seaweed producers to collaborate in an entrepreneurial space will boost the growth of seaweed aquaculture. Whereas the biophysical limits to the expansion of seaweed aquaculture may be reached before 2050 within China and possibly other Asian nations, such as Korea and Japan, where seaweed aquaculture is already mature, we anticipate most of the future growth to be rooted in the tropics and the Arctic, with their massive coastlines. It is in these areas where partnerships, across governments, industry, investors and local communities, will be most needed.

In conclusion, seaweed aquaculture stands out through its many simultaneous benefits for sustainable development among the broad range of industries that humans deploy in the ocean (Fig. 3). The major benefits of seaweed aquaculture include food provision (UN SDG 2) supporting healthy populations (UN SDG 3), poverty alleviation (UN SDG 1), affordable and clean energy (UN SDG 7), contributing to climate action (UN SDG 13) with prospects for future development through industry innovation (UN SDG 9) and responsible production systems (UN SDG 12), and a prevalence of positive impacts on the environment (UN SDGs 14 and 15), along with additional societal benefits (Fig. 3). Realizing this potential requires partnerships (UN SDG 17) to drive innovation through West–East and South–North collaborations across the full production chain to ensure a balance between supply and demand. A triple-helix partnership between academia, industry and government is essential for the delivery of the full potential of benefits of the seaweed industry, and, hence, a sustainable ocean economy.

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Author contributions

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The authors declare no competing interests.

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