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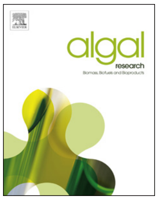

Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation

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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 MJ_{ex} biomass. For Ireland and France, results of the Exergetic Life Cycle Assessment (ELCA) are 1.7 $MJ_{ex}\ MJ_{ex}^{-1}$ and 8.7 $MJ_{ex}\ MJ_{ex}^{-1}$, 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 $MJ_{ex}\ MJ_{ex}^{-1}$, 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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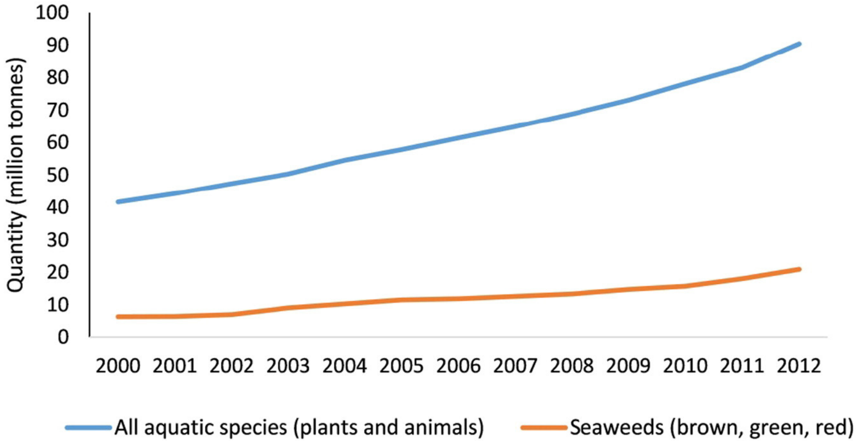

Fig. 1. Worldwide aquaculture production of aquatic organisms and seaweed (million tonnes) between 2000 and 2012 [2].

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 biofuel production from seaweeds at high yields is possible. Nevertheless, obtaining energy from seaweeds is not yet available on a large commercial scale [22].

1.4. How can the environmental sustainability of seaweed cultivation be measured?

As seaweed cultivation and the search for markets in Europe is still in its infancy, an estimation of the environmental sustainability may assist in their further development. A useful tool to determine the environmental burdens and benefits of seaweed production is life cycle assessment (LCA), able to quantify all relevant emissions and resources consumed, as well as the related environmental impacts and resource depletion associated with a product's life cycle. LCA takes into account the full life cycle: from the extraction of resources, through production, use, recycling, to disposal of the remaining waste [23]. Despite the great pressure on global natural resources, no LCA studies of which the authors are aware of have focused on total resource consumption during seaweed production. However, such an assessment is highly relevant in order to improve the ecological performance of these cultivation systems.

Resources such as energy, fresh water, fossils, minerals, metals and, amongst others, land, should be taken into account. Nevertheless, only a few life cycle impact assessment (LCIA) methods are available to quantify the effect of using terrestrial land resources on the environment. Examples include the ecological footprint method [24], the RECIPE method [25] and the Cumulative Exergy Extraction from the Natural Environment (CEENE) method [26,27]. The latter provides spatially differentiated characterization factors, which can be used to assess the impact of using land resources in different countries. While seaweed farming takes place mainly at sea, it is important to account for sea surface occupation as well when determining the life cycle resource footprint. Taelman et al. [6] developed a LCIA method capable of analyzing the environmental resource footprint of sea surface occupation: CEENE 2014, in which the framework developed by Alvarenga et al. [27] was further developed for marine systems. Spatially differentiated characterization factors for marine realms, provinces and ecoregions were calculated based on the potential net primary production (NPP) available in the photic zone. In the case of platforms or artificial islands, the occupation of marine surface fully blocks sunlight penetration in the waterbody which automatically avoids natural NPP production. However, when sea surface occupation by human-made systems does not occupy this photic zone completely, i.e. allowing sunlight to partly penetrate the water body (e.g. seaweed farming), natural NPP production is not fully avoided and an occupation factor α is introduced. In this situation, the α factor will be between zero and one [6].

In this study, the environmental resource footprint of cultivating seaweed in the Atlantic Ocean on the West coast of Ireland was compared to seaweed farming on the Northern coast of France (Brittany). Different seeding procedures and nearshore cultivation systems were applied (single longline system in Ireland versus raft system in France). A cradle-to gate life cycle analysis has been performed, using the CEENE LCIA method to determine the overall consumption of natural resources to produce 1 MJ_{ex} seaweed (dry weight (DW)). To be able to quantify all resources used (also including marine resources), the occupation factor α was calculated for both production sites.

The objectives of this study are fourfold: 1) Examine environmental sustainability in terms of natural resource use of seaweed production at different production regions in North West Europe (NWE), 2) Provide a case-study in which sea surface occupation factors α are calculated [6], 3) Compare the resource footprint of seaweed with that of microalgae and different types of terrestrial biomass (maize, potatoes and sugar beet) and 4) Analyze feasible options to improve the footprint of seaweed production in NWE.

2. Material and methods

2.1. Process description

Within the context of the INTERREG IVB NWE EnAlgae project, the large brown seaweed (*S. latissima*) was cultivated near the coasts of Ireland and France. The seedling production in the hatcheries and the nearshore site requirements are discussed in Sections 2.1.1 and 2.1.2, respectively. As seaweed production in Europe is still in its initial stage and data regarding processing of the biomass towards a final application is scarce, focus should be first on optimizing the cultivation processes.

2.1.1. Seaweed cultivation in Ireland

2.1.1.1. Seedling production in the hatchery. In the West of Ireland, the National University of Ireland, Galway (NUIG) operates an aquaculture research facility (The Ryan Institute Carna Research Station) in Carna, Co. Galway (Supplementary Information (SI), Fig. SI.1). The facility is located at a local pier, and has a complex water treatment system installed (Fig. SI.2) that can supply seawater for use in large-scale experimental flow-through and recirculation systems. The facility currently operates an Atlantic cod (*Gadhus morhua*) breeding program and a seaweed hatchery facility amongst other experimental research programs.

Seawater is supplied by 2 Fybroc centrifugal pumps of 15 kW (one operating and one standby) at a continuous mode with a speed of approximately 21 L s^{-1}. A Liquivac Priming pump is necessary to start the 2 main Fibroc pumps. Further, the water passes through a Bernoulli pneumatically controlled filter system (250 μm) to remove suspended solids and compressed air is delivered by Atlas Copco compressors. There are 2 filters and 2 compressors available, but only one of each is on duty at the time. Most of this filtered seawater is used in the fish breeding units, only a small part (about 45 m^3 $year^{-1}$) is pumped to the seaweed hatchery facility tanks where the water quality is further improved by 2 inline TMC cartridge filters of 10 μm and 1 μm mesh size, running under pressure from the incoming water, and a TMC UV sterilizer to eliminate harmful microorganisms. Seawater required for flask culture of gametophytes is sent to an Astell autoclave for complete sterilization (Fig. SI.2). In advance, flasks are cleaned using a phosphate-free laboratory detergent (Decon 90).

The production of seedlings starts at collecting fertile *S. latissima* in the lower intertidal and subtidal coastal zones (Fig. SI.3). In the hatchery (120 m^2), the reproductive sori, which are clusters of sporangia containing many millions of zoospores, are cut out from the blade of seaweed, cleaned and air-dried (24 h) before being placed in small flasks (6 L) with autoclaved water. The numerous flagellated male and female zoospores (haploid) that are released after this process develop into male and female gametophytes (also haploid). Under laboratory conditions, the gametophytes produce gametes and a fusion between a male and female gamete leads to a diploid zygote that develops into juvenile sporophytes, or seedlings. Light intensity and spectra is an important parameter during these reproductive phases; red/white light is used at the beginning and blue light is required for gametogenesis later on [28]. The sporophyte culture is sprayed on 12 collectors (each containing 50 m of polyvinyl alcohol fibers or culture string). These collectors are placed in 5 culture tanks filled with UV-sterilized seawater for at least a month. F/2 culture medium containing nitrates ($NaNO_3$) and phosphates ($NaH_2PO_4.H_2O$), vitamins (B1, B12 and H) and trace elements (e.g. $FeCl_3$), is used in the flasks and tanks [29]. The cultures are kept at 10 °C using a room air chiller, which is the optimum temperature for all life cycle stages. Agitation and aeration is provided by a blower device operational 24 h a day (one on standby). Approximately three batches (of ±5 weeks) per year provide 9000 m of seeded cultivation string in total.

All wastewater from the hatchery is collected and pre-filtered in a hydrotech drumfilter. A Grundfos pump is installed for backwashing.

Suspended solids are removed in order to improve the efficiency of the Wedeco UV disinfection unit where bacteria and viruses are destroyed by high intensity UV (Fig. SI.2).

2.1.1.2. Grow out phase in the sea. The seaweed grow out phase is located in the South West of Ireland within Ventry Harbour, Co. Kerry and is owned and operated by the commercial seaweed farm Dingle Bay Seaweeds (Castletownbere, Co. Cork) (Fig. SI.1). In total, 18 ha of sea site is licensed for seaweed aquaculture (Fig. SI.5). Therefore, a van is used to transport the seeded collectors between the hatchery and Ventry Harbour. Other equipment (e.g. culture rope, anchor chains, buoys) are transported from Castletownbere to Cuan Pier, Ventry Harbour by lorry and from Cuan Pier to the seaweed site by several boats. These boats were also used for maintenance and harvest of *S. latissima*.

In December, the seeded seaweed collectors are wrapped around the culture rope (280 m per longline) at deployment. Fig. 2 gives a schematic representation of the equipment used at sea to cultivate *S. latissima*; 4 anchors and 6 large buoys are used for 3 longlines. Manual harvesting takes place in May, when the quality of the seaweed is optimal. About 25 kg seaweed (9.7% DW) per m longline can be harvested.

2.1.2. Seaweed cultivation in France

2.1.2.1. Seedling production in the hatchery. The seaweed hatchery of 165 m^2 in France is located in Pleubian, at the CEVA (Centre d'Etude et de Valorisation des Algues) facility (Fig. SI.1). Seawater is pumped (1.5 kW, 12 $m^3\ h^{-1}$) from the sea to a 20 m^3 storage tank. A second pump (0.55 kW, 4 $m^3\ h^{-1}$) is used to deliver water at the hatchery. Seedling breeding starts at the collection of local fertile *S. latissima* (Fig. SI.4). Sori are cut from the blades and gently brushed to remove animals and epiphytes. Autoclaved seawater is used for the preparation of fertile material (autoclave specification: SMI AVX 5091). Further, the cleaned seaweed material is stored in dark conditions at 10–15 °C for one night to dehydrate the seaweed pieces. On day 2, the fertile seaweed parts are submerged in autoclaved seawater to release the spores (spore solution).

The seedlings are produced in filtered seawater (2-step filtration procedure using 10 μm and 1 μm Hydrex™ filter cartridges). Because of membrane fouling, the cartridges are changed every year. When the seawater is poured into the tanks, sodium hypochlorite is added to sterilize and sodium thiosulfate is used to neutralize the bleach. Afterwards, the spore solution is poured into 2 cultivation tanks (2 batches per year). A blower device (operational 24 h a day) is used to provide mixing and aeration. As nitrogen and phosphorous source in the culture medium, NH_4NO_3 and $PO_4HNa_2 \cdot 2H_2O$ is used, respectively. Compared to the seeding procedure at NUIG, there is no gametophyte development in CEVA. Direct seeding of mobile zoospores is cheaper (no maintenance of the immobile gametophyte phase), but, as a disadvantage, more fertile sporophyte is necessary because of the avoided gametophyte step. On a yearly basis, 4000 m of cultivation string is seeded, i.e. 80 collectors are prepared. The development of seedlings under controlled conditions lasts for about 5 weeks, until they reach 3–5 mm in length. Each collector contains 60 m of string, which is wrapped around 50 m of culture rope. This procedure takes place in the hatchery, not at sea.

2.1.2.2. Grow out phase in the sea. Around mid-December, the nursery culture is transferred to the sea. The sea farm is located 2 km from shore and 8 km from the nearest harbor of Lézardrieux (use of boat and lorry is required) (Fig. SI.1). Because of the many surface currents at the sea site, a raft system was chosen over a longline system. The main reason behind this choice is the lower areal yield of a longline system under these conditions because a large distance between the ropes is required to avoid friction.

Fig. 3 illustrates the raft system used for the grow out phase of *S. latissima*. In total, about 6 ha of sea site is licensed for CEVA to use. There are two types of raft systems (for experimental reasons), and 4 raft units available. The 1st type is 20 m × 50 m with 11 longlines (2 units) and the 2nd type is 20 m × 100 m with 11 longlines (2 units). These cultivation units occupy 6000 m^2 of sea surface and about 2.85 ha of sea site (taking into account anchoring). A schematic representation of the sea farm is shown in Fig. SI.6. Each raft system contains 2 main PEHD tubes at each side, some intermediate PEHD tubes (2 tubes of 10 m in type 1, 6 tubes of 10 m in type 2), 2 anchors, 4 anchor blocks, 2 buoys of 1000 L and 2 buoys of 300 L. The longlines are at 1.5 m depth below the sea surface. In total, 3300 m culture rope is harvested manually in May, keeping in mind that harvesting in June yields more biomass but, due to more epiphytes, food and feed applications are limited. A maximum yield of 20.3 kg fresh weight (FW) m^{-1} could be achieved with this system but due to friction of culture ropes with buoys and tubes the yield drops to an average of 5 kg seaweed (9.7% DW) per m longline.

2.2. Life cycle assessment (LCA)

An environmental LCA was carried out according to the ISO standards 14040 and 14044. As explained by these standards, LCA is a 4-phase process. The goal and scope definition is critical in accurately drawing a boundary for an LCA. A functional unit should be defined, providing a reference to which all material and energy inputs/outputs and

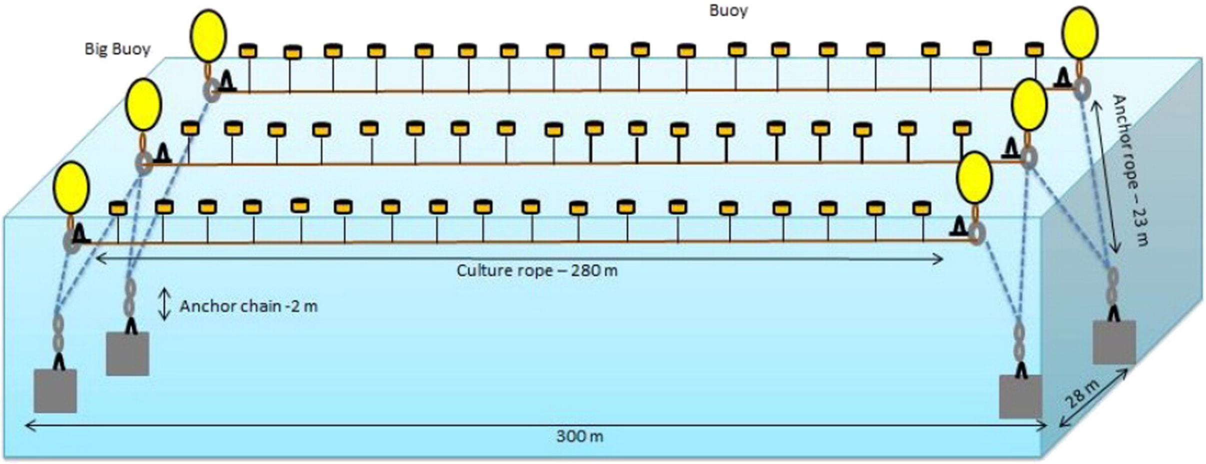

Fig. 2. Equipment for nearshore seaweed cultivation in Ventry Harbour, Co. Kerry, Ireland. A cultivation unit contains 3 longlines, 4 anchors and anchor chains, 8 anchor ropes and buoyancy is required to maintain the longlines at 0.5–1 m below the water's surface.

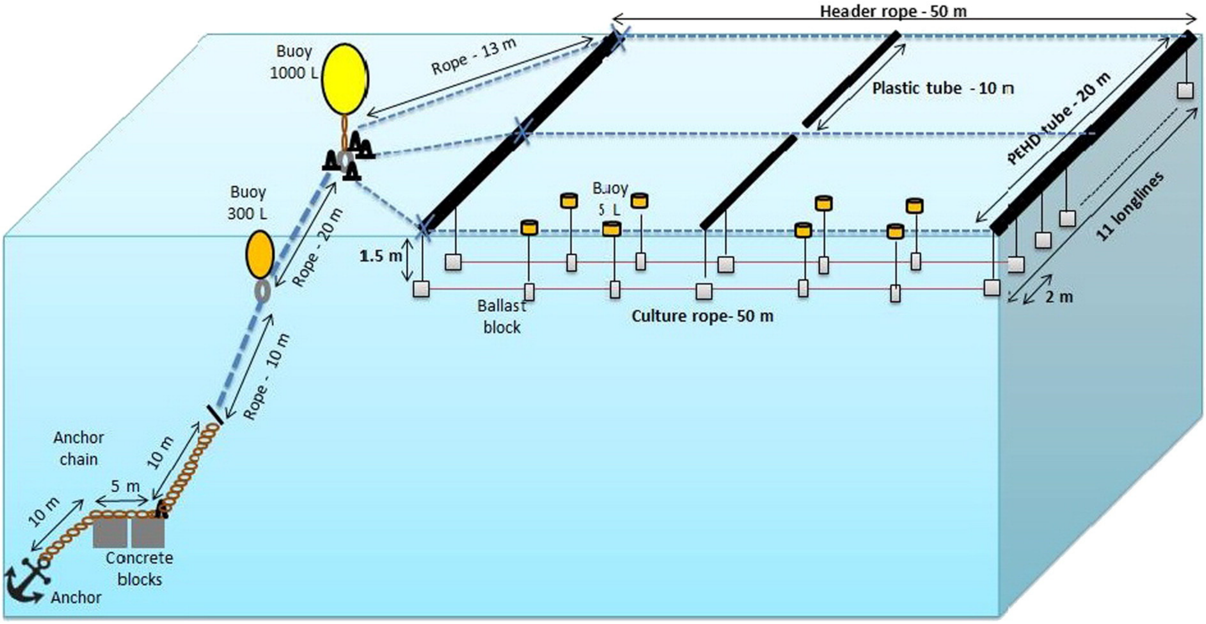

Fig. 3. Schematic representation of a raft system (20 m × 50 m, type 1) and anchoring used at the sea farm (6000 m^2) near the coast of Lézardrieux, France. Only 2 culture ropes (1.5 m below the sea surface) are shown.

waste outputs (quantified during the data inventory step) are normalized. Performing an impact assessment results in converting the inputs and outputs into their impacts on the environment. As a last step, interpretation of the results, conclusions can be formulated and improvements proposed [30,31].

2.2.1. Goal and scope and inventory analysis

Comparing the environmental sustainability in terms of natural resource use for two different seaweed production scenarios in North West Europe requires a common functional unit and system boundaries. In this study, results are expressed per MJ_{ex} *S. latissima*. Data on the composition was obtained from CEVA and was assumed to be applicable for both cases (Table SI.1). Processes related to the seaweed hatchery and grow-out phase at sea are included in the foreground system. A schematic representation of the foreground system and background system can be found in Fig. 4.

All processes related to seaweed production are taken into account; e.g. illumination of juvenile sporophytes, cooling of the seaweed hatchery rooms, fresh water use, air sparging in the cultivation tanks, transport of the ropes to the sea site, the use of boats for maintenance and harvest of the biomass and land (hatchery) and sea surface (grow-out phase) occupation. Data related to the foreground system is collected at the production sites (Table SI.3 and SI.4). Potential emissions at the foreground system were not quantified. Data about the products and processes from the supply chain (i.e. background data) were selected from the ecoinvent version 2.2 database [32]. This LCA study applied a cradle-to-gate boundary.

In the case of Ireland, the impact of using electricity and infrastructure during pre- and post-treatment of seawater is allocated to the volume of water used within the hatchery. The main part of the seawater (99%) is used for breeding fish instead of seaweed. In the hatchery, a blower provides aeration and mixing in the seaweed tanks but this device is also used for aeration in other (fish) tanks. Therefore, the electricity consumption of the blower is allocated on the basis of the volume of the seaweed tanks (which represents only 0.05% of the total volume). In France, the blower in the hatchery supplies air for microalgae (330 L) and macroalgae (600 L) cultivation, i.e. the same allocation method (volume-based) was applied as in the case of Ireland.

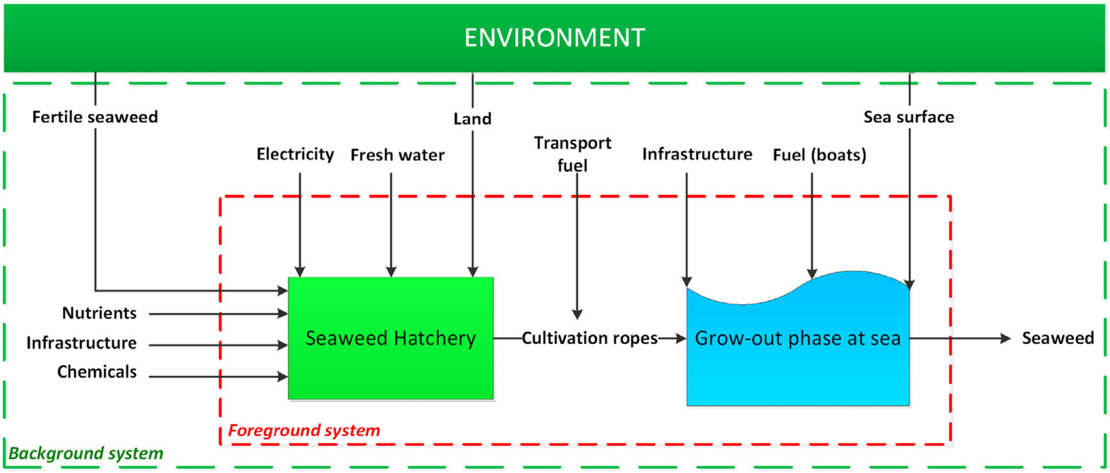

Fig. 4. Schematic representation of the foreground (red dotted line) and background system (green dotted line) of both seaweed production systems located in Ireland and France. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In Section 3.2, the resource footprint of seaweed production is compared to the cultivation of marine microalgae and some terrestrial plants (sugar beet, maize, potatoes). Inventory data related to *Nannochloropsis* sp. production was available in Taelman et al. [33]. Database ecoinvent version 2.2 provided data for the terrestrial plants [32]. Table SI.2 shows the chemical composition and exergy content of the terrestrial plants [34].

2.2.2. Impact assessment

2.2.2.1. Resource accounting method. Environmental issues are often related to the production, transformation and end use of energy. In this regard, increasing the energy efficiency (i.e. reducing energy losses) of a production process can reduce the environmental impact [35]. To address the impact of using energy and natural resources in general, it is best to quantify this in terms of exergy. Exergy is a thermodynamic unit which refers to the maximum amount of useful work obtainable from a system or resource, as it is brought to equilibrium with a reference environment (as defined by Szargut et al. [36] with its reference temperature T_0 (298.15 K), pressure P_0 (1 atm) and composition) through reversible processes. Exergy is not subject to conservation rules; exergy can be destroyed due to irreversibilities during any process, i.e. the final exergy embodied in delivered work, heat, (by)products and waste is not equal to the initial exergy content of the resources [37].

In this study, the environmental impact assessment was performed based on the CEENE (2014) method, which is an exergetic LCIA method. This method quantifies the impact on the environment through the extraction and/or consumption of several natural resources; abiotic renewables, atmospheric resources, fossil fuels, land resources, marine resources, metal ores, minerals, nuclear energy and water. As explained in the studies of Alvarenga et al. [27] and Taelman et al. [6], the natural environment can be divided in two main systems: human-made and natural (production without human intervention). In natural systems, the extraction of land and marine resources was accounted for through their exergy content (e.g. of fish, wood) because the land/sea surface itself was not (fully) occupied by mankind. In human-made systems (e.g. industry, offshore aquaculture), terrestrial land/marine surface area is deprived from the ecosphere. Therefore, CEENE accounts for the occupation of land or sea area in human-made systems based on the exergy content of potential net primary production (NPP). This potential NPP represents the NPP that an area would produce without human intervention.

Spatially differentiated characterization factors (CF) were calculated for both types of occupation: terrestrial land [27] and marine sea surface [6]. The CFs for direct land occupation in Ireland and France are 25.7 $\mathrm{MJ_{ex}\,m^{-2}\,y^{-1}}$ and 28.0 $\mathrm{MJ_{ex}\,m^{-2}\,y^{-1}}$, respectively, and for direct marine sea surface occupation 22.7 $\mathrm{MJ_{ex}\,m^{-2}\,y^{-1}}$, as both nearshore regions are located in the Celtic Sea. When compared to the production of microalgae and some terrestrial plants, different CF's for land occupation were used (26.9 $\mathrm{MJ_{ex}\,m^{-2}\,y^{-1}}$ for Belgium and 24.4 $\mathrm{MJ_{ex}\,m^{-2}\,y^{-1}}$ for Switzerland). For the upstream processes (background system), about 95% of the occupied land has its origin in Europe and no sea surface occupation is considered. Therefore, the impact of land occupation in the background system is calculated according to the average CF of Europe (23.2 $\mathrm{MJ_{ex}\,m^{-2}\,y^{-1}}$).

2.2.2.2. Marine sea surface occupation factor α. An important point regarding marine area occupation compared to land occupation is the three-dimensionality of the ocean. NPP production is possible in the upper layers of the water body, i.e. the photic zone, where sufficient sunlight can penetrate to stimulate growth. In the study of Taelman et al. [6], an occupation factor α was introduced to deal with the possibility of occupying only part of the photic zone. For example, nearshore seaweed farming on 1 ha sea surface still allows sunlight to penetrate the waterbody due to the longline/grid structure used for cultivation. In this study, the α factor is calculated for the infrastructure used at the West coast of Ireland and the Northern coast of France. These coastal areas provide sufficient nutrients (the coast of Brittany in particular provides nutrients in excess), therefore sunlight availability may be regarded as the limiting factor for NPP production [17,38,39].

In Ireland and France, the cultivation systems occupy a total sea surface area of 176,400 $\mathrm{m^2}$ and 6000 $\mathrm{m^2}$, respectively. However, this is not necessarily a full occupation because of the open/grid structure, i.e. sunlight can still penetrate the surface between the culture ropes which allows natural NPP production. At the time of deployment (December 15th), the effective sea surface occupation (culture ropes, PEHD tubes, buoys, etc.) amounts to 1180 $\mathrm{m^2}$ and 336 $\mathrm{m^2}$ for Ireland and France, respectively. The culture ropes are positioned parallel to the direction of the water movement (Fig. 5).

It is assumed that the seaweed blades float under an angle of 20° (estimation based on sea site visits). The length of the blades can be considered as the hypotenuse A of a right triangle. A standard cylinder, with a culture rope as its axis, represents the seaweed biomass. The radius of the cylinder becomes larger as the biomass grows over time, i.e. less sunlight can penetrate the underlying water column which reduces the natural NPP production. It is assumed that seaweed plants can be observed by the human eye after 1 month at sea. The growth rate of *S. latissima* is characterized by a sigmoidal curve (Eq. (1) and Fig. 6), which is developed based on experimental data of the length of the seaweed blades sampled at different times (March, April, May and even June when harvest was postponed for experimental reasons).

$$\mathrm{Y} = \frac{\mathrm{A}}{1 + \exp\left(-\left(\frac{\mathrm{X}-\mathrm{X_0}}{\mathrm{B}}\right)\right)} \tag{1}$$

where Y is the radius of the cylinder (m) and X represents the day (X = 1 represents the day of deployment, December 15$^{\mathrm{th}}$). In order to fit Eq. (1) to the experimental data, the optimal value of the parameters A, B and $\mathrm{X_0}$ have to be found: A = 0.74, B = 27.58, $\mathrm{X_0}$ = 128.63 for Ireland and A = 0.78, B = 19.35, $\mathrm{X_0}$ = 105.28 for France.

The sea surface occupation related to biomass growth is then calculated as 2 times the radius of the cylinder multiplied by the total length of culture ropes present at sea, i.e. the occupation is modeled as a widening rectangle (two-dimensional top view). Due to the high spore density, the seaweed plants overlap each other during their growth. The natural phenomenon of light scattering together with the dynamic movement of seaweed blades provides a complex light environment with bursts of alternating light and shadow. This complex system is simplified by assuming that the canopy formed by the seaweed blades is dense enough to block light penetration into deeper water layers, i.e. no 'gaps' are assumed within the widening rectangle. At the time of harvest (May 31st), some equipment are removed from the sea (culture ropes, small buoys, etc.). The effective sea surface occupation in the period May 31st–December 15th amounts to 94 $\mathrm{m^2}$ and 124 $\mathrm{m^2}$ for Ireland and France, respectively.

The average annual occupation factor α (%) is then calculated according to Eq. (2):

$$\alpha = \left(\sum_{X=1}^{365} \frac{effective\ \ sea\ \ surface\ \ occupation\ (\mathrm{X})}{total\ \ sea\ \ surface\ \ occupation}\mathrm{x100}\right)/365. \tag{2}$$

3. Results and discussion

3.1. Sea surface occupation factor α

Sea surface occupation of cultivated seaweed, as expressed by factor α (%), was calculated for nearshore seaweed cultivation in Ireland and France throughout the year, taking into account the active growing season and fallow periods preceding and following this season (Fig. 7). At

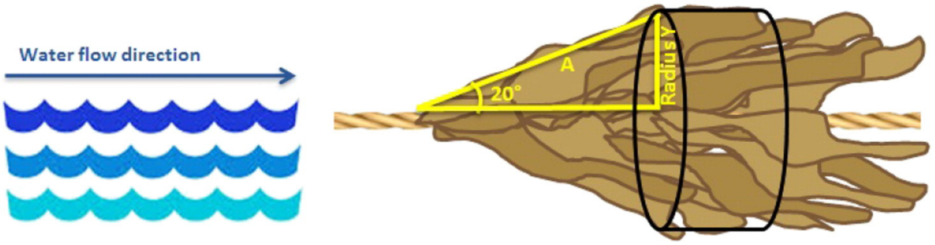

Fig. 5. Modeling principle sea surface occupation related to seaweed growth on culture ropes positioned parallel to the direction of the water movement at sea.

the time of deployment, the factor α is 1% (Ireland) and 6% (France) due to the type of equipment used for cultivating the biomass (as shown in Figs. 2 and 3). The factor α reaches a maximum value of 9% for Ireland and 88% for France at the time of harvest (end of May), i.e. no full sea surface occupation occurs during the cultivation season. After harvest, site activity is different between the two sites; in France, culture ropes and most buoys are removed from the sea (α factor drops to 2%), whereas in Ireland, the sea surface occupied between the time of harvesting and deployment is negligible (α below 1%).

To calculate the life cycle resource footprint of *S. latissima* cultivation at both regions, it is necessary to determine the annual average sea surface occupation factor α, which is 2% and 18% for Ireland and France, respectively. As the model assumed a 20 degree angle and a dense, non-light penetrating canopy, this may lead to an overestimation of the α factor as the complexity of the marine environment is not fully taken into account. More research and experimental data are required on light scattering, turbulent conditions, the way seaweeds hang in the water column and the light permeability of seaweed blades. Despite the fact that the light environment in coastal regions can be greater than suggested in this study, this factor is useful as a first indication of the impact of sea surface occupation and gives insight into the relative difference between both seaweed systems.

3.2. Resource footprint of seaweed cultivation

3.2.1. Ireland

The environmental resource footprint of *S. latissima* cultivation in Ireland is presented in Table 1. In total, 1.7 MJ_{ex} of natural resources is extracted to produce 1 MJ_{ex} seaweed biomass, which corresponds to 1997.4 MJ_{ex} day^{-1} (Table SI.5). Due to the long distance between the hatchery and grow-out phase at sea (Fig. SI.1), the diesel consumption for transport makes a large contribution to the overall footprint (44.3%). Furthermore, the production of materials (infrastructure) used at the hatchery and sea site requires a considerable amount of raw resources and contribute to 36.6% of the footprint. Especially the production of the culture and anchor ropes is resource demanding (Fig. SI.7). The environmental resource footprint of seaweed cultivation also considers the occupation of land and sea surface that partially or completely prohibits the production of natural NPP. In Ireland's case, this is translated to a relative contribution of 11.9% (6% due to land occupation and 94% due to sea surface occupation). The direct electricity consumption of machinery has a contribution of 6.8% with the majority of electricity used for lighting the cultivation bottles and tanks in the hatchery (Fig. SI.9). The impact of fresh water, nutrients and chemicals consumed during the seedling production is less than 1.0%.

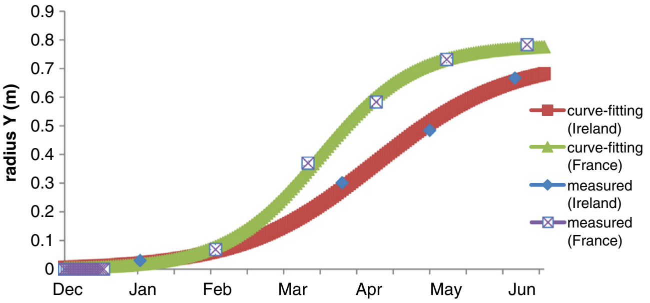

Fig. 6. Radius Y of the cylinder over time (from deployment to harvest period); the growth of *Saccharina latissima* is characterized by a sigmoidal curve.

It can be concluded that fossil resources are mainly consumed during seaweed cultivation (contribution of 75.1%); diesel is produced on the basis of crude oil and power production in Ireland relies mainly on natural gas (54%), hard coal (17%) and peat (9%) [40]. This has an implication on the use of nuclear resources, which is lower than in countries such as France having a large share in nuclear power. Furthermore, the extraction of marine resources, i.e. sea surface occupation by a human made system, contributes to 11.2% of the overall resource demand. Table SI.7 shows more detailed information about the contribution of each flow (material and energy) to the total environmental resource footprint.

3.2.2. France

The cultivation of seaweed in France has a resource footprint of 8.7 MJ_{ex} MJ_{ex}^{-1} (Table 2), which is a factor 5 more than the footprint in Ireland. However, only 512.31 MJ_{ex} of resources are extracted per day from nature (Table SI.6), which is much lower compared to the case in Ireland because cultivation is at smaller scale at Ventry Harbour. The impact of infrastructure used at the hatchery (CEVA) and for deployment at sea has the biggest contribution (54.7%). Compared to the seaweed facility in Ireland, this could be expected due to material-intensive cultivation system used in France. Fig. SI.8 shows that the plastic tubes that make the raft system float have a particularly large impact (20.5%) on the resource footprint. This is related to the impact of direct surface occupation (15.6%), of which 84% is due to sea surface occupation and 16% due to land occupation. The production of electricity and use in the hatchery contributes a significant 16.2% to the overall footprint. Thus, although electricity is mainly used for only 2 batches of collectors, 5 weeks per year, it is still an important issue. The use of the air blower makes a conspicuous contribution to electricity consumption in the French hatchery (Fig. SI.10). Furthermore, direct gasoline consumption (approximately 550 L yr^{-1}) used for transport by boat during deployment of the equipment, maintenance and harvest of the biomass contributes to 13.4%. Less transport fuel is used in France compared to Ireland, as the hatchery and sea site are situated much closer to each other (Fig. SI.1). Similar to the life cycle of seaweed production in Ireland, the impacts of fresh water, nutrients and chemicals are negligible.

A major impact is identified for fossil resources due to the consumption of gasoline and energy during the production of equipment (61.0%). According to the International Energy Agency (IEA) statistics, the electricity production in France relies mainly on nuclear resources (75%), e.g. uranium [40]. Therefore, electricity-intensive processes such as air blowing consumes nuclear resources, which is translated in 17.1% of the total resource footprint. Moreover, the demand for marine resources of raft systems that have a higher average sea surface occupation factor α than a single longline system cannot be ignored (13.1%). More detailed information about the contribution of each flow (material and

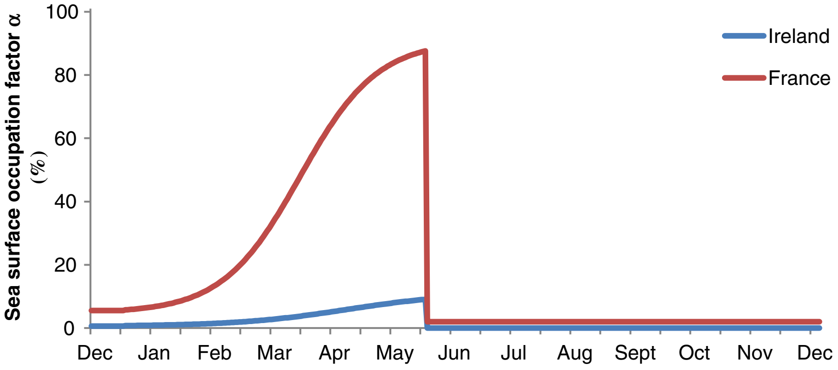

Fig. 7. Sea surface occupation factor α (%) on a daily basis for nearshore *Saccharina latissima* cultivation in Ireland (longlines) and France (raft system).

energy) to the total environmental resource footprint can be found in Table SI.8.

3.3. Resource footprint of seaweed compared to microalgae and terrestrial plants

As the competition for terrestrial land is high, especially in Europe, it is interesting to compare the resource footprint of seaweed production in Ireland and France (Sections 3.1.1 and 3.1.2, respectively) to the cultivation of microalgae and some terrestrial crops with similar moisture content (Fig. 8). The study of Taelman et al. [33] provided the resource footprint (CEENE results) of *Nannochloropsis* sp. production in Belgium at pilot scale (240 m^2) and for 2 hypothetical scenarios (1320 m^2 and 2.5 ha). Life cycle data of the cultivation of sugar beet, maize and potato in Switzerland was taken from the database ecoinvent version 2.2 [32]. Detailed information regarding the resource footprint of these crops are available in Tables SI.9–SI.13.

Life cycle data are expressed in $MJ_{ex}\,MJ_{ex}^{-1}$ and are limited to the cultivation and harvest of the biomass, i.e. no further processing steps are considered. For microalgae, cultivation took place in plastic bags and the harvesting stages (microfiltration membrane and centrifuge) were taken into account. After the centrifuge, a concentrate of 18% DW was obtained. For the terrestrial plants, agricultural machinery (e.g. tractors and trailers) were used to harvest. According to database ecoinvent version 2.2, the DW content of the harvested sugar beet, maize and potato was 25%, 23%, 28% and 22%, respectively.

The total resource demand of seaweed production depends mainly on fossil fuels (especially due to the electricity use of the air blower in the hatchery, the production of infrastructure and the fuel demand for transport). This trend is similar for microalgae production as this biomass can only be cultivated and harvested using energy-intensive processes. The Belgian and French electricity production mix depends more on nuclear resources than the production in Ireland, so more nuclear resources will be extracted to produce the same amount of electricity.

For the terrestrial plants, more than 90% of all required resources is land, especially for organically produced crops. Direct arable land occupation for cultivating the biomass and indirect land occupation for the production of manure are the biggest contributors (Tables SI.9–SI.13). Interestingly, organic production requires more natural resources (especially land) than inorganic production as more green manure (organically produced) and more direct land are used to achieve the same biomass yield (Tables SI.10–SI.13).

Seaweed production in Ireland is already quite efficient in terms of natural resource demand compared to the production of terrestrial plants (e.g. 1.7 $MJ_{ex}\,MJ_{ex}^{-1}$ for seaweed production versus 0.9–3.9 $MJ_{ex}\,MJ_{ex}^{-1}$ for terrestrial crop production) and is even more efficient than the third (hypothetical) scenario of microalgae cultivation (1.9 $MJ_{ex}\,MJ_{ex}^{-1}$). Note that a careful interpretation is required as the composition and functionality of the different biomass types are not the same. This could have an effect on the further processing of the biomass, e.g. the higher moisture content of seaweed (10% DW) compared to these terrestrial crops (approx. 24%) will require more drying. Therefore, further research into the sustainability of the entire process chain is recommended.

In this study, the biggest potential to improve the footprint of seaweed production is reducing the fuel demand for transport, which contributes to 44% of the total resource footprint, i.e. benefits could be obtained by locating the hatchery and grow-out facility in the same area. In France, at a first trial, the raft system used at sea is subject to

Table 1
Environmental resource footprint of *Saccharina latissima* cultivation (Ireland), expressed in $MJ_{ex}\,MJ_{ex}^{-1}$.

$MJ_{ex}\,MJ_{ex}^{-1}$	Abiotic renewables	Fossil fuels	Nuclear resources	Metal ores	Minerals	Water	Land resources	Atmospheric resources	Marine resources	Total	Contribution (%)
Infrastructure[a]	1.9E−02	4.4E−01	7.9E−02	1.3E−03	2.0E−03	7.8E−02	6.4E−03	0.0E+00	0.0E+00	**6.3E−01**	*36.6*
Fresh water[b]	1.2E−06	9.4E−06	4.4E−06	1.8E−08	1.3E−07	1.5E−04	2.3E−06	0.0E+00	0.0E+00	**1.7E−04**	*0.0*
Electricity [c]	5.6E−03	1.1E−01	1.9E−03	8.8E−06	2.2E−05	6.8E−03	2.1E−03	0.0E+00	0.0E+00	**1.2E−01**	*7.1*
Transport fuel[d]	2.1E−03	7.4E−01	8.1E−03	6.1E−05	9.2E−05	8.0E−03	2.7E−03	0.0E+00	0.0E+00	**7.6E−01**	*44.3*
Nutrients[e]	5.1E−07	3.1E−05	1.3E−06	6.7E−08	5.1E−08	1.2E−06	1.8E−06	0.0E+00	0.0E+00	**3.6E−05**	*0.0*
Chemicals[f]	4.2E−07	5.4E−06	1.5E−06	7.1E−09	6.6E−08	5.9E−07	2.9E−07	0.0E+00	0.0E+00	**8.3E−06**	*0.0*
Surface occupation[g]	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.3E−02	0.0E+00	1.9E−01	**2.1E−01**	*11.9*
Total	**2.7E−02**	**1.3E+00**	**8.9E−02**	**1.4E−03**	**2.2E−03**	**9.3E−02**	**2.4E−02**	**0.0E+00**	**1.9E−01**	**1.7E+00**	
Contribution (%)	*1.6*	*75.1*	*5.2*	*0.1*	*0.1*	*5.4*	*1.4*	*0.0*	*11.2*		

[a] Pumps, UV units, compressors, hatchery tanks, glass bottles, ropes, tubes, room chiller, air blower, lighting, autoclave, filters, pipes, anchor blocks, chains, buoys and transport infrastructure.

[b] To clean the hatchery tanks.

[c] Electricity consumption of TMC UC unit, autoclave, lighting, air blower, room chiller, pumping, compressors, hydrotech drum filter and Wedeco UV unit.

[d] Diesel consumption of transport by lorry, van and boat.

[e] $NaNO_3$ and $NaH_2PO_4 \cdot H_2O$.

[f] Decon 90 detergent.

[g] Land and sea surface occupation.

Table 2
Environmental resource footprint of *Saccharina latissima* cultivation (France), expressed in $MJ_{ex}\ MJ_{ex}^{-1}$.

$MJ_{ex}\ MJ_{ex}^{-1}$	Abiotic renewables	Fossil fuels	Nuclear resources	Metal ores	Minerals	Water	Land resources	Atmospheric resources	Marine resources	Total	Contribution (%)
Infrastructure[a]	1.0E−01	4.0E+00	3.3E−01	1.5E−02	1.9E−02	1.8E−01	7.2E−02	0.0E+00	0.0E+00	**4.8E+00**	*54.7*
Fresh water[b]	4.1E−05	3.3E−04	1.6E−04	6.4E−07	4.4E−06	5.3E−03	8.1E−05	0.0E+00	0.0E+00	**5.9E−03**	*0.1*
Electricity[c]	7.4E−02	1.3E−01	1.1E+00	8.4E−05	1.3E−04	5.3E−02	8.4E−03	0.0E+00	0.0E+00	**1.4E+00**	*16.2*
Transport fuel[d]	3.9E−03	1.1E+00	1.5E−02	1.0E−04	1.5E−04	1.3E−02	4.5E−03	0.0E+00	0.0E+00	**1.2E+00**	*13.4*
Nutrients[e]	1.3E−05	7.0E−04	3.5E−05	1.5E−06	1.7E−06	4.2E−05	5.5E−05	0.0E+00	0.0E+00	**8.5E−04**	*0.0*
Chemicals[f]	3.4E−04	3.1E−03	1.1E−03	8.5E-05	3.4E−05	8.6E−04	2.1E−04	0.0E+00	0.0E+00	**5.8E−03**	*0.1*
Surface occupation[g]	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.1E−01	0.0E+00	1.1E+00	**1.4E+00**	*15.6*
Total	**1.8E−01**	**5.3E+00**	**1.5E+00**	**1.5E-02**	**1.9E−02**	**2.5E−01**	**3.0E−01**	**0.0E+00**	**1.1E+00**	**8.7E+00**	
Contribution (%)	*2.1*	*61.0*	*17.1*	*0.2*	*0.2*	*2.9*	*3.5*	*0.0*	*13.1*		

[a] Hatchery tanks, glass bottles, ropes, tubes, pumps, room chiller, air blower, lighting, autoclave, filters, pipes, anchors, concrete ballast blocks, chains, buoys.

[b] To clean the hatchery tanks.

[c] Electricity consumption of room chiller, pumping, air blower, lighting and autoclave.

[d] Gasoline consumption of transport by boat.

[e] NH_4NO_3 and $PO_4HNa_2 \cdot 2H_2O$.

[f] Sodium hypochlorite solution and sodium thiosulfate.

[g] Land and sea surface occupation.

friction which results in loss of biomass and an average biomass yield of 5 kg FW m^{-1} culture rope, which is much lower than in Ireland (25 kg FW m^{-1}). However, at places where there was no friction, a maximum yield of 20 kg m^{-1} culture rope could already be achieved. Therefore, modifications to the structure of the raft to limit friction are required in order to produce seaweed in a more environmentally sustainable way. At present, attempts are being made to modify the systems to improve the yield.

3.4. Possible environmental improvements

According to Table SI.7 and SI.8, the main bottleneck for seaweed production in Ireland is the fuel demand for transport. In France, the resource footprint is five times as large, mainly because of the lower biomass yield of the system. As the raft structure occupies more sea surface than the single longline system, it is interesting to have a look at the effect of having a greater distance between the culture ropes. Furthermore, the use of plastic tubes at sea is resource demanding, so a scenario with an alternative floating material is analyzed. The aeration device used in the hatchery is also over-sized and thus more efficient equipment could be used.

Table 3 gives a brief overview of possible improvements for the seaweed production systems. In Ireland, the distance between the hatchery (Carna), the sea site (Ventry) and Dingle Bay Seaweeds (Castletownbere) is approx. 490 km. Assuming that 3 hatchery sites at the West coast of Ireland are sufficient to provide seeded culture ropes to all possible near-shore cultivation areas, the distance between a hatchery and cultivation site would be in a range of 100 km (personal communication). The impact of reducing transport is analyzed with this scenario. In France, the air blower used in the hatchery during seedling production is oversized. There are only 2 culture tanks (300 L) in operation at the same time, so a small 55 W blower device per tank at full capacity should provide sufficient aeration (personal communication). Continuous aeration allows a good mixing in the tanks which is important for the seedlings to develop their holdfast and attach strongly to the culture string. Therefore, lowering the operation time of the blower is not recommended. High density polyethylene (HDPE) is used for the main and intermediate tubes of the raft system. The plastic tubes can be replaced by softwood (e.g. pine), which is also a floating material because it is less dense than water and the tensile strength appears to be higher than HDPE [41,42]. The process 'industrial wood, softwood, under bark, u = 140%, at forest road' is used from the ecoinvent database. Softwood with low porosity is recommended, otherwise the pores become filled with water and the wood sinks faster. Additionally, wood could provide a more suitable surface area for settlement of epiphytes, therefore, a faster replacement of softwood than HDPE is required (personal communication). In this study, half of the life time of the HDPE tubes is assumed for the wooden planks. Moreover, the influence of 5 m distance between the culture ropes instead of 2 m in the original setup in France is investigated. This has an effect on the average sea surface occupation factor α which drops from 18% to 8% with a maximum of 36%. Furthermore, the sensitivity of the biomass yield is tested; a scenario with the same average annual yield of 25 kg FW m^{-1} rope as in Ireland is developed.

In the case of Ireland, limiting the distance between the facilities up to 100 km improves the footprint with 11.4% compared to the footprint of the base case (Fig. 9). In the case of France, reducing the power consumption of the air blower reduces the footprint with 17.7% (IS_2). When HDPE tubes are replaced by wooden planks, the original resource

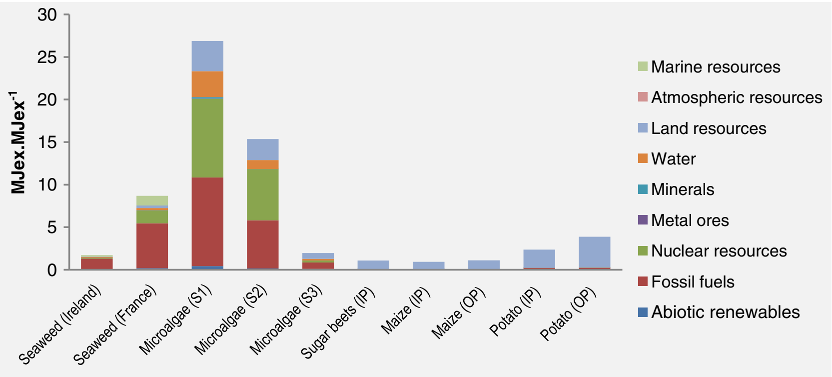

Fig. 8. Environmental resource footprint (expressed in $MJ_{ex}.MJ_{ex}^{-1}$) of aquatic and terrestrial biomass production; seaweed from Ireland and France, microalgae from Belgium (S1 = 240 m^2, S2 = 1320 m^2, S3 = 2.5 ha) and sugar beet, maize and potatoes from Switzerland. IP = inorganic production, OP = organic production.

Table 3
Possible improvements to the life cycle resource footprint of *Saccharina latissima* cultivation in Ireland and France.

Improvement scenario (IS)		Seaweed production (Ireland)		Seaweed production (France)	
		Base case	Improvement	Base case	Improvement
IS_1	Distance between facilities	335 km (hatchery — sea site) 150 km (sea site — DBS[b])	Range of 100 km	10 km	–
IS_2	Blower device (power)	0.23 W	–	1.4 kW	0.11 kW
IS_3	Floating tubes	–	–	HDPE[a]	Softwood
IS_4	Distance between culture ropes	Approx. 14 m	–	Approx. 2 m	Approx. 5 m
IS_5	Biomass yield	25 kg FW m^{-1} culture rope	–	5 kg FW m^{-1} culture rope	25 kg FW m^{-1} culture rope

[a] High density polyethylene.
[b] Company: Dingle Bay seaweeds.

footprint drops with 17.9% (IS_3). Most notably, increasing the distance between the culture ropes of the raft system to 5 m increases the life cycle demand for resources during seaweed production with 4%, i.e. despite the fact that the impact of sea surface occupation has been reduced, the demand for more HDPE because of the longer tubes per cultivation unit (50 m instead of 20 m per main tube and 25 m instead of 10 m per intermediate tube) results in a higher footprint than the base case. From Fig. 9, it is clear that the environmental impact reduces considerably with a higher productivity; the footprint decreases from 8.7 MJ_{ex} MJ_{ex}^{-1} to 1.7 MJ_{ex} MJ_{ex}^{-1} (comparable footprint as the Ireland base case) which emphasizes the importance of achieving a high yield. Ultimately, it is possible to achieve a life cycle resource footprint of 1.6 MJ_{ex} MJ_{ex}^{-1} (IS_1) and 1.3 MJ_{ex} MJ_{ex}^{-1} (IS_2 + 3 + 5) for Ireland and France, respectively, which is comparable to the footprint of the terrestrial plants as discussed in Section 3.3 (Fig. 9).

4. Conclusions and perspectives

This study highlights the usefulness of quantifying the total resource footprint (including marine resources) in a life cycle perspective. A case study on *S. latissima* production in Ireland and France is performed and the sea surface occupation factor is determined for both sea sites. The resource footprint is expressed in MJ_{ex} extracted from natural resources per MJ_{ex} available in the biomass. Mainly fossil resources (75.1%) are consumed in Ireland because of the high fossil-based fuel demand for transport between the different facilities. In France, fossil resources also take the largest share of the resource footprint, albeit at a lower rate than Ireland (61.0%), followed by nuclear resources (17.1%) and marine resources (13.1%). Fossils are used for gasoline production (transport fuel) and, together with nuclear resources, for electricity production. The raft system occupies more sea surface than single longline structures, which increases the consumption of marine resources (higher α factor). As the impact of sea surface occupation is based on, amongst others, the availability of sunlight for NPP production, it is important to fully take into account the complex and dynamic light environment (e.g. light scattering) of the ocean. A need for more experimental data (e.g. light intensity measurements below the seaweed blades in the ocean and remote-sensing data) as well as the necessity for combining fields of expertise around the complex marine environment could avoid a possible overestimation of the sea surface occupation factor α. As the raft systems used near the coast of France are subject to friction, a large amount of seaweed biomass is lost. Despite this, previous experience suggests that the use of single longlines are not an option due to the turbulent marine conditions close to the harbor of Lézardrieux. Therefore, further research that focuses on enhanced yet environmentally suitable cultivation techniques in France is necessary, especially because an improved biomass yield has the most significant impact on the overall LCA results. Compared to the footprint of microalgae and several terrestrial plants (sugar beet, maize and potatoes), seaweed production in North West Europe (particularly in Ireland) is already relatively resource-efficient, despite the small scale of European seaweed aquaculture to date. Moreover, there is great potential to reduce the resource footprint of seaweed cultivation when less transport and electricity is used and the biomass productivity increases. With respect to the type of resources used, more fossil resources are consumed during marine biomass production while more

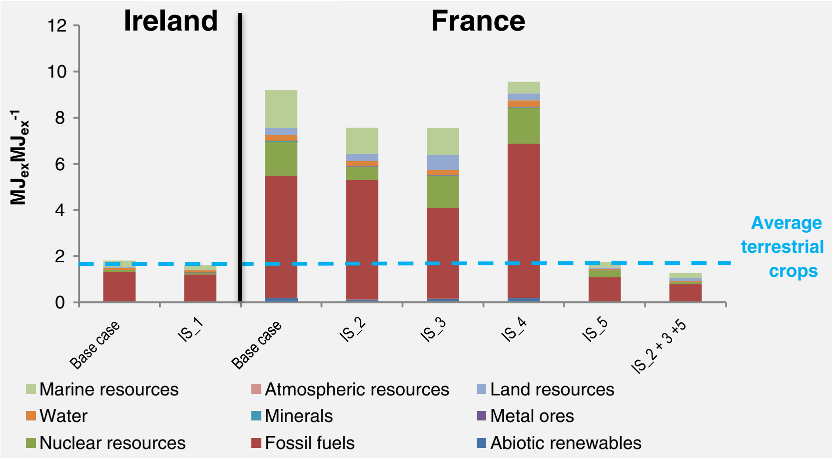

Fig. 9. Environmental resource footprint (expressed in MJ_{ex} MJ_{ex}^{-1}) of seaweed production (*Saccharina latissima*) in Ireland and France. Results of the base cases as explained in Sections 3.2.1 and 3.2.2 are shown next to 5 improvement scenarios (IS); (IS_1) distance between facilities, (IS_2) power of blower device, (IS_3) floating tubes, (IS_4) distance between culture ropes, (IS_5) biomass yield. IS_2 + 3 + 5 represents the resource footprint of 3 improvements.

land resources are used for terrestrial biomass production. It seems that marine biomass meets the requirements to reduce pressure on land. As it is expected that the energy mix will become more renewable, it is anticipated that the footprint of seaweed production will be even smaller in the future. At that point, seaweed could be cultivated as a sustainable feedstock in (North West) Europe as it avoids much of the competition for land and fresh water. However, when valuable data of potential processing steps become available, more research will be required to fully quantify the life cycle footprint of the whole process chain. Furthermore, additional effects of seaweed production on the environment (emissions, biodiversity, nutrient bioremediation etc.) and the economic feasibility should be assessed and compared to the existing alternatives. As the assessment of terrestrial land use (or land occupation) has gained already wide attention in LCA, it can be expected that the same efforts will be made to quantify the impact of extracting marine resources or occupying sea surface. Therefore, a multidisciplinary approach is required and joint initiatives of research institutions, policy and industry are essential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.algal.2015.06.018.

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