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Contribution to the Themed Section: '*Marine aquaculture in the Anthropocene*'

Original Article

A comparative environmental life cycle assessment of hatchery, cultivation, and preservation of the kelp *Saccharina latissima*

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Seaweed cultivation and processing industries could contribute to sustainable blue growth and the European bioeconomy. This article contributes a case study evaluation of environmental sustainability of preserved brown seaweed *Saccharina latissima* by means of environmental life cycle assessment of a pilot facility in Sweden. The study accounts for nutrient bioremediation and carbon capture and includes two alternative hatchery processes, a 2-ha longline cultivation, and four alternative preservation methods (hang-drying outdoors, heated air-cabinet drying, ensiling, and freezing). The study found that as a result of carbon capture and nitrogen and phosphorus uptake (bioremediation) by seaweed, more CO_2 and PO_4 equivalents are (temporarily) absorbed than emitted by the supply chain. The extent of emissions is most affected by preservation methods undertaken. Impact profiles of the supply chain show that the greatest impact shares result from freezing and air-cabinet drying, both the two most energy-intensive processes, followed by the cultivation infrastructure, highlighting strategic optimization opportunities. Hatchery processes, harvesting, and the low-energy ensilage and hang-drying outdoors were found to have relatively small impact shares. These findings presage the environmentally friendliness of seaweed-based products by documenting their potential to mitigate eutrophication and climate change, even when taking a life cycle perspective.

Keywords: aquaculture, bioremediation, blue growth, brown seaweed or kelp cultivation and preservation, climate change mitigation, environmental impacts, eutrophication mitigation, life cycle assessment, marine bioeconomy

Introduction

Virgil could not have been farther from the truth when proclaiming "nihil vilior alga", which roughly translates as "nothing is more worthless than seaweed" (Virgil, 1922). Seaweed extracts are used in a range of industries including the food processing, pharmaceutics, and textiles industries (Van Hal *et al.*, 2014). In one form or another seaweed pervades everyday life owing to the valuable proteins, lipids, carbohydrates, and other compounds they contain. Seaweeds are concealed in toothpastes, cosmetic creams, ready meals, and a host of other household goods and also more directly used as food and feed, as well as fertilizer (McHugh, 2003).

Of the estimated 28.5 million tonnes of seaweed harvested in 2014 (FAO, 2016), the vast majority was cultivated in just four countries, namely China, South Korea, Japan, and Indonesia. In Europe, present production comes mainly from the harvest of wild biomass (NetAlgae, 2012). However, European interest in cultivation has been gaining momentum over the past few years. This shows, amongst others, in communications for the development of blue growth strategies (European Commission, 2012a) as part of the wider bioeconomy (European Commission, 2012b). Seaweed is seen as a future contributor to the European bioeconomy. Research is ongoing to unlock their potential as food and feed (Harrysson *et al.*, 2018), to produce plastic-like bio-based polymers (Rinaudo, 2014; Sterner and Edlund, 2018), biofuels (Pechsiri *et al.*, 2016), and a range of other materials and chemicals (Pangestuti and Kim, 2015).

Seaweeds are valuable not just in terms of their end uses; they are increasingly being recognized as an environmentally friendly biomass that does not need typical agricultural inputs such as fresh water, fertilizers, and pesticides (Dhargalkar and Pereira, 2005). Furthermore, they have potential to capture carbon though sequestration depending on use and end-of-life (Seghetta *et al.*, 2017), to contribute to addressing local eutrophication by means of bioremediation through the uptake of nitrogen and phosphorus (Marinho *et al.*, 2015; Xiao *et al.*, 2017; Neveux *et al.*, 2018), and to help manage nutrient balances in finfish aquaculture (Chopin *et al.*, 1999; Troell *et al.*, 1999), while also providing other ecosystem services such as habitat provision (Phillips, 1990). Indeed, to resolve some of the societal and environmental issues that we already face now and that will exacerbate in the coming decades, one might contradict Virgil and argue that little has *more* worth than seaweed.

Seaweed cultivation practices have been emerging along the European Atlantic coast over the past few years to supply fresh biomass for existing industries. In support of these activities, environmental life cycle assessments (LCAs) have been performed to evaluate the overall environmental sustainability of seaweed supply chains (Langlois *et al.*, 2012; Alvarado-Morales *et al.*, 2013; Aitken *et al.*, 2014; Taelman *et al.*, 2015; Seghetta *et al.*, 2016; Czyrnek-Delêtre *et al.*, 2017; Seghetta *et al.*, 2017; Van Oirschot *et al.*, 2017; Parsons *et al.*, 2019). LCA is a method to draw the environmental performance of product systems, in this case for seaweed supply chains, by covering the whole supply chain and assessing a range of environmental impacts (Guinée, 2002; Baumann and Tillmann, 2004; ISO 14044, 2006). In Sweden, research is ongoing into marine-biomass cultivation, preservation, and specialized biorefineries, to explore key sustainability aspects and to optimize these stages in the seaweed supply chains (Sterner, 2018; Thomas, 2018; Harrysson, 2019; Visch, 2019; Olsson, 2020). Environmental LCA has been performed for evaluating the overall environmental sustainability of seaweed supply chains.

Notably, an explorative environmental LCA was undertaken by Van Oirschot *et al.* (2017) to shed early insights on cultivation, harvesting, and heated air-cabinet drying of the brown seaweed *Saccharina latissima*, typically referred to as kelp. The results highlighted the heated air cabinet, responsible for the largest shares of impacts, as in need of optimization from an environmental point of view. Little research has yet been conducted to compare alternative seaweed preservation methods as freezing and ensiling to drying (Milledge *et al.*, 2014).

This article reports on an LCA covering three additional kelp preservation processes and two alternative hatchery processes, while using robust new case data from a kelp farm in Sweden. The cultivation site is located in a sheltered location of the Koster archipelago and uses a longline cultivation infrastructure configured for a sheltered bay. This LCA accounts for bioremediation by considering nutrient uptake from the sea as negative emissions, i.e. impact mitigation. More specifically the present LCA covers the seaweed supply chain from hatchery up to and including preservation and compares (i) two alternative hatchery approaches referred to as submersion and spray seeding and (ii) four alternative biomass preservation methods referred to as drying by hanging longlines outdoors, drying with a heated air-cabinet, ensilage, and freezing in a shipping container. These comparisons serve to identify supply chain pathways of least environmental impact or greatest impact mitigation potential for the production and preservation of *S. latissima*. This is particularly valuable for decision-makers and in the design, development, or management of seaweed-based supply chains.

Methodology

LCA has become a well-established method for gaining an overview of the environmental impacts resulting from product systems with defined functions. Encompassed by the ISO standard 14040 series hereafter summarized, LCA is a method that serves to assess the contribution of a product system to a range of environmental impact categories by the use of resources and the environmental releases throughout the product system. Such product systems, in LCA usually referred to as a product's life cycle, typically run from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e. cradle to grave) (ISO 14044, 2006). LCA studies can also be narrowed down from cradle to grave to cradle to gate (e.g. from raw material to manufactured product) or gate to gate (e.g. use phases only). The LCA here represents a cradle-to-grave study, i.e. from hatchery to producing preserved kelp (or the preserved seaweed supply chain), and does not account for impacts in use or end-of-life phases.

Results from LCA are commonly used to support decision making. Many LCA studies involve a comparison of more than one product systems, either by comparing a product system with an improved version of itself or by comparing different product systems providing a same product function. Results from the first type, i.e. LCA studies comparing a product system with an improved version of itself, typically inform product improvement processes aiming at environmental optimization of product systems. This type of LCA studies usually start with identifying impact hotspots, and their results shed light on trade-offs between different impact categories. The LCA study here belongs to this type of LCA. The versatility and holistic perspectives granted by LCA have led to its recognition and wide by industry, governments, and non-government agencies the world over.

LCA consists of four iterative methodological phases. The first phase establishes the goal and scope of the study. Goal definitions state the purpose of the study. Scope definition specifies the boundaries, context and function of the product system, and how the other three methodological phases will be conducted. The second phase, life cycle inventory (LCI), involves the quantification of all the environmental and economic inputs and outputs that the product system requires to achieve its function. The environmental impacts are typically obtained from inventory databases as contained in LCA software. The third phase, impact assessment, involves the translation of the environmental inputs and outputs into contributions to a range of environmental impact categories. Also, this translation typically makes use of impact databases as contained in LCA software. The fourth and final phase, known as the interpretation, involves the evaluation of results from phases two and three to draw conclusions in relation to the goal and scope of the study. (Guinée, 2002; Baumann and Tillmann, 2004; ISO 14044, 2006).

The goal of this study is to make an environmental impact-based cradle-to-gate comparison of alternative supply chain pathways for preserved kelp production, accounting for local nutrient bioremediation and temporary carbon capture. The LCA here will elaborate from Van Oirschot *et al.* (2017) by largely following the same methodology but by adding the quantification of bioremediation and carbon capture through nutrient and carbon uptake. Furthermore, it covers a similar though much extended production system (see Figure 1) based on the designs and processes as developed and tested at a real facility, a kelp farm in the Koster archipelago. LCI data for this LCA are to the extent possible taken from this kelp farm, thereby representing case-specific LCI data. Other LCI data were typically taken from the ecoinvent database. The ecoinvent database is broadly considered to be one of the more reliable database sources of emissions (Wernet *et al.*, 2016). The methodological approach is detailed in the following subsections. First, the choice of functional unit is motivated ("Functional unit" section) and then the supply chain of kelp cultivation and preservation and associated LCI are described in detail ("Description of case study and LCI analysis" section). This is followed descriptions of the life cycle impact assessment (LCIA) method ("Life cycle impact assessment" section) and the approach followed for the sensitivity analysis ("Sensitivity analysis" section).

Functional unit

The choice of functional unit, that is the unit in which all impacts are expressed, should typically be based on the function of the studied product system (Guinée, 2002). The primary function of

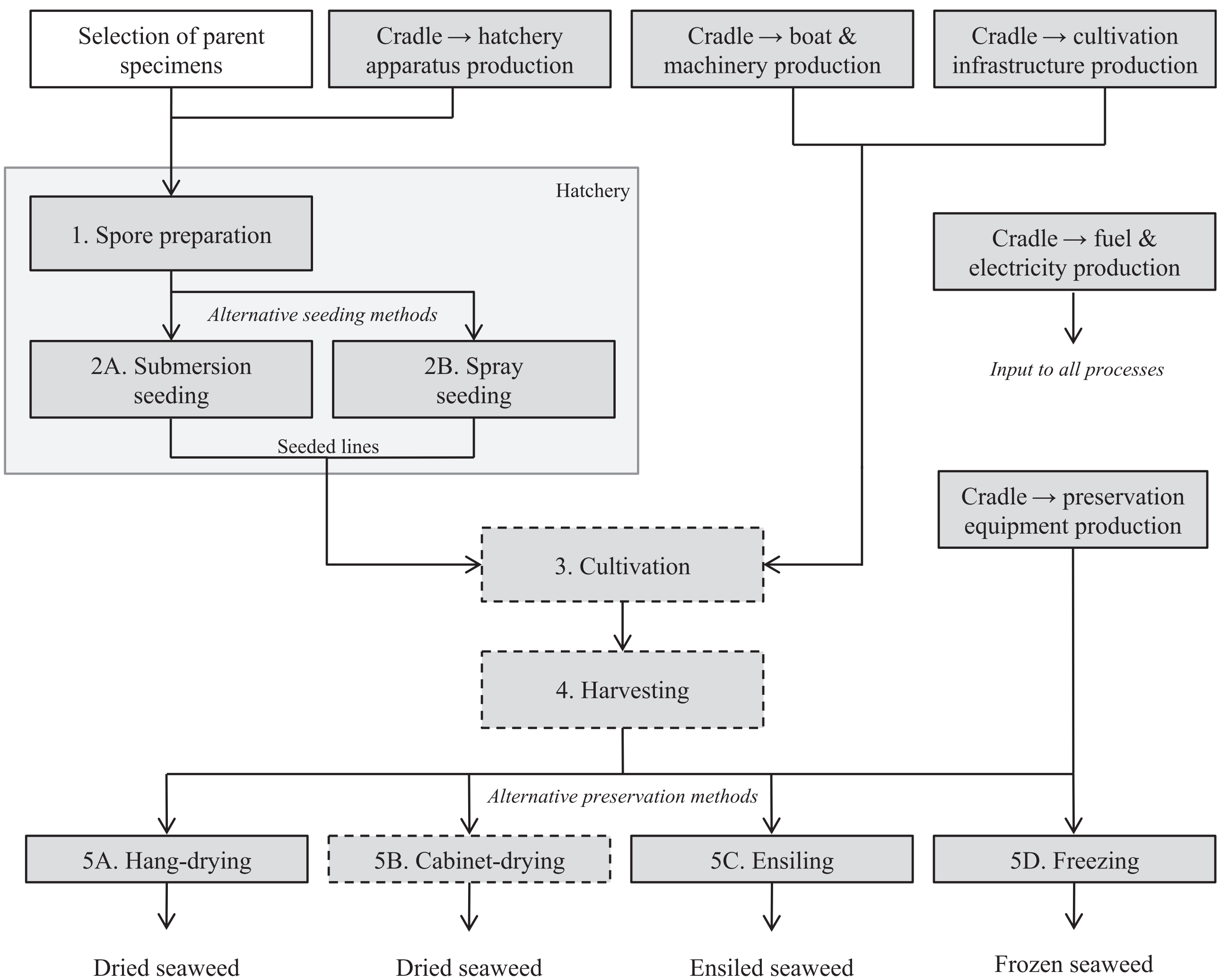

Figure 1. The case study supply chain, including supply chain alternatives, showing all processes for the production and preservation of kelp biomass [grey boxes included, white boxes excluded from the LCA; the LCA by Van Oirschot *et al.* (2017) was limited to the boxes framed with dotted lines].

the present product system or supply chain is to produce preserved kelp, more specifically *S. latissima*, albeit following four alternative preservation treatments. The four alternative preservation treatments are hang-drying outdoors, drying in an air cabinet, freezing, and ensilage. Each of these preservation treatments has an effect on the properties, form, and composition of the biomass, i.e. it will produce biomass with different functions. The function of the system studied here is therefore not to produce preserved kelp of uniform specifications, but rather to *produce and preserve* kelp. The functional unit selected for this study is therefore 1 tonne of fresh kelp, cultivated *S. latissima*, before undergoing preservation treatment. Such functional unit enables light to be shed on the impacts of preserving a given quantity of biomass in four different ways.

Defining the functional unit of a study based on a process *input* is common for LCA's comparing *downstream* product system alternatives, e.g. waste treatment methods. However, the LCA here is rather interested to find the most environmentally friendly *upstream* system. LCAs for *upstream* systems typically employ an *output*-based functional unit as they are typically interested in alternative ways to produce something with equivalent specification. Using an input-based functional unit for comparing purposes of an upstream system, as in this study, has not been done before to our knowledge.

The product system in this LCA consists of two sub-systems for which alternatives are compared, both comparisons using the same functional units of 1 tonne of fresh harvested biomass. The first sub-system is an initial cradle-to-gate study starting with the hatchery, including submersion seeding and spray seeding as alternatives, up to and including the harvest. This first sub-system results in fresh harvested biomass and the functional unit is thus based in the sub-system's product or *output*. The second sub-system is a gate-to-gate sub-system comparing alternative ways of preserving biomass, which is the preservation's *input* material. Selecting the fresh biomass as the functional unit will also facilitate comparisons with literature.

Description of case study and LCI analysis

The supply chain considered in the present study consists of five consecutive life cycle stages (Figure 1), namely (i) the spore preparation and (ii) seeding of juvenile kelp onto string that can be deployed to sea, (iii) the cultivation period at sea, (iv) the harvest of the biomass, and finally, (v) biomass preservation and storage. The LCIs of the spore preparation (i), cultivation (iii), and harvest (iv) steps are found in Table 1. The hatchery includes both the first and second stages of the supply chain and compares two alternative seeding methods (2A and 2B); their LCIs are found in Table 2. Four alternatives biomass preservation methods—drying outdoors, drying in an air cabinet, ensilage, and freezing—are compared in the fifth stage (5A–5D); their LCIs are listed in Table 3. Sensitivity analysis was conducted to handle the uncertainties associated with these processes and also to handle uncertainties with the main parametric inputs of the model as a whole (see section 2.4). LCIs are presented with the names of corresponding processes from the ecoinvent database.

Spore preparation

First and prior to the preparation of macroalgae spores for reproduction, parent specimen should be selected. This selection process can be continuous and is not definite. It may require a variety of approaches to handle a range of parameters, from monitoring genetics of the specimens and tolerance to local conditions to the identification of resistance to specific diseases and high biomass yields. For the purpose of this study, these selection processes are excluded as they are so context depended and variable; the supply chain begins with selected parent specimen.

The spore preparation (stage 1, LCI included in Table 1) includes all the processes involved in obtaining a concentrated solution of healthy spores from parent specimen. First, parent specimen must be induced to develop spores. To stimulate spore development, the base of the specimen blades (meristem) is cut away (Pang and Lüning, 2004; Forbord *et al.*, 2012). The rest of the blades are then cleaned and left for a period of 6–10 weeks in an artificially lit and temperature-controlled flow-through system (containing a medium of filtered, aerated, and stirred seawater). By the end of this period, fertile tissue has developed and the spores are released in a beaker of sterilized water. Due to a lack of fluorescent lighting systems in ecoinvent, a customized lighting system was built in SimaPro based on the material components of a 38 Watt T8 fluorescent light tube from Sangwan *et al.* (2014) and adjusted to the mass of the 58 Watt XLR T8 fluorescent light tubes used in the hatchery.

Seeding lines

Next comes the seeding (stage 2, LCI included in Table 2), involving all the processes to obtain a spool of string covered in juvenile kelp (henceforth seeded line) wrapped around a plastic pipe to enable deployment at sea (string and pipe together henceforth referred to as collector). Two alternative methods are examined in this study as scenarios; they are referred to as submersion seeding (2A) and spray seeding (2B). Both methods, like the previous spore preparation stage, take place in a laboratory providing the right conditions for the spores to settle onto the string and grow into juveniles that are large enough to thrive at sea. The medium in which the seeding takes place, referred to as the nutrient mix in Table 2, is made in the laboratory and follows half-strength Provasoli-enriched seawater formula (McLachlan, 1973). The two seeding methods differ in terms of how the settling on the string takes place. The submersion seeding (2A) involves putting the collector in a concentrated spore solution to allow spores to settle directly onto the string. The spray seeding (2B) involves an extra step, which allows for the spores to develop into fertile gametophytes before they are sprayed onto the collectors. In practice, the submersion and spray methods can differ in terms of the time required to produce collectors ready for deployment, density of settling on the string, and associated subsequent yields. In the present study, however, the comparison between the methods is made with the assumption that they produce collectors of the same quality (no difference in subsequent yields, only in the process).

After the spores or gametophytes have settled on the collectors, they are transferred into aquaria and mature into juveniles over a period of 3–5 weeks with long day photoperiod (16 h light), filtered (0.2 μm) half-strength PES medium at 10°C, and a light intensity of ~100 μmol photons m^{-2} s^{-1}; only then they are finally ready to be deployed to sea.

Cultivation

The next stage in the supply chain is the cultivation (stage 3, LCI included in Table 1), which includes deployment of the juveniles

Table 1. The LCI of the spore preparation (1), cultivation (3), and harvest (4) steps of the supply chain, specifying aggregated amounts of each item required to produce 1 tonne of fresh harvested biomass and the names of the ecoinvent processes selected for the present study.

Inventory item or process	Energy or material input	Unit	Input per functional unit	EcoInvent 3.2
Spore preparation				
Aeration and stirring system	Energy[a]	MJ	3.53E+00	Ventilation system, decentralized, 6 × 120 m^3 h^{-1}, polyethylene ducts {GLO}| market for | Alloc Def, U
Bucket	Polyethylene	kg	5.67E−03	Extrusion, plastic pipes {GLO}| market for | Alloc Def, U; adjusted by replacing plastic inputs with "Polyethylene, high density, granulate"
Lighting system	Customized item[b]	MJ	7.57E+00	Customized process based on material components of lighting system, table 2 in Sangwan *et al.* (2014)
Seawater filters	Polypropylene	kg	1.68E−02	90% Fleece, polypropylene {GLO}| market for | Alloc Def, U; 10% Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, S
Seawater source and filter system	Energy[a]	MJ	5.34E−02	Electric motor, vehicle {GLO}| market for | Alloc Def, S; Proxy for the pump motor
Temperature control system	Energy[a]	MJ	1.24E+01	Refrigeration machine, carbon dioxide, liquid as refrigerant {GLO}| production | Alloc Def, U
Cultivation at sea				
Anchor (g)	Concrete	kg	2.83E−02	Concrete, normal {RoW}| market for | Alloc Def, S
Anchoring buoy (a)	Polyethylene	kg	6.56E−01	Stretch blow moulding {GLO}| market for | Alloc Def, U; Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
Buoys (b)	PVC	kg	5.68E−01	Stretch blow moulding {GLO}| market for | Alloc Def, U; Polyvinylchloride, bulk polymerized {GLO}| market for | Alloc Def, U
Chain (e)	Low-alloy steel	kg	2.55E+00	Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, U
Longline (c_1)	Polyester silk	kg	3.45E+00	Proxy: Fleece, polyethylene {GLO}| market for | Alloc Def, U
Longline (c_2)	Polyester silk	kg	1.63E−01	Proxy: Fleece, polyethylene {GLO}| market for | Alloc Def, U
Longline (d_1/d_2)	Polypropylene	kg	7.96E−01	Proxy: Fleece, polyethylene {GLO}| market for | Alloc Def, U; adjusted by replacing plastic inputs with "Polypropylene, granulate"
Longline (d_3)	Polypropylene	kg	5.68E−02	Proxy: Fleece, polyethylene {GLO}| market for | Alloc Def, U; adjusted by replacing plastic inputs with "Polypropylene, granulate"
Vessel (Nereus)	Customized item[b]	tkm	3.92E+00	Transport, barge/RER; adjusted by removing the canal related sub-processes and adding estimated fuel consumption as the process "Diesel {Europe without Switzerland}| market for | Alloc Def, U"
Shackle (f)	Low-alloy steel	kg	1.47E−01	Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, U
Harvest at sea and transport				
Fresh biomass (DM)[c]	Customized item[b]	kg	1.51E+02	Customized elemental composition, based on means values for water (dry matter), total nitrogen, total carbon, and metal content from Schiener *et al.* (2015) ; author measurements for phosphorus. Values are entered as "emissions to water" in SimaPro and then converted to negatives to convert to bioremediation uptake
Harvest bags	Polypropylene	kg	4.55E−01	Proxy: Fleece, polyethylene {GLO}| market for | Alloc Def, U; adjusted by replacing polyethylene inputs with "Polypropylene, granulate"
Vessel (Nereus)	Motorised barge	tkm	2.17E+01	Transport, barge/RER; adjusted by removing the canal related sub-processes and adding estimated fuel consumption as the process "Diesel {Europe without Switzerland}| market for | Alloc Def, U"
Tractor	Tractor	Tkm	1.00E+00	Transport, tractor, agricultural {RoW}

[a]Processes whose inputs per functional unit are energetic (MJ) also include impact contributions from the life cycles of the equipment or system that consumes the energy. All of these processes use "Electricity, medium voltage {SE}| market for | Alloc Def, S" from EcoInvent 3.2.
[b]Consists of several material and/or energy inputs combined in SimaPro into one customized item.
[c]DM = dry matter, 0% water content.

to the cultivation infrastructure at sea by wrapping the seeded line around the longlines as it is unwound from the collectors. Stage 3 also includes regular monitoring while the kelp matures. Figure 2 represents the cultivation infrastructure currently installed over 2 ha in a sheltered part of the Koster Archipelago. It consists of a series of 26 longlines (c_1) running parallel to one another and separated by 4-m access corridors. This covers altogether 2 ha of sea space and provides a total of nearly 5 km of longline upon which juvenile kelp can mature at sea.

The longlines are hang at a depth of 2 m from ropes (d_3) connected to buoys (b) at the surface, which are interspersed every 10 m down their length. Strong buoyancy is maintained at the extremity of each longline by a large anchoring buoy (a) connected to an anchor (g) on the seafloor by a series of thick and strong ropes (d_1 and d_2) as well as chains (e) and a shackle (f). Additional structural reinforcement is provided by an additional longline (c_2) running laterally across the midpoints of each longline, also held in place by anchoring buoys (a) linked to concrete anchors (g) by means of thick ropes (d_1 and d_2), chains (e), and shackles (f).

Table 2. The LCI of the two alternative hatchery processes for seeding juvenile kelp onto string (2A and 2B), specifying amounts of each item required to produce 1 tonne of fresh, harvested biomass, and the names of the ecoinvent processes selected for the present study.

Inventory item or process	Energy or material input	Unit	Input per functional unit: 2A Submersion seeding	2B Spray seeding	EcoInvent 3.2
Aeration and stirring system	Energy[a]	MJ	7.35E+00	4.46E+00	Ventilation system, decentralized, 6 × 120 $m^3 h^{-1}$, polyethylene ducts {GLO}| market for | Alloc Def, U
Aquaria	Acrylic Perspex	kg	2.91E−01	2.91E−01	Polymethyl methacrylate, sheet {GLO}| market for | Alloc Def, S; Injection moulding {GLO}| market for | Alloc Def, S
Autoclave	Energy[a]	MJ	–	1.68E−01	Tap water {RER}| market group for | Alloc Def, U; Electricity, medium voltage {SE}| market for | Alloc Def, S; contribution of heating element considered negligible
Bucket	Polyethylene	kg	1.13E−02	1.13E−02	Extrusion, plastic pipes {GLO}| market for | Alloc Def, U; adjusted by replacing plastic inputs with "Polyethylene, high density, granulate"
Collectors	PVC	kg	2.75E−01	2.75E−01	Extrusion, plastic pipes {GLO}| market for | Alloc Def, U; adjusted by replacing plastic inputs with "Polyvinylidenchloride, granulate"
Lighting system	Customized item[b]	MJ	3.31E+01	2.08E+01	Customized process based on material components of lighting system, table 2 in Sangwan *et al.* (2014)
Nutrient mix	Customized item[b]	L	6.68E−01	4.01E−01	Customized process based on Provasoli-enriched seawater solution (McLachlan, 1973)
Seawater filters	Polypropylene	kg	3.36E−02	3.36E−02	90% Fleece, polypropylene {GLO}| market for | Alloc Def, U; 10% Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, S
Seawater source and filter system	Energy[a]	MJ	9.44E−02	5.45E−02	Electric motor, vehicle {GLO}| market for | Alloc Def, S; Proxy for the pump motor
Seeding line	Nylon	kg	1.58E−01	1.58E−01	Nylon 6 {GLO}| market for | Alloc Def, S
Temperature control system	Energy[a]	MJ	2.55E+01	1.55E+01	Refrigeration machine, carbon dioxide, liquid as refrigerant {GLO}| production | Alloc Def, U
Water heating system	Energy[a]	MJ	1.20E+00	1.20E+00	Tap water {RER}| market group for | Alloc Def, U; Electricity, medium voltage {SE}| market for | Alloc Def, S; contribution of heating element considered negligible

[a]Processes whose inputs per functional unit are energetic (MJ) also include impact contributions from the life cycles of the equipment or system that consumes the energy. All of these processes use "Electricity, medium voltage {SE}| market for | Alloc Def, S" from EcoInvent 3.2.
[b]Consists of several material and/or energy inputs combined in SimaPro into one customized item.

Harvesting

Between early winter and early summer, the sugar kelp (*S. latissima*) mature until they reach 1–2 m in length, at which time they are harvested from the infrastructure (stage 4, LCI included in Table 1). The uptake of nutrients from the water until the moment of harvest is commonly referred to as bioremediation or bioextraction in the literature, and the carbon that is fixed by photosynthesis is referred to as captured carbon. Given the location of the kelp farm in the Skagerrak, which according to the Swedish EPA may be both N and P limited at different times of the year (Swedish EPA, 2008, p. 16), the uptake and removal of both N and P during the harvest are considered to be bioremediative and mitigating eutrophication. The values for the bioremediative uptake of nutrients and the capture of carbon are based on the composition of *S. latissima* (carbon: 26.2% of dry matter ±3.00 SE; nitrogen: 2.7% of dry matter ±0.54 SE; number of samples = 21), and the phosphorus content of 0.24% of dry matter is based on measurements by Pechsiri *et al.* (2016). These values for the uptake of carbon, nitrogen, and phosphorus in the harvested kelp are converted to CO_2 and PO_4 equivalents and counted as mitigating impacts (negative numbers) following the same method as Seghetta *et al.* (2017).

The harvest at the Koster farm is currently a labour and time-intensive process, limited by the 3-tonne loading capacity of the research vessel used for this purpose. This process is therefore, from an economic point of view, one of those most in need of optimization to enable the upscaling of operations (Brock, 2018). The current practice involves lifting the longline above the vessel's deck, from where the kelp is torn off and packed into 1 m^3 polypropylene harvest bags ready for transport back to shore. The longlines and seeding lines are left at sea. The exception is for the hang-drying method where the longline is removed with biomass still attached.

The cultivation site is located ∼10 km away from the quay. A total of 17 return trips are needed to complete the harvest. Once delivered to shore, the harvest bags are offloaded from the vessel and transported to a hypothetical preservation facility. It is assumed that 20% of the water content of the biomass is lost from drippage during transport back to shore, offloading at the quay and prior to the next stage in the supply chain (preservation) (Konda *et al.*, 2015).

Table 3. The LCI of the four alternative drying methods (5A–5D), specifying amounts of each item required to produce 1 tonne of fresh, harvested biomass, and the names of the ecoinvent processes selected for the present study.

Inventory item or process	Description	Energy or material input	Unit	Input per functional unit: 5A Hanging outdoors	5B Air cabinet	5C Ensiling	5D Freezing	EcoInvent 3.2
Air cabinet	Specific moisture extraction rate of 3 MJ kg^{-1} 1 H_2O	Energy[a]	MJ	–	1.94E+03	–	–	Blower and heat exchange unit, Storkair G 90 {GLO}| market for | Alloc Def, U
Concrete silo	3 silos: 11.25 m^3 of blocks and 2 m^3 of foundations	Concrete	m^3	–	–	1.05E+00	–	Concrete block {GLO}| market for | Alloc Def, S; Concrete, normal {RoW}| market for | Alloc Def, U; Ratio of 11–2 m^3 per silo, respectively.
Drying racks	2× 10 kg steel with maximum load of 250 kg	Steel	kg	–	4.05E−02	–	–	Proxy: Ventilation duct, steel, 100x50 mm {RER} | production | Alloc Def, U
Ensilage chemicals	85% formic acid and 15% fresh water	Customized item[b]	L	–	–	1.66E+00	–	85% Formic acid {RER}| market for | Alloc Def, S; 15% Tap water {RER}| market group for | Alloc Def, S
Ensilage effluent	Leakage from silos ~28% of fresh weight input	Customized item[b]	L	–	–	2.32E+02	–	1 m^3 Biogas {GLO}| market for | Alloc Def, U (of project Ecoinvent 3—allocation at point of substitution—unit); avoided production of biogas, adjusted by balancing biomethane potential to that of the effluent, as measured by Herrmann *et al.* (2015)
Ensilage effluent tanks	1 000-l tank weighing 28 kg for each silo	Polyethylene	kg	–	–	6.80E−01	–	Extrusion, plastic pipes {GLO}| market for | Alloc Def, U; adjusted by replacing plastic inputs with "Polyethylene, high density, granulate"
Freezing container	Estimated energy consumption of freezing and storage	Energy[a]	Days	–	–	–	9.00E+01	Operation, reefer, freezing {GLO}| 40-foot, high-cube, R134a as refrigerant; adjusted to electrical energy input
Gravel	Total of 300 kg to weigh down plastic wrap	Gravel	kg	–	–	2.43E+00	–	Gravel, crushed {GLO}| market for | Alloc Def, S
Plastic wrap	Total of 95 kg needed to maintain air-tight seal	Polyethylene	kg	–	–	1.53E+00	–	Packaging film, low-density polyethylene {GLO}| market for | Alloc Def, U
Screws	4 kg of screws to build 15 supports	Low-alloy steel	kg	3.26E-02	–	–	–	Steel, low-alloyed {GLO}| market for | Alloc Def, S
Shredder	2.4 kW shredder to shred biomass prior to storage/ensilage	Energy[a]	MJ	–	3.25E+01	3.25E+01	3.25E+01	Proxy: Electric motor, vehicle {GLO}| market for | Alloc Def, S
Storage bags	2.5 kg max load, weighing 0.14 kg each	Polyethylene	kg	1.66E+00	1.66E+00	–	7.49E+00	Packaging film, low-density polyethylene {GLO}| market for | Alloc Def, U
Tractor	Tractor use included as part of 1 km transport to preservation facility	Tractor	tkm	–	–	5.00E−02	–	Transport, tractor, agricultural {RoW}
Vacuum packing	2.5 kW vacuum packing machine	Energy[a]	MJ	2.21E+00	2.21E+00		9.96E+00	Proxy: Electric motor, vehicle {GLO}| market for | Alloc Def, S
Wooden supports	14.21 MJ of electricity for construction	Energy[a]	MJ	1.15E+00	–	–	–	Electricity, medium voltage {SE}| market for | Alloc Def, S
Wooden supports	2 357 kg of wood used to build 15 supports	Timber	kg	1.91E+02	–	–	–	Cleft timber, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Alloc Def, S

[a]Processes whose inputs per functional unit are energetic (MJ) also include impact contributions from the life cycles of the equipment or system that consumes the energy. All of these processes use "Electricity, medium voltage {SE}| market for | Alloc Def, S" from EcoInvent 3.2.
[b]Consists of several material and/or energy inputs combined in SimaPro into one customized item.

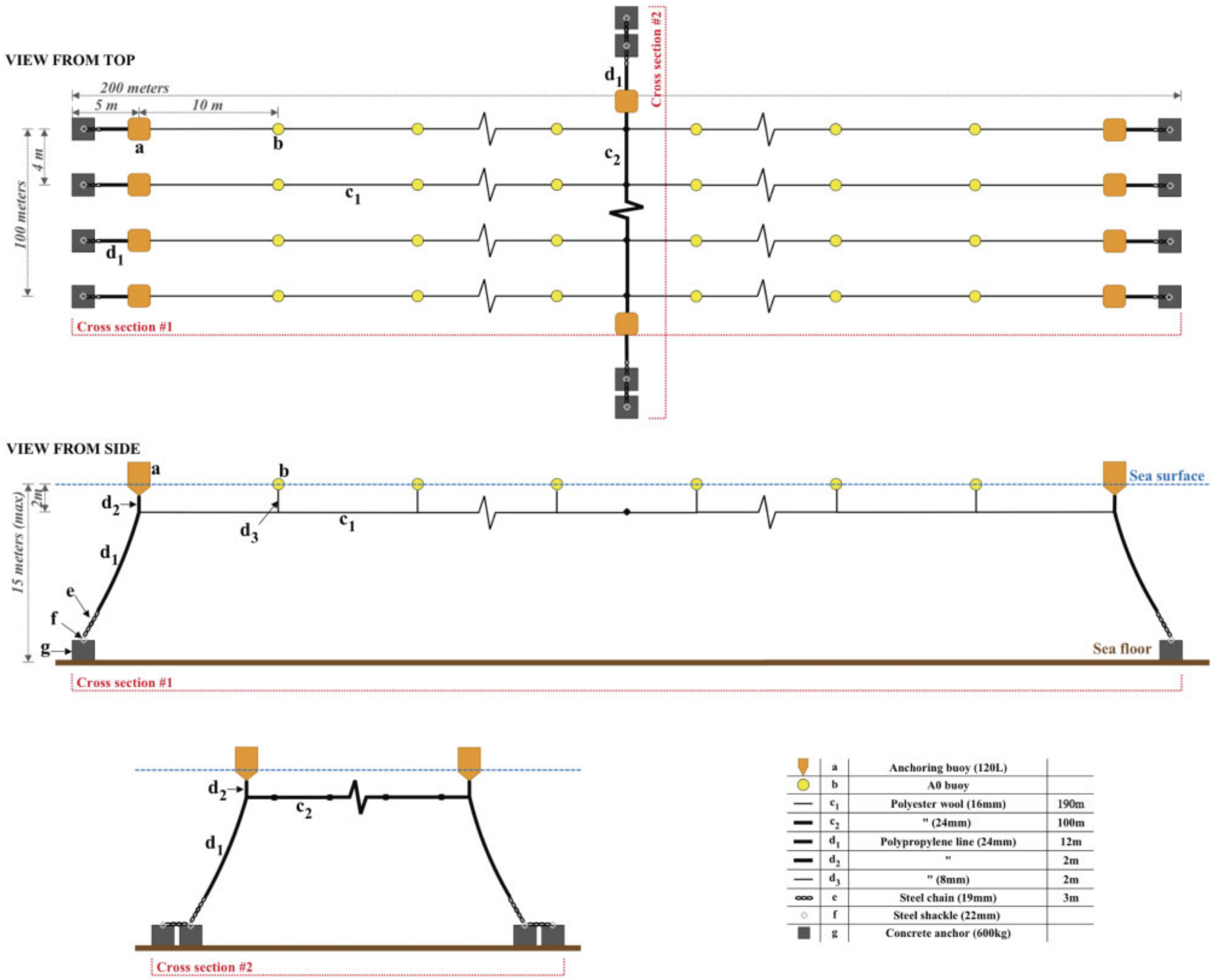

Figure 2. The cultivation infrastructure, as seen from above and from two cross-sections. The infrastructure consists of anchoring buoys (a), longline buoys (b), longline ropes (c_1 and c_2), anchoring ropes (d_1, d_2 and d_3), chains (e), shackles (f), and concrete anchors (g). Quantities of each input are listed in terms of the functional unit in Table 1.

In the present case, the alternative preservation processes are undertaken in several different locations, some <50 m from the quay where they are offloaded, others are further away; however, for the sake of comparison in the present study, they are all assumed to be located in a preservation facility 1 km from the quay. The biomass is transported there by tractor, and this transportation is included as a part of the harvest (see Table 1 for LCI).

Preservation

Four alternative preservation methods are compared in the present study, i.e. hang-drying outdoors (5A), drying in a heated air cabinet (5B), ensiling (5C), and freezing (5D), and their LCIs are presented in Table 3. Of these four alternative preservation methods, only the freezing has been applied at large scale. The three other preservation methods have been modelled for this LCA according to the capacity needed for handling the entire harvest from the 2-ha cultivation. The modelled preservation methods represent scaled up processes based on literature and on the experience gathered by the authors when conducting small to large scale experiments (up to 10 tonnes fresh weight).

The outdoor drying method requires the biomass to still be attached to the longlines so that it can be suspended from wooden A-frame structures. The three other methods are more effective at preserving shredded biomass. As such, the other methods all begin by shredding the biomass using a garden shredder, breaking up the fronds into smaller pieces to facilitate preservation. The LCA includes the electricity needed for the shredder (32.5 MJ per tonne of freshly harvested kelp). Furthermore, the number of vacuum bags used in the hang drying, air cabinet drying, and freezing methods is estimated as a function of the vacuum bag weight or volume limit and the mass of biomass being packed into the bags.

The hang-drying method, as modelled in this LCA, takes place outdoors and involves hanging the longlines with the biomass still attached directly onto a series of 15 wooden A-frames (constructed from cleft timber and low-alloy steel screws). The longlines are separated by 50 cm gaps to ensure aeration. With this approach, the biomass takes a few days to dry and then it is removed from the ropes and vacuum packed into storage bags.

For the air cabinet drying in this LCA, the shredded biomass is assumed to be manually spread out evenly across the shelves of mobile steel racks, like those used in industrial bakeries. The loaded racks are moved into a heated and aerated room fitted with a blower and heat exchanger (moisture extraction rate of 3 MJ per kg of water). After drying, the kelp is vacuum packed for storage in bags.

For the ensilage in this LCA, first the biomass is transferred to the silos at the preservation facility. As the biomass is loaded into 12 m^3 concrete silos, 2 l of ensilage chemicals is mixed to each tonne of biomass. The mixture is then covered with plastic sheeting and gravel to create and maintain an air-tight seal and avoid oxygen contamination while it is stored (thus no storage bags needed here). Liquid ensilage effluent, a by-product of the ensilage process, is collected and used for the production of biogas as suggested by Herrmann *et al.* (2015). Herrmann *et al.* (2015) reports that 1 m^3 of biogas requires ~14.9 kg of ensilage effluent. A biogas production process in ecoinvent has been identified, and it is assumed that the effluent produced in the current ensilage stage results in the avoided production of biogas. For comparison in the sensitivity analysis, another ecoinvent process was identified for grass a biogas substrate, which could be directly substituted by the ensilage effluent.

The fourth and final preservation method included in the LCA is the freezing. The shredded biomass is packed into vacuum sealed polyethylene storage bags before being placed in cold storage at −18°C (40-ft cold storage shipping container). Each of the four-preservation method assumes 3 months (90 days) of storage time. Unlike fisheries products that can be caught at any time of year, this kelp species can only be harvested during the end of spring/early summer in Swedish waters. Longer storage time is therefore relevant for kelp biomass to ensure a steady supply to meet market demand year-round. A storage time of 90 days was selected as a reasonable midpoint based on available case data. The supply chain thus ends after the preservation of biomass in these four alternative ways.

Life cycle impact assessment

The impact assessment of the kelp cultivation and preservation system follows Van Oirschot *et al.* (2017), which uses the CML 2 baseline 2000 (v2.05) (Guinée, 2002) and Cumulative Energy Demand or CED (v1.09) (Frischknecht *et al.*, 2007). CML 2 baseline 2000 is a commonly used method for calculating impacts across ten categories, i.e. abiotic depletion, acidification, eutrophication, global warming potential over 100 years, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation. The CML baseline 2000 (v2.05) was complemented, for additional perspective on energy use, with Cumulative Energy Demand or CED (v1.09) (Frischknecht *et al.*, 2007). The six categories of CED are combined into two clusters: renewable and non-renewable cumulative energy demand.

The LCI data were collected and processed in Microsoft Excel, wherein all calculations were made to quantify LCI data per functional unit. SimaPro 8 was used to match inventory items with processes from the ecoinvent database (version 3.2). The impacts resulting from these processes were exported back to Excel for further analysis.

Sensitivity analysis

There are numerous variables and uncertainties that affect a kelp cultivation and preservation supply chains in practice. Numerical variations in each of these variables and uncertainties, notably of harvest yield due to seasonal variation, may have varying degrees of effects on the outcomes of a life cycle environmental analysis. A combined sensitivity/uncertainty analysis for numerical input was therefore undertaken on a series of parameters by varying their initial input values (100%) from 50 to 150% in 10% increments. Inputs were selected for analysis based on (i) whether they were subject to variability or uncertainty of data and (ii) if that input has a relatively large contribution to total impacts in one or several categories. Besides numerical sensitivity analysis, an additional sensitivity analysis was performed for the modelling choice of crediting avoided production of ensilage effluent with either grass or biogas production.

Results and discussion

Comparison of seeding methods

Figure 3 presents a comparison of the impacts of the two seeding methods of the hatchery. On the whole, the two methods perform similarly though submersion seeding performs slightly worse than spray seeding, i.e. 30–35% higher for ozone layer depletion and renewable cumulative energy demand, 20% higher for terrestrial ecotoxicity and non-renewable cumulative energy demand, and accounting for 5–10% higher impacts in the other impact categories. The main differences between the two seeding methods seem to be a direct result of differences in duration of both methods, and the energy consumption of related processes such as the temperature control in particular (except for ozone layer depletion), aeration, and the lighting. The energy-consuming processes dominate across most impact categories, with the exceptions of abiotic depletion, acidification, global warming potential, and photochemical oxidation. However, lighting contributes approximately the same as cooling does in ozone layer depletion, whereas lighting exceeds the contributions of cooling in the two cumulative energy demand categories.

The spray and submersion seeding methods require the same items and amounts of material inputs (notably the collectors' pipes and seeding lines, aquaria, filters, and other basic laboratory equipment, see Table 2). The cradle to production of these materials thus contributes equally to the impacts of both methods. Of these material inputs, first aquaria (Acrylic Perspex) and next the collectors (PVC) contribute most to all impact categories. The contribution of the seeding line though is comparable to that of the collectors in global warming potential and abiotic depletion. Material inputs together contribute more than energy inputs to certain impact categories, notably in abiotic depletion, acidification, global warming potential, and photochemical oxidation. However, the energy inputs clearly dominate other impact categories, particularly ozone layer depletion, renewable cumulative energy demand, and the toxicity categories. The nutrient mix used to fertilize the juveniles during their maturation makes a very small contribution to all impact categories, including eutrophication and freshwater aquatic ecotoxicity (see Figure 3). Nevertheless, experimental work is taking place on the use of alternative organic nutrient sources such as waste water or slurry as these might enable organic certification. This would improve the impact profile of the seeding methods, particularly in the

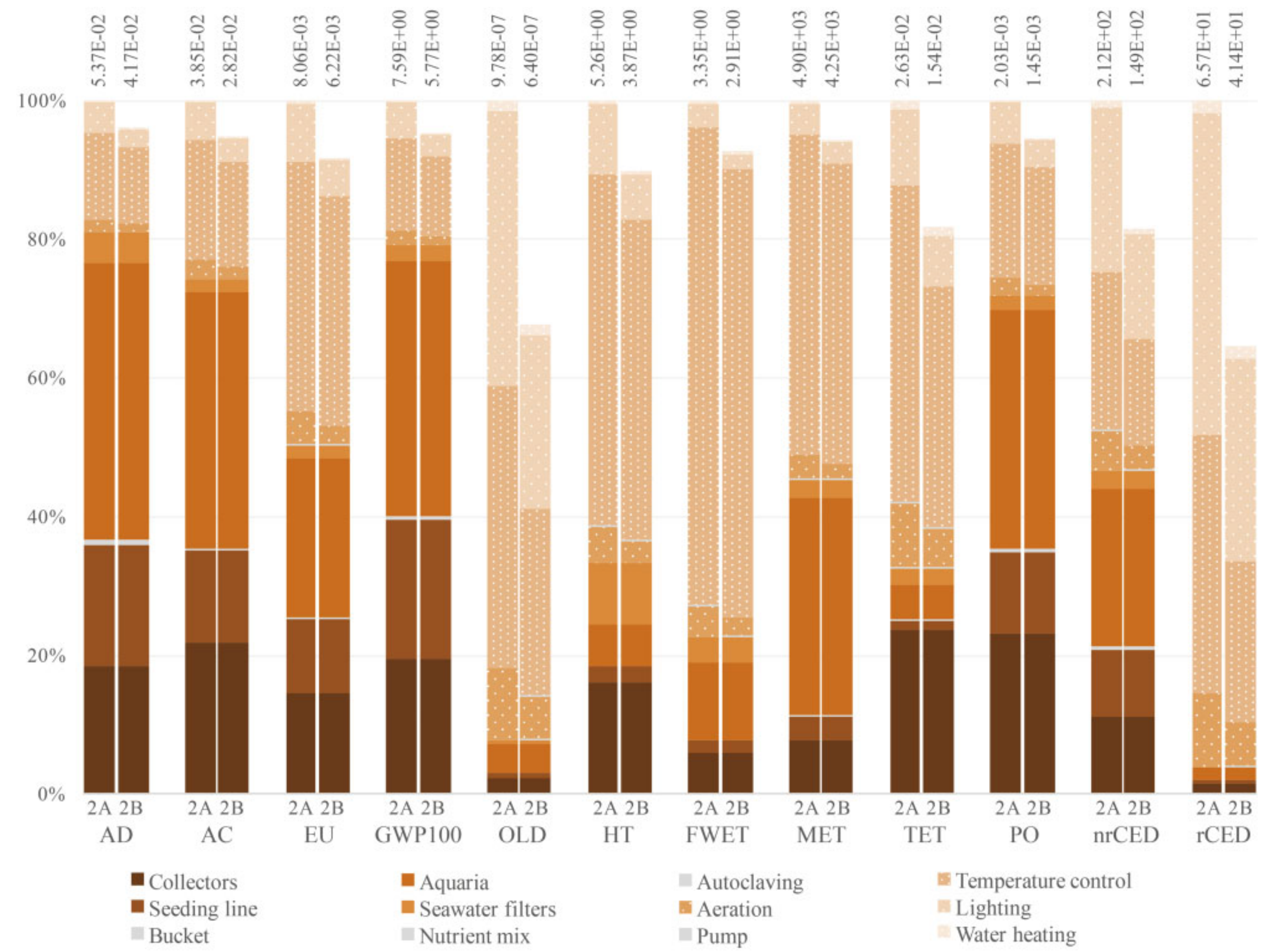

Figure 3. Comparison of total impacts of the submersion seeding (2A) and spray seeding (2B) methods employed at the hatchery, thereby showing the share in total impact of those processes for which both hatchery processes differ. For more information about the alternative hatchery processes and their differences, see Table 2 for their LCIs and "Seeding lines" section for process descriptions. Impact category key: abiotic depletion (AD), acidification (AC), eutrophication (EU), global warming potential (GWP100), ozone layer depletion (OLD), human toxicity (HT), freshwater aquatic ecotoxicity (FWET), marine aquatic ecotoxicity (MET), terrestrial ecotoxicity (TET), photochemical oxidation (PO), renewable cumulative energy demand (rCED), and non-renewable cumulative energy demand (nrCED).

eutrophication and toxicity categories, and the right nutrient source may even help practitioners to obtain organic production licences.

It should also be considered that the laboratory-scale processes portrayed in this study represent a worst case, and the authors anticipate that efficiency savings in material and energy use would take place at larger scale operations.

The comparison of the two seeding methods is based on the assumption that they perform equally well in their provision of seeded collectors. In practice, however, these two methods do not necessarily produce seeded lines of the same quality every time. Adjusting for unequal performance in the task of delivering healthy seeded lines may have yielded slightly different results to those in the present study. Other seeding methods exist besides the two compared in the present study. Some are more labour intensive, others employing patented glue-like substances to attach juvenile kelp directly to long lines at sea. However, the spray and submersion methods are the most successful methods employed at the case hatchery and are the only ones for which reliable data could be acquired. Future studies could review additional methods and pursue optimization strategies to improve the energy efficiency of hatcheries, especially in countries with high emissions energy mixes.

Comparison of preservation methods

Figure 4 compares the impacts from the four different methods to preserving 1 tonne of biomass (the impacts of all other stages are the same and are discussed in the next section). The hang drying has the lowest environmental impact, and ensiling has the second-best environmental performance. The energy-intensive freezing process is the worst performing preservation method, particularly in the cumulative energy demand and ozone layer depletion categories due to the high-energy requirements. It is also the only preservation method whose impacts are affected by the 90 days of storage time (considered a reasonable assumption, see "Preservation" section), since the frozen biomass requires constant energy expenditure to maintain a safe cold storage

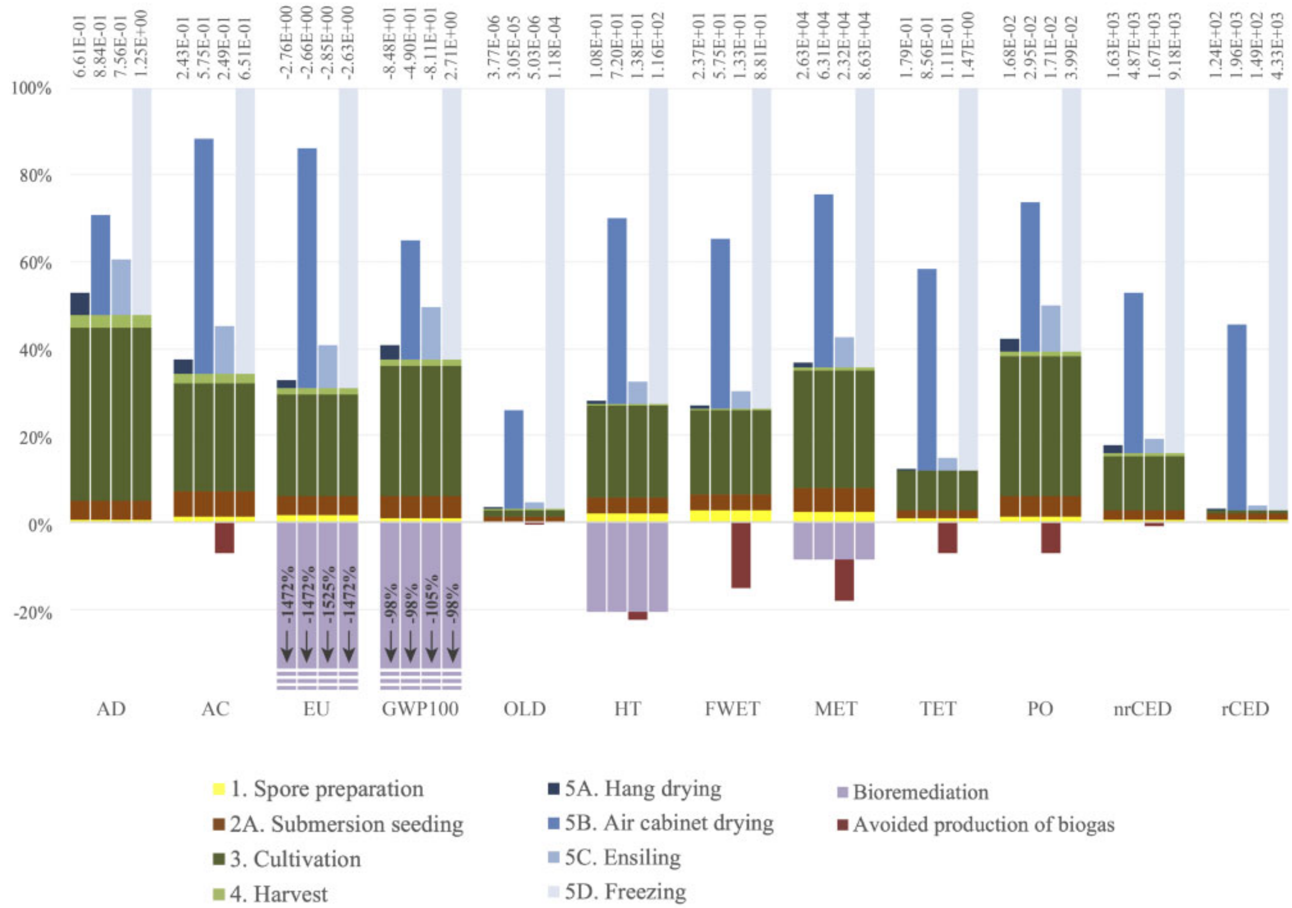

Figure 4. Overview of supply chain impacts, including a comparison of the impacts resulting from the four alternative preservation methods (in blue), thereby showing the importance of those preservation methods relative to total impacts, and including impact mitigation contributions due to bioremediation (in purple). For more information about sub-processes, see Tables 1 and 3 for LCIs and "Spore preparation", "Seeding lines", 'Cultivation", 'Harvesting", and "Preservation" sections for process descriptions. Impact category key: abiotic depletion (AD), acidification (AC), eutrophication (EU), global warming potential (GWP100), ozone layer depletion (OLD), human toxicity (HT), freshwater aquatic ecotoxicity (FWET), marine aquatic ecotoxicity (MET), terrestrial ecotoxicity (TET), photochemical oxidation (PO), renewable cumulative energy demand (rCED), and non-renewable cumulative energy demand (nrCED).

temperature. The impacts of freezing could therefore be reduced by decreasing storage time, by utilizing energy efficient freezing systems, or by using a better insulated storage space to reduce daily energy consumption if longer storage periods are needed. Once ensiled or dried and vacuum packed, the biomass can be stored at room temperature for months with no additional energy expenditure.

The air-cabinet drying was also found to perform relatively poorly, principally owing to high-energy consumption. The energy expenditure and associated impacts in this case are due to dewatering the biomass, and minimizing these requires drying methods that are as efficient as possible. On average, impacts were found to be between 40 and 60% lower for the air-cabinet drying than for the freezing. This did not apply to estimated eutrophication and acidification impacts, however, which were around 20% lower for the freezing as a result of the high impacts of the steel drying racks in these categories. In ozone layer depletion, on the other hand, the particularly high impacts of the freezing method dwarf those of the air-cabinet drying. In summary, the high-energy use of the air-cabinet drying was identified as the principle cause of this preservation approach's relatively high share of impacts. Further research is needed to develop and assess innovative and energy efficient bulk drying methods tailored to end uses, both for food-grade products and for low-grade uses like alginate extraction or biopolymer production. Hybrid drying approaches, for instance combining hang-drying and air-cabinet drying approaches, should also be evaluated as a way to reduce impacts while maintaining the greater degree of control over moisture content of the dried kelp offered by air-cabinet drying.

The ensilage method performed the third best across all impact categories. Contributions were relatively more elevated in abiotic depletion, acidification, eutrophication, and global warming potential than in the other categories, owing to the contributions of the concrete silos. The impacts in acidification and eutrophication were largely offset by the ensilage effluent, which may result in the avoided production biogas or of grass as a biogas substrate (see methods in section 2.5 and sensitivity discussion in "Sensitivity analysis" section).

Overall supply chain impacts

Figure 4 also compares the environmental impacts from all stages in the supply chain, i.e. spore preparation, seeding, cultivation, harvesting, and preservation methods. All these stages, except the preservation approaches, are the same across all preservation scenarios. The uptake of carbon, nitrogen, and phosphorous by kelp is considered a mitigation of environmental impacts and therefore is credited with a negative contribution (see the next section for details).

The environmental performance of the freezing stage was worse than the rest of the supply chain combined (stages 1–4), contributing between 60 and 70% of total impacts to most impact categories. The share was even above 80%, however, for ozone layer depletion, terrestrial ecotoxicity, and the two cumulative energy demand categories. The next greatest shares of contributions across the supply chain are those of the air-cabinet drying, which is also relatively energy intensive, contributing between 30 and 50% of total impacts, though with particularly high shares in eutrophication and acidification categories. As a proof-of-concept and venture project, the present supply chain was not yet optimized to minimize impacts, and this LCA study aims to inform improvement decisions. If freezing or air-cabinet drying cannot be avoided, both methods need to become more energy efficient and the drying could utilize bioenergy heat sources to reduce overall impacts from a life cycle perspective (Hansson *et al.*, 2018).

The cultivation stage, which includes the infrastructure at sea, its installation, and monitoring, is also significant across all impact categories, contributing between 20 and 30% in the scenario with freezing as preservation method. Those stages of the supply chain with the smallest shares of impacts were found to be the harvest, spore preparation, and the seeding methods. Their combined contribution to the impacts for the freezing scenario did not exceed 10% in any impact category. Given that to the authors' knowledge seeding processes have not been included in LCAs of kelp or seaweed production systems to date, "Comparison of seeding methods" section specifically provides a higher resolution analysis of the impacts of the seeding stages.

On the whole, the energy-intensive freezing and air-cabinet drying are responsible for the greatest shares of impacts followed by the contributions of the cultivation infrastructure. This is consistent with Van Oirschot *et al.* (2017). However, their relative shares differ between the two studies, due to a range of differences in infrastructures and supply chain configurations. The present case uses low-alloy instead of stainless steel chains in its infrastructure, responding to the considerable shares of the latter in the toxicity impacts in Van Oirschot *et al.* (2017). The impact contributions of the other material components in the cultivation infrastructure show similar results to those in Van Oirschot *et al.* (2017). In particular, the plastic longline ropes are still relatively high contributors to abiotic depletion impacts as well as the non-renewable cumulative energy demand due to the crude oil used to manufacture them. This suggests that alternative non-toxic rope materials, e.g. hemp or manila, should be explored as lower-impact alternatives particularly as these would biodegrade and not contribute to microplastic pollution.

Impact mitigation by carbon capture and nutrient bioremediation

Mitigation of impacts occurs in eutrophication and global warming potential categories and to a lesser extent in the human toxicity and marine aquatic ecotoxicity categories, as a result of the uptake of phosphorus, nitrogen and carbon by the kelp. The yearly average content in dry matter *S. latissima* is 0.24% phosphorus (Pechsiri *et al.*, 2016), and 2.7% nitrogen and 26.2% carbon (author measurements). These compositional data are from samples from the farm in question and do not account for seasonal variation, which should be considered as a source of uncertainty.

For every tonne of fresh harvested biomass, there is an estimated capture of 39.6 kg of carbon (corresponding to mitigation of 145 kg of CO_2 equivalent), and a bioremediative uptake of 4.08 kg nitrogen and 0.4 kg phosphorus (corresponding to an eutrophication impact mitigation of 2.82 kg of PO_4 equivalents). Resulting cradle-to-gate negative emissions from carbon capture and nutrient bioremediation are considerable compared to the positive emissions. Supply chain emissions amount to 55.2 kg of CO_2 equivalent and 0.06 kg of PO_4 equivalent to cultivate and harvest 1 tonne of biomass (stages 1–4), with preservation resulting in an additional 4.9, 40.8, 18.2, and 92.5 kg of CO_2 equivalent and 0.0036, 0.11, 0.019, and 0.13 kg of PO_4 equivalent for stages 5A–5D, respectively. These findings are in line with other studies in literature, notably Seghetta *et al.* (2017) reporting net negative impacts in climate change and both nitrogen and phosphorus limited eutrophication impact categories.

It should be emphasized that these net negative emissions are temporary; they only relate to a cradle-to-gate system and do not account for subsequent processing, use or disposal. It is generally observed that time horizons are of critical importance, for instance with longer carbon storage periods of product systems resulting in more pronounced climate impact mitigation effects. The accounting of biogenic carbon fluxes and translation of these into climate impact mitigation can be conducted by a range of methodological approaches (Brandão *et al.*, 2019). Given that most of the kelp currently produced in the Koster archipelago is consumed locally as food, the phosphorous, nitrogen, and carbon uptake will be short lived, returning as emissions to the environment after only a short period of time. Nevertheless, even temporary carbon storage in biomaterials is argued to account for some climate impact mitigation, by contributing to the avoidance or delay to crossing the climatic target level of 450 ppm of CO_2 equivalents (Jørgensen *et al.*, 2015). In the present cradle-to-gate study, the use and end-of-life phases of kelp products are not considered, only the carbon uptake by the biomass at point of harvest and emissions of the supply chain up to the production of preserved kelp. Downstream carbon considerations should be explored in future research to determine the climate mitigation potential of cultivated kelp products.

With regard to nutrient uptake, the impact mitigation considerations are different to those for carbon: whereas anthropogenic carbon emissions are primarily atmospheric and lead to global climate impacts, nutrient emissions are primarily water borne and lead to localized eutrophication impacts. As aforementioned, the kelp farm is located in the Skagerrak, which may be both nitrogen and phosphorus limited at different times of the year (Swedish EPA, 2008, p. 16), thus motivating that the uptake of both N and P from these waters during the harvest will contribute to bioremediation of local eutrophication. The net nutrient uptake taking place and resulting bioremediation is a highlight of this study. It also highlights that seaweed biomass can be used as a vector to close the loop on finite phosphorus (Cordell *et al.*, 2009), capturing it from its principle sink, the marine environment, and returning it to human consumption systems. Further research is also needed to fully map out such marine-land nutrient loop closure, notably from a cradle to grave perspective which would include nutrient flows (as kelp products) to ultimate sinks. Such research should also attempt to shed light on the use of marine recovered nutrients and their effect on reducing dependence on finite nutrient sources such as mineral phosphates.

Sensitivity analysis

Figure 5 presents the results of the numerical sensitivity analysis for six key parameters. These parameters were identified on the basis of their impact contribution and/or data variability or uncertainty (see section 2.5). Similar as Van Oirschot *et al.* (2017), the sensitivity analysis revealed that biomass yield was one of the most influential parameters across most impact categories. An increasing yield reduces the impacts per tonne fresh biomass produced (and preserved). The stated yield of 10 kg fresh weight per metre of longline is considered as a reasonable estimation based on case data from the cultivation site over several years. It is also comparable to yields in literature, for instance the 9.1 kg fresh weight per metre of longline reported by Seghetta *et al.* (2017). Nevertheless, yields in practice are highly uncertain, mostly due to variations in conditions from year to year, due to possible risk factors such as disease or storms, and variability resulting from slight changes in technical protocols, for instance in the hatchery. Where possible, however, measures should be taken to maximize yields, for instance by optimizing the density of juveniles on the seeded line produced or optimal positioning of cultivation sites. Similarly, the use of preventative measures to avoid significant yield losses, such as the use of more robust, storm-resistant infrastructure, should be considered a strategic priority, even though these measures may increase impacts in the short term.

The most influential parameter in the freezing model was found to be the duration of storage. Shortening storage duration reduces energy consumed and thus related impacts. The Specific Moisture Extraction Rate (SMER) of the energy-intensive air-cabinet drying is another variable identified to be highly influential. The high influence of both parameters can be explained by the large impact contributions of the freezing and drying processes to overall life cycle impact. Small improvements in their efficiency therefore may have significant potential to reduce impacts, particularly in categories where those processes had particularly large shares of impacts.

Sensitivity analysis was also conducted for the life expectancy of cultivation infrastructure components. Such variations in life expectancies are likely depending on exposure and conditions at cultivation sites, but also resulting from the selection of specific materials such as low-alloy steel, which may degrade faster than stainless steel alternatives. Varying the initial input value for life expectancy of infrastructure at sea, estimated to last for 5 years for the longline ropes and 10 years for the rest of the cultivation infrastructure, showed results varying accordingly. A decreased life expectancy results in the need for more frequent replacements, resulting in greater corresponding impacts across all categories; the reverse is the case for increased life expectancy, which corresponds to a need for less frequent replacement and thus lower impacts. However, the changes in impacts are small relative to those of the rest of the supply chain in most impact categories, suggesting that, though variation in life expectancy is likely, these will only affect overall impacts to a minor extent.

The number of collectors produced by the hatchery was also included in the sensitivity analysis to account for failed juvenile development in the hatchery as is often experienced in practice. This was done by increasing total production of seeded collectors to a maximum of 150% (~75 collectors); a decrease to a minimum of 50% was seen as irrelevant. This increase in productivity also only results in a slight increase in impacts across all categories, owing to the additional material and energy used in the increased production.

Although not included in Figure 5, the numerical sensitivity analysis was also applied to consider the assumed distance of 10 km from the port to the cultivation site, potentially influential because of the number of return trips needed to complete the harvest. Even assuming a 100-km distance (1000% increase) total impacts did not increase by >10% in any category. However, the ecoinvent database lacks an adequate sea-worthy, small-scale transport vessel of <100 tonnes. Therefore, it is recommended to conduct a more detailed analysis of the potential impacts of transport at sea in future studies.

An additional modelling sensitivity analysis quantified the influence of crediting the ensilage effluent by-product by either avoided conventional biogas production or production of grass as a biogas substrate. Both crediting choices are considered justified by the well-developed Swedish biogas market, notably for public transport. When comparing these two alternative crediting approaches, the credit for the avoided biogas production showed slightly greater (30% on average across impact categories) than the credit for avoided grass production. However, both yielded a small change compared to the rest of the supply chain. The coproduced biogas could also have been credited with avoided production of natural gas, or with combustion of natural gas or conventional biogas. These processes were not readily available in ecoinvent but may have larger effects on overall results than crediting with avoided biogas or grass production. This illustrates the need for precaution in the choice how to credit by-products.

Environmental aspects not well covered by LCA

The life cycle perspective in this study sheds light on a broad spectrum of impacts resulting from the production and preservation of kelp at our case study site. LCA provides particular insight on the inputs and outputs of a product system and therefore does not account for all environmental impacts. Some types of environmental impacts cannot be accounted for by input/output assessment, such as effects on biodiversity (e.g. habitat loss/provision) or due to benthic shading, but rather require environmental impact assessment specially catering to these cases. Hasselström *et al.* (2018) and Visch *et al.* (2020) investigated ecosystem services and local environmental impacts of kelp farming at this same case site. These studies suggest that negative local environmental impacts are minimal or negligible at the current 2-ha scales of operation. Combined, the three studies provide a comprehensive view of environmental impacts from kelp farming.

The CML baseline method used in the present study does not differentiate between phosphorus- or nitrogen-limited eutrophication. According to Hauschild and Potting (2005), eutrophication is typically phosphorus limited in freshwaters and nitrogen limited in marine waters and therefore proposes to distinguish between both nutrients. Henryson *et al.* (2018) points to brackish water often being phosphorus and nitrogen limited. Some LCA studies of seaweed supply chains, for instance Seghetta *et al.* (2017), do indeed differentiate between the two nutrients. The present study lacks this valuable, additional perspective.

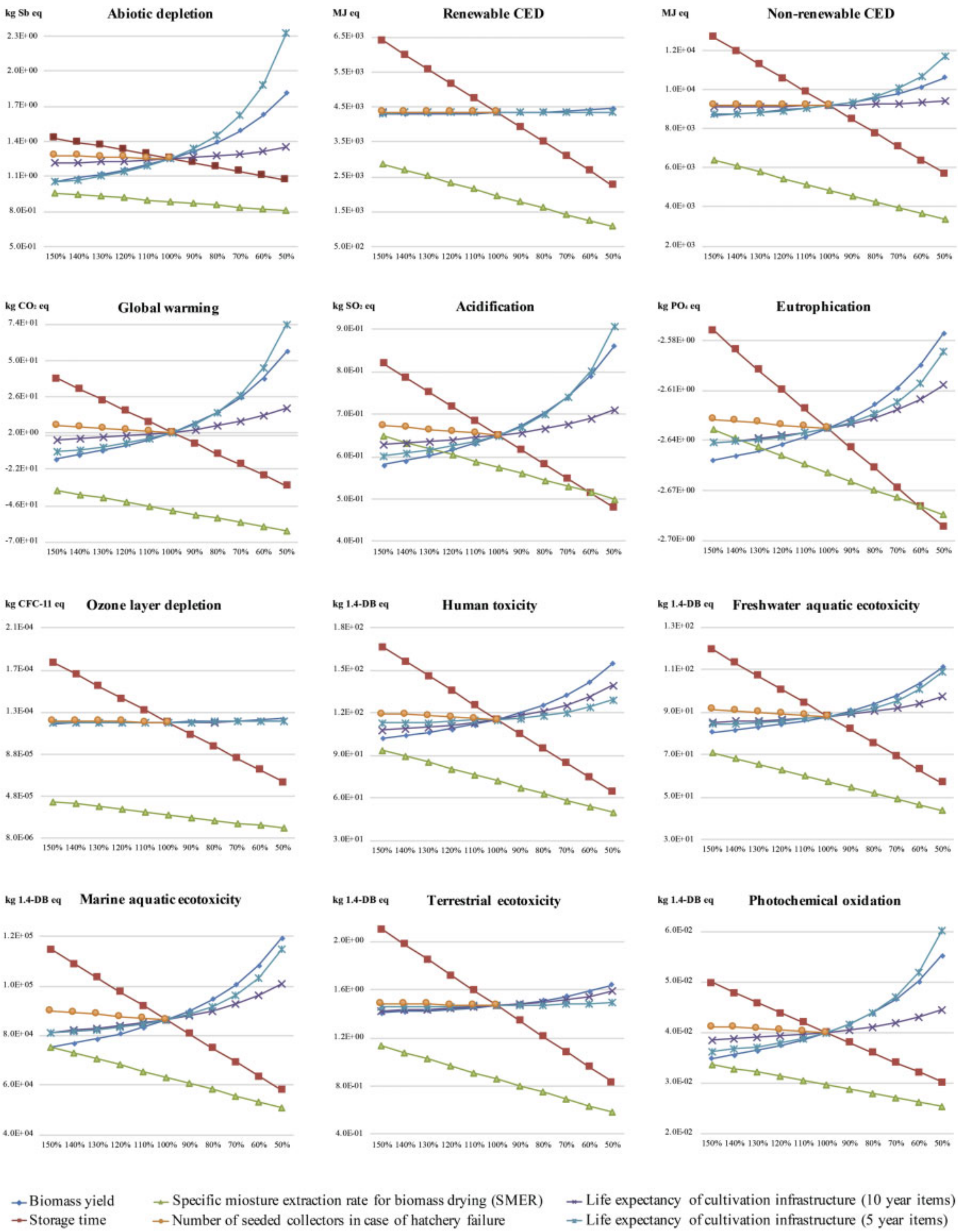

Figure 5. Numerical sensitivity analysis of key input values for the air-drying (green line only) and freezing (all other lines) scenarios of the modelled supply chain. Inputs with a high influence on results or of particular uncertainty are numerically varied at 10% increments from 50 to 150% of the base case (100%). The curves therefore represent plausible variations in impacts, while also illustrating the relative influence of key parameters. These parameters are: biomass yield (*dark blue squares*) varied from 5 to 15 kg FW m^{-1} longline (base case = 10), duration of storage (*red squares*) varied from 45 to 135 days (base case = 90), SMER value of the air cabinet dryer (*green triangles*) varied from 1.5 to 4.5 MJ kg^{-1} of extracted water (base case = 3), cultivation infrastructure component life expectancy varied from 2.5 to 7.5 years (base case = 5) for longline ropes (*light blue crosses*), and from 5 to 15 years (base case = 10) for all other infrastructure components (*purple crosses*). The final parameter accounted for in the sensitivity analysis, the collectors consisting of a pipe and seeded lines, demonstrates the increased impacts due to additional production of seeded collectors (*orange circle*) owing to hatchery failure, and so is only varied from the base case to 150%.

A pertinent environmental issue to which seaweed farms may be contributing and that is not covered by LCA; thus, neither by the scope of the present study is the contribution to microplastic pollution resulting from the degradation of plastic cultivation infrastructure components such as ropes and buoys. In the course of the next decade labelled the "United Nations Decade of Ocean Science for Sustainable Development" (UNESCO, 2017), advancements in the field of LCA are urgently needed to shed light on a wider range of possible environmental impacts that product systems have on marine environments.

Conclusions

This study highlights that cultivated kelp supply chains can contribute to the European bioeconomy with low-carbon biomass while also locally mitigating eutrophication through nutrient bioremediation. More carbon was found to be captured by photosynthesis than was emitted by the cultivation and preservation of kelp. Downstream processing into products, alternative uses and end of life of scenarios need to be explored in future research to shed light on the carbon sequestration potential of kelp products and on the nutrient loop closure role of kelp farming. Another highlight is the choice of preservation method having a major influence on total impacts in a kelp cultivation and preservation supply chains (i.e. cradle to gate preserved seaweed production system). The preservation method with the greatest contribution to environmental impacts was found to be the freezing process followed closely by the air-cabinet drying, both due to their high-energy requirements and for the freezing process, also because of the long duration of storage. The ensiling and outdoor drying processes were found to have comparably low impacts primarily as a result of their much lower energy consumption.

Effectively, the environmental performance of preserved kelp production is, to a large extent, determined by the manner in which the fresh kelp is preserved. However, preservation methods in turn will affect potential end uses of the biomass. The four processes compared here yield totally different end products, with the ensilaged biomass being most different in terms of composition (Abdollahi *et al.*, 2019). More research is thus needed to shed light on downstream processing of preserved biomass into market-ready products and to draw comparisons with other equivalent products or materials that these may seek to replace. European seaweed production is on the rise—as it evolves and scales up in the coming decades, more LCAs will be needed to ensure that it remains an environmentally optimized industry that provides net environmental benefits and low-carbon products to society.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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