Chapter 14. Seaweeds

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1. Introduction

Seaweeds are a group of photosynthetic non-flowering plant-like organisms (called macroalgae) that live in the sea. They belong to three major groups based on their dominant pigmentation: red (Rhodophyta), brown (Phaeophyta) and green (Chlorophyta). Seaweeds were traditionally and are currently still used as food in China, Japan and the Republic of Korea. About 33 genera of seaweeds, mostly red and brown, are harvested and farmed commercially (McHugh, 2003), although close to 500 species in about 100 genera are collected and utilized locally (Mouritsen, 2013). Currently about 80 per cent of total seaweed production is for direct human consumption, eaten dried or fresh for its nutritional value or for flavouring (see Kilinc et al., 2013 for a comprehensive listing of nutrients and compounds) in the form of sushi, salad, soup, dessert and condiments, and the remaining 20 per cent is used as a source of the phycocolloids extracted for use in the food, industrial, cosmetic, and medical industry (Browdy et al., 2012, Critchly et al., 2006, Lahaye, 2001, McHugh, 2003, Mouritsen, 2013, Ohno and Critchley, 1993), as well as for animal feed additive, fertilizer, water purifier, and probiotics in aquaculture (Abreu et al., 2011, Chopin, 2012, Chopin et al., 2001, Chopin et al., 2012, Fleurence et al., 2012, Kim et al., (2014), Neori et al., 2004, Pereira and Yarish, 2008, 2010, Rose et al., 2010). Carrageenan and agar are extracted from red seaweeds, and alginates and fucoidan are extracted from brown seaweeds, generally from kelp species. Recently, the kelp species *Saccharina lattisima* was considered for bioethanol production (Adams et al., 2009).

2. Production

World production of seaweeds comes from two sources: harvesting from wild stocks and from aquaculture (including land-based culture, mariculture and farming). Production from harvesting of wild stocks has been stable at over 1 million tons (wet weight) in the last 10 years (2003 to 2012) according to FAO (2014) statistics (see Figure 1). Top producers in 2012 were Chile (436,035 tons representing 39 per cent of total world production), China (257,640 tons or 23 per cent), Norway (140,336 or 13 per cent), Japan (98,514 or 9 per cent), France (41,229 tons or 4 per cent), Ireland (29,500 tons or 2.73 per cent), Iceland (18,079 tons or 2 per cent), South Africa (14,509 tons or 1 per cent) and Canada (13,833 tons or 1 per cent). Contributing less than 1 per cent each were 24 other countries. Chile has consistently been the number one top producer since 2003, except in 2007 when China exceeded Chile's production by 1 per cent. Norway and Japan have maintained their position as third and fourth top producers, respectively, since 2003.

Three countries posted only one year's production in 10 years (Namibia in 2003 with 408 tons, Samoa in 2004 with 478 tons, Senegal in 2012 with 1,028 tons. India posted 1 ton of production in 2004 to 2008, except in 2005 when it posted 2 tons of production).

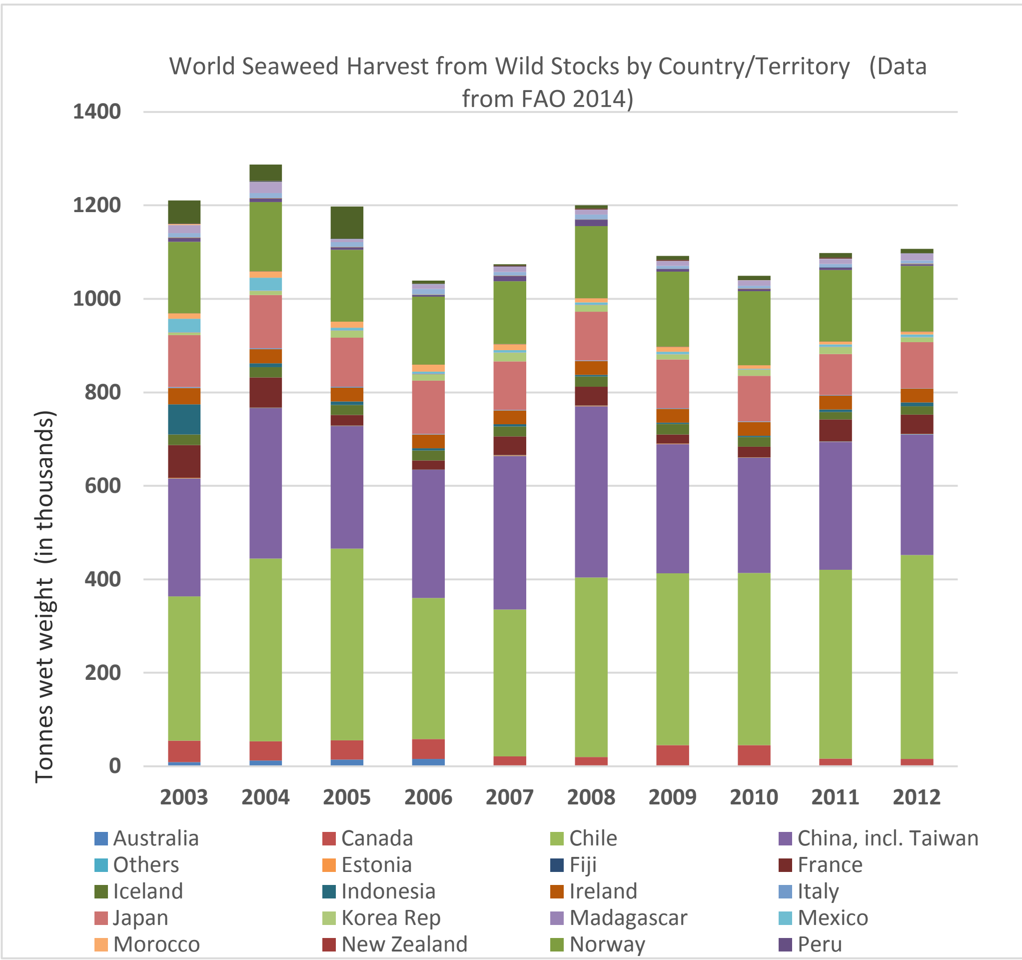

Figure 1. World seaweed production from wild stocks in 2003-2012 by country/territory in tons wet weight. Data from FAO, 2014. Four countries with production in 10 years of less than 1000 tons or with only one production within 10 years are lumped under Others (see text). tp://www.fao.org/fishery/statistics/software/fishstatj/en.

The bulk of seaweeds produced worldwide come from aquaculture. The FAO (2014) reported that the production of aquatic seaweeds from mariculture, reached 24.9 million tons in 2012, valued at about $6 billion United States dollars. The red, brown and green seaweeds constitute about 88 per cent (21 million tons). About 96 per cent (23.8 million tons) of the total production were produced from aquaculture (see Figure 14.2). Data from FAO showed a steady increase of about 8 per cent per year over the last 10 years (range of 4-12 per cent), specifically for red seaweeds (Figure 3) with the brown seaweeds showing stable production. The cultured seaweeds are mainly those that produce carrageenan (*Kappaphycus alvarezii* and *Eucheuma* spp. - 8.3 million tons), followed by the alginate-producing brown seaweeds (kelps - 5.7 million tons). China is the consistent top supplier, although showing a decreasing trend, with 50 per cent of the world production over a 10-year period (2003-2012). The Philippines ranked second in 2003 to 2006, producing 9-10 per cent, after which it was overtaken by Indonesia. The Democratic People's Republic of Korea, the Republic of Korea, and Japan produced between 2-5 per cent of the annual total, and 31 other countries produced less than 1 per cent of the annual total, except for Malaysia, which showed an increasing production equivalent to 1.09-1.39 per cent of the annual global quantity during 2010 to 2012.

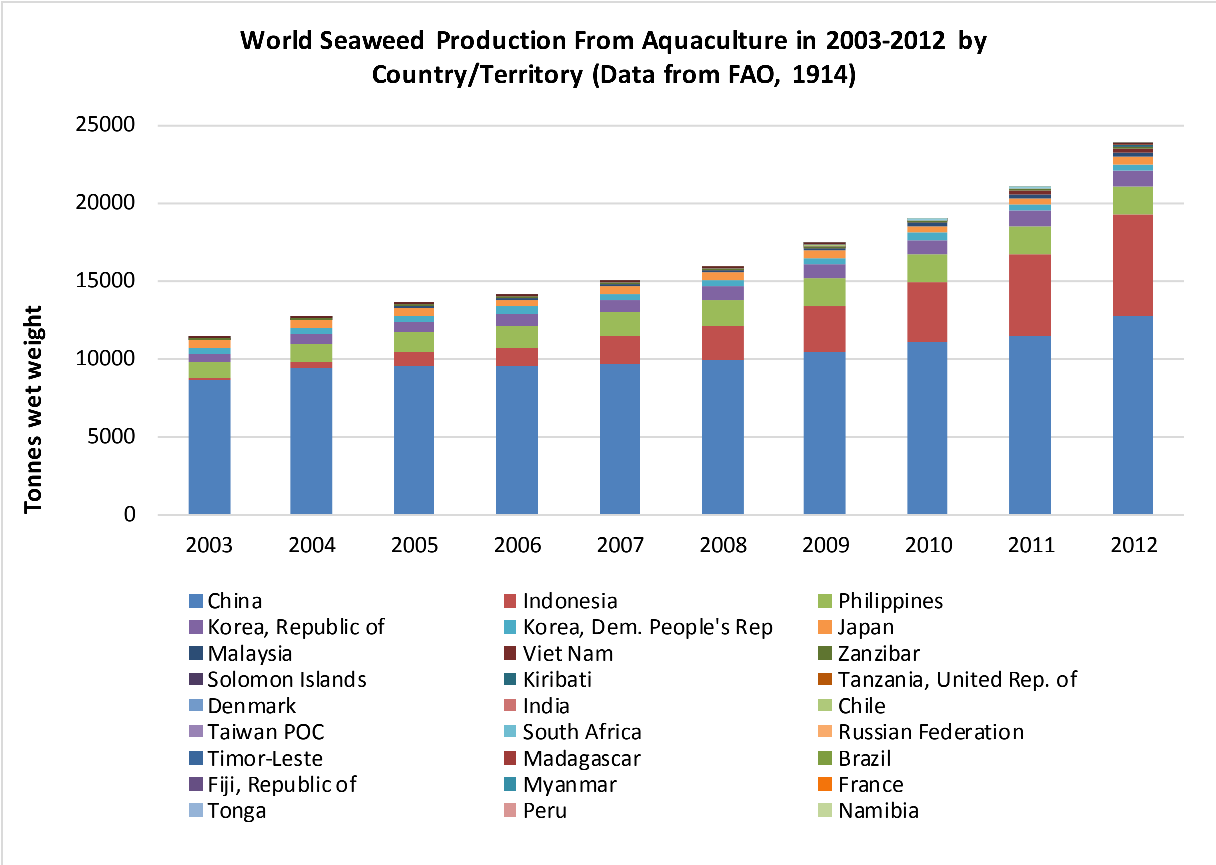

Figure 2. World seaweed production from aquaculture in 2003-2012 by country/territory in tons wet weight. Data from FAO 2014. http://www.fao.org/fishery/statistics/software/fishstatj/en.

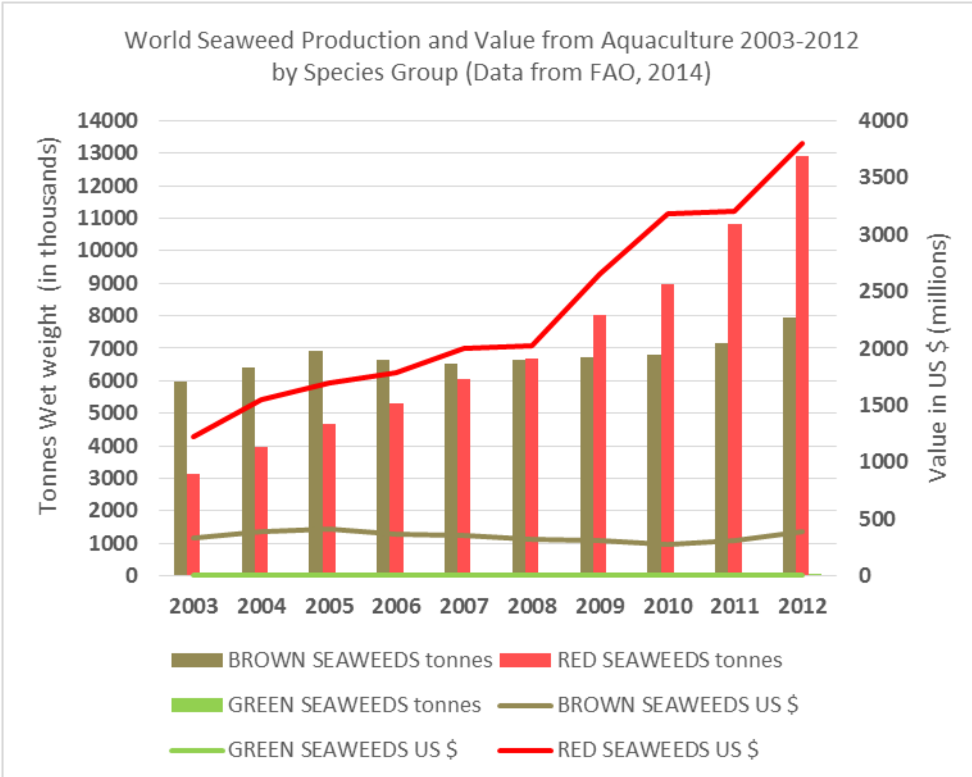

Figure 3. World aquaculture production from 2003-2012 by species groups in tons wet weight and total value in United States dollars per group. (Unidentified aquatic plants excluded.) Green algae production is minimal, as shown in this graph. Data from FAO 2014.

3. Social and economic impacts and challenges

Harvests from wild populations are affected by overexploitation and climatic changes. In Northern Ireland, for example, which is listed as one of the top 10 producers of wild stocks globally (FAO, 2014), McLaughlin et al., (2006) described in detail the adverse impacts of seaweed harvesting at small, artisanal and commercial scales on areas of conservation importance, protected and priority habitats and species, including disturbance of birds and wildlife, disruption of food webs, damage to substrata, habitat destruction, localized biodiversity changes, and changes in particle-size distribution in sediments. Direct effects on the seaweed population include mortalities due to increased growth rate and cover of other algae which are not harvested, such as filamentous green algae and the brown seaweed, *Fucus vesiculosus,* which outcompete the desired species, and die-back due to increased predation. In several areas of Norway, the kelp *Saccharina lattisima* has been reported by Moy and Christie (2012) to have suffered dieback by 40-80 per cent due to sea urchin predation.

The brown seaweed kelps are most affected by rising water temperature, because sexual reproduction (gamete formation) in most kelps will not occur above 20°C (Dayton 1985, Dayton et al., 1999). Already along the European coasts and especially in Brittany, France, the brown kelp, *Laminaria digitata*, which is heavily harvested for commercial uses, is reported to be on the verge of local extinction. The already reduced reproductive potential of the kelp due to dwindling population and harvesting-induced ecosystem changes may be exacerbated by climate-caused increase in sea temperature (Brodie et al., 2014, Raybaud et al., 2013). Two other kelp species, *Laminaria ochroleuca,* a warm-temperate perennial, and *Saccorhiza polyschides*, a wide-ranging cool- to warm-temperate annual, have somewhat higher temperature tolerances for sexual reproduction than other kelps (Pereira et al., 2011); however, *Saccorhiza* outcompetes *L. ochroleuca* in shared habitats. Brittany is the northern limit of *L. ochroleuca*'s range. Since 1940, *L. ochroleuca* has been found on the coasts of southern England, which is apparently indicative of a slow northward extension of warmer waters. Anticipated increasing ocean temperatures in the future in the boreal region may result in *L. ochroleuca* possibly replacing *L. hyperborea* (Brodie et al., 2014). On the other hand, the kelp *Ecklonia maxima* is extending eastward on the tip of South Africa because of a northward intrusion by cooler inshore water (Bolton et al., 2012); this could greatly benefit the whole ecosystem and provide more food for the abalone industry there. All this is quite a contrast from southward intrusion patterns by warm water on the east and west coasts of Australia, causing extensive retreat of kelps and fucoids (another group of brown algae) southward from their previous northern-most limits (Wernberg et al., 2011, Millar, 2007).

Seaweed farming and culture are seriously affected by diseases. *Ice-ice* disease has impacted the farming of the kappa-carrageenan-producing *Kappaphycus alvarezii,* commercially called "cottonii". Another species, *Eucheuma denticulatum,* commercially called "spinosum," is *ice-ice*-resistant, but contains iota-carrageenan which fetches a much lower price on the world market (Valderrama, 2012). This problem may be a result of the low genetic variation in *K. alvarezii,* all of whose cultured stocks around the world have a similar mitochondrial haplotype, which is not the case for *E. denticulatum* (Halling et al., 2013; Zuccarello et al., 2006). Significant diseases affecting cultivated kelps (e.g., *Saccharina japonica*) include green-rot, white-rot, blister disease, which may be environmentally induced, and malformation disease of summer sporelings and swollen stipe or "frond twist disease" which are caused by bacteria (Brinkhaus et al., 1987, Tseng, 1986). Parasites such as *Pythium*, an oomycete fungus, causes "red rot" or "red wasting" disease in the red seaweed *Pyropia* commonly used in making sushi (Hurd et al., 2014). However, based on case studies from six countries, Valderrama (2012) reported that the socioeconomic impacts of seaweed farming have been positive. He attributed this mainly to small-scale, family operations resulting in the generation of substantial employment as compared to other forms of aquaculture. He added that seaweed farming is often undertaken in remote areas where coastal communities face fewer economic alternatives and where many of these communities have traditionally relied on coastal fisheries which are currently being affected by overexploitation. Valderrama stated that the impact of seaweed farming in these cases goes beyond its immediate economic benefits to communities as it also reduces the incentives for overfishing. However, one challenge faced by farmers in these remote areas is low profits due to high shipping costs. This disadvantage is exacerbated by the dependence of farmers on processors for the procurement of their farming materials and their lack of farm-management skills. In addition, food safety issues can sometimes affect markets and prices. This is because seaweeds are efficient nutrient extractors (Kim et al., 2014) and may accumulate compounds that pose harm to human health (Mouritsen 2013; see also Chapter 10).

4. Information and Knowledge Gaps

Despite the long history of utilization, it is reported that kelp-dominated habitats along much of the NE Atlantic coastline have been chronically understudied over recent decades in comparison with other regions such as Australasia and North America. For example, McLaughlin et al. (2006) noted that information on the distribution and biomass of commercial seaweeds in Northern Ireland is lacking. Smale and Wernberg (2013) highlight the changing structure of kelp forests in the North- East Atlantic in response to climate- and non-climate-related stressors, which will have major implications for the structure and functioning of coastal ecosystems. This paucity of field-based research is impeding ability to conserve and manage this important resource.

References

Abreu, M.H., Pereira, R., Yarish, C., Buschmann, A.H., Sousa-Pinto, I. (2011). IMTA with Gracilaria vermiculophylla: productivity and nutrient removal performance of the seaweed in a Land-based pilot scale system. *Aquaculture* 312 (1-4): 77-87.

Adams, J., Gallagher, J., Donnison, I. (2009). Fermentation study on Saccharina lattisima for bioethanol production considering variable pre-treatments. *Journal of Applied Phycology* 21: 569-574.

Bolton, J., Anderson, R., Smit, A., Rothman, M. (2012). South African kelp moving eastwards: the discovery of Ecklonia maxima (Osbeck) Papenfuss at De Hoop Nature Reserve on the South Coast of South Africa, *African Journal of Marine Science* 34: 147-151.

Brinkhuis, B.H., Levine, H.G.,Schlenk, C.G., Tobin, S. (1987). Laminaria cultivation in the far-east and North America. In: *Seaweed Cultivation for Renewable Resources*. (Bird, K.T. Benson, P.H., eds.). Developments in Aquaculture and Fisheries Science 16: 107-146.

Brodie, J., Williamson, C.J., Smale, D.A., Kamenos, N.A., Mieszkowska, N., Santos, R., Cunliffe, M., Steinke, M., Yesson, C., Anderson, K.M., Asnaghi, V., Brownlee, C., Burdett, H.L., Burrows, M.T., Collins, S., Donohue, P.J.C., Harvey, B., Noisette, F., Nunes, J., Ragazzola, F., Raven, J.A., Foggo, A., Schmidt, D.N., Suggett, D., Teichberg, M., Jason M. Hall-Spencer, J.M. (2014). The future of the northeast Atlantic benthic flora in a high CO2 World. *Ecology and Evolution* 1-12. doi:10.1002/ece3.1105.

Browdy, C.L., Hulata, G., Liu, Z., Allan, G.L., Sommerville, C., Passos de Andrade, T., Pereira, R., Yarish, C., Shpigel, M., Chopin, T., Robinson, S., Avnimelech, Y., Lovatelli, A. (2012). Novel and emerging technologies: can they contribute to improving aquaculture Sustainability? In Subasinghe, R.P., Arthur, J.R., Bartley, D.M., De Silva, S.S., Halwart, M., Hishamunda, N., Mohan, C.V., Sorgeloos, P. (eds.), Farming the Waters for People and Food. *Proceedings of the Global Conference on Aquaculture 2010*, Phuket, Thailand. 22–25 September 2010. pp. 149–191. FAO, Rome and NACA, Bangkok.

Chopin, T. (2012). Aquaculture, Integrated Multi-Trophic (IMTA). In: Meyers, R.A. (ed.), *Encyclopedia of Sustainability Science and Technology*. Springer, Dordrecht, The Netherlands. pp. 542–64.

Chopin, T., Buschmann, A. H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-Gonzales, 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. ,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.

Critchley, A.T., Ohno, M,. Largo, D.B. (2006). *World Seaweed Resources: An Authoritative Reference System*. DVD–ROM. Wokingham, UK: ETI Information Services.

Dayton, P.K. (1985). Ecology of kelp communities. *Annual Review of Ecology and Systematics* 16: 215–245.

Dayton, P.K., Tegner, M.J., Edwards, P.B., Riser, K.L. (1999). Temporal and spatial scales of kelp demography: the role of oceanography and climate. *Ecological Monographs* 69: 219–250.

FAO. (2014). *Fishery and Aquaculture Statistics. Aquaculture production 1950-2012 (FishstatJ).* In: FAO Fisheries and Aquaculture Department [online or CD-ROM]. Rome. Updated 2014. http://www.fao.org/fishery/statistics/software/fishstatj/en.

Fleurence, J., Morançais, M., Dumay, J., Decottignies, P., Turpin, V., Munier, M., Garcia Bueno, N., Jaouen, P. (2012). What are the prospects for using seaweed in human nutrition and for marine animals raised through aquaculture? *Trends in Food Science & Technology* 27:57-61.

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, doi: 10.1007/s10811-012-9842-0.

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

Kılınç, B. Cirik, S., Turan, G., Tekogul, H., Koru, E. (2013). *Seaweeds for Food and Industrial Applications*. http://dx.doi.org/10.5772/53172. In: *Food Industry* http://cdn.intechopen.com/pdfs/41694/InTech-Seaweeds_for_food_and_industrial_applications.pdf

Kim, J.K., Kraemer, G.P., Yarish, C. (2014). Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary. *Aquaculture* 433: 148-156.

Lahaye, M. (2001). Chemistry and physico-chemistry of phycocolloids, *Cahiers de Biologie Marine*. 42: 137-157.

McHugh, D.J. (2003). A Guide to the Seaweed Industry*. FAO Fisheries Technical Paper* 441.

McLaughlin, E., Kelly, J., Birkett, D., Maggs, C., Dring, M. (2006). *Assessment of the Effects of Commercial Seaweed Harvesting on Intertidal and Subtidal Ecology in Northern Ireland.* Environment and Heritage Service Research and Development Series. No. 06/26.

Millar, A.J.K. (2007). The Flindersian and Peronian Provinces. In: McCarthy, P., Orchard, A., (eds.), *Algae of Australia. An Introduction*. CSIRO Publishing, Melbourne, pp. 554-559.

Mouritsen, O.G. (2013). *Seaweeds Edible, Available & Sustainable*. The University of Chicago Press, Chicago & London, 287 pp.

Moy, F., Christie, H. (2012). Large-scale shift from sugar kelp (Saccharina latissima) to ephemeral algae along the south and west coast of Norway. *Marine Biology Research* 8: 309-321.

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

Ohno, M., Critchley, A., (eds.). (1993). *Seaweed Cultivation and Marine Ranching*. JICA, Yokosuka, Japan, i-xvii, 431, i-xii pp.

Pereira, T., Engelen, A., Pearson, G., Serrão, E., Destombe, C., Valero, M. (2011). Temperature effects on the microscopic haploid stage development of Laminaria ochroleuca and Sacchoriza polyschides, kelps with contrasting life histories. *Cahiers de Biologie Marine* 52: 395-403.

Pereira, R., Yarish, C. (2008). Mass production of Marine Macroalgae. In: Jørgensen, S.E., Fath, B.D., (eds.), *Ecological Engineering*. Vol. [3] of Encyclopedia of Ecology, 5 vols. pp. 2236-2247. Elsevier: Oxford.

Pereira, R., Yarish, C. (2010). The role of Porphyra in sustainable culture systems: Physiology and Applications. In: Israel, A., Einav, R., (eds.), *Role of Seaweeds in a Globally Changing Environment*. Springer Publishers, pp. 339-354.

Pereira, R., Yarish, C., Critchley, A. (2012). Seaweed Aquaculture for Human Foods in Land Based and IMTA Systems. In: Meyers, R. (eds.), *Encyclopedia of Sustainability Science and Technology.* Springer Science, N.Y. pp. 9109-9128.

Raybaud,V., Beaugrand, G., Goberville, E., Delebecq, G., Destombe, C. Valero, M., Davoult, D., Morin, P., Gevaert, F. (2013). Decline in Kelp in West Europe and Climate. *PLoS ONE* 8(6): e66044. doi:10.1371/journal.pone.0066044.

Rose, J.M., Tedesco, M., Wikfors, G.H., Yarish, C. (2010). *International Workshop on Bioextractive Technologies for Nutrient Remediation Summary Report*. US Department of Commerce, Northeast Fisheries Science Center Reference Document 10-19; Available from: National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, or online at http://www.nefsc.noaa.gov/nefsc/publications/12 p.

Smale, D.A., Wernberg, T. (2013). Extreme climatic event drives range contraction of a habitat-forming species. *Proceedings of the Royal Society B* 280: 20122829.

Tseng, C.K. (1986). Laminaria mariculture in China. In: Doty, M.S., Caddy, J.F., Santelices, B. (eds.), Case studies of seven commercial seaweed resources. *FAO Fisheries Technical Papers*, (281): 311 p.

Valderrama, D. (2012). *Social and economic dimensions of seaweed farming: a global review*. IIFET Tanzania Proceedings. https://ir.library.oregonstate.edu/xmlui/handle/1957/33886

Wernberg, T., Russell, B., Thomsen, M., Gurgel, F., Bradshaw, C., Poloczanska, E., Connell, S. (2011). Seaweed communities in retreat from Ocean Warming. *Current Biology* 21: 1828-1832.

Zuccarello G.C., Critchley, A.T., Smith, J., Sieber, V., Lhonneur, G.B. (2006). Systematics and genetic variation in commercial Kappaphycus and Eucheuma (Solieriaceae, Rhodophyta). *Journal of Applied Phycology* (2006) 18: 643-651doi: 10.1007/s10811-006-9066-2.

