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Seaweed production: overview of the global state of exploitation, farming and emerging research activity

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ABSTRACT
The use of seaweeds has a long history, as does the cultivation of a select and relatively small group of species. This review presents several aspects of seaweed production, such as an update on the volumes of seaweeds produced globally by both extraction from natural beds and cultivation. We discuss uses, production trends and economic analysis. We also focus on what is viewed as the huge potential for growing industrial-scale volumes of seaweeds to provide sufficient, sustainable biomass to be processed into a multitude of products to benefit humankind. The biorefinery approach is proposed as a sustainable strategy to achieve this goal. There are many different technologies available to produce seaweed, but optimization and more efficient developments are still required. We conclude that there are some fundamental and very significant hurdles yet to overcome in order to achieve the potential contributions that seaweed cultivation may provide the world. There are critical aspects, such as improving the value of seaweed biomass, along with a proper consideration of the ecosystem services that seaweed farming can provide, e.g. a reduction in coastal nutrient loads. Additional considerations are environmental risks associated with climate change, pathogens, epibionts and grazers, as well as the preservation of the genetic diversity of cultivated seaweeds. Importantly, we provide an outline for future needs in the anticipation that phycologists around the world will rise to the challenge, such that the potential to be derived from seaweed biomass becomes a reality.

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KEYWORDS Biomass production; biorefinery; seaweed aquaculture; seaweed economy; seaweed fisheries; seaweed uses

Introduction

Global concern has been rising regarding the impact of climate change on seaweed abundance, distribution and quality (Straub *et al.*, 2016). While kelps seem to possess a certain degree of resilience to global climate change (Krumhansl *et al.*, 2016), biomass availability can vary greatly on a local basis (Bell *et al.*, 2015). It is therefore relevant and timely to develop alternative production strategies. In this review, we analyse current exploitation and aquaculture activities, including some economic trends in the usage of seaweeds, as a test case for the development of these strategies. Finally, we explore whether published research is moving in this direction and address the knowledge gaps that are apparent from this analysis.

Historical overview of the development of seaweed exploitation and cultivation

Human and seaweed interactions seem to date back to the Neolithic period (Dillehay *et al.*, 2008; Ainis *et al.*, 2014; Erlandson *et al.*, 2015), but the earliest written record of their human usage originates from China, about 1700 years ago (Yang *et al.*, 2017). For centuries, coastal populations harvested a wide variety of seaweeds from all algal groups. Initially, seaweeds were most often used for domestic purposes as food and feed, whereas later, industrial uses (gels, fertilizers) emerged (Delaney *et al.*, 2016). Early examples of utilization of seaweeds for medicinal purposes include the Chinese use of brown algae for goitre (16th century, Chinese herbal, 'Pen Tsae Kan Mu'), *Gelidium* for intestinal afflictions and dehydrated *Laminaria* stipes for the dilation of the cervix in difficult childbirths (Levine, 2016).

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The industrial use of seaweed biomass has shifted over the years, from exploiting beach-cast seaweeds as fertilizers and a source of potash, via iodine production, to hydrocolloid extraction (Synytsya *et al.*, 2015). At all stages, the 'potential' of the future industry has been viewed as being larger than its actual scale and this is as relevant today as it was 100 years ago or more, when the industry looked very different (Hafting *et al.*, 2015). Many researchers foresee a future where seaweeds will be grown for more valuable purposes than commodity food and feeds (Neori, 2016). These include higher value uses as raw materials for specialty polysaccharides (e.g. agar, carrageenan and alginates: Bixler & Porse, 2011), or transformation of the biomass into products for technical, specialty agronomic applications (Buschmann *et al.*, 2008; Craigie, 2011). In addition, further up in the value pyramid one can find functional products such as valuable ingredients for food and feed (Fleurence, 2016), cosmeceuticals (Balboa *et al.*, 2015), nutraceuticals (Himaya & Kim, 2015), pharmaceuticals (Thanh-Sang Vo *et al.*, 2012; Cao *et al.*, 2016; Anis *et al.*, 2017), and bioenergy as a low value but very high volume application (Korzen *et al.*, 2015; Fernand *et al.*, 2016). As these different applications can be complementary, different processing options (see e.g. Camus *et al.*, 2016), including holistic approaches, have been developed. The holistic 'biorefinery approach' sequentially extracts the most valuable components from algal biomass, leaving the remainder unadulterated for commodity purposes, i.e. food, feed, fertilizer and fuel, while minimizing waste and environmental impacts of the process (Baghel *et al.*, 2015; Trivedi *et al.*, 2015).

Seaweed uses

Seaweeds produce a varied and versatile biomass useful for multiple applications. They can be used in a broad variety of formats (e.g. fresh, dried, powder or flakes, salted, canned, liquid extracts or as prepared foods) for direct human consumption or processed into food additives and nutraceuticals, feeds, fertilizers, biofuels, cosmetics and medicines, amongst others (McHugh, 2003; Bixler & Porse, 2011; Anis *et al.*, 2017). Global demand for seaweeds has been growing together with increases in usage beyond former traditional applications (e.g. hydrocolloids: Rebours *et al.*, 2014; Hafting *et al.*, 2015). There is an increasing body of evidence that the consumption of algal food/feed products may have health and nutritional benefits. However, several basic questions remain unanswered, including the impacts of seasonal and geographical variation on the composition and nutritional value of algal biomass (Wells *et al.*, 2016). Furthermore, the quantitative roles of genetics and environment on seaweed biomass have yet to be established. Similarly, there is still only limited solid evidence on the digestibility and bioavailability of many 'beneficial seaweed compounds' to humans or animals (Wells *et al.*, 2016), leaving this topic as something of a 'black box'. This lack of information affects even basic exploitation, e.g. when timing the harvest, approaches to de-watering, drying, storage and processing (e.g. optimal drying as in Chan *et al.*, 1997).

According to FAO statistics (FAO, 2014, 2016), of the top seven most cultivated seaweed taxa, three were used mainly for hydrocolloid extraction: *Eucheuma* spp. and *Kappaphycus alvarezii* for carrageenans, and *Gracilaria* spp. for agar; *Saccharina japonica* (formerly *Laminaria japonica*), *Undaria pinnatifida, Pyropia* spp. (formerly *Porphyra*) and *Sargassum fusiforme* were most important in human food usage (Fig. 1). The main producing countries were China, Indonesia and the Philippines, which were also those that cultivated the greatest diversity of seaweed species (7, 6 and 4, respectively; FAO, 2014, 2016).

While seaweed consumption in South-east Asia has been common and traditional, and has depended on taste and price, seaweed use as food in non-Asian European and USA markets has considered additional parameters such as nutritional value and 'food for health', with a strong consumer preference towards organic, sustainable and fair trade products (representing low impacts both on the environment and biodiversity) (Chapman *et al.*, 2015; Gomez Pinchetti & Martel Quintana, 2016). However, the global market share of seaweed farming production used for food and 'other uses', i.e. other than for hydrocolloids, is still below 1% of the total biomass production (Fig. 1).

Recent production: exploitation and farming techniques

China and Indonesia are by far the largest seaweed producers with over 23 million tonnes of aggregated production in 2014 (Fig. 2a). China produces mostly kelp for food (i.e. *Saccharina japonica* and *Undaria pinnatifida*), and red algae belonging to the genera *Gracilaria* and *Pyropia* (FAO, 2016). On the other hand, Indonesia produces mainly the carrageenophytes *Kappaphycus* and *Eucheuma* (FAO, 2016). Taken together, these leading five genera – *Saccharina, Undaria*, *Porphyra*, *Eucheuma/Kappaphycus* and *Gracilaria* – represent *c.* 98% of the world's cultivated seaweed production (Suo & Wang, 1992; Pereira & Yarish, 2008). Furthermore, Chile, China and Norway lead the exploitation of the wild stocks of seaweeds (Fig. 2b), of which kelps are the most sought after (FAO, 2016).

In 2014, the leading seaweed farming countries, China and Indonesia, each produced more than 10 million tonnes, the Philippines and the Korean

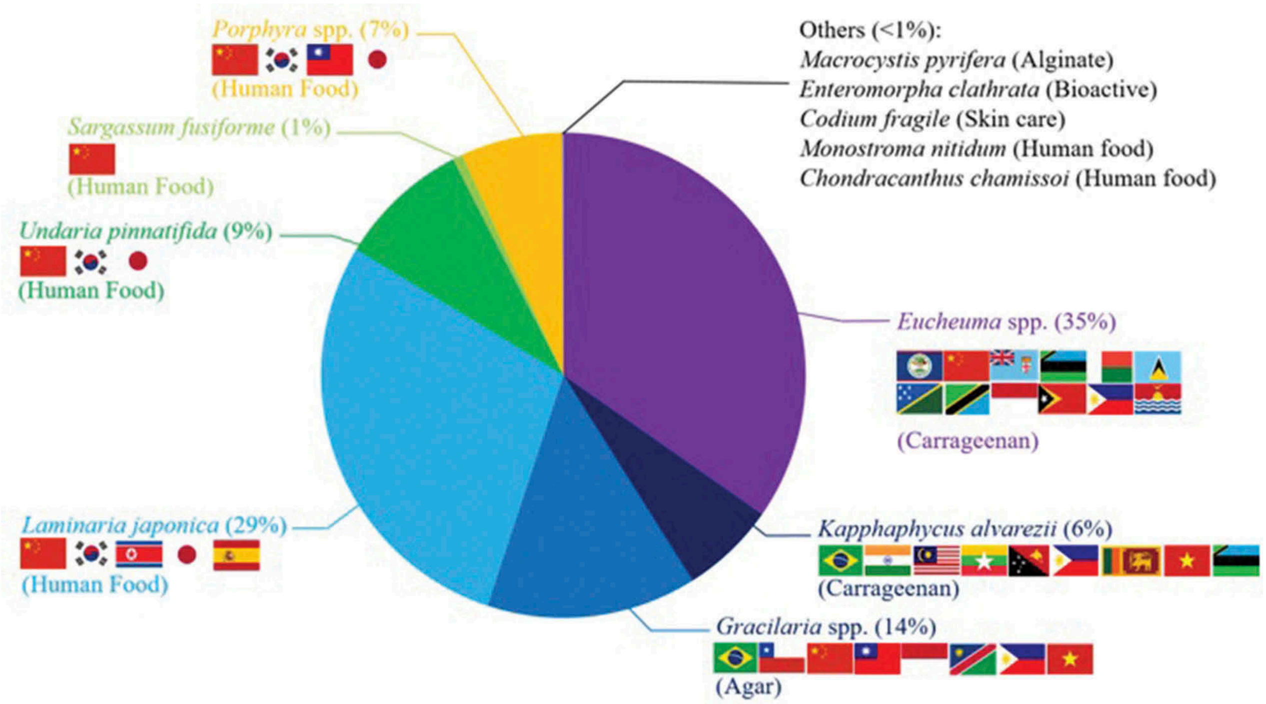

Fig. 1. Per cent seaweed aquaculture production per species and countries – year 2014. Actual main uses of each species were included. Source: FAO (2016).

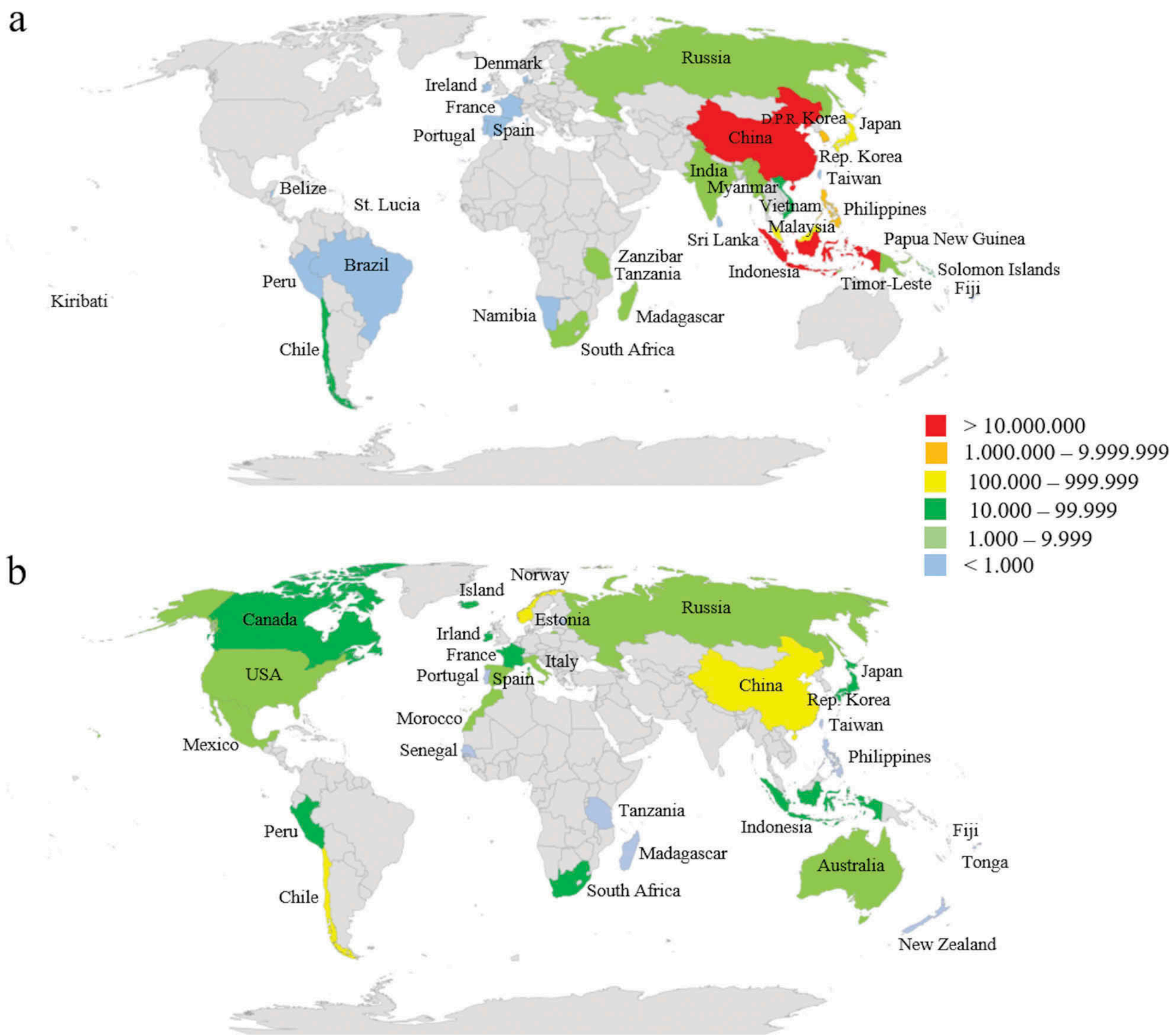

Fig. 2. Seaweed production in the year 2014: **a**, Aquaculture and **b**, Fisheries. Colour scale in wet metric tonnes. Source: FAO (2016).

Republic over 1 million tonnes, whilst the Popular Democratic Republic of Korea, Japan, Malaysia and Zanzibar produced over 100 000 tonnes each (Fig. 2a). In the Americas, only Chile has appeared in the farming statistics tables, with 12 836 tonnes of cultivated *Gracilaria*. Most European and African countries do not produce seaweeds and the few countries that do produce minute quantities (Fig. 2a).

In contrast, the European, Canadian and Latin American seaweed industries still rely on harvesting natural resources (Rebours *et al*., 2014). In Chile there is exploitation of the brown algae *Lessonia* and *Macrocystis*, and the carrageenophytes *Sarcothalia crispata, Gigartina skottsbergii* and *Chondracanthus chamissoii*, but farming is limited only to a relatively small amount of *Gracilaria chilensis* (Buschmann *et al*., 2008). In Portugal, sustainable production of seaweed and seaweed-based products (see www.algaplus.pt) uses the Integrated Multi-Trophic Aquaculture (IMTA) concept, farming seaweeds in proximity to several species at different trophic levels, allowing the reduction of aquaculture wastes (Troell *et al*., 2009). IMTA is practiced in a controlled environment on land, with organic certification for quality, traceability, stability of supply and a small carbon footprint. Cultivation of *Ulva* has been set up in South Africa, based on a similar IMTA concept (Bolton *et al*., 2009) and was adopted on a small scale in Israel (Shpigel, 2013; Neori *et al*., 2017). In Brazil, the commercial cultivation of *Kappaphycus alvarezii* has been implemented during the last decade in coastal waters on the southern and south-eastern coasts (Pellizzari & Reis, 2011). In Norway, seaweed exploitation (largely *Laminaria hyperborea* and *Ascophyllum nodosum*) has a long tradition (Meland & Rebours, 2012), and although the country was early to develop a knowledge-based, integrated coastal zone management system, it was recognized that the growing demand of the industry could not be satisfied solely from the wild (Stévant *et al*., 2017). To tackle this issue the development of seaweed aquaculture was initiated, based on research and pilot-scale production, and moved quickly to obtain commercial permits for cultivation of mainly *Saccharina latissima* in coastal water (Stévant *et al*., 2017). In the countries mentioned above, wild seaweed exploitation has been carried out sustainably for decades (Rebours *et al*., 2014; Cottier-Cook *et al*., 2016). However, over-harvesting of *Gelidium* spp. in Japan (Fujita *et al*., 2006) and Morocco has greatly diminished *Gelidium* spp. beds, with potentially devastating consequences for the production of microbiology-grade agar (Callaway, 2015). For this reason, efforts towards cultivation and replacement of wild harvest are even more relevant.

In general, depending on their organization (e.g. clonal vs. unitary organisms) seaweeds are cultivated in one or multiple-step farming systems (Santelices, 1999). Clonal species, such as *Gracilaria* and *Kappaphycus*, can be fragmented vegetatively and propagated directly for growth in culture systems. This can be done at different scales, moving from intensive on-land tanks or ponds to extensive open-sea culture systems using long-lines or rafts. On the other hand, propagation of the unitary seaweeds such as kelp for industrial cultivation requires a hatchery/nursery. The different cultivation systems have been thoroughly tested experimentally, but the most commercially successful systems have been those that culture seaweeds at sea, due to lower operational and capital costs (Sahoo & Yarish, 2005).

Seaweed farming and modelling productivity

To date, seaweeds only produce a small fraction of the global supply of biomass with below 30 $\times 10^6$ fresh weight (FW) tonnes of seaweed, in comparison to 16 $\times 10^{11}$ tonnes of terrestrial crops, grasses and forests (see below in this article). An expanding body of evidence suggests that off-shore cultivated seaweeds, which do not compete with food crops for arable land or potable water, could provide an alternative source of biomass for the sustainable production of food, chemicals and fuels (Radulovich *et al*., 2015; Lehahn *et al*., 2016; Neori, 2016). However, increasing the global production of seaweeds requires an understanding of the critical points that currently limit their production. Several studies developed models for estimating the net primary productivity (NPP, defined as g DW m^{-2} day^{-1}, a measurement of the efficiency of conversion of solar to potentially useful chemical energy) of selected seaweeds for ecological and environmental applications. Duarte & Ferreira (1997) published a dynamic model, which predicted NPP for *Gelidium sesquipedale*. The physiological model was useful for the management of natural stocks of this species as raw material for multiple industries. The model considered depth, productivity as a function of light intensity, temperature and rates of respiration, product exudation, frond breakage and mortality and included a conversion factor between carbon and dry weight. Another model was developed for the optimization of harvesting *Ascophyllum nodosum* from natural populations (Seip, 1980) that allowed for the determination of the optimum density of seaweeds within the population, and the rate and frequency of harvesting, allowing only 7% of the estimated standing crop to be harvested, to produce a sustainable harvest over a period of several decades of exploitation (Lee & Ang, 1991; Ugarte & Sharp, 2001). A linear model for pond-cultured *Gracilaria conferta* showed a positive relationship between growth and temperature, where growth responded differently in different seasons, and where nitrogen concentration in the ambient seawater inhibited development of epiphytes, under conditions of weekly nitrogen pulse feeding (Friedlander *et al.*, 1990; Friedlander, 1991).

These models and their responses to harvesting are of vital importance for the development of policies required for those parts of the commercial seaweed exploitation industry which are still based on natural resources. Regardless of how helpful these models might be, they cannot be used directly for modelling seaweed farming sites yet, as environmental conditions in those cultivation sites are different from those occurring in nature (as used by the model).

Estimations for the global potential of offshore seaweed farming are rare. However, a mathematical model for *Ulva* spp. metabolism and growth rate was recently developed (Lehahn *et al.*, 2016). The model ran on a global 1° grid with one output file for each month of the year. Algal growth rate (μ) was calculated as a function of light intensity (I), temperature (T), salinity (S) and dissolved nutrients (nitrate and phosphate) and respiration rate. The model assumed that each of the environmental factors had a separate impact on the growth rate of the biomass. This model, based on oceanographic data, was used to identify the potential global productivity of *Ulva* spp. in regions up to 400 km from the shore, associated with up to 100 m deep mooring installations and defined as 'near-future, deployable biorefinery provinces' (NDBP) (Lehahn *et al.*, 2016). The model provided an estimation of the theoretical, potential biomass production as 10^{11} dry weight (DW) tonnes year^{-1}, over a surface area of ~10^8 km^2. By using one of the most productive seaweeds, e.g. *Macrocystis pyrifera*, it was shown that a total of 200 wet tonnes ha^{-1} year^{-1} could be obtained (Buschmann *et al.*, 2014; Correa *et al.*, 2016). However, when scaling up, production efficiency could drop with strong variations in time and space (Camus *et al.*, 2016). These studies call for great caution to be exercised as some results might be rather unrealistic and what was perceived as 'high potential' may not become a 'practical reality'. Lehahn *et al.* (2016) suggested that a major limiting factor for large-scale seaweed production was biomass yield. Thus, under normal sunlight conditions such as outdoor growth, the number of photons does not limit photosynthetic rate, instead (as indicated by numerous other seaweed studies) the rate of photosynthesis was limited by multiple physiological processes, e.g. diffusion and intrinsic plant and carbon-fixation metabolisms (Hurd *et al.*, 2014). Studies showed that equal photosynthetic rates could be achieved by continuous and pulsed light with specific frequencies (Tennessen *et al.*, 1995). This property has been widely used in the design of on-shore, algal photobioreactors, where mixing is controlled to intensify the total micro- and macroalgal yields (Bidwell *et al.*, 1985; Buschmann *et al.*, 1994; Bruhn *et al.*, 2011). Mixing has usually been intended to improve nutrient diffusion for the algae and to optimize light exposure (Msuya & Neori, 2008). A new concept for offshore cultivation of seaweeds increases yield per unit area by applying external mixing to exploit natural photon capture and carbon fixation rates. The ultimate goal of this system was to increase the total energy efficiency of offshore seaweed production by optimization of photon utilization per unit area for an offshore farm (Golberg & Liberzon, 2015). Mixing would utilize the large volume of the floating offshore seaweed reactor by exposing algal cells to solar energy for a short time to capture photons then moving the algae to a defined depth for a period of time for carbon fixation so a new layer of seaweed would be exposed to available sun, resembling what happens in high rate production ponds on land. A practical technology that can achieve that is being researched and developed (A. Golberg, personal communication).

In addition to the technological improvements required for large-scale cultivation, significant additional efforts and resources are required to develop and select seaweed species and strains with specific properties tailored for food, chemical or fuel applications (Zhang *et al.*, 2007; Robinson *et al.*, 2013; Li *et al.*, 2016). Industrial strain development in agricultural crops was transformed by the introduction of high-throughput phenotyping with imaging. Imaging spectroscopy and thermal-infrared-, fluorescence-, 3D- and tomographic imaging have been used to successfully determine the required properties of terrestrial plants for robust, cost-effective, downstream processing (Cabrera-Bosquet *et al.*, 2012; Li *et al.*, 2014; Mutka & Bart, 2015; Walter *et al.*, 2015) and have also been used for green algae (Shefer *et al.*, 2017). However, the effectiveness of these and other modern tools in increasing seaweed productivity on a commercial large scale at sea has still to be demonstrated.

Economic considerations vis-à-vis large-scale seaweed cultivation

Ecosystem services as provided by seaweed farms

The commercial production of seaweeds provides several crucial ecosystem services, e.g. oxygenation and uptake of nutrients (Vásquez *et al.*, 2014). The evaluation of ecosystem goods and services links between the state of natural ecosystems and socio-economic welfare has been summarized in several publications (Mangos *et al.*, 2010; Vásquez *et al.*, 2014; Bennett *et al.*, 2015*a*; Krause *et al.*, 2015). For example, kelp forests that cover ~71 000 km^2 of the southern coast of Australia function as a great reef, supporting biodiversity and generating an estimated value of US$7.7 billion annually (~US$110 000 km^{-2} year^{-1}) in fishing (provisioning services), tourism and cultural services (Bennett *et al.*, 2015*b*). The European Commission (2012, 2016) recognized that algae (seaweeds and microalgae) were such a promising option for food security that by 2054 algal collective cultivation could reach the production of 56 million metric tonnes of protein, which would constitute 18% of the global alternative protein market. A diagram of alternative protein sources and market proportions over time is provided in the Lux Spotlight blog (2015).

Undoubtedly, seaweed cultivation enhances primary production and therefore contributes to the global carbon, oxygen and nutrient cycles (Chung *et al*., 2011), in addition to reducing eutrophication and greenhouse gases, such as the release of methane associated with rearing herbivores (European Commission, 2016). Algae perform about half of the global fixation of carbon (Chung *et al*., 2011) and may also account for much of global biological carbon storage, thereby being a natural means for the reduction of greenhouse gas emissions. Both natural beds and cultivated farms of seaweeds provide nutrient cycling as well as waste purification and treatment services (Manninen *et al*., 2016).

The commercial production of seaweeds also provides ecosystem services such as food, habitat and refuge for a diverse array of fish and invertebrates of conservation importance (Almanza & Buschmann, 2013; Vásquez *et al*., 2014). New habitat in the form of large-scale seaweed farms can host diverse species (Skjermo *et al*., 2014) and therefore support biodiversity. Negative impacts may be: cross-breeding between domesticated and wild strains and the harbouring of parasites (Skjermo *et al*., 2014), as well as unintentional introduction of non-indigenous 'hitchhiker' species, including pathogens (Cottier-Cook *et al*., 2016).

As healthy sources of nutrition for human and animal foods and supplements, various seaweeds could also contribute to health services such as a reduction in cardiovascular disease (Cornish *et al*., 2015), the cost of which approaches a trillion USD (Barquera *et al*., 2015). Dietary seaweeds also hold promise for healthy brain development and maintenance (Cornish *et al*., 2017).

Sustainable production of seaweeds through cultivation could contribute to the welfare of society through the creation of jobs: at the first level i.e. hatcheries, grow-out operations and processing; at the second level through industries supplying goods and services to mariculture such as feed, equipment and advice; and at the third level through the provision of associated jobs i.e. spending by those employed directly and indirectly in seaweed cultivation (Gardner Pinfold, 2013). The socio-economic impacts of the introduction of seaweed farming on poor, rural, coastal communities on many islands, such as Zanzibar, have been notable (Msuya, 2011).

Since ecosystem services and biodiversity are 'non-market' public goods (Pascual *et al*., 2010; Tietenberg & Lewis, 2016) they tend to be over-consumed by society (e.g. over-exploitation of wild fish and over harvesting of wild seaweed beds). In this context, seaweed cultivation on an industrial scale, especially within an IMTA framework, could reduce overall pressure on the environment, as has been demonstrated in China (Feng *et al*., 2004; Yang *et al*., 2015*a*). Enhancing ecosystem services can reduce, for example, harmful algal bloom events (Yang *et al*., 2015*b*).

Externalities and economic feasibility

The term 'externalities' is taken from economic theory and is used here to express risks, damages or benefits imposed on human beings, ecosystems and materials as a direct result of an entity (person or institution) activity (Garraín *et al*., 2016). Those burdens are external to the activity, merely because they are not considered economically by the entity that generates them. Sustainable development requires a change in this state. Quantifying and monetarizing damages and benefits helps in assessing economic value and the 'shadow price' which is being paid by society, or provided to it, on account of the entity's activity. External costs or benefits expressed in monetary value units can then be used in a cost–benefit analysis (CBA).

The Millennium Ecosystem Assessment (a series of reports under the auspices of the United Nations Secretary-General Assessment ME 2005) and research by Tinch & Mathieu (2011) identified three categories of ecosystem services provided by marine environments that are relevant to seaweed cultivation: (1) provisioning services such as raw materials, food, feed, energy and aquaculture; (2) regulating services of ecosystem processes, such as natural cycles of oxygenation, CO_2 sequestration, nutrient cycling, waste purification and treatment; and (3) cultural services that benefit humanity, through experiences of natural environments, leisure activities and the value of marine biodiversity.

Assigning unequivocal monetary figures to the ecosystem services provided by seaweed farms is difficult, since it is both site- and scientist-specific (Cabral *et al*., 2016). However, it is conceivable that the monetarization of all the services provided by large-scale seaweed production could often raise the true economic value of the algal biomass far beyond the value of the derived constituents alone (Chopin *et al*., 2001; Vásquez *et al*., 2014).

Various economic analyses of different components of the collective global seaweed industry have considered a diversity of products derived from cultured seaweeds. However, the analyses have not sufficiently evaluated the impacts, in monetary value, of externalities related to seaweed cultivation (Neori *et al*., 2007; Troell *et al*., 2009; Nobre *et al*., 2010; Chopin *et al*., 2012; Korzen *et al*., 2015; Cabral *et al*., 2016).

Currently active research fields

By searching the Web of Knowledge (searched 28 December 2016) for the words macroalgae* OR seaweed* OR chlorophyta* OR phaeophyta* OR rhodophyta* AND farming* OR mariculture* OR cultivation*, NOT (microalgae*), we found 1646 publications covering the period between 1975 and 2016. During the late 1990s, 17–39 publications were produced globally per year on seaweed farming. This increased to 65 and 78 in 2009 and 2010 respectively, and by 2015 and 2016 the number was over 180 publications per year. This scientific information was produced principally by researchers in the People's Republic of China, USA, Chile, Japan, Brazil, Australia, Spain, France, Canada and India (i.e. the top 10 seaweed research countries produced over 75% of the publications).

When classifying these farming-focused publications by their main stated purposes, the top 100 most-cited papers showed that bioremediation, environmental impacts (mostly impacts of introduction) and the development of farming technologies were the main subjects of interest (Fig. 3). A slightly different tendency was observed when the 100 most recent papers published (i.e. in 2016) were analysed (Fig. 3). Bioremediation, environmental impacts and farming technologies were still important topics, but chemical products (bioactives) and general biology of farmed species appeared more frequently, indicating a higher diversification of the objectives. These data also suggest gaps, e.g. selection, breeding, economic evaluation of farming practices, fouling epiphytes and diseases, and diversification through alternative species selection, which need considerable attention to support the future needs of enhanced seaweed production and quality (Fig. 3).

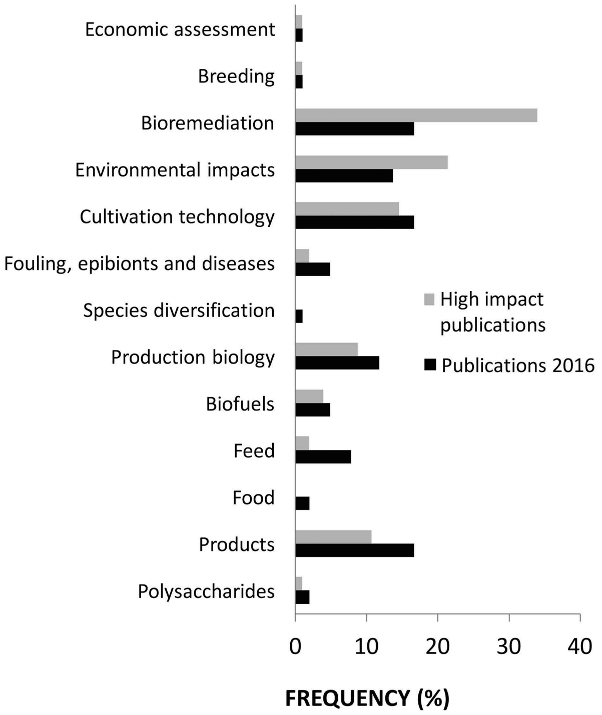

Fig. 3. Research tendencies in seaweed farming. The 100 most cited papers and the 100 most recent papers published in 2016. Source Web of Science (search made 28 December 2016).

It is important to bear in mind that this bibliographic search was focused on seaweed farming and not on specific products (i.e. biofuels, feed, food and chemicals), as they were not highly relevant (< 20%; Fig. 3) in comparison to biological, environmental and technical aspects. However, we noted that if the search of the Web of Knowledge was modified for keywords such as: seaweed* AND macroalgae* AND uses* AND products* instead of farming and cultivation, the number of publications increased to above 6500 publications, for the same period. For this reason, we must emphasize that our analysis is based on aquaculture and not on biomass production and products.

A global imbalance in seaweed production, research efforts and final product markets has also been discussed by Mazarrasa *et al.* (2014). Their analysis showed how world seaweed patent applications and the rate of scientific publications have grown significantly since 1990, probably related to efforts in developing seaweed aquaculture and the associated biotechnological markets. The study also indicated recent interest from non-traditional seaweed-producing countries in increasing the focus of their seaweed-based patents to more technological and sophisticated products, in marked contrast to traditional areas, where biomass production is higher and interest was mostly focused on traditional uses, e.g. food consumption. In general the private sector is responsible for these products being developed so they are not widely referred to in academic papers.

The future: can seaweed farming become equivalent to terrestrial agriculture in output?

The scale of terrestrial agriculture surpasses seaweed aquaculture by two orders of magnitude (Neori *et al.*, 2016). Adjusting this immense production imbalance is a daunting challenge (Neori, 2016; Neori *et al.*, 2016). However, several authors claim that seaweed aquaculture can produce several billion tonnes year^{-1} of macroalgae, which would provide a sustainable supply of affordable and healthy food in the centuries to come (Lenstra *et al.*, 2011; Radulovich *et al.*, 2015; Bjerregaard *et al.*, 2016; Kim *et al.*, 2017). Land-based agriculture produces over 10 billion tonnes year^{-1} of various products, most of which are plants. It is hard to imagine how this figure could grow much further, considering that growth of the global industry has been stifled by stagnant and diminishing resources of arable land, fertilizers and water for irrigation. Strikingly, marine aquaculture produces merely *c.* 100 million tonnes year^{-1} (according to various FAO reports and Duarte *et al.*, 2007). This is astonishing in a world whose surface is 70% water, that therefore receives most of the world's sunshine. Furthermore, this water contains huge amounts of nutrients (e.g. 10^{11} tonnes phosphorus), especially in the Pacific Ocean (Benitez-Nelson, 2000). The use of offshore large-scale seaweed aquaculture can in this context become a relevant tool for carbon sequestration and global climate change mitigation (Duarte *et al.*, 2017). Part of the globe that also receives much sunshine but little agricultural attention is the desert lands. They cover the 'sunniest' third of the land surface, yet lack water and nutrients necessary to become productive. It has been proposed that by recycling water and nutrients some of these regions could become productive if algae were one of the main components (Iersel & Flammini, 2010; see also ULPGC-Acceda: http://hdl.handle.net/10553/4557). Rectification of the global food imbalance by increasing efforts in aquaculture, and especially mariculture, to match terrestrial agriculture is challenging because of the small starting scale of current mariculture. With an annual growth rate of 6%, as reported by the FAO, it would take the aquaculture industry about 80 years to reach the 10 billion tonnes year^{-1} mark. Therefore, to double the world's food supply by 2050, mariculture would need to grow by 14% year^{-1}.

Such large-scale efforts in mariculture could be located on the surface of the oceans (Fig. 4) and in coastal deserts (Fig. 5), using seawater with natural nutrients or aquacultural waste. Raising industrial output by two orders of magnitude would require that the 'new aquaculture' is operated at an unprecedented scale, which would also require it to be sustainable environmentally, economically and socially. Indeed seaweed, the ultimate sustainable crop, should lead this growth (Lenstra *et al.*, 2011; Bjerregaard *et al.*, 2016), just as land plants led agriculture. Seaweeds should be able to cost-effectively supply food, feed and high value biochemical products (bioactives), whilst also contributing several beneficial ecosystem services, helping nature to do much of the work.

Engineering solutions to seaweed farming

Artificial enhancement of ocean nutrients by supplying nutrient-rich water via upwelling, the discharge of secondary sewage water, or proximity to large fish farms, could be attained by an array of approaches, from the fully engineered (chemical fertilization of surface water around seaweed raft farms, as proposed in Notoya 2010), to the minimally engineered passive pumping of nutrient-rich water to the surface, to support naturally floating beds of, e.g. *Sargassum muticum*. Based on Ryther's proposition from the 1960s, the Japanese 'TAKUMI' near Japan and the 'OTEC' projects near Hawaii have already demonstrated the capacity to

Fig. 4. Large-scale seaweed farming in a multi-trophic aquaculture region of the coast of China. Sanggou Bay, a 130 km^2 bay in northern China annually produces 100 tonnes (fresh weight) of fed fish, 130 000 tonnes of bivalves, 2000 tonnes of abalone and 800 000 tonnes of kelp, for a total production of ~ 7000 tonnes km^{-2} year^{-1}. Photo courtesy of Max Troell.

Fig. 5. A draft of a proposed land-based Integrated Multi-Trophic Aquaculture (IMTA) farm gravity-fed by Atlantic Ocean water (Green Sahara) a vision of the late Guillermo García-Blairsy Reina (courtesy of Bioagramar Foundation).

pump deep, nutrient-rich, Pacific Ocean water to the surface by means of huge pipes either passively (Masutani & Takahashi, 1999) or using solar-powered pumps (Masuda *et al.*, 2010). In this manner, large regions of current 'ocean deserts' could become rich seaweed beds and associated fishing grounds. These technologies of course involve environmental impacts, both positive and negative which can be controlled by, for instance, proper siting and spacing (Pelc & Fujita, 2002).

Seaweed farms offshore

Different types of seaweed have been cultured profitably for decades. Over 30 million tonnes fresh weight year^{-1} is the latest figure from FAO (2016), with an average market value of \$400 ton^{-1} dry weight. Most of this production takes place in coastal areas and shallow oceans.

A proposal by M. Notoya and co-workers is to have seaweed beds growing on 100 km^2 rafts. These would be left floating, away from shipping lanes, until ready for harvest (Notoya, 2010). Each raft could produce roughly 10^6 tonnes year^{-1} fresh weight of seaweed. Therefore, matching the present terrestrial agricultural output with seaweed biomass using this approach would require 10 000 such rafts, covering 500 000–1 000 000 km^2 of ocean surface (or merely 0.3% of the world's oceanic area; Bjerregaard *et al.*, 2016). A generally similar idea has also been considered as a promising enterprise for different areas of the Atlantic Ocean (Notoya, 2010).

Large-scale algal culture on land

Schemes for very large seaweed farms to be built on coastal deserts have been proposed. One such vision was presented by the late Guillermo Garcia-Blairsy Reina (Iersel & Flammini, 2010). The 'Green Sahara Concept' proposed having millions m^3 year^{-1} of relatively nutrient-rich, deep Atlantic seawater gravity-fed into IMTA-farming operations based in the Sahara's shebkhas – salty flatlands (i.e. below sea-level, dry lakebeds, up to 10^4 km^2 each). The visionary project used the principle of equilibrated diversification based on polyculture; it was proposed to produce both simultaneously and sustainably, fish, crustaceans, molluscs, seaweeds, additional aquatic crops, aquaponic crops, biogas and hydro-electric power. The final saline effluent would drain to reservoirs at a lower region of the shebkhas for the production of saline, 'green water' microalgae such as *Dunaliella* that would in turn feed brine shrimp, planktivorous fish, molluscs and birds. The resulting brine would then be evaporated at the shebkhas' lowest level, thus ultimately sequestering salt and minerals from the sea (~ 10^5 tonnes km^{-2} year^{-1}) whilst also having a humidifying effect on the desert air (Iersel & Flammini, 2010).

Once adopted, the Green Sahara Concept could produce cost-effective (micro- and macro-) algae in the Sahara and similar deserts, thanks to the benefits of gravity-fed seawater with fertilizers (i.e. N and P), plus available CO_2, lower-cost labour and the availability of affordable, coastal flatlands in those latitudes below 30° (e.g. Clery, 2011; Moustafa, 2017). The project was proposed to start with several 20 km^2 farms on shebkhas on various coasts of North Africa and in the Arava Valley of Israel and Jordan, where the World Bank already plans to fund a huge water conduit from the Red Sea to the Dead Sea (a drop of *c*. 400 m). The water conduit project is planned to be commissioned in 2021, but the aquaculture facilities have not been decided upon (Reed, 2017).

Future perspectives

Our analyses showed that only a small number of seaweed genera are currently in commercial aquaculture. Many additional species have experienced over-harvesting, most notably Gelidiales on the European–North African Atlantic coast (Callaway, 2015) and similarly, red and brown algae on the Chilean coast (Vásquez, 2008). Undoubtedly, science-based management plans can maintain a sustainable but relatively limited, stable extraction of biomass over several decades, e.g. *Ascophyllum nodosum* in Canada (Ugarte & Sharp, 2001). Furthermore, seaweed farming has mitigated the over-harvesting of *Gracilaria* in Chile (Santelices & Doty, 1989; Buschmann *et al*., 1995). Therefore, we propose that, as with the progression of terrestrial plant and animal production, inevitably 'culture' will replace 'capture' of marine organisms. This situation, however, creates ever-increasing demands for practical, sustainable and profitable algal cultivation technologies.

Regardless of the different Research & Development (R&D) efforts into new cultivation techniques, commercial farming of seaweeds is still predominantly carried out at sea using floating lines, nets or rafts (Sahoo & Yarish, 2005). These culture systems are generally installed in coastal waters, which have strong water movement and are rich in inorganic nutrient concentrations (often from anthropogenic sources) to enhance nutrient uptake (Harrison & Hurd, 2001). Several other culture systems have been proposed, e.g. those anchored to the seabed, wherever it receives sufficient solar radiation e.g. for *Gigartina skottsbergii* (Westermeier *et al*., 2012) or *Gracilaria chilensis* in Chile (Buschmann *et al*., 1995). There have been efforts to cultivate different species of *Gracilaria* (Buschmann *et al*., 1994; Friedlander & Levy, 1995), *Gelidium* (Friedlander, 2008) and *Chondrus crispus* (Bidwell *et al*., 1985) in land-based systems, ranging from simple ponds to intensively operated tanks, with aeration and dividers for agitation and CO_2 adjustments for pH control. Notwithstanding these developments, there are also relatively small quantities of *Gracilaria* and other seaweeds (e.g. *Caulerpa* spp.) cultivated for human food in simple earthen ponds in some countries (e.g. Taiwan and the Philippines). One of the first commercial-scale pond facilities operates in the Canadian Maritimes, to produce *Chondrus crispus*, branded as: Hana Tsunomata^{TM} (Hafting *et al*., 2015). Commercial on-land, pond cultivation has also been developed in South Africa for *Ulva* spp. (Bolton *et al*., 2009) and Israel for *Ulva* spp. and *Gracilaria* sp. (see: www.seakura.net).

The higher costs of pond-produced seaweeds have restricted their use to high-value products, as seaweeds cultivated for commodity-type products (e.g. polysaccharides) are not profitable in such systems (Hafting *et al*., 2015). It is encouraging to note that in addition to the developments in seaweed aquaculture in countries such as China, Japan, Korea, Indonesia and the Philippines, there are also pilot-scale and pre-commercial farming projects for selected brown and red algae in Europe (Callaway *et al*., 2012; Hughes *et al*., 2012; Peteiro *et al*., 2016; Stévant *et al*., 2017), Latin America, Chile (Buschmann *et al*., 2014; Camus *et al*., 2016), Brazil (Pellizzari & Reis, 2011) and parts of Africa (Msuya, 2011). Additionally, there is a call for proposals for the installation of seaweed farms in the USA (ARPA-e, Mariner, 2016). Taken together, these developments should boost commercial seaweed farming in the countries in the west, in particular Europe and the USA.

One of the key differences between the farming-oriented production strategies developed in the Orient as compared with Western fisheries is that there is a higher demand in the Orient for edible seaweeds, which generate higher revenues than the macroalgal sources for the polysaccharide industry in the developed countries (Hafting *et al*., 2015). Use of the biomass for biofuel would generate even smaller revenues per tonnes, even though the scale of demand for biofuel feedstock would be huge. The revenues from the biomass could be increased, however, through multiple products in a biorefinery scenario (Camus *et al*., 2016).

As identified in the gap analysis, additional impediments to large-scale commercialization of the farming of seaweeds include insufficient knowledge of critical aspects of seaweed biology, physiology and reproduction – knowledge essential for the sustainable farming of a larger diversity of seaweeds. One example of this is the pivotal discovery of the conchocelis-phase of *Pyropia*, which allowed for the commercialization of a huge seaweed industry (video accessed 27.5.2017, https://www.youtube.com/watch?v=3PCxnwhxdXM). Similarly, Professor C.K. Tseng in China worked to resolve the heteromorphic life history of kelp (Laminariales), which then led to the industrialization of seeding lines of species from a range of genera, including *Saccharina*, *Undaria* and *Alaria* (Tseng & Fei, 1987). Further issues facing marine farming that need to be challenged include algal diseases, epibionts and grazers which can reduce the productivity of the crop and quality of the derived products (Kuschel & Buschmann, 1991; Fletcher, 1995; Neill *et al.*, 2008; Cottier-Cook *et al.*, 2016). Other relevant issues requiring attention are related to genetic conservation and management strategies. As shown in Fig. 3, large scientific investments are needed to determine the ecological effects of climate-related chemical, ecological and biological (e.g. invasive algae) processes that may impact the seaweed industry (Harley *et al.*, 2012; Ji *et al.*, 2016; Krueger-Hadfield *et al.*, 2017). The R&D on preserving the genetic diversity of some seaweed species, even the most commonly cultivated (Guillemin *et al.*, 2008; Halling *et al.*, 2013), is also far from being complete (Valero *et al.*, 2017). The creation of a germplasm bank for commercial seaweed species may become an essential tool to produce better strains while preserving desirable traits and genetic diversity (Barrento *et al.*, 2016). However, there is also an over-arching need to incorporate these critical aspects into the regulations affecting seaweed cultivation, as applied in different countries. This is especially critical in regions and countries that already practice a developed level of exploitation of their seaweed resources. Policies that allow the enhancement and expansion of small-scale seaweed aquaculture and the re-population of denuded, formerly productive harvest sites are still needed in many regions. However, these aquaculture regulatory changes demand that environmental and sanitary regulations also change, since they often do not match the existing fish and shellfish regulations, as is the case in Chile (Buschmann *et al.*, 2013).

There is a strong global tendency to study the use of seaweeds for their beneficial ‘environmental services’, e.g. inorganic nutrient extraction in eutrophic waters (Fei, 2004) (Fig. 3) or in places in which intensively cultured, fed-fish species are the point-source of high levels of dissolved nutrients in the surrounding waters (Chopin *et al.*, 2001; Neori *et al.*, 2004; Neori, 2016). In those regions where seaweed aquaculture is a large, developed economic activity (e.g. China), it has been shown that seaweed farming can act as a nutrient-sink, helping with the control of phytoplankton blooms (Yang *et al.*, 2015*b*). However, there has yet to be a demonstration that seaweeds and their cultivation technologies are a tool for coastal bioremediation if integrated into a business model which enhances both the production and value of the cultivated algal biomass (Neori *et al.*, 2007; Chopin *et al.*, 2012). A non-political, international body such as the International Society for Applied Phycology (ISAP) or the International Seaweed Association (ISA) could create an organization in which the different needs, developments and knowledge are collected and made accessible to all stakeholders. Workshops, extension services and demonstration, pilot-scale farms and processing units should be a next step in the right direction.

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Author contributions

A.H. Buschmann wrote the manuscript, with expert guidance and contributions from C. Camus, A. Critchley, J. Infante, M.C. Hernández-González, S.V. Pereda, A. Neori, A. Israel, J.L. Gomez-Pinchetti, A. Golberg and N. Tadmor-Shalev.

References

Ainis, A., Vellanoweth, R., Lapeña, Q. & Thornber, C.S. (2014). Using non-dietary gastropods in coastal shell middens to infer kelp and seagrass harvesting and paleoenvironmental conditions. *Journal of Archaeological Science*, **49**: 343–360.

Almanza, V. & Buschmann, A.H. (2013). The ecological importance of *Macrocystis pyrifera* (Phaeophyta) forests towards a sustainable management and exploitation of Chilean coastal benthic co-management areas. *International Journal of Environment and Sustainable Development*, **12**: 342–360.

Anis, M., Ahmed, S. & Hasan, M. (2017). Algae as nutrition, medicine and cosmetic: the forgotten history, present status and future trend. *World Journal of Pharmacy and Pharmaceutical Sciences*, **6**: 1934–1959.

ARPA-e. (2016). *Macroalgae research inspiring novel energy resources (MARINER)*. U.S. Department of Energy. Available at https://arpa-e-foa.energy-gov.

Baghel, R.R.S., Trivedi, N., Gupta, V., Neori, A., Reddy, C. R.K., Lali, A. & Jha, B. (2015). Biorefining of marine macroalgal biomass for production of biofuel and commodity chemicals. *Green Chemistry*, **17**: 2436–2443.

Balboa, E.M., Conde, E., Soto, M.L., Pérez-Armada, L. & Domínguez, H. (2015). Cosmetics from marine sources. In *Handbook of Marine Biotechnology* (Kim, S.K., editor), 1015–1042. Springer, Berlin.

Barquera, S., Pedroza-Tobías, A., Medina, C., Hernández-Barrera, L., Bibbins-Domingo, K., Lozano, R. & Moran, A.E. (2015). Global overview of the epidemiology of atherosclerotic cardiovascular disease. *Archives of Medical Research*, **46**: 328–338.

Barrento, S., Camus, C., Sousa-Pinto, I. & Buschmann, A. H. (2016). Germplasm banking of the giant kelp: our biological insurance in a changing environment. *Algal Research*, **13**: 134–140.

Bell, T.W., Cavanaugh, K.C., Reed, D.C. & Siegel, D.A. (2015). Geographical variability in the controls of giant kelp biomass dynamics. *Journal of Biogeography*, **42**: 2010–2021.

Benitez-Nelson, C.R. (2000). The biogeochemical cycling of phosphorus in marine systems. *Earth-Science Reviews*, **51**: 109–135.

Bennett, E.E.M., Cramer, W., Begossi, A., Cundill, G., Díaz, S., Egoh, B.N., Geijzendorffer, I.R., Krug, C.B., Lavorel, S., Lazos, E., Lebel, L., Martín-López, B., Meyfroidt, P., Mooney, H.A., Nel, J.L., Pascual, U., Payet, K., Harguindeguy, N.P., Peterson, G.D., Prieur-Richard, A.-H., Reyers, B., Roebeling, P., Seppelt, R., Solan, M., Tschakert, P., Tscharntke, T., Turner, B., Verburg, P.H., Viglizzo, E.F., White, P.C. & Woodward, G. (2015a). Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. *Current Opinion in Environmental Sustainability*, **14**: 76–85.

Bennett, S., Wernberg, T., Connell, S.S.D., Hobday, A.J.A., Johnson, C.R. & Poloczanska, E.S. (2015b). The "Great Southern Reef": social, ecological and economic value of Australia's neglected kelp forests. *Marine and Freshwater Research*, **67**: 47–56.

Bidwell, R., McLachlan, J. & Lloyd, N. (1985). Tank cultivation of Irish moss, *Chondrus crispus* Stackh. *Botanica Marina*, **28**: 87–97.

Bixler, H.H.J. & Porse, H. (2011). A decade of change in the seaweed hydrocolloids industry. *Journal of Applied Phycology*, **23**: 321–335.

Bjerregaard, R., Valderrama, D., Radulovich, R., Diana, J., Capron, M., Mckinnie, C.A., Cedric, M., Hopkins, K., Yarish, C., Goudey, C. & Forster, J. (2016). Seaweed aquaculture for food security, income generation and environmental health in Tropical Developing Countries. World Bank Group, Washington, DC.

Bolton, J.J., Robertson-Andersson, D. V., Shuuluka, D. & Kandjengo, L. (2009). Growing *Ulva* (Chlorophyta) in integrated systems as a commercial crop for abalone feed in South Africa: a SWOT analysis. *Journal of Applied Phycology*, **21**: 575–583.

Bruhn, A., Dahl, J., Nielsen, H.H.B., Nikolaisen, L., Rasmussen, M.B., Markager, S., Olesen, B., Arias, C. & Jensen, P.D. (2011). Bioenergy potential of *Ulva lactuca*: biomass yield, methane production and combustion. *Bioresource Technology Journal*, **102**: 2595–2604.

Buschmann, A.H., Mora, O., Gómez, P., Böttger, M., Buitano, S., Retamales, C., Vergara, P. & Gutierrez, A. (1994). *Gracilaria chilensis* outdoor tank cultivation in Chile: use of land-based salmon culture effluents. *Aquacultural Engineering*, **13**: 283–300.

Buschmann, A.H., Westermeier, R. & Retamales, C.A. (1995). Cultivation of *Gracilaria* on the sea-bottom in southern Chile: a review. *Journal of Applied Phycology*, **7**: 291–301.

Buschmann, A.H., Gonzalez, M. del C.H. & Varela, D. (2008). Seaweed future cultivation in Chile: perspectives and challenges. *International Journal of Environment and Pollution*, **33**: 432–456.

Buschmann, A.H., Stead, R.A., Hernández-Gonazález, M. C., Pereda, S. V., Paredes, J.E. & Maldonado, M.A. (2013). Un análisis crítico sobre el uso de macroalgas como base para una acuicultura sustentable. *Revista Chilena de Historia Natural*, **86**: 251–264.

Buschmann, A.H., Prescott, S., Potin, P., Faugeron, S., Vásquez, J.A., Camus, C., Infante, J., Hernández-González, M.C., Gutíerrez, A., Varela, D.A., Gutierrez, A. & Varela, D.A. (2014). The status of kelp exploitation and marine agronomy, with emphasis on *Macrocystis pyrifera*, in Chile. *Advances in Botanical Research*, **71**: 161–188.

Cabral, P., Levrel, H., Viard, F., Frangoudes, K., Girard, S. & Scemama, P. (2016). Ecosystem services assessment and compensation costs for installing seaweed farms. *Marine Policy*, **71**: 157–165.

Cabrera-Bosquet, L., Crossa, J., von Zitzewitz, J., Serret, M.D. & Luis Araus, J. (2012). High-throughput phenotyping and genomic selection: the frontiers of crop breeding converge. *Journal of Integrative Plant Biology*, **54**: 312–320.

Callaway, E. (2015). Lab staple agar hit by seaweed shortage. *Nature*, **528**: 171–172.

Callaway, R., Shinn, A.P., Grenfell, S.E., Bron, J.E., Burnell, G., Cook, E.J., Crumlish, M., Culloty, S., Davidson, K., Ellis, R.P., Flynn, K.J., Fox, C., Green, D.M., Hays, G.C., Hughes, A.D., Johnston, E., Lowe, C.D., Lupatsch, I., Malham, S., Mendzil, A.F., Nickell, T., Pickerell, T., Rowley, A.F., Stanley, M.S., Tocher, D.R., Turnbull, J. F., Webb, G., Wootton, E. & Shields, R.J. (2012). Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **22**: 389–421.

Camus, C., Ballerino, P., Delgado, R., Olivera-Nappa, Á., Leyton, C. & Buschmann, A.H. (2016). Scaling up bioethanol production from the farmed brown macroalga *Macrocystis pyrifera* in Chile. *Biofuels, Bioproducts and Biorefining*, **10**: 673–685.

Camus, C., Infante, J. & Buschmann, A.H. (2016). Overview of 3 year precommercial seafarming of *Macrocystis pyrifera* along the Chilean coast. *Reviews in Aquaculture*. doi: 10.1111/raq.12185.

Cao, J., Wang, J., Wang, S. & Xu, X. (2016). *Porphyra* species: a mini-review of its pharmacological and nutritional properties. *Journal of Medicinal Food*, **19**: 111–119.

Chan, J. C. C., Cheung, P. C. K. & Ang, P. O. (1997). Comparative studies on the effect of three drying methods on the nutritional composition of seaweed *Sargassum hemiphyllum* (Turn.) C. Ag. *Journal of Agricultural and Food Chemistry*, **45**: 3056–3059.

Chapman, A.S., Stévant, P., Larssen, W.E., Stévant, P. & Larssen, W.E. (2015). Food or fad? Challenges and opportunities for including seaweeds in a Nordic diet. *Botanica Marina*, **58**: 423–433.

Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-González, J.A., Yarish, C. & Neefus, C. (2001). Integrating seaweeds into marine aquaculture systems: a key toward sustainability. *Journal of Phycology*, **37**: 975–986.

Chopin, T., Cooper, J.A.J., Reid, G., Cross, S. & Moore, C. (2012). Open-water integrated multi-trophic aquaculture: environmental biomitigation and economic diversification of fed aquaculture by extractive aquaculture. *Reviews in Aquaculture*, **4**: 209–220.

Chung, I.K., Beardall, J., Mehta, S., Sahoo, D. & Stojkovic, S. (2011). Using marine macroalgae for carbon sequestration: a critical appraisal. *Journal of Applied Phycology*, **23**: 877–886.

Clery, D. (2011). Greenhouse–power plant hybrid set to make Jordan's desert bloom. *Science*, **331**: 136.

Cornish, M.L., Critchley, A.T. & Mouritsen, O.G. (2015). A role for dietary macroalgae in the amelioration of certain risk factors associated with cardiovascular disease. *Phycologia*, **54**: 649–666.

Cornish, M., Critchley, A. & Mouritsen, O. (2017). Consumption of seaweeds and the human brain. *Journal of Applied Phycology*. doi: 10.1007/s10811-016-1049-3.

Correa, T., Gutiérrez, A., Flores, R., Buschmann, A.H., Cornejo, P. & Bucarey, C. (2016). Production and economic assessment of giant kelp *Macrocystis pyrifera* cultivation for abalone feed in the south of Chile. *Aquaculture Research*, **47**: 698–707.

Cottier-Cook, E.J., Nagabhatla, N., Badis, Y., Campbell, M. L., Chopin, T., Dai, W., Fang, J., He, P., Hewitt, C.L., Kim, G.H., Huo, Y., Jiang, Z., Kema, G., Li, X., Liu, F., Liu, H., Liu, Y., Lu, Q., Luo, Q., Mao, Y., Msuya, F.E., Rebours, C., Shen, H., Stentiford, G.D., Yarish, C., Wu, H., Yang, X., Zhang, J., Zhou, Y. & Gachon, C.M.M. (2016). *Policy brief: safeguarding the future of the global seaweed aquaculture industry*. UNU-INWEH and SAMS.

Craigie, J.S.J. (2011). Seaweed extract stimuli in plant science and agriculture. *Journal of Applied Phycology*, **23**: 371–393.

Delaney, A., Frangoudes, K. & Li, S.-A. (2016). Society and seaweed: understanding the past and present. In *Seaweed in Health and Disease Prevention* (Fleurence, J. & Levine, I. editors), 7–40. Elsevier Academic Press, London.

Dillehay, T.T.D., Ramirez, C., Pino, M., Collins, M.B., Rossen, J. & Pino-Navarro, J.D. (2008). Monte Verde: seaweed, food, medicine, and the peopling of South America. *Science*, **320**: 784–786.

Duarte, C.M., Marbá, N. & Holmer, M. (2007). Rapid domestication of marine species. *Science*, **316**: 382–383.

Duarte, C.M., Wu, J., Xiao, X., Bruhn, A. & Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science*, **4**: 100.

Duarte, P. & Ferreira, J. (1997). A model for the simulation of macroalgal population dynamics and productivity. *Ecological Modelling*, **98**: 199–214.

Erlandson, J., Braje, T., Gill, K. & Graham, M.H. (2015). Ecology of the kelp highway: did marine resources facilitate human dispersal from Northeast Asia to the Americas? *Journal of Island and Coastal Archaeology*, **10**: 392–411.

European Commission (2012). *Blue Growth: Opportunities for Marine and Maritime Sustainable Growth*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels.

European Commission (2016). *Salmon Aquaculture could Incorporate Seaweed and Sea Urchins to Reduce Nitrogen Enrichment*. Science for Environment Policy, DG Environment News Alert Service, Bristol.

FAO (2014). The State of World Fisheries and Aquaculture 2014 (SOFIA).

FAO (2016). The State of World Fisheries and Aquaculture 2016 (SOFIA).

Fei, X. (2004). Solving the coastal eutrophication problem by large scale seaweed cultivation. *Hydrobiologia*, **512**: 145–151.

Feng, Y.Y., Hou, L.C., Ping, N.X., Ling, T.D. & Kyo, C.I. (2004). Development of mariculture and its impacts in Chinese coastal waters. *Reviews in Fish Biology and Fisheries*, **14**: 1–10.

Fernand, F., Israel, A., Skjermo, J., Wichard, T., Timmermans, K.R. & Golberg, A. (2016). Offshore macroalgae biomass for bioenergy production: environmental aspects, technological achievements and challenges. *Renewable and Sustainable Energy Reviews*, **75**: 35–45.

Fletcher, R.L. (1995). Epiphytism and fouling in *Gracilaria* cultivation: an overview. *Journal of Applied Phycology*, **7**: 325–333.

Fleurence, J. (2016). Seaweeds as food. In *Seaweed in Health and Disease Prevention* (Fleurence, J. & Levine, I., editors), 149–167. Elsevier Academic Press, London.

Friedlander, M. (1991). Growth rate, epiphyte biomass and agar yield of *Gracilaria conferta* in an annual outdoor experiment. 1. Irradiance and nitrogen. *Bioresource Technology*, **38**: 203–208.

Friedlander, M. (2008). Advances in cultivation of Gelidiales. *Journal of Applied Phycology*, **20**: 451–456.

Friedlander, M. & Levy, I. (1995). Cultivation of *Gracilaria* in outdoor tanks and ponds. *Journal of Applied Phycology*, **7**: 315–324.

Friedlander, M., Galai, N. & Farbstein, H. (1990). A model of seaweed growth in an outdoor culture in Israel. *Hydrobiologia*, **204–205**: 367–373.

Fujita, D., Ishikawa, T., Kodama, S., Kato, Y. & Notoya, M. (2006). Distribution and recent reduction of *Gelidium* beds in Toyama Bay, Japan. *Journal of Applied Phycology*, **18**: 591–598.

Gardner Pinfold (2013). *Socio-economic Impact of Aquaculture in Canada*. Fisheries and Oceans Canada Aquaculture Management Directorate. Gardner Pinfold Consultants Inc., Nova Scotia.

Garraín, D., Lechón, Y. & Santamaría, M. (2016). Environmental externalities assessment of a palm hydrotreated vegetable oil. *Clean Technologies and Environmental Policy*, **18**: 1239–1244.

Golberg, A. & Liberzon, A. (2015). Modeling of smart mixing regimes to improve marine biorefinery productivity and energy efficiency. *Algal Research*, **11**: 28–32.

Gomez Pinchetti, J.L. & Martel Quintana, A. (2016). Algae production and their potential contribution to a nutritional sustainability. *Journal of Environment and Health Science*, **2**: 1–3.

Guillemin, M.-L., Faugeron, S., Destombe, C., Viard, F., Correa, J.A. & Valero, M. (2008). Genetic variation in wild and cultivated populations of the haploid– diploid red alga *Gracilaria chilensis*: how farming practices favor asexual reproduction and heterozygosity. *Evolution*, **62**: 1500–1519.

Hafting, J.J.T., Craigie, J.S.J.J.S., Stengel, D.B.D., Loureiro, R.R., Buschmann, A.H., Yarish, C., Edwards, M.D. & Critchley, A.T. (2015). Prospects and challenges for industrial production of seaweed bioactives. *Journal of Phycology*, **51**: 821–837.

Halling, C., Wikström, S.A., Lilliesköld-Sjöö, G., Mörk, E., Lundsør, E. & Zuccarello, G.C. (2013). Introduction of Asian strains and low genetic variation in farmed seaweeds: indications for new management practices. *Journal of Applied Phycology*, **25**: 89–95.

Harley, C.D.G., Anderson, K.M., Demes, K.W., Jorve, J.P., Kordas, R.L., Coyle, T.A. & Graham, M.H. (2012). Effects of climate change on global seaweed communities. *Journal of Phycology*, **48**: 1064–1078.

Harrison, P.J. & Hurd, C.L. (2001). Nutrient physiology of seaweeds: application of concepts to aquaculture. *Cahiers de Biologie Marine*, **42**: 71–82.

Himaya, S.W.A. & Kim, S.-K. (2015). Marine nutraceuticals. In *Handbook of Marine Biotechnology* (Kim, S.-K., editor), 995–1014. Springer, Berlin.

Hughes, A.D., Kelly, M.S., Black, K.D. & Stanley, M.S. (2012). Biogas from macroalgae: is it time to revisit the idea? *Biotechnology for Biofuels*, **5**: 86.

Hurd, C.L., Harrison, P.J., Bischof, K. & Lobban, C.S. (2014). *Seaweed Ecology and Physiology*. 2nd ed. Cambridge University Press, Cambridge.

Iersel, S. Van & Flammini, A. (2010). Algae-based Biofuels: Applications and Co-products. FAO Aquatic Biofuels Working Group Review. FAO.

Ji, Y., Xu, Z., Zou, D. & Gao, K. (2016). Ecophysiological responses of marine macroalgae to climate change factors. *Journal of Applied Phycology*, **28**: 2953–2967.

Kim, J. K., Yarish, C., Hwang, E.K., Park, M. & Kim, Y. (2017). Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae*, **32**: 1–13.

Korzen, L., Peled, Y., Shamir, S.Z., Shechter, M., Gedanken, A., Abelson, A. & Israel, A. (2015). An economic analysis of bioethanol production from the marine macroalga *Ulva* (Chlorophyta). *Technology*, **3**: 114–118.

Krause, G., Brugere, C., Diedrich, A., Ebeling, M.M.W., Ferse, S.C.A., Mikkelsen, E., Pérez Agúndez, J.A., Stead, S.M., Stybel, N. & Troell, M. (2015). A revolution without people? Closing the people–policy gap in aquaculture development. *Aquaculture*, **447**: 44–55.

Krueger-Hadfield, S.A., Kollars, N.M., Strand, A.E., Byers, J. E., Shainker, S.J., Terada, R., Greig, T.W., Hammann, T., Murray, D.C., Weinberger, F. & Sotka, E.E. (2017). Genetic identification of source and likely vector of a widespread marine invader. *Ecology and Evolution*, 7: 4432–4447.

Krumhansl, K.A.K., Okamoto, D.D.K.D., Rassweiler, A., Novak, M., Bolton, J.J., Cavanaugh, K.C., Connell, S.D., Johnson, C.R., Konar, B., Ling, S.D., Micheli, F., Norderhaug, K.M., Pérez-Matus, A., Sousa-Pinto, I., Reed, D.C., Salomon, A.K., Shears, N.T., Wernberg, T., Anderson, R.J., Barrett, N.S., Buschmann, A.H., Carr, M. H., Caselle, J.E., Derrien-Courtel, S., Edgar, G.J., Edwards, M., Estes, J.A., Goodwin, C., Kenner, M.C., Kushner, D.J., Moy, F.E., Nunn, J., Steneck, R.S., Vásquez, J., Watson, J., Witman, J.D. & Byrnes, J.E.K. (2016). Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Sciences of the United States of America*, **113**: 13785–13790.

Kuschel, F. & Buschmann, A.H. (1991). Abundance, effects and management of epiphytism in intertidal cultures of *Gracilaria* (Rhodophyta) in southern Chile. *Aquaculture*, **92**: 7–19.

Lee, C.S.C. & Ang, P. (1991). A simple model for seaweed growth and optimal harvesting strategy. *Ecological Modelling*, **55**: 67–74.

Lehahn, Y., Ingle, K.N. & Golberg, A. (2016). Global potential of offshore and shallow waters macroalgal biorefineries to provide for food, chemicals and energy: feasibility and sustainability. *Algal Research*, **17**: 150–160.

Lenstra, W., Hal, J.J. Van, Reith, J., Lenstra, J., Hal, J.J. Van & Reith, H. (2011). *Economic Aspects of Open Ocean Seaweed Cultivation*. Energy Research Centre of the Netherlands.

Levine, I. (2016). Algae: a way of life and health. In *Seaweed in Health and Disease Prevention* (Fleurence, J. & Levine, I. A., editors), 1–5. Elsevier Academic Press, London.

Li, L., Zhang, Q. & Huang, D. (2014). A review of imaging techniques for plant phenotyping. *Sensors*, **14**: 20078–20111.

Li, X., Zhang, Z., Qu, S., Liang, G., Zhao, N., Sun, J., Song, S., Cao, Z., Li, X., Pan, J., Luo, S., Zhang, L., Cui, C., Peng, J., Li, Y., Wu, R., Zhao, J., Qian, R., Wang, L., Sai, S. & Yang, G. (2016). Breeding of an intraspecific kelp hybrid Dongfang no. 6 (*Saccharina japonica*, Phaeophyceae, Laminariales) for suitable processing products and evaluation of its culture performance. *Journal of Applied Phycology* **28**: 439–447.

Lux Spotlight blog (2015). New Protein Sources and the Billions of Mouths and Dollars That Will Follow |Lux Spotlight. Available at http://blog.luxresearchinc.com/blog/2015/02/new-protein-sources-and-the-billions-of-mouths-and-dollars-that-will-follow/(last accessed 24 February 2017).

Mangos, A., Bassino, J.-P. & Sauzade, D. (2010). The economic value of sustainable benefits rendered by the Mediterranean marine ecosystems. Blue Plan Papers 8 UNEP/MAP Regional Activity Centre. 79 pp.

Manninen, K., Huttunen, S., Seppälä, J., Laitinen, J. & Spilling, K. (2016). Resource recycling with algal cultivation: environmental and social perspectives. *Journal of Cleaner Production*, **124**: 495–505.

Masuda, T., Furuya, K., Kohashi, N., Sato, M., Takeda, S., Uchiyama, M., Horimoto, N. & Ishimaru, T. (2010). Lagrangian observation of phytoplankton dynamics at an artificially enriched subsurface water in Sagami Bay, Japan. *Journal of Oceanography*, **66**: 801–813.

Masutani, S.M. & Takahashi, P.K. (1999). Ocean thermal energy conversion. In *Wiley Encyclopedia of Electrical and Electronics Engineering* (Peterca, M., editor). John Wiley & Sons, Chichester.

Mazarrasa, I., Olsen, Y.S., Mayol, E., Marbà, N. & Duarte, C.M. (2014). Global unbalance in seaweed production, research effort and biotechnology markets. *Biotechnology Advances*, **32**: 1028–1036.

McHugh, D.J. (2003). Seaweeds uses as human foods. In *A Guide to the Seaweed Industry*. FAO Fisheries Technical Paper 441. FAO, Rome.

Meland, M. & Rebours, C. (2012). Short description of the Norwegian seaweed industry. *Bioforsk FOKUS*, **7**: 275–277.

Moustafa, K. (2017). Greening drylands with seawater easily and naturally. *Trends in Biotechnology*, **35**: 189–191.

Msuya, F.E. (2011). The impact of seaweed farming on the socioeconomic status of coastal communities in Zanzibar, Tanzania. *World Aquaculture*, **42**: 45–48.

Msuya, F.E. & Neori, A. (2008). Effect of water aeration and nutrient load level on biomass yield, N uptake and protein content of the seaweed *Ulva lactuca* cultured in seawater tanks. *Journal of Applied Phycology*, **20**: 1021–1031.

Mutka, A.M. & Bart, R.S. (2015). Image-based phenotyping of plant disease symptoms. *Frontiers in Plant Science*, **5**: 1–7.

Neill, K., Heesch, S. & Nelson, W. (2008). Diseases, pathogens and parasites of *Undaria pinnatifida*. Ministry of Agriculture and Forestry, Wellington, NZ.

Neori, A. (2016). Can sustainable mariculture match agriculture' s output? *Global Aquaculture advocate*.

Available on-line at: http://advocate.gaalliance.org/can-sustainable-mariculture-match-agricultures-output/.

Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M. & Yarish, C. (2004). Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. *Aquaculture*, **231**: 361–391.

Neori, A., Troell, M., Chopin, T., Yarish, C., Critchley, A. & Buschmann, A.H. (2007). The need for a balanced ecosystem approach to blue revolution aquaculture. *Environment: Science and Policy for Sustainable Development*, **49**: 36–43.

Neori, A., Tadmor Shalev, N. & Agami, M. (2016). Seaweed aquaculture as a match for agriculture. In *22nd International Seaweed Symposium*, Copenhagen.

Neori, A., Shpigel, M., Guttman, L. & Israel, A. (2017). The development of polyculture and integrated multi-trophic aquaculture (IMTA) in Israel: a review. *Israeli Journal of Aquaculture – Bamidgeh*, **69**: IJA_69.2017.1385.

Nobre, A. M., Robertson-Andersson, D., Neori, A. & Sankar, K. (2010). Ecological–economic assessment of aquaculture options: comparison between abalone monoculture and integrated multi-trophic aquaculture of abalone and seaweeds. *Aquaculture*, **306**: 116–126.

Notoya, M. (2010). Production of biofuel by macroalgae with preservation of marine resources and environment. In *Seaweeds and their Role in Globally Changing Environments* (Seckbach J., Einav R. & Israel, A., editors), 217–228. Springer, Dordrecht.

Pascual, U., Muradian, R., Brander, L., Gómez-Baggethun, E., Martín-López, B., Verma, M., Armsworth, P., Christie, M., Cornelissen, H., Eppink, F. & Farley, J. (2010). The economics of valuing ecosystem services and biodiversity. In *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations* (Kumar, P., editor), 183–256. TEEB, Earthscan, London and Washington.

Pelc, R. & Fujita, R.M. (2002). Renewable energy from the ocean. *Marine Policy*, **26**: 471–479.

Pellizzari, F. & Reis, R.P. (2011). Seaweed cultivation on the southern and southeastern Brazilian coast. *Revista Brasileira de Farmacognosia*, **21**: 305–312.

Pereira, R. & Yarish, C. (2008). Mass production of marine macroalgae. In *Ecological Engineering, Vol. 3 of Encyclopedia of Ecology* (Jørgensen, S.E. & Fath, B.D., editors), 2236–2247. Elsevier, Oxford.

Peteiro, C., Sánchez, N. & Martínez, B. (2016). Mariculture of the Asian kelp *Undaria pinnatifida* and the native kelp *Saccharina latissima* along the Atlantic coast of Southern Europe: an overview. *Algal Research*, **15**: 9–23.

Radulovich, R., Neori, A., Valderrama, D., Reddy, C.R.K., Cronin, H. & Forster, J. (2015). Farming of seaweeds. In *Seaweed Sustainability – Food and Nonfood Applications* (Tiwari, B. and Troy, D., editors). 27–59. Academic Press, London.

Rebours, C., Marinho-Soriano, E., Zertuche-González, J.A., Hayashi, L., Vásquez, J.A., Kradolfer, P., Soriano, G., Ugarte, R., Abreu, M.H., Bay-Larsen, I., Hovelsrud, G., Rødven, R. & Robledo, D. (2014). Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. *Journal of Applied Phycology*, **26**: 1939–1951.

Reed, J. (2017). New pipeline plan may help save the Dead Sea. *Financial Times*, 23 March 2017. Available at: https://www.ft.com/content/c9a188c4-bad1-11e6-8b45-b8b81dd5d080?mhq5j=e3.

Robinson, N., Winberg, P. & Kirkendale, L. (2013). Genetic improvement of macroalgae: status to date and needs for the future. *Journal of Applied Phycology*, **25**: 703–716.

Sahoo, D. & Yarish, C. (2005). Mariculture of seaweeds. In *Phycological Methods: Algal Culturing Techniques* (Andersen, R.A., editor), 219–237. Elsevier Academic Press, Burlington.

Santelices, B. (1999). A conceptual framework for marine agronomy. *Hydrobiologia*, **398/399**: 15–23.

Santelices, B. & Doty, M. (1989). A review of *Gracilaria* farming. *Aquaculture*, **78**: 95–133.

Seip, K.L. (1980). A computational model for growth and harvesting of the marine alga *Ascophyllum nodosum*. *Ecological Modeling*, **8**: 189–199.

Shefer, S., Israel, A., Golberg, A. & Chudnovsky, A. (2017). Carbohydrate-based phenotyping of the green macroalga *Ulva fasciata* using near-infrared spectrometry: potential implications for marine biorefinery. *Botanica Marina*, 1–11.

Shpigel, M. (2013). Mariculture mariculture systems, integrated land-based. In *Sustainable Food Production* (Christou, P., Savin, R., Costa-Pierce, B.A., Misztal, I. & Whitelaw, C.B.A., editors), 1111–1120. Springer, New York.

Skjermo, J., Aasen, I.M., Arff, J., Broch, O.J., Carvajal, A., Christie, H., Forbord, S., Olsen, Y., Reitan, K.I., Rustad, T., Sandquist, J., Solbakken, R., Wittgens, K.B.S.B., Wolff, R. & Handå, A. (2014). *A New Norwegian Bioeconomy Based on Cultivation and Processing of Seaweeds: Opportunities and R&D Needs*. SINTEF Fisheries and Aquaculture. Sintef, Trondheim.

Stévant, P., Rebours, C. & Chapman, A. (2017). Seaweed aquaculture in Norway: recent industrial developments and future perspectives. *Aquaculture International*, **25**: 1373–1390.

Straub, S., Thomsen, M. & Wernberg, T. (2016). The dynamic biogeography of the Anthropocene: the speed of recent range shifts in seaweeds. In *Seaweed Phylogeography* (Hu, Z.-M. & Fraser, C., editors), 63–93. Springer, Amsterdam.

Suo, R. & Wang, Q. (1992). Laminaria culture in china. *INFOFISH International*, **1**: 40–42

Synytsya, A., Čopíková, J., Kim, W.J. & Park, Y. I. (2015). Cell wall polysaccharides of marine algae. In *Handbook of Marine Biotechnology* (Kim, S.-K., editor), 543–590. Springer, Berlin.

Tennessen, D.J., Bula, R.J. & Sharkey, T.D. (1995). Efficiency of photosynthesis in continuous and pulsed light emitting diode irradiation. *Photosynthesis Research*, **44**: 261–269.

Thanh-Sang Vo, Ngo, D.-H. & Kim, S.-K. (2012). Marine algae as a potential pharmaceutical source for anti-allergic therapeutics. *Process Biochemistry*, **47**: 386–394.

Tietenberg, T. & Lewis, L. (2016). *Environmental and Natural Resource Economics*. 10th ed. Routledge, New York.

Tinch, R. & Mathieu, L. (2011). *Marine and Coastal Ecosystem Services: Valuation Methods and their Practical Application*. Regional Seas UNEP-WCMC Biodiversity Series, Cambridge.

Trivedi, J., Aila, M., Bangwal, D.D.P., Kaul, S. & Garg, M. O. (2015). Algae based biorefinery – how to make sense? *Renewable and Sustainable Energy Reviews*, **47**: 295–307.

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A. H. & Fang, J.G. (2009). Ecological engineering in aquaculture – potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture*, **297**: 1–9.

Tseng, C.K. & Fei, X.G. (1987). Macroalgal commercialization in the Orient. In *Twelfth International Seaweed Symposium* (Ragan, M.A. & Bird, C.J., editors), 167–172. Springer, Amsterdam.

Ugarte, R. & Sharp, G. (2001). A new approach to seaweed management in eastern Canada: the case of *Ascophyllum nodosum*. *Cahiers de Biologie Marine*, **42**: 63–70.

Valero, M., Guillemin, M.-L., Destombe, C., Jacquemin, B., Gachon, C., Badis, Y., Buschmann, A.H., Camus, C. & Faugeron, S. (2017). Perspectives on domestication research for sustainable seaweed aquaculture. *Perspectives in Phycology*, **4**: 33–46.

Vásquez, J.A. (2008). Production, use and fate of Chilean brown seaweeds: resources for a sustainable fishery. *Journal of Applied Phycology*, **20**: 457–467.

Vásquez, J.A.J., Zuñiga, S., Tala, F., Piaget, N., Rodríguez, D.C. & Vega, J.M.A. (2014). Economic valuation of kelp forests in northern Chile: values of goods and services of the ecosystem. *Journal of Applied Phycology*, **26**: 1081–1088.

Walter, A., Liebisch, F. & Hund, A. (2015). Plant phenotyping: from bean weighing to image analysis. *Plant Methods*, **11**: 1–11.

Wells, M.M.L., Potin, P., Craigie, J.S., Raven, J.A., Merchant, S.S., Helliwell, K.E., Smith, A.G., Camire, M. E. & Brawley, S.H. (2016). Algae as nutritional and functional food sources: revisiting our understanding. *Journal of Applied Phycology*, **29**: 949–982.

Westermeier, R., Patiño, D.J., Murúa, P., Quintanilla, J.C., Correa, J., Buschmann, A.H. & Barros, I. (2012). A pilot-scale study of the vegetative propagation and suspended cultivation of the carrageenophyte alga *Gigartina skottsbergii* in southern Chile. *Journal of Applied Phycology*, **24**: 11–20.

Yang, Y., Chai, Z., Wang, Q., Chen, W., He, Z. & Jiang, S. (2015a). Cultivation of seaweed *Gracilaria* in Chinese coastal waters and its contribution to environmental improvements. *Algal Research*, **9**: 236–244.

Yang, Y., Liu, Q., Chai, Z. & Tang, Y. (2015b). Inhibition of marine coastal bloom-forming phytoplankton by commercially cultivated *Gracilaria lemaneiformis* (Rhodophyta). *Journal of Applied Phycology*, **27**: 2341–2352.

Yang, L.-E., Lu, Q.-Q. & Brodie, J. (2017). A review of the bladed Bangiales (Rhodophyta) in China: history, culture and taxonomy. *European Journal of Phycology*, **52**: 1–13.

Zhang, Q.S., Tang, X.X., Cong, Y.Z., Qu, S.C., Luo, S.J., Yang, G.P. (2007). Breeding of an elite *Laminaria* variety 90-1 through inter-specific gametophyte crossing. *Journal of Applied Phycology*, **19**: 303–311.