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Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation

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ABSTRACT

Environmental concerns regarding natural resource depletion have led to the cultivation of more renewable resources such as seaweed biomass. As the cultivation in Europe is still in its early stages, an estimation of the environmental sustainability may boost further development of this sector by highlighting its competitiveness. A case study on the resource footprint of *Saccharina latissima* production near the West coast of Ireland (18 ha of floating longlines) and France (0.6 ha of raft systems) is performed. The Cumulative Exergy Extraction from the Natural Environment (CEENE) method is used to quantify the exergy deprived from 8 types of natural resources (incl. marine resources) to produce 1 $\mathrm{MJ_{ex}}$ biomass. For Ireland and France, results of the Exergetic Life Cycle Assessment (ELCA) are 1.7 $\mathrm{MJ_{ex}\ MJ_{ex}^{-1}}$ and 8.7 $\mathrm{MJ_{ex}\ MJ_{ex}^{-1}}$, respectively. Compared to the footprint of microalgae and several terrestrial plants (sugar beets, maize and potatoes), typically showing values in the range of 0.92–3.88 $\mathrm{MJ_{ex}\ MJ_{ex}^{-1}}$, seaweed production in North West Europe (especially in Ireland) is relatively resource-efficient. Moreover, the potential to improve the resource footprint of seaweed production is investigated; in the short-term, seaweed can be cultivated with a comparable life cycle resource demand as several land plants.

1. Introduction

1.1. Aquaculture production

Over the last few decades, aquaculture has become highly important in the supply of food and nutrition for the growing world population. In 2012, an unprecedented 90.4 million tonnes of aquatic plants and animals were farmed and this amount is expected to expand until around 2030, at which time it is estimated that capture fisheries and aquaculture will deliver equal amounts [1]. Worldwide environmental concerns about the depletion of natural resources and industrial pollution have led to the cultivation of more renewable resources such as seaweed biomass, which is translated in high aquaculture production rates of 20.8 million tonnes (wet weight) in 2012 compared to 6.4 million tonnes in 2000 (Fig. 1; [2]). Due to the high demand for food and phycocolloid products, seaweed farming has become economically important for many countries. It is especially profitable in Asian countries, where a relatively low-technological business provides income, employment and foreign trade [3]. As potential economic and ecological benefits become apparent, a wave of interest from government, research institutions and industry has developed over the last few years [4].

1.2. Seaweed cultivation

1.2.1. Worldwide

Seaweeds, which are also known as macroalgae, are multicellular marine plant-like organisms. Depending on their pigmentation, they can be grouped in three diverse phyla: Ochrophyta (brown seaweeds), Rhodophyta (red seaweeds) and Chlorophyta (green seaweeds). While most species live in marine conditions, a few algal species thrive well in brackish water or freshwater [5]. As seaweeds produce energy from photosynthesis, they are present in the upper sunlit aquatic euphotic zone. Their photosynthetic mechanisms are similar to that of terrestrial land-based plants but, generally, they are more efficient in converting sunlight into biomass because of a less complex cellular structure and their direct access to water, nutrients and CO_2 [4]. Although they survive in a wide range of habitats, most species of macroalgae can be found in coastal regions where they attach to fixed substrates (bedrock, boulders etc.) under suitable light and nutrient (upwelling) conditions [6].

Some seaweeds can be cultivated vegetatively, others only by controlling the sexual life cycle of the seaweed [7]. In vegetative cultivation,

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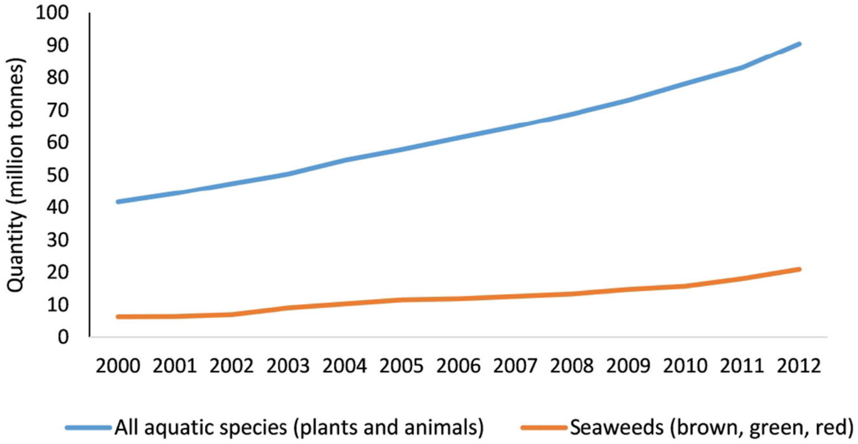

Fig. 1. Worldwide aquaculture production of aquatic organisms and seaweed (million tonnes) between 2000 and 2012 [2].

new plants are grown from small fragments of seaweed in a suitable environment. However, monitoring the reproductive cycle is essential for many seaweeds, especially for many brown seaweeds (e.g. the Laminariales). Their life cycle involves an alternation of generations (gametophytes and sporophytes) and successful cultivation requires greater control of the life cycle than seaweeds that are grown vegetatively.

Worldwide, there are at least three near-shore seaweed cultivation methods demonstrated; the off-bottom method, a raft system and single longline ropes [8]. The off-bottom monoline method is most used because of its simplicity, cheapness, easy installation and maintenance. This method is suitable in shallow waters (e.g. lagoons) and sandy sea bottoms, where farmers can work on foot and by boat. Stakes, usually made of wood, are used to hold the ropes that are approximately 10 m long [9,10]. In contrast, floating longline methods are used in deeper waters, further from the shore. This indicates the need for a boat for access, the anchoring of lines to the sea bottom as well as the use of buoys to provide stability in the water column. A raft system, constructed from floating material (e.g. bamboo or plastic), also serves as a basis for the attachment of the seaweed culture ropes.

Identifying the best harvest times are dependent on the type of species, the environmental conditions, the production cycle and the season. Analysis of the effect of seasonal variation on the chemical composition of seaweed can be used to determine the optimal harvesting time related to components of most interest commercially. For example, it was reported that the highest alginate concentration in *Saccharina latissima* was found in September, which indicates the importance of harvesting in September for the phycocolloid industry in Europe [11]. Nevertheless, for human food, it seems better to harvest at the end of the spring season when the quality of the biomass is still high and not affected by epiphytes [5].

1.2.2. European context

The majority of seaweed (99% in 2012) is produced on a commercial scale in Asian countries, especially in the People's Republic of China (54%), Indonesia (28%), the Philippines (7%) and North and South Korea (4%) [2]. These countries have a long history of eating a wide variety of seaweeds including *Pyropia* and *Porphyra* spp., *Laminaria* spp., *Saccharina* spp. and *Undaria pinnatifida*. EU imports of seaweeds have traditionally been used by the pharmaceutical, cosmetic and food industry for their useful extracts (e.g. phycocolloids such as agar) or as products for agriculture (fertilizer, animal feed) and are less commonly used for direct human consumption [12]. Compared to Asia, seaweed production in Europe is still small in scale and can be found in countries such as France, Spain, Portugal, Ireland and Norway, amongst others, either as commercial or experimental setups. The main cultivated species to date are *S. latissima* (sugar kelp) and *U. pinnatifida* (Wakame) [13].

Efforts have been made to develop suitable seaweed cultivation techniques, which are adapted to cold–temperate conditions. The off-bottom method is not used in Europe because of the associated high labor costs and exposed coastlines but the floating longline and raft methods have been developed for seaweed cultivation in Europe [9]. Lately, in the context of the EU-funded AT~SEA project, advanced textiles are being developed and tested which may allow easier and more efficient mechanization of seaweed cultivation and harvesting in North West Europe [14]. Because of the high population density in Europe, there is greater competition for land arising from the growing demand for food, energy and accommodation. Therefore, seaweed cultivation in European seas could be a solution to reduce the pressure on land and its resources.

1.3. Seaweed applications

As algae (micro- and macroalgae) are important primary producers (autotrophs), they form the basis of oceanic aquatic food webs and assist in regulating the effect of climate change by consuming carbon dioxide for growth. Furthermore, carbon can be stored for a long time in the sediment due to the burial of dead algae [15]. Moreover, because seaweed takes up nutrients such as nitrates and phosphates that are often present in excess in coastal waters, they can reduce eutrophication or purify wastewater [16,17]. Some selected species of seaweed are also capable of immobilizing heavy metal ions due to their specific sorption capacities [18].

Apart from their potential for pollution control, seaweed can be used as feedstock for a wide variety of applications due to their natural richness in minerals, amino acids, vitamins and trace elements. About 66% of the worldwide seaweed production is used as a low-calorie, high nutritional value source of human food [1,4]. Edible seaweeds are stated to have beneficial effects on human health; biologically active components (carotenoids, phlorotannins, fucoidan, peptides) play an important role in the prevention of diseases such as cancer and diabetes [12]. Another major application of seaweed cultivation is the extraction of phycocolloids (e.g. alginates, agars, and carrageenans) as thickening or gelling agents, used in many industrial sectors such as the food, pharmaceutical, cosmetics and chemical industries. Seaweed can also be used as a fertilizer and soil conditioner, as an animal feed ingredient or as a feedstock for energy production [19]. Although seaweeds cannot be used for biodiesel production because of their low amount of extractable lipids, an alternative is to produce biogas via anaerobic digestion or ethanol via fermentation with yeasts, the latter production pathway still being in its infancy [20]. According to a study of Vanegas and Bartlett [21], a methane yield of 244 ml per g volatile solids (g_{vs}) is achieved through co-digestion of *S. latissima* with bovine slurry which is higher than grass (168 ml g_{vs}^{-1}) but lower than rice (264 ml g_{vs}^{-1}). It indicates that