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Bioextraction potential of seaweed in Denmark — An instrument for circular nutrient management

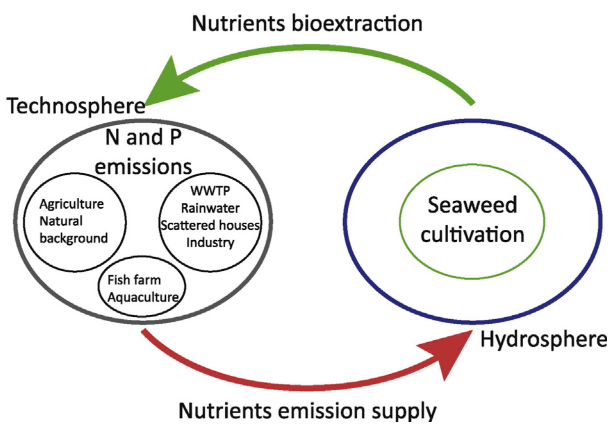
Michele Seghetta [a], Ditte Tørring [b], Annette Bruhn [c], Marianne Thomsen [a,*]

[a] Research Group on EcoIndustrial System Analysis, Department of Environmental Science, Faculty of Science and Technology, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark
[b] Orbicon A/S, Jens Juuls Vej 16, 8260 Viby, Denmark
[c] Department of Bioscience, Faculty of Science and Technology, Aarhus University, Vejlsøvej 25, 8600 Silkeborg, Denmark

HIGHLIGHTS

- Offshore seaweed production for nutrient circular management is assessed.
- The impact of different management strategies on eutrophication is calculated.
- LCA of nutrient and biomass management strategies is developed.
- Seaweed bioextraction of nutrients is a key for circular resource management.
- Seaweed cultivation is an instrument to achieve national water quality goals.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of the study is to assess the efficacy of seaweed for circular nutrient management to reduce eutrophication levels in the aquatic environment. We performed a comparative Life Cycle Assessment (LCA) of two reference waste management systems treating seaweed as biowaste, i.e. landfill disposal and combustion, and an alternative scenario using the seaweed *Saccharina latissima* as a resource for biobased fertilizer production. Life Cycle Impact Assessment (LCIA) methods were improved by using a cradle-to-cradle approach, quantifying fate factors for nitrogen and phosphorus loss from fertilized agriculture to the aquatic environment. We also differentiated between nitrogen- and phosphorus-limited marine water to improve the traditional freshwater impact category, making this indicator suitable for decision support in relation to coastal water management schemes. Offshore cultivation of *Saccharina latissima* with an average productivity of 150 Mg/km^2 in Danish waters in 2014 was applied to a cultivation scenario of 208 km^2. The bioresource scenario performs better than conventional biowaste management systems, delivering a net reduction in aquatic eutrophication levels of 32.29 kg N eq. and 16.58 kg PO_4^{3-} eq. per Mg (dry weight) of seaweed, quantified by the ReCiPe and CML impact assessment methods, respectively. Seaweed cultivation, harvest and reuse of excess nutrients from the aquatic environment is a promising approach for sustainable resource cycling in a future regenerative economy that exploits manmade emissions as a resource for closed loop biobased production while significantly reducing

* Corresponding author.
E-mail address: mth@envs.au.dk (M. Thomsen).

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eutrophication levels in 3 out of 7 Danish river basin districts. We obtained at least 10% bioextraction of phosphorus manmade emissions (10%, 89% and >100%) and contributed significantly to local nitrogen reduction goals according to the Water Framework Directive (23%, 78% and >100% of the target).

1. Introduction

Marine biomass accounts for over 50% of the primary production of global biomass (Carlsson et al., 2007). Compared to terrestrial biomass, only a small fraction of this is used for production. Coastal ecosystems, which cover <0.5% of the sea bed, capture 55% of world green (biological) carbon (Nellemann et al., 2009).

This fundamental service is endangered by linear production systems characterized by one-way flow of nutrients, i.e. manmade emissions, from the lithosphere to the hydrosphere, resulting in excess nitrogen and phosphorus that give rise to eutrophication of natural marine and freshwater ecosystems. Manmade emissions are nutrients lost to marine water bodies from Danish land-based activities, e.g. NO_3^- from agriculture, NH_3^+ from fish farming; here referred as "emission supply to seaweed cultivation".

Green-engineered nutrient bioextraction, presented in this study as offshore seaweed production systems floating in open waters, may be used to mitigate continuing eutrophication of marine systems. Cultivation of seaweed in green-engineered open water systems, i.e. on an artificial substrate (ropes deployed in marine water), is isolated from natural habitats since it does not compete with the natural benthic community for the occupation of the sea bottom (Buschmann et al., 2014; Zhang et al., 2009).

Such biobased production systems are a key for transforming linear production systems into circular systems. Engineered production of blue carbon is a circular nutrient management system using land-based emission as a resource for biobased production, thus contributing to restoration of biogeochemical balance. Offshore cultivation of seaweed is a relatively new technology in Europe (www.netalgae.eu), but is developing rapidly and attracting funding in northern European countries such as Denmark (e.g. www.MAB3.dk, www.submariner-project.eu), the Netherlands, Ireland and Scotland (e.g. www.noordzeeboerderij.nl, www.enalgae.eu, www.atsea-project.eu, www.biomara.org).

Conceiving emissions as a resource for seaweed cultivation, if successfully implemented, may be a key green-engineered system for future sustainable blue growth (COM, 2012; Quilliam et al., 2015). Furthermore, seaweed production and utilization is compatible with the circular economy principle of transforming CCS into carbon capture and use (CCU) by biobased production systems. In this regard, it is important to evaluate the key factors making engineered seaweed cultivation systems sustainable with respect to restoration of marine environmental conditions supporting the conservation of natural ecosystem services (Nellemann et al., 2009).

In this study we consider the most simple and immediate example of how seaweed can transform emissions into bioresources, establishing a circular flow through using harvested seaweed biomass as fertilizer. Loss of nutrients from the lithosphere to the hydrosphere is therefore reduced by returning them to soil. Denmark used cast seaweed as soil fertilizer and conditioner in the 19th century, a practice which has also been popular in other parts of the world, e.g. Spain and Ireland (Villares et al., 2007; Mouritsen, 2013). Seaweed enhances soil quality by improving soil texture and water retention (Craigie, 2011). It also enhances soil microbial biomass and soil respiration rate (Haslam and Hopkins, 1996). The value of the world's seaweed industries producing agrochemicals (fertilizers and biostimulants) is estimated at about US$ 10 m (Craigie, 2011).

The purpose of this paper is: 1) to evaluate the impact of seaweed production and utilization on aquatic eutrophication and 2) to assess to what extent it is possible to counterbalance yearly manmade emissions with a seaweed bioextraction system.

To meet the first aim we perform a Life Cycle Assessment (LCA) on the production and use of seaweed, considering Denmark as case study. For the second aim we compare the bioextraction potential of seaweed with yearly manmade emissions for three different time horizons, taking Denmark as case study.

2. Goal and scope

We performed comparative LCA of three scenarios for production and utilization of seaweed biomass. The goal of the LCA is to evaluate the impact of three different seaweed biomass management options on aquatic eutrophication (Fig. 1): one scenario applies the bioresource management option, in which 1. macroalgae used as fertilizer (MaFe); the others use two existing disposal options: 2. landfilling and 3. incineration.

The MaFe scenario is a simple system for circular nutrient management to maintain ecosystem health and promote biobased production. Excess nitrogen and phosphorus from agriculture entering marine water bodies are bioextracted by seaweed growth. The seaweed-based fertilizer is then returned to the soil for crop production. Thus a quantity of mineral N and P fertilizer is substituted, reducing fossil resource depletion (Niero et al., 2014; Jensen et al., 2015).

The choice of including incineration and landfilling scenarios is based on the fact that seaweed biomass composition varies during the year and from place to place (Bruhn et al., 2016; Nielsen et al., 2016). It is therefore possible that the concentration of heavy metals may exceed the limit allowed for return to the soil as regulated by the European Sludge Directive (Sludge Directive 86/278/EEC) or Statutory Order no. 1650 (Sludge order), e.g. Cd > 0.8 mg/kg dry matter (Seghetta et al., 2016a). In such cases, incineration with energy recovery or landfill are the common management options, e.g. for beach-cast seaweed (Kaspersen et al., 2016; Fredenslund et al., 2010; Seghetta et al., 2014).

The results are presented for a functional unit of 1 Mg dry weight (DW) of seaweed biomass produced per year.

The system boundaries are drawn to include all the inputs from cradle to cradle, i.e. seaweed cultivation, in the case of the biofertilizer production system 1 (MaFe), or to grave, in case of waste management systems 2 and 3 (Fig. 1). Emissions to water from manmade activities, e.g. agriculture, are excluded from the system boundaries of the LCA. Only emissions related to production, processing and disposal of seaweed are included.

The calculation was performed using the software SimaPro 8.0.4 (PRé consultants, 2008) and the integrated inventory Ecoinvent v3.1 (Weidema et al., 2013). The Life Cycle Inventory is described in detail in Section 3.

3. Life Cycle Inventory (LCI)

The Life Cycle Inventory for the system includes nutrient bioextraction during seaweed cultivation, during which element bioextraction occurs, transport for: 1. pretreatment for biofertilizer production and use; 2. landfilling; 3. incineration with energy production and associated emissions to air and water (Fig. 1). The collected data is presented in Tables 1 and 2.