



<http://www.diva-portal.org>

This is the published version of a paper published in *Journal of Industrial Ecology*.

Citation for the original published paper (version of record):

Thomas, J E., Sinha, R., Strand, Å., Söderqvist, T., Stadmark, J. et al. (2021)
Marine biomass for a circular blue#green bioeconomy? A life cycle perspective on
closing nitrogen and phosphorus land#marine loops
Journal of Industrial Ecology, : jiec.13177
<https://doi.org/10.1111/jiec.13177>

Access to the published version may require subscription.


N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-303328>

Marine biomass for a circular blue-green bioeconomy?

A life cycle perspective on closing nitrogen and phosphorus land-marine loops

Jean-Baptiste E. Thomas¹  | Rajib Sinha¹ | Åsa Strand² | Tore Söderqvist^{3,4} | Johanna Stadmark⁵ | Frida Franzén⁶ | Ida Ingmansson⁶ | Fredrik Gröndahl¹ | Linus Hasselström¹

¹ KTH Royal Institute of Technology, Department of Sustainable Development, Environmental Science and Engineering, Stockholm, Sweden

² IVL Svenska Miljöinstitutet/IVL Swedish Environmental Research Institute, Kristineberg, Sweden

³ Anthesis Enveco AB, Stockholm, Sweden

⁴ Holmboe & Skarp AB, Sorunda, Sweden

⁵ IVL Svenska Miljöinstitutet/IVL Swedish Environmental Research Institute, Gothenburg, Sweden

⁶ Tyrens AB, Stockholm, Sweden

Correspondence

Jean-Baptiste E. Thomas, Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Teknikringen 10B, SE-100 44 Stockholm, Sweden.
Email: jbthomas@kth.se

Editor Managing Review: Helen Hamilton

Funding information

The study was funded by the Swedish Research Council FORMAS (grant number 2017-00213) as part of the project—“Marine bioeconomy for circular nitrogen and phosphorus flows in Sweden: Alternatives, hurdles and policy tools.”

Abstract

A blue-green bioeconomy revolution is underway in Europe, with particular attention being paid to the development of new or underutilized marine biomass resources. The wild harvest and mariculture of low-trophic non-fed species of marine biomass may be contributing to circular economies, the mitigation of environmental problems such as eutrophication and climate change through the uptake of nutrients and carbon, while also recovering finite phosphorus from marine coastal environments, thus contributing to food security. The present study provides a cradle-to-gate life cycle perspective on seven established or innovative/emerging marine biomass utilization cases in Sweden: mariculture of sugar kelp, blue mussels, and ascidians and the harvest of invasive Pacific oysters along the Skagerrak coast, the mariculture of blue mussels in the Baltic sea, the harvest of common reed in the Stockholm archipelago, and the harvest of beach-cast seaweed in Gotland. Results showed that the mariculture cases were found to contribute to eutrophication and climate impact mitigation (at gate). All cases were found to contribute to closing the loop on phosphorus by enabling recovery from marine or coastal environments, bridging marine–land flows, all while performing well from an environmental perspective with a relatively low cumulative energy demand and low carbon and nutrient footprints. This highlights the potential of low-trophic biomass to contribute to phosphorus security in the future, and demonstrates the value of industrial ecology tools such as LCA in support of this imminent Decade of Ocean Science for Sustainable Development.

KEYWORDS

aquaculture, blue-green bioeconomy, close the loop, industrial ecology, marine biomass, phosphorus

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. *Journal of Industrial Ecology* published by Wiley Periodicals LLC on behalf of Yale University

1 | INTRODUCTION

The reversal of the planetary boundary transgressions for the biogeochemical cycles of nitrogen (N) and phosphorus (P), and the safeguarding of P resources for future generations, are amongst the most urgent global societal challenges (Cordell et al., 2009; Rockström et al., 2009; Steffen et al., 2015; Withers, 2019). While the Haber–Bosch process and the burning of fossil fuels have made reactive forms of N (organic N, NH₃, and NO_x) globally abundant over the past century (Gruber & Galloway, 2008), P is a finite resource whose phosphate mineral reserves may last 50 to 100 years at current extraction rates (Cordell et al., 2009). Yet it too underpins global food security and is an irreplaceable building block of life (Cordell & White, 2014; Elser & Bennett, 2011; Steen, 1998); thus P scarcity is being recognized as a major and imminent sustainability challenge or “crisis” (Carrington, 2019; Vaccari, 2009; Withers, 2019). Compared to natural inputs of P to the environment in pre-industrial times due to weathering, the mining of P and its use in fertilizers has more than doubled P inputs to the environment (Bennett et al., 2001), much of which ends up in aquatic sinks (Smil, 2000).

Anthropogenic N and P loading to marine environments has disrupted natural cycles and is an important contributor to a wide range of environmental consequences including eutrophication (Elser & Bennett, 2011; Gruber & Galloway, 2008) and associated effects (further detailed in Supporting Information 1). The Baltic Sea, often referred to as one of the world's most polluted seas, suffers from severe eutrophication, deoxygenation, and comprises one of the world's largest dead zones (Carstensen et al., 2014; Murray et al., 2019). In the last few decades, the emissions of N and P have decreased due to improvements in agriculture and improved waste water treatment facilities (Andersen et al., 2017). Still, the total N and P loads from Sweden to marine environments were 123,000 and 3,800 tons¹, respectively, in 2016, of which anthropogenic shares were 37% for N and 46% for P (Hansson et al., 2019; SMED, 2016). Further, as a legacy of earlier emissions and notably of P that has accumulated in sediment, conditions are still poor in the Baltic Sea (Limburg et al., 2020; McCrackin et al., 2018).

Circular economy approaches show much promise in supporting the development of holistic management strategies for both N and P “by slowing, closing and narrowing material and energy loops” (Geissdoerfer et al., 2017). Studies have explored the closing of P loops in urban-hinterland regions (Trimmer & Guest, 2018; Verbyla et al., 2013; Wu et al., 2016), by capturing it in human waste and waste water systems (Amann et al., 2018; Ciešlik & Konieczka, 2017; Mihelcic et al., 2011), and by slowing and narrowing of P loops with more efficient livestock production, agriculture, and fertilizer use (Bateman et al., 2011; Bouwman et al., 2013; Nesme et al., 2014; Schoumans et al., 2014; Willett et al., 2019). These strategies comprise a mixture of cleaner production and end-of-pipe approaches with a focus on land-based mitigation of N and P losses, and are summarized by Barquet et al. (2020) for the Baltic Sea Region. They also align with the first three levels of the Arlidge et al. (2018) impact mitigation hierarchy—avoidance, minimization, and remediation—as applied to the context of nutrient emissions mitigation by Soininen et al. (2019). This highlights a need for complementary *post* end-of-pipe measures that focus on the two lowest levels of the environmental impact mitigation hierarchy—remediation and offsetting—to assimilate and recycle nutrients that have already entered marine environments.

A range of wild marine biomasses are explored for their nutrient uptake capacities; harvesting biomass such as beach-cast, reed, or the invasive Pacific oyster (see Supporting Information 1) can reduce levels of nutrients in the marine environment as well as provide concentrated N and P sources for further use (Gröndahl et al., 2009; Quilliam et al., 2015). This activity may also help to restore desirable environmental conditions such as clear waters or clean beaches, which the public has been repeatedly documented as being willing to pay for (Czajkowski et al., 2015; Östberg et al., 2012; Risén et al., 2017; Söderqvist et al., 2005). Indeed, a number of companies in Sweden offer shore and lake cleaning services to private individuals, communities, and municipalities, and some of the harvestable biomass is being considered as raw materials for the bioeconomy (Emadodin et al., 2020). An overarching concern for harvest of all the studied types of biomass is, apart from the benefits of nutrient uptake, harvesting the right species at the right time, at the right place, and in the right amounts to avoid or minimize negative effects on ecosystems.

In complement to the harvest of wild biomass, studies have recognized the nutrient reduction potential of the mariculture of non-fed low-trophic species, such as of blue mussels in the Baltic and Skagerrak (Gren et al., 2009; Lindahl et al., 2005; Petersen et al., 2014; Petersen et al., 2020), though Stadmark and Conley (2011) questioned the effectiveness of mussel farms as measures to reduce dissolved N and P in the water column. In a recent study by Kotta et al. (2020), blue-growth initiatives such as mussel farming are highlighted as contributing to marine remediation and to nutrient circular economies. Kelp mariculture is also recognized as a potentially profitable remediation measure (Hasselström et al., 2020) taking up nutrients to mitigate eutrophication locally (Thomas et al., 2020) and potentially also at regional scales (SwAM, 2015; Xiao et al., 2017), with the added benefit of producing a useful low-carbon raw material for the bioeconomy even when taking a life cycle perspective (Seghetta et al., 2016; Thomas et al., 2020). Ascidians, another group of low-trophic extractive species with similar remediative potential to that of mussels but from the tunicate subphylum, have recently started to be cultivated in the Skagerrak to be used as a feed supplement for fish and animals as well as for human consumption (Hackl et al., 2018; Hřůzová et al., 2020). Given the Swedish government ambition to enhance shellfish mariculture (Jordbruksverket, 2012) and recent recommendations to focus on non-fed or low-trophic aquaculture (EASAC, 2016), momentum is gathering in mussel and kelp mariculture and it looks likely that oyster mariculture may soon follow suit; however, the sea-based mariculture of low–mid trophic fish species remains unlikely given a strict approach to nutrient release in fish aquaculture (Langlet & Mahmoudi, 2016; Soininen et al., 2019). In summary, a range of blue-growth initiatives that involve the wild harvest or mariculture of marine biomass are on the rise in Sweden, and these may help to reduce eutrophication by capturing nutrients, be conducive to the restoration of desirable environmental conditions and nutrient circularity, all the while providing useful biomass for the bioeconomy.

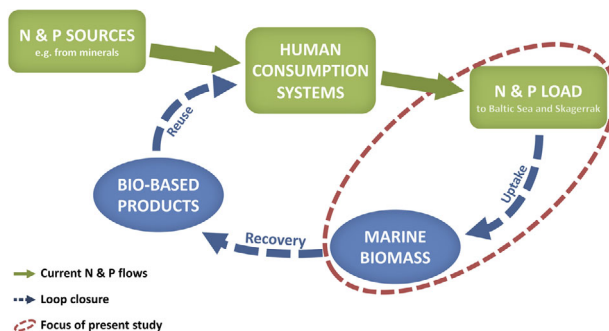


FIGURE 1 Schematic representation of the predominantly linear flows of nitrogen (N) and phosphorus (P) through human consumption systems, and of the potential loop closing role of marine biomass. The focus of the present study is on the life cycle performance of the mariculture or wild harvest of marine biomass that enable the uptake of nutrients from marine sinks

This study aims to explore the *nutrient uptake potential* of a range of blue-growth initiatives in Sweden (Figure 1), with a focus on whether these activities provide net nutrient uptake services in a cradle-to-gate life cycle perspective, and to shed light on environmental performance vis-à-vis of eutrophication impacts, climate impacts (global warming potential or GWP), and cumulative energy demand (CED). Seven case studies of biomass harvest/mariculture were selected for evaluation—four cases of extractive aquaculture and three cases of wild biomass management—due to their merit as ongoing activities that may contribute to blue growth and to N and P circular economies in Sweden. This study therefore attempts to gauge the extent to which the harvest and use of such low-trophic biomass could close land–marine nutrient loops, mitigate further nutrient accumulation, and potentially reduce legacy nutrient stocks. Building on LCA literature with a similar aim but focusing on a single production system (e.g., Seghetta et al., 2016), the seven cases are assessed within a comparative framework that seeks to neutralize some of the variables between the cases to enable a comparison of extractive potentials—an original strength of this study. The roles of industrial ecology and LCA in support of ocean science and marine sustainable development are also discussed in light of the experiences gathered in the course of this study. It is intended that the results of this study should be of value to a wide audience interested in food and phosphorus security as well as blue growth resulting from the development of underutilized blue resources (e.g., public, business and industry actors, policy makers, and the academic community).

2 | METHODS

Environmental life cycle assessments (LCAs) were conducted for each case to shed light on their environmental performance, especially nutrient (N and P) and carbon (C) equivalent emissions. LCA is a widely accepted methodology for the quantification of impacts across a product's life cycle and is conducted in four iterative phases: (i) goal and scope definition, (ii) life cycle inventorying, (iii) life cycle impact assessment, and (iv) interpretation (Baumann & Tillmann, 2004; Guinée, 2002; ISO 14044, 2006). The first and second steps are detailed in the following sections.

2.1 | Goal and scope

Given that the focus of this LCA is on activities leading to the capture and removal (uptake) of nutrients from marine environments, the scope is limited to a cradle-to-gate perspective (see Figure 1), the gate having been set after the harvest and transport to hypothetical processing facilities. The environmental performance is explored in terms of eutrophication and GWP over 100 years (expressed in kilograms of PO_4 and CO_2 equivalents, respectively), calculated following the CML2 baseline 2000 (v2.05) (Guinée, 2002), and complemented with CED (v1.09, expressed in MJ) as a proxy for overall environmental performance and to highlight opportunities for energy use optimization (Frischknecht et al., 2007). Life cycle inventory (LCI) processes were obtained from the Ecoinvent database using SimaPro 7.3 (Ecoinvent Centre, 2016). Processes selected from Ecoinvent are listed in the Supporting Information S1 (Table ST1).

Bioremediation is accounted for in the mariculture cases in the present study by converting total N and P content in the biomass into PO_4 equivalents (multiply by 0.42 and 3.07, respectively) following suggested equivalency factors for the CML method (GHK & Biols, 2006). Carbon uptake is similarly accounted for by converting total C content in the biomass into CO_2 equivalents (multiply by 3.67, ratio of the molecular weight ratio of C to that of CO_2). The N, P, and C (converted to PO_4 and CO_2 equivalents) assimilated in the biomass that is then harvested are accounted for as negative water emissions (i.e., uptake from water). Literature was reviewed to compile biomass composition data for each case study species, notably N, P, C and dry matter/water content, to enable the quantification of nutrient and C removal from their respective environments.

The environmental effects of metabolic emissions are not included in the present study. Potential examples of such emissions include fecal nutrient accumulation under bivalve or tunicate farms, CO₂ equivalent emissions from respiration or shell calcification, and even possible waterborne emissions of dissolved oxygen from kelp photosynthesis. Similarly, the wild biomass harvest cases are subject to complex ecosystem dynamics, such as emissions from natural decomposition of beach-cast or carbon fluxes in reed beds over prolonged timeframes. Consequently, metabolic emissions were excluded from this study due to high variance, a lack of consistent data across the seven present cases, and due to a lack of methodological consensus on how to account for the complex ecosystem interactions resulting from such metabolic emissions (Filgueira et al., 2019).

To provide a comparison of the seven biomass cases that provides relevant perspectives and that is fair to the inherent differences between each biomass, three functional units were selected. The first functional unit expresses impacts per ton harvested biomass (fresh weight or FW) and was selected as relatable to industry actors and future research. The second functional unit expresses impacts per ton of dry matter (DM, 0% moisture) and was selected to enable comparisons between the different cases given the great variation in moisture content across the biomass cases. The third functional unit expresses impacts per kg of P uptake to shed light on the P uptake efficiency of each case. This third functional unit serves as a key indicator for P recovery and thus of loop closure potential, across all seven cases.

In addition, loop closure potential is further scrutinized for the low-trophic mariculture cases (only) in terms of net emissions potential for both climate and eutrophication impacts, which take into account both the sum of cradle-to-gate emissions (emissions^{C2G}) of each activity and the carbon and nutrient content in the biomass that is removed from marine environments at harvest (see Equations 1 and 2, respectively). For additional perspective on the loop closure efficiency of each low-trophic mariculture case, ratios of carbon and nutrient return on investment (ROI) were calculated, that is, ratio of carbon (C-ROI) and nutrient (Nutrient-ROI) in harvested biomass relative to invested cradle-to-gate CO₂ and PO₄ equivalents emissions (see ROI Equations 3 and 4 for C-ROI and Nutrient-ROI, respectively). Given that LCA should typically account only for environmental effects due to changes in emissions directly resulting from human activities, neither net emissions nor ROI perspectives were applied to the three wild biomass cases. These cases are not comparable to mariculture, given that the growth of those biomasses predominantly occurs "naturally" without human intervention, whereas cultivated biomass is a direct result of human activities. It should be noted, however, that this could and perhaps should be challenged given that the eutrophic state of the Baltic is largely considered to be due to human activity. Regardless, the harvest of wild-occurring biomass is a human activity—thus future studies could consider emission changes between harvesting and subsequent use of the biomass, versus leaving the biomass in situ (i.e., not harvesting). In the present study, however, the third functional unit that expresses impact potential per kg P remains the main indicator of P loop-closing potential for those cases.

$$\text{Net CO}_{2\text{-eq}} \text{ emissions} = \Sigma (\text{CO}_{2\text{-eq}} \text{ emissions}^{\text{C2G}}) - (\text{C content} \times 3.67), \quad (1)$$

$$\text{Net PO}_{4\text{-eq}} \text{ emissions} = \Sigma (\text{PO}_{4\text{-eq}} \text{ emissions}^{\text{C2G}}) - [(\text{N content} \times 0.42) + (\text{P content} \times 3.07)], \quad (2)$$

$$\text{C ROI} = \frac{(\text{C content} \times 3.67)}{\Sigma (\text{CO}_{2\text{-eq}} \text{ emissions}^{\text{C2G}})}, \quad (3)$$

$$\text{Nutrient ROI} = [(\text{N content} \times 0.42) + (\text{P content} \times 3.07)] : \Sigma (\text{PO}_{4\text{-eq}} \text{ emissions}^{\text{C2G}}). \quad (4)$$

2.2 | Sensitivity analysis

The supply chain (or product system) operations and associated modeled LCI parameters are subject to certain unavoidable variations, notably with regards to biomass yields and composition, particularly dry matter, N, P, and C content. This exemplifies a key challenge for bioeconomy-related activities: growth and composition of biomass is subject to seasonal variation and other factors, which may have knock-on effects notably on biomass processing, end-product market value, and indeed, on the results of an LCA. To assess the consistency of model behavior and the robustness of results to uncertain inputs or model assumptions (such as seasonal variation), a common solution is to apply a "what if" approach whereby key input factors are identified and varied, and the effect of these variations on overall model results is noted (Pianosi et al., 2016).

Following this approach, sensitivity analysis was conducted on estimated biomass yields by varying these in each case by $\pm 20\%$, a range considered sufficiently wide to account for both seasonal variation in composition and variations in biomass yield based on available data. In addition, most cases were found to be subject to one or two impact hotspots resulting from specific system inputs, such as boat fuel consumption or specific infrastructural components with high impact contributions. Thus, the two items with the greatest influence on the cradle-to-gate nutrient emissions (eutrophication impact hotspots) for each case were also selected for sensitivity analysis. The numerical inputs of each selected hotspot item were

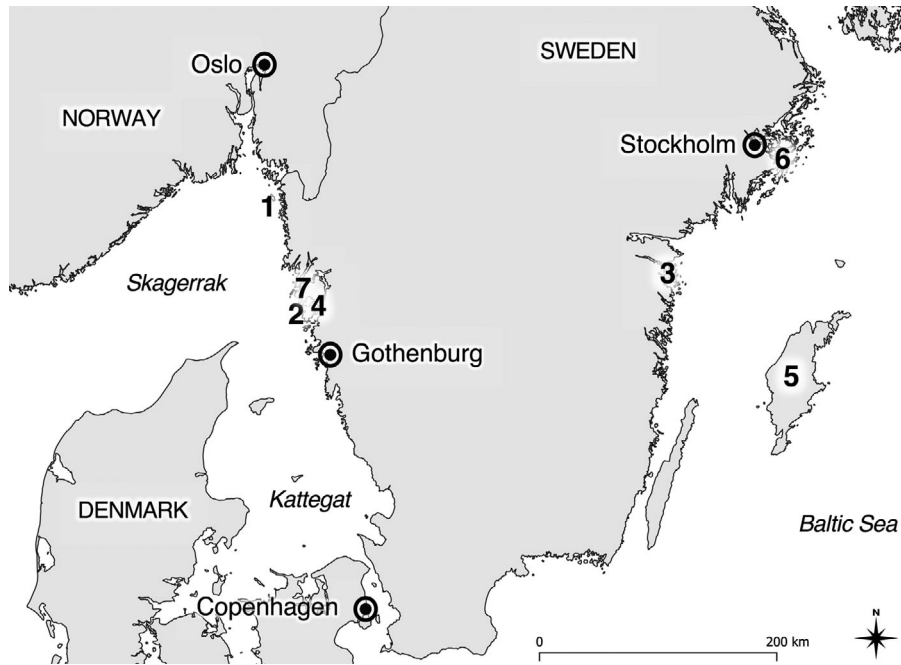


FIGURE 2 Map of southern Sweden, showing the approximate locations of the seven low-trophic mariculture or wild biomass utilization case studies. (1) Kelp mariculture (Koster Archipelago); (2) Blue mussel mariculture (West coast, Skagerrak); (3) Blue mussel mariculture (East coast, Sankt Anna); (4) Ascidian mariculture (Skagerrak); (5) Harvest of beach-cast seaweed (Gotland); (6) Harvest of common reed (Stockholm Archipelago); (7) Harvest of the invasive Pacific oyster (Orust)

also varied by $\pm 20\%$ simultaneously to those of the biomass yields. Combined, the variations portray *maximum* and *minimum* results under scenarios considered to be extreme and are represented by error bars in the main results.

3 | CASE STUDIES AND LIFE CYCLE INVENTORIES

Four cases of low-trophic mariculture and three cases of wild biomass utilization were selected to explore low-trophic blue growth developing in different parts of Sweden today, namely on the West coast (Skagerrak) and the Baltic sea (see Figure 2). In Table 1, the seven cases are summarized including species names, productivity estimates, and a brief description of system boundaries. Some context for each case is further described in the text. Table 2 presents the biomass composition collected from the literature and interviews. For each of the seven cases of marine biomass utilization, one or several stakeholders, typically project or company representatives, were interviewed using a semi-structured approach to build LCIs. The LCIs are presented in Table 3. For both the wild biomass harvest and the mariculture cases, interviewees were asked to describe typical operations and biomass usage, and to compile LCIs including all material and energy inputs of typical activities, and estimations of life expectancy of infrastructure or machinery. When possible, these inventories were validated by follow-up interviews, published material, and laboratory-based quantifications (e.g., of biomass composition) as a way of minimizing potential bias from interviews.

For the aquaculture cases, wide ranges or likely variations of typical operations needed to be managed to enable comparison of extractive potentials. For instance, mussel farm sites may be located less than 1 km from the port while other farms were located more than 20 km away. To balance these variations and present the result for each case in a context of fair comparison, key parameters were selected to be standardized as though each case (1–4) had exactly the same equipment available to conduct operations. This was done in line with the (estimated or mean) values from the large commercial-scale activity, the West coast mussel mariculture case. Specifically, standardized parameters for cases 1–4 include the number of harvest boxes (limited to 2), boat fuel consumption (13.3 L/h), max boat load at harvest (15 tons), harvest duration (3 h), travel time at sea (48 min one way).

In terms of transportation, each of the seven cases (detailed in Section 3) assume 1 km of transport to processing facilities by means of a tractor, following their arrival to land. However, the cases differ in terms of transport during the harvest. Transport at sea for each of the four mariculture cases are based on the assumptions outlined in the previous paragraph. However, given that transportation (at sea and/or on land) makes up a much larger share of the LCI of the three wild biomass harvest cases compared to the cultured cases, vehicles and transportation distances were selected to be representative of usual practices (specified hereafter as each case is presented).

TABLE 1 Case studies' summary table

Case study (location)	Species	Biomass yields	Cradle-to-gate system description	Case references
(1) Kelp mariculture (Koster Archipelago)	<i>Saccharina latissima</i>	≈25 tons FW ha ⁻¹ year ⁻¹	Hatchery, longline cultivation, harvest, transport at sea, and transport of biomass for 1 km on land	Thomas et al. (2020)
(2) Blue mussel mariculture (West coast, Skagerrak)	<i>Mytilus edulis</i>	≈100 tons FW ha ⁻¹ year ⁻¹	Dropline cultivation, harvest, transport at sea, and transport of biomass for 1 km on land	Bergentz (2017); Granhed (2018)
(3) Blue mussel mariculture (East coast, Sankt Anna)	<i>Mytilus edulis</i>	≈10 tons FW ha ⁻¹ year ⁻¹	Dropline cultivation with "fuzzy" rope, harvest, transport at sea, and transport of biomass for 1 km on land	Emilsson and Bailey (2018)
(4) Ascidian mariculture (Skagerrak)	<i>Ciona intestinalis</i>	≈900 tons FW ha ⁻¹ year ⁻¹	Dropline cultivation, harvest, transport at sea, and transport of biomass for 1 km on land	Bergentz (2017); Hackl et al. (2018); Norén (2018)
(5) Harvest of beach-cast seaweed (Gotland)	Mix ^a	≈00–300 tons FW day ⁻¹ , or 10,000–12,000 tons FW year ⁻¹	Transport (equipment to and from location) and harvest using a specially adapted tractor	Dessle (2017); Franzén et al. (2019)
(6) Harvest of common reed (Stockholm Archipelago)	<i>Phragmites australis</i>	≈6 tons FW day ⁻¹ or up to 360 tons FW year ^{-1b}	Transport (equipment to and from location) and harvest by specialized amphibious machinery	Hahlin (2018); Gillerblad (2018); Spörndly (2020)
(7) Harvest of invasive Pacific oyster (Orust)	<i>Magallana gigas</i>	≈160 kg FW day ⁻¹ , or 9 tons FW year ⁻¹	Transport (equipment to and from location) and harvest by hand, transport back to storage facility	Van Der Plasse (2018)

^aThe mixture of species found in beach-cast is known to vary considerably. Franzén et al. (2019) report samples consisting of a mixture of the eelgrass *Zostera marina*, *Furcellaria lumbricalis*, a range of other species including *Polysiphonia spp.*, *Ceramium spp.*, *Fucus vesiculosus*, *Cladophora glomerata*, and *Potamogeton pectinatus*.

^bOver a 60-day harvest window from July to September.

The potential of seaweed biomass as a raw material has long been apparent in Sweden. Projects were first initiated in the 1970s and 1990s; however, financial viability was not achieved. Following calls for bioeconomy and blue-growth strategies to be developed 20 years later (European Commission, 2012a, 2012b), the Seafarm project was initiated as a collaboration of five universities in Sweden to lay the foundations of a seaweed-based industry with the aim of developing a biorefinery approach to producing food, feed, biomaterials, and fuel from cultivated seaweed (Gröndahl et al., 2013). The project was concluded in 2020 and from it has emerged a start-up that produces cultivated kelp (*Saccharina latissima*) for food and serves as the basis of the present case study using data from Thomas et al. (2020).

Mussel farming (*Mytilus edulis*) on the Swedish west coast was pioneered in the mid 1970s and has since then increased to a peak of approximately 2,500 tons per year in the end of the 1980s, after which the production has varied between 1,000 and 2,000 tons per year (FAO global aquaculture production). In 2018 the production was 1986 tons (Kielén, 2019). The mussels are mostly cultured using traditional longline systems although new systems are under development. Mussel farms have also been tested at several locations on the east coast of Sweden during the last decade (e.g., Sankt Anna, Hagby, and in the Stockholm archipelago). Due to the brackish conditions in the Baltic Proper, adult mussels are too small for human consumption, so other products such as feed for livestock or fish (Wilhelmsson et al., 2019) or organic fertilizer (Spångberg et al., 2013) have been suggested as alternatives. Pilot projects in the Baltic have preliminarily harvested approximately 8–10 tons (FW) of mussels per hectare farm and year (Emilsson & Bailey, 2018). The technical development of the farms (longline, nets, etc.) is ongoing, notably at the Sankt Anna site that forms the basis of the current case.

Typically perceived as marine fouling and a nuisance, ascidians (*Ciona intestinalis*, a type of tunicate commonly known as sea squirts) are also seen as having significant biomass potential. Over the past few years, cultivation trials have been successful using mussel farming rigs on the west coast and a start-up is producing food products and driving the exploration of alternative potential uses such as fish feed (Hackl et al., 2018).

Since 2007, the Pacific oyster (*Magallana gigas*, formerly *Crassostrea gigas*) established self-sustaining populations in Scandinavian coastal waters (Laugen et al., 2015; Wrange et al., 2010). Aquaculture of the species is not allowed in Scandinavia due to the species status as invasive, but both commercial harvest of wild populations and harvest for management purposes is now established (Mortensen et al., 2019). This LCA case therefore depicts a small-scale wild harvest operation contributing to invasive species management near to the island of Orust and includes transport back to a storage facility 50 km away from the harvest location (Van Der Plasse, 2018).

Beach-cast algae and seaweed have traditionally been harvested for fertilization in agriculture in coastal Baltic Sea provinces such as the island of Gotland (Linnæus, 1975 [1745]) but is largely out phased in modern agricultural practice. However, its harvest has been gaining attention in recent years notably due to, amongst other reasons, increases in eutrophication and associated filamentous algae drifts (Chubarenko et al., 2021).

TABLE 2 Dry matter, N, P, and C composition data of the biomass presented in both kg per ton fresh weight (FW) and as a percentage of dry matter (in brackets)

Marine biomass case studies	Dry matter content % fraction of FW	Nitrogen content kg ton ⁻¹ FW (% of dry matter)	Phosphorus content kg ton ⁻¹ FW (% of dry matter)	Carbon content kg ton ⁻¹ FW (% of dry matter)
Cultivated kelp: <i>Saccharina latissima</i>	15.1 (Schiener et al., 2015)	2.42 (1.60) (Pechsiri et al., 2016)	0.362 (0.24) (Pechsiri et al., 2016)	40.2 (26.6) (Schiener et al., 2015)
West coast cultivated blue mussels: <i>Mytilus edulis</i>	38.5 (Strand, 2019)	7.47 (0.68 ^c 9.93 ^d) (Hedberg et al., 2018)	0.669 (0.02 ^c 1.15 ^d) (Hedberg et al., 2018)	28.9 (12.7 ^c 46.0 ^d) (Zhou et al., 2002)
East coast cultivated blue mussels: <i>Mytilus edulis</i>	32.7 BBG Submariner ^a	7.60 (2.05) BBG Submariner ^a	0.642 (0.16) BBG Submariner ^a	45.0 (13.8) (Bailey, 2020)
Cultivated ascidians: <i>Ciona intestinalis</i>	5.0 (Hackl et al., 2018)	2.55 (5.10) (Hackl et al., 2018)	0.270 (0.54) (Hackl et al., 2018)	25.0 (50) (Hackl et al., 2018)
Mix of beach-cast seaweed species	23.7 (Franzén et al., 2019)	4.43 (1.87) (Dessle, 2017)	0.369 (0.16) (Dessle, 2017)	66.5 (28) Average ^b from species in Schiener et al. (2015)
Wild common reed: <i>Phragmites australis</i>	35.0 (P.-A. Hansson & Fredriksson, 2004)	3.14 (0.90) (P.-A. Hansson & Fredriksson, 2004)	0.313 (0.09) (P.-A. Hansson & Fredriksson, 2004)	150.5 (43.0) (Soetaert et al., 2004)
Wild invasive Pacific oyster: <i>Magallana gigas</i>	63.2 (Strand, 2019)	3.95 (0.21 ^c 9.27 ^d) (Kellogg et al., 2013)	0.606 (0.04 ^c 1.26 ^d) (Kellogg et al., 2013)	48.5 (11.5 ^c 44.9 ^d) (Zhou et al., 2002)

^aBaltic Blue Growth project data. Average DM, N, and P content data of mussels from the Ecopelag test sites and the established Sankt Anna farm.

^bAverage carbon content accounting for seasonal variation of four common seaweed species (*Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima*, and *Alaria esculenta*) reported in Schiener et al. (2015).

^cPercentage N, P, or C content as a fraction of shell dry matter.

^dPercentage N, P, or C content as a fraction of meat dry matter.

The nutrient capture potential combined with a demand for reducing the nuisances that excessive amounts of beach-cast imply for beach visitors has motivated the Swedish government to introduce funding for harvest initiatives. Our case study is based on harvest initiatives on the island of Gotland, where more than 40 projects have harvested about 11,000 tons FW per year during the last decade, with local farmers as the main end-users. The data for this LCA case include transport of harvesting equipment to and from beaches over an average distance 175 ± 25 km per day (Smedberg, 2018). The harvested biomass is collected in piles, emissions from which are not included in the present case as it is assumed that the piled beach-cast will be utilized.

The common reed (*Phragmites australis*) is one of Sweden's most ubiquitous biological resources and is virtually untapped, covering an estimated 230,000 ha (Spörndly, 2020) of which around 200,000 ha are thought to be in coastal marine environments (Kiessling & Rustas, 2020). Most reed harvesting today is either undertaken privately for water quality or aesthetic management of water bodies/fronts. Only a small fraction of total harvested biomass is currently used, either in agriculture or animal husbandry, though a range of possible uses are well established (Köbbing et al., 2013). Research is ongoing to revisit traditional uses of reed, notably as animal feed, bedding, and as a roofing material, and to develop new uses that would contribute to the bioeconomy/circular economy. The present case study depicts the harvest of reed in the Stockholm archipelago using an amphibious harvesting machine and includes transport of harvesting equipment to and from harvest locations by flatbed truck over an average distance of 390 ± 60 km per day (Gillerblad, 2018).

4 | RESULTS

Table 4 presents a summary of the main results from the LCA of the seven cases. Results show that supply chain emissions (CO₂-eq and PO₄-eq) are typically low when compared to the amount of N, P, and C contained in the harvested biomass. This highlights that the acquisition of the biomass (through wild harvest or mariculture) may indeed contribute to low-carbon circular flows of nutrients. In addition, specifically for the mariculture cases only—for which climate and eutrophication impact mitigation can be accounted as nutrient and carbon assimilation is specifically the result of human activities—more PO₄-eq and CO₂-eq are removed from marine environments than are emitted from the mariculture value chains to gate (i.e., they resulted in net impact mitigation, and C-ROI and Nutrient-ROI values > 1). It should be noted that some of the cases could be the subject

TABLE 3 Life cycle inventories of the seven cases with each input expressed per ton fresh weight of harvested biomass

Inventory items or process	Units	Kelp mari-culture	Blue mussels mariculture (west coast)	Blue mussels mariculture (east coast)	Ascidians mariculture	Harvest of beach-cast seaweed	Harvest of common reed	Harvest of invasive Pacific oysters
Aeration unit ¹	MJ	7.98						
Anchoring buoys ²	kg	0.66		0.48				
Anchors (concrete) ²	m ³	0.03		0.06				
Anchors (steel) ²	kg		8.40*		0.93*			
Aquaria ²	kg	0.29						
Autoclave ¹	MJ	0.17						
Bottom rail ²	kg		6.00		0.67			
Bucket ²	kg	0.02						
Buoys (PET) ²	kg		0.12		0.27			
Buoys (PVC) ²	kg	0.57		0.60				
Carrying cable (PP fraction) ²	kg		1.77		0.20			
Carrying cable (steel fraction) ²	kg		0.44		0.05			
Chains ²	kg	2.55*						
Collector ²	kg	0.27						
Culture rope "Christmas tree" (PP) ²	kg			5.52*				
Diesel: during harvest ¹	L					0.75*	3.65*	
Growing lights ¹	MJ	28.40						
Harvest bags ²	kg	0.32	0.48	1.60	0.05			0.70
Hawser ²	kg		0.14		0.02			
Longlines (PET) ²	kg	7.23	0.04	2.78	0.00			
Longlines (PP) ²	kg	1.65	3.53		0.39			
Nutrient mix ²	L	0.40						
Rebar ²	kg		4.23		0.47			
Seawater filters ²	kg	0.05						
Seeding line ²	kg	0.16						
Shackles ²	kg	0.15		0.10				
Temperature control ¹	MJ	27.80						
Tractor harvest plough ²	kg					0.01		
Transport (during harvest): Diesel at sea ¹	L	3.20*	3.20*	3.20*	3.20*			6.00*
Transport (during harvest): Diesel on land ¹	L					0.47*	16.70*	60*
Transport: deployment and maintenance of infrastructure ¹	tkm	0.61	0.27	3.97	0.02			
Transport biomass to gate (processing facility) ¹	tkm	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Truxor harvester (aluminum fraction) ²	kg						0.003	
Truxor harvester (steel fraction) ²	kg						0.003	
Water heating ¹	MJ	1.20						
Water pump ¹	MJ	0.11						

¹Item or process categorized as "energy and transport" contribution.

²Item or process categorized as "material and infrastructure" contribution.

*Item or process resulting in a eutrophication impact hotspot and therefore selected to be included in the sensitivity analysis.

TABLE 4 Overview of eutrophication and climate impact potential, cumulative energy demand, nutrient and carbon uptake, and net emissions across the three functional units: (a) per ton fresh weight, (b) per kg of phosphorus uptake from the water, and return on investment ratios for nutrients and carbon

Case study Functional unit	Kelp			Mussel (W)			Mussels (E)			Ascidians			Beach-cast			Reed			Oysters		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Eutrophication	0.0822	0.544	0.227	0.152	0.394	0.227	0.0662	0.202	0.103	0.0428	0.856	0.159	0.0108	0.0456	0.0293	0.176	0.503	0.562	0.575	0.910	0.948
Cradle-to-gate emissions																					
impacts (kg PO ₄ -eq)	2.13	14.1	5.87	5.19	13.5	7.76	5.16	15.8	8.04	1.90	38.0	7.04	—	—	—	—	—	—	—	—	—
NET emissions	-2.05	-13.5	-5.64	-5.04	-13.1	-7.53	-5.10	-15.6	-7.94	-1.86	-37.1	-6.88	—	—	—	—	—	—	—	—	—
Nutrient-return on investment	26:1			34:1			78:1			44:1											
Climate impacts (kg CO ₂ -eq)	60.3	400	166	63.2	164	94.5	58.8	180	92	17.0	340	63.0	3.98	16.8	10.8	63.6	182	203	210	333	347
Cradle-to-gate emissions																					
Carbon uptake	147	976	407	106	275	159	165	505	257	91.7	1833	340	—	—	—	—	—	—	—	—	—
NET emissions	-87.1	-577	-240	-42.8	-111	-64.0	-106	-325	-165	-74.7	-1493	-277	—	—	—	—	—	—	—	—	—
Carbon-return on investment	2.4:1			1.7:1			2.8:1			5.4:1											
CED or cumulative energy demand (MJ)	115	759	316	41	106	61	25	75	38	6	124	23	0	1	0	2	7	8	10	15	16
Renewable CED																					
Non-renewable CED	1487	9846	4102	1091	2834	1631	1247	3816	1942	271	5420	1004	55	230	148	867	2478	2769	2880	4559	4749
Total CED	1601	10605	4419	1132	2940	1692	1272	3891	1981	277	5543	1027	55	230	148	870	2485	2777	2890	4575	4765

of additional emissions, for example, from metabolic activities that are not accounted for in the present study. Furthermore, this is a cradle-to-gate study, so while emissions are low relative to assimilated N, P, and C, this study does not account for downstream processing into bioproducts, their use, nor their end-of-life disposal.

When comparing the seven cases as a whole, the best performing case was found to be the beach-cast harvest, which had relatively low CED, climate impact, and eutrophication impact potentials across all functional units. While the assimilation nutrients (N and P) and C in the wild-harvested biomass (in this case beach-cast) means these should not be accounted for as human activity-based impact mitigation, the harvest does involve the capture of these elements for eventual reuse in human consumption systems, and thus as a form of resource acquisition. With this in mind and given an estimated harvest of around 13,750 tons FW per year of beach-cast in Gotland (Smedberg, 2018), linear scaling of results suggests this could amount to an annual capture of approximately 61 tons N and 5 tons of P that could be returned to human consumption systems for an emission of around 0.148 tons of $\text{PO}_4\text{-eq}$. Thus, beach-cast has high potential to close nutrient loops by recirculating N and P to human consumption systems, and it may also provide long-term sequestration of C depending on later stages of the life cycle. Stabilizing C content while maintaining the availability of N and P, for instance by pyrolyzing beach-cast to produce biochar to be used for soil enrichment, may allow the N and P to be re-captured in agriculture while sequestering the C for longer timeframes in the ground (Macreadie et al., 2017). Recent studies suggest beach-cast can decompose and produce greenhouse gases if left in situ on beaches or in piles (Liu et al., 2019), which indicates that harvesting and utilizing the biomass as soon as possible after being cast on the beach should be preferred from an environmental performance point of view. Further research is needed to understand these dynamics so that avoided emissions (e.g., from decomposition when harvested) can be accounted for to lend greater accuracy to follow-up studies.

All the mariculture cases were found to have net nutrient uptake potential and net C uptake potential (i.e., negative net emissions in Table 4) from a cradle-to-gate perspective. The ROI indicators give a sense of the relationship between emissions, uptake, and net emissions of $\text{CO}_2\text{-eq}$ and $\text{PO}_4\text{-eq}$ for the mariculture cases. The higher the ROI, the greater the uptake efficiency will be, that is, the more N, P, or C will be taken up per unit of equivalent emissions. This in turn is indicative of the upstream environmental performance of each biomass as inputs to the (downstream) bioeconomy, that is, ROI enables the comparison of the production performance of the different biomasses. For example, the C-ROI of the ascidians was found to be the highest at 5.4:1, meaning that for each unit of cradle-to-gate $\text{CO}_2\text{-eq}$ emissions there are 5.4 units of $\text{CO}_2\text{-eq}$ s assimilated in the biomass as carbon. In other words, there is a high relative surplus of assimilated carbon (having discounted emissions to gate) that might be converted into long-term climate impact mitigation depending on downstream use, substitution effects from products, and end-of-life destinies of the assimilated carbon in the ascidians. Similarly, the Nutrient-ROI result for the Baltic mussel farming case (Mussels E) case is 78:1, meaning that for each unit of cradle-to-gate emission there are 78 units of nutrients taken up from the water when the mussels are harvested, a relatively high Nutrient-ROI compared to that for kelp (26:1). The differences between the Nutrient-ROIs of kelp and Baltic mussel mariculture are a function of emissions per functional unit: whereas both the kelp and Baltic mussel mariculture systems are based on similar mariculture infrastructures, the Baltic mussel case results in greater total yields of biomass, thus providing the same unit of function (e.g., 1 kg of P or 1 ton DM) with relatively less infrastructure and operations (energy and material inputs, and associated emissions).

The eutrophication and climate impacts as well as renewable and non-renewable CED of the seven cases are broken down in detail in Figure 3, with contributions of the LCI items and processes categorized in two groups. The first is energy and transport contributions, which includes emissions from the consumption of electricity (e.g., in hatcheries) or other energy sources notably for transport (e.g., diesel consumed in boats). The second are contributions owing to material and infrastructure use (e.g., from the production, installation, and maintenance of infrastructure at sea, vehicles in use). From Figure 3, some patterns can be linked to our three functional units. First, impacts per ton of dry matter (B) are always greater than those expressed per ton fresh weight (A), with the relative difference being due to the water content of each biomass type. For instance, the blue mussels dry matter fraction ranges from 32.7% to 38.5% in Table 2, and so impacts are approximately 3 times higher when expressed per ton of dry matter in contrast to 20 times higher for the ascidians given their dry matter content of around 5%. Similarly, impacts expressed per kg of P uptake (C) are also always greater than those expressed per ton fresh weight (A), because there is less than 1 kg P per ton FW of each studied biomass. The three functional units together provide a perspective that would be missing if choosing one single functional unit, as there is much variation between the biomasses in water and nutrient content. For example, for eutrophication, ascidians perform worse than kelp if measured per ton DW, but better than kelp if measured per kg P uptake. This is an effect of relatively higher water content in ascidians but also relatively higher P content.

The efficiency of the seven cases in terms of inputs (energy and material inputs) per unit output product (FW biomass) seems to be closely related to the operational scale of each case. The larger the scale (i.e., the more gross tonnage of biomass produced/yielded), the lower the contributions of the rest of the supply chain become. For instance, mariculture of ascidians uses a similar infrastructure as mussel mariculture on the west coast; however, as can be seen from Table 1, far more ascidians can be harvested per hectare of similar infrastructure, thus reducing the impact of ascidians per ton fresh weight (but not per ton dry matter). A similar pattern is evident with the wild harvest cases. The relatively large average daily harvest of around 200 tons FW of beach-cast is achieved using approximately 180 L of diesel (equivalent to 0.9 L per ton FW), as compared to the relatively small daily harvest of 6 tons FW of reed achieved from an estimated 122 L of diesel (20 L per ton FW) or the even smaller daily harvest of 0.16 tons FW of oysters achieved from 11 L of diesel (equivalent to around 69 L per ton FW). Thus, comparing the cases *per day*, the beach-cast case utilizes the most diesel, followed by the reed case, and with the oyster harvesting case utilizing the least diesel; however, in the present study the focus is on

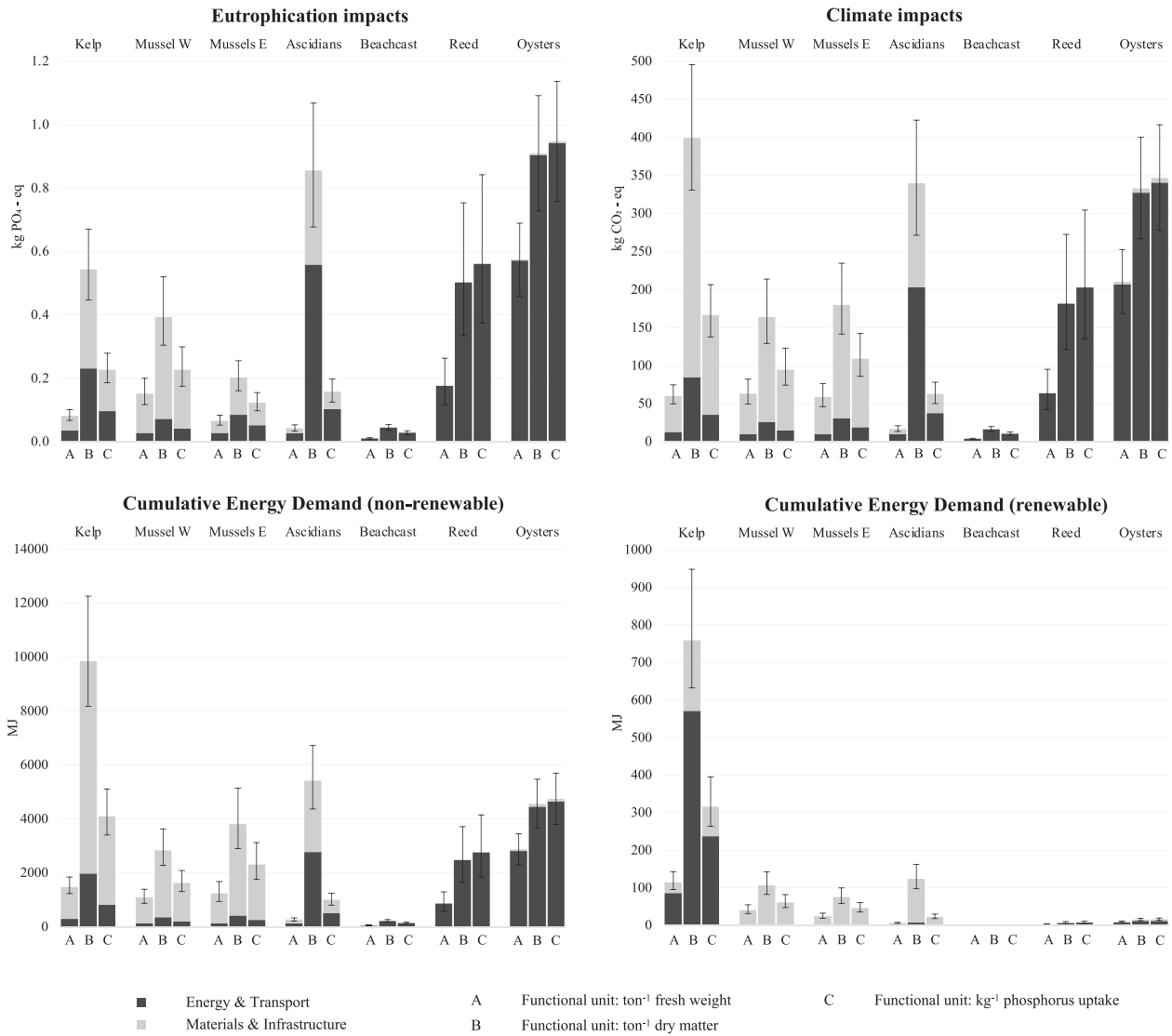


FIGURE 3 Environmental impact profiles for eutrophication potential, climate impact potential, renewable and non-renewable cumulative energy demand of the seven cases. The impacts of each case are expressed in terms of the three functional units: (a) per ton fresh weight, (b) per ton dry matter, and (c) per kg of phosphorus uptake from the water. Impacts are also classified in two groups: materials and infrastructure contributions, such as cultivation rigs and harvesting vehicles, and energy and transport contributions such as diesel or electricity use. The error bars represent plausible ranges of results and model sensitivity to the numerical variation of key parameters by $\pm 20\%$ (see items marked with * in Table 3), specifically for biomass yields and hotspot LCI items. Underlying data used in this figure are provided in Tables ST2-5 in Supporting Information S1 and are additionally provided in numerical form in Supporting Information S2.

nutrient/biomass uptake from the water, and when comparing the cases in these terms, the beach-cast performs best while oysters perform worst. In summary, the cases indicate that the scale of biomass production is closely tied to efficiency in terms of environmental performance across all the selected functional units.

The wild harvest and mariculture cases contrast strongly with one another as they represent very different types of activity, as reflected in their LCIs. While the wild harvest activities typically involve fossil fuel intensive machinery and transportation but little material and infrastructure, mariculture requires infrastructure and material investments at the production stage. Accordingly, the impact profiles of the mariculture cases show large material and infrastructure shares of impacts, whereas those of the wild harvest cases are largely dominated by energy and transport contributions. Only the ascidians have a larger proportion of energy and transport contributions when compared to material and infrastructure contributions, owing to the high biomass yield per rig that offsets the contribution of the infrastructure per ton but does not offset contributions of transport, which still require the same number of trips per ton. The relative differences in energy and transport versus material and infrastructure inputs for the mariculture and wild harvest cases is also reflected in the renewable CED charts. Wild harvest renewable CED contributions are

negligible given they mostly depend on diesel to function. In contrast, the mariculture cases contribute both to the renewable and non-renewable CED: the manufacture of materials and infrastructure requires both renewable and non-renewable primary energy, transport contributions depend primarily on non-renewable primary energy, and kelp mariculture stands out as the most energy intensive case due to the energy intensive hatchery on land. Kelp mariculture also performs worse (on average) than the other mariculture cases in terms of eutrophication and climate impacts across all functional units, with the exception of the ascidian eutrophication impacts per ton dry weight, because of the ascidians high water content. It should also be mentioned that while the present mussel farming cases do not involve hatcheries, some mussel farming techniques do (Kamermans & Capelle, 2019). This exemplifies likely variations that are possible between each case and across averages of their sectors.

Some impact hotspots were identified across the LCAs (see Supporting Information S1 for impact profiles of infrastructure of mariculture systems (SF1–4), and associated impact hotspots). One of the most important identified hotspots recurring across the cases was for transport-related diesel emissions. These account for a majority of the wild harvest cases' LCIs, so any gains in efficiency related to diesel consumption or alternative transport and harvest energy sources (e.g., low emission biofuels or electric alternatives, or reduction in transport distances) will appreciably improve environmental performance, especially the non-renewable CED and climate impacts. Transport-related diesel emissions, especially resulting from the use of boats during the harvest, were also relevant hotspots for the mariculture cases. This finding is in line with other studies of marine-based production, for example, Ziegler et al. (2016). It also suggests that small improvements to marine transport in the direction of reducing diesel emissions may result in large impact reductions, for example, more efficient engines, use of alternative fuels, faster harvesting, higher boat-load capacities, and selecting mariculture sites near shore. Other key impact hotspots for the mariculture cases relate to the use of steel components (e.g., steel anchors, rebar, and chains) and of polyethylene or polypropylene components (e.g., longlines/culture lines or other cultivation rig ropes), which together make up most of the infrastructural inputs by mass. These findings are also in line with similar LCAs in literature (e.g., Aubin et al., 2018; Seghetta et al., 2017; Thomas et al., 2020), and highlights that major gains in overall environmental performance could be made by tailoring mariculture infrastructure designs to the conditions and requirements of each site.

5 | DISCUSSION

The results of this study indicate that the four mariculture cases and three wild harvest cases all contribute to P loop closure by securing P for human consumption, while displaying relatively low climate and eutrophication-related emissions and CED. Though performance in terms of P uptake and the provision of biomass (dry or wet) is slightly lower for the mariculture cases on average, these should not be compared as they are fully human-induced activities that would not take place without human intervention. This also means that nutrient and carbon assimilated in biomass as a result of low-trophic mariculture can be accounted for as a form of impact mitigation. Though providing unique insights on the circular economy roles (contribution potential to phosphorus security) of these biomass mariculture/harvest activities, this study is subject to methodological uncertainties and limitations, which are discussed in detail in the Supporting Information S1 (Section SI3). Overcoming these challenges and enhancing the relevance of LCA to marine sustainability research questions will be key for industrial ecology to contribute to the imminent decade of ocean science for sustainable development. In the following section, the potential and usefulness of industrial ecology tools such as LCA to support ocean science for sustainable development are discussed (Section 5.1). This is followed by a discussion of the potential of marine biomass utilization to bridge marine–land loops in Swedish coastal regions, and key research gaps that should be addressed to catalyze the emergence of such activities (Section 5.2).

5.1 | LCA and industrial ecology in support of ocean science for sustainable development

A wide range of assumptions, methodological choices, and limitations affect the results of this study (elaborated in Supporting Information S1 – Section SI3), many of which provide key opportunities to build a stronger knowledge base for more reliable LCAs to be conducted in support of ocean-based sustainable development. Ocean science has been progressing at a rapid pace over the past few decades, and from it has emerged new environmental concerns for which new impact categories are needed. Examples could be related to the marine-specific degradation of materials that may contribute to nanoparticle and microplastic pollution (e.g., ropes, chains, buoys, anchors), underwater sound pollution (e.g., due to installing screw anchors in the sea floor), or associated with marine ecosystem services (e.g., habitat provision, oxygenation). Inherent to and coupled with the development of new impact categories, spatial integration of LCA methods will be needed to account for spatial aspects of waterborne emissions and assimilations that are typically more localized than atmospheric emissions and assimilations. There is a need to catalyze transdisciplinary efforts between ocean science and industrial ecology so that tools may serve—more reliably and effectively—to shed light on sustainability questions. This is most notable in the context of critical sustainability concerns such as climate change and ocean acidification that represent significant risks to blue sector and associated human welfare.

While such developments would add value to LCAs of marine production systems, opportunities to add robustness to LCAs also exist in smaller, more strategic tasks. The present LCA, for instance, would have benefited from availability of processes in the Ecoinvent database relating to the

use of vessels typically used in small–medium scale aquaculture, with deck loading limits ranging from 5 to 20 tons and operating with a range of different types of marine-grade fuels. Similarly, there is currently a lack of specific processes for commonly utilized materials in aquaculture, fisheries, or other blue-growth marine activities such as different types or thicknesses of marine-grade ropes and chains. Such small steps may go a long way to increase the reliability of findings, to strengthen comparability, and improve the relevance of ocean-based production LCAs.

From the complexity of marine ecosystem dynamics to single organism metabolic fluxes, much marine and/or coastal ecology and biology remain a mystery, is subject of debate or of ongoing research. A critical example affecting the methodology applied to cases 5–7, for instance, relates to whether or not to consider the growth of wild biomass as a direct result of human intervention (i.e., Baltic eutrophication), and thus how to account for carbon and nutrient assimilation and associated changes in emissions relative to “natural” baselines. Similarly, a lack of consensus in the literature can have an important effect on the certainty and generalizability of results. In carbon accounting studies of shellfish aquaculture, some studies include emissions of CO₂ equivalents owing to calcification (i.e., shell production) while others do not (Filgueira et al., 2019), resulting in very different conclusions. A recent study by Ray et al. (2018) highlights that CO₂ emissions resulting from calcification may increase emissions in cradle-to-gate studies by approximately 250%; in contrast, another recent study by Alonso et al. (2021) reports lower calcification emissions while also suggesting pathways for net negative carbon balances from cradle-to-grave, highlighting that much depends on the collection of shell waste and finding applications for these shells that ensures inertization of assimilated carbon for as long as possible (e.g., using shells in construction materials). Similarly, some practices common to present small-scale operations may have unintended consequences, both positive and negative. For instance, when beach-cast is piled up for temporary storage on a beach, anaerobic conditions inside the pile may result in methane emissions that would greatly affect the climate impact of beach-cast harvesting activities (Liu et al., 2019). Such unknowns and unidentified emissions can therefore be involuntarily overlooked by LCA practitioners, or may be intentionally excluded given the high degrees of uncertainty, as is the case in the present study. It will therefore also be important to continue the scrutiny of blue bioeconomy developments in parallel with the study of the complex dynamics of organism metabolisms and marine ecosystems, how these affect each other and how they are affected by human activity over prolonged time horizons, in view to inform—with a high degree of certainty—environmentally optimized supply chain practices.

In summary, industrial ecology tools such as LCA have an important role to play in shedding light on critical issues and in support of ocean science for sustainable development. There are literally vast oceans of issues and questions relating to the marine environment that need to be addressed, to protect and conserve biodiversity, to bring climate change and ocean acidification under control, and to sustain life as we know it on this planet. But it is also clear that this is a two-way street: not only will industrial ecology clearly have a role in the support of ocean science for sustainable development, but ocean science will also contribute to enhance the relevance and effectiveness of industrial ecology.

5.2 | Growing the blue bioeconomy to close nutrient loops

Recognized as a key part of the European bioeconomy strategy, a European “blue revolution” is now well underway, and it is hoped to trigger economic opportunity and sustainable growth that can contribute to revitalizing coastal regions, notably by developing the utilization of untapped marine resources, such as marine biomass (European Commission, 2012a). In Sweden, Europe, and indeed across the world, low-trophic marine biomass is already being harvested or cultivated, for many species at small scales. Given the results of this study, there is a need to map out these contributions to circular economies and their associated social and economic benefits, a need that is particularly urgent in the context of the twin looming climate and phosphorus crises. One particular challenge will be to explore how seasonality affects biomass composition and properties, and usage, something already explored in the context of cultivated kelp (e.g., Forbord et al., 2020) but lacking for other biomass such as reed. Studies should also focus on the role that blue growth could have for securing phosphorus (and thus food security) at national/regional scales in the context of scenarios for coming decades. Sinha et al. (2021) have produced a first attempt at such a study, setting the N and P loop closing potential of the same seven cases that are portrayed in the present study using element flow analysis. Follow-up LCAs with extended scopes (to include the whole system as depicted in Figure 1) will be needed to assess P uptake to biomass, reuse in products, and recovery at end-of-life (cradle-to-grave and cradle-to-cradle perspectives) to inform how P can most efficiently be used to reduce dependence on finite mineral P sources.

Of the seven biomass harvest cases, only the west coast mussel mariculture can be considered to be well established; most cases are either innovative blue-growth start-ups from a Swedish perspective and European perspective (e.g., kelp mariculture, ascidian mariculture, Baltic mussel mariculture, and Pacific oyster harvesting) or are driven by societal benefits such as having clean seafronts or improved water quality (beach-cast and reed harvesting). To catalyze the development of these young initiatives into sectors that can substantially contribute to phosphorus recovery and circular blue-green bioeconomies, a range of measures are needed. In the course of the interviews conducted to develop the LCIs of the seven low-trophic marine biomass utilization cases, stakeholders shared some preliminary ideas that might facilitate scaling for more widespread marine biomass utilization. Stakeholders noted, for instance, that the often case-specific and dynamic social and economic benefits associated with the harvest or mariculture of low-trophic biomass need to be better understood. Improved knowledge of such benefits may be crucial to create an enabling environment to unlock and catalyze the development of marine biomass activities, by providing a more solid basis for motivating governmental support to initiatives such as start-ups and small businesses for ecosystem services rendered. Stakeholders also often referred to the complex and often outdated policy and regulatory landscapes, which often hinder the development of marine biomass and of innovative uses, discouraging investors

from blue-growth-related enterprises. Efficient and targeted governance may support blue growth (Hishamunda et al., 2014; Stead, 2019), as exemplified by, for example, Norway, Canada, and the United Kingdom (BIM, 2020; Hishamunda et al., 2014; Walker, 2019). Lessons could be extracted from those cases to enhance a sustainable blue growth of marine biomass utilization in Sweden. The salience and relevance of these stakeholder insights are a stark reminder of the need to bridge the knowledge chasms between researchers, industry, policy makers, and the public as efforts are directed toward blue growth, both to enhance smooth development and to ensure that the benefits of these activities are reaped by humans and society (Costa-Pierce, 2010; Diana et al., 2013; Krause et al., 2015).

6 | CONCLUSIONS

The results of this study confirm that, when taking into account emissions from a cradle-to-gate life cycle perspective, the linear flows of nutrients and notably of finite P can be captured by low-trophic marine biomass and recirculated for use in human consumption systems, bridging the marine-land loop. Furthermore, the mariculture cases assimilate more nutrients (N and P) and carbon (C) from marine environments than are emitted (as PO₄-eqs. and CO₂-eqs.), thus resulting in net impact mitigations (in a short-term cradle-to-gate perspective) as indicated by nutrient and carbon ROI indicators. As raw materials for the bioeconomy, therefore, low-trophic marine biomass should be recognized as a renewable/circular source of P, whose harvest can reduce nutrient levels in marine environments (thus potentially mitigating local eutrophication) and from which low-carbon products could be made. The study also demonstrates the value of and points toward useful future developments of industrial ecology concepts and tools (LCA in particular) in support of a more sustainable development of circular blue-green bioeconomies.

ACKNOWLEDGMENTS

The authors would like to thank all the interviewees for their time and participation in this study. In particular, the authors would like to thank Fredrik Norén and Joakim Gillerblad for their thoughtful comments on the manuscript, and José Potting for her insightful support. The authors would also like to acknowledge the anonymous reviewers for their valuable feedback.

CONFLICT OF INTEREST

Fredrik Gröndahl is a co-founder of a seaweed production company, Koster Alg AB. All other authors declare no conflict of interest.

ORCID

Jean-Baptiste E. Thomas  <https://orcid.org/0000-0002-0354-7189>

NOTE

¹ "Tons," as used throughout this article, always refers to metric tons.

REFERENCES

- Alonso, A. A., Álvarez-Salgado, X. A., & Antelo, L. T. (2021). Assessing the impact of bivalve aquaculture on the carbon circular economy. *Journal of Cleaner Production*, 279, 123873. <https://doi.org/10.1016/j.jclepro.2020.123873>
- Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., & Egle, L. (2018). Environmental impacts of phosphorus recovery from municipal wastewater. *Resources, Conservation and Recycling*, 130, 127–139. <https://doi.org/10.1016/j.resconrec.2017.11.002>
- Andersen, J. H., Carstensen, J., Conley, D. J., Dromph, K., Fleming-Lehtinen, V., Gustafsson, B. G., Josefson, A. B., Norkko, A., Villnäs, A., & Murray, C. (2017). Long-term temporal and spatial trends in eutrophication status of the Baltic Sea. *Biological Reviews*, 92(1), 135–149. <https://doi.org/10.1111/brv.12221>
- Arlidge, W. N. S., Bull, J. W., Addison, P. F. E., Burgass, M. J., Gianuca, D., Gorham, T. M., Jacob, C., Shumway, N., Sinclair, S. P., Watson, J. E. M., Wilcox, C., & Milner-Gulland, E. J. (2018). A global mitigation hierarchy for nature conservation. *Bioscience*, 68(5), 336–347. <https://doi.org/10.1093/biosci/biy029>
- Aubin, J., Fontaine, C., Callier, M., & d'orbcastel, E. R. (2018). Blue mussel (*Mytilus edulis*) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication. *The International Journal of Life Cycle Assessment*, 23(5), 1030–1041. <https://doi.org/10.1007/s11367-017-1403-y>
- Bailey, J. (2020). [Personal communication about the carbon content of blue mussels cultivated on the east coast, January 13, 2020].
- Barquet, K., Järnberg, L., Rosemarin, A., & Macura, B. (2020). Identifying barriers and opportunities for a circular phosphorus economy in the Baltic Sea region. *Water Research*, 171, 115433. <https://doi.org/10.1016/j.watres.2019.115433>
- Bateman, A., van der Horst, D., Boardman, D., Kansal, A., & Carliell-Marquet, C. (2011). Closing the phosphorus loop in England: The spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. *Resources, Conservation and Recycling*, 55(12), 1146–1153. <https://doi.org/10.1016/j.resconrec.2011.07.004>
- Baumann, H., & Tillmann, A.-M. (2004). *The hitch hikers's guide to LCA: An orientation in life cycle assessment methodology and application*. Studentlitteratur.
- Bennett, E. M., Carpenter, S. R., & Caraco, N. F. (2001). Human impact on erodable phosphorus and eutrophication: A global perspective: Increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. *Bioscience*, 51(3), 227–234. https://doi.org/10.1641/0006/3568_2001_051/0227_HIOEPA/2.0.CO_2
- Bergentz, E. (2017). *Utilization of Ciona intestinalis as a feed ingredient - A screening LCA based on Marin Biogas AB small-scale cultivation*. (Environmental Engineering). Mittuniversitetet, Mid Sweden University,
- BIM. (2020). *Ireland's seafood development agency*. <https://www.bim.ie>

- Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, J., Rufino, M. C., & Stehfest, E. (2013). Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. *Proceedings of the National Academy of Sciences of the United States of America*, 110(52), 20882. <https://doi.org/10.1073/pnas.1012878108>
- Carrington, D. (2019). Phosphate fertiliser 'crisis' threatens world food supply. *The Guardian*. <https://www.theguardian.com/environment/2019/sep/06/phosphate-fertiliser-crisis-threatens-world-food-supply>
- Carstensen, J., Andersen, J. H., Gustafsson, B. G., & Conley, D. J. (2014). Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences of the United States of America*, 111(15), 5628–5633. <https://doi.org/10.1073/pnas.1323156111>
- Chubarenko, B., Woelfel, J., Hofmann, J., Aldag, S., Beldowski, J., Burlakovs, J., Garrels T., Gorbunova J., Guizani S., Kupczyk A., Kotwicki L., Domnin D., Gajewska M., Hogland W., Kolečka K., Nielsen J., & Schubert, H. (2021). Converting beach wrack into a resource as a challenge for the Baltic Sea (an overview). *Ocean & Coastal Management*, 200, 105413. <https://doi.org/10.1016/j.ocecoaman.2020.105413>
- Cieślak, B., & Konieczka, P. (2017). A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of “no solid waste generation” and analytical methods. *Journal of Cleaner Production*, 142, 1728–1740. <https://doi.org/10.1016/j.jclepro.2016.11.116>
- Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change*, 19(2), 292–305. <https://doi.org/10.1016/j.gloenvcha.2008.10.009>
- Cordell, D., & White, S. (2014). Life's bottleneck: Sustaining the world's phosphorus for a food secure future. *Annual Review of Environment and Resources*, 39(1), 161–188. <https://doi.org/10.1146/annurev-environ-010213-113300>
- Costa-Pierce, B. A. (2010). Sustainable ecological aquaculture systems: The need for a new social contract for aquaculture development. *Marine Technology Society Journal*, 44(3), 88–112. <https://doi.org/10.4031/MTSJ.44.3.3>
- Czajkowski, M., Ahtiainen, H., Artell, J., Budziński, W., Hasler, B., Hasselström, L., Meyerhoff, J., Nömmann, T., Semeniene, D., Söderqvist, T., Tuhkanen, H., Lankia, T., Vanags, A., Zandersen, M., Żylicz, T., & Hanley, N. (2015). Valuing the commons: An international study on the recreational benefits of the Baltic Sea. *Journal of Environmental Management*, 156, 209–217.
- Dessle, F. (2017). *Harvesting and utilizing beach cast on Gotland: A study of the benefits, challenges and opportunities of turning a waste into a resource*. (Independent thesis Advanced level (degree of Master (Two Years)) Student thesis). KTH The Royal Institute of Technology, Sweden. <https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-226527>
- Diana, J. S., Egna, H. S., Chopin, T., Peterson, M. S., Cao, L., Pomeroy, R., Verdegem M., Slack W. T., Bondad-Reantaso M. G., & Cabello, F. (2013). Responsible aquaculture in 2050: Valuing local conditions and human innovations will be key to success. *Bioscience*, 63(4), 255–262. <https://doi.org/10.1525/bio.2013.63.4.5>
- EASAC. (2016). *Marine sustainability in an age of changing oceans and seas*. Publications Office of the European Union:
- Ecoinvent Centre. (2016). Ecoinvent database (Version 3.2) [Cut-off system model]. Retrieved from Simapro Software version 7.3.
- Elser, J., & Bennett, E. (2011). A broken biogeochemical cycle. *Nature*, 478(7367), 29–31. <https://doi.org/10.1038/478029a>
- Emadodin, I., Reinsch, T., Rotter, A., Orlando-Bonaca, M., Taube, F., & Javidpour, J. (2020). A perspective on the potential of using marine organic fertilizers for the sustainable management of coastal ecosystem services. *Environmental Sustainability*, 3(1), 105–115. <https://doi.org/10.1007/s42398-020-00097-y>
- Emilsson, M., & Bailey, J. (2018). [Personal communication about mussel farming at the Sankt Anna farm in the Baltic Sea, November 21, 2018].
- European Commission. (2012a). *Blue growth opportunities for marine and maritime sustainable growth – Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions*. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52012DC0494&from=EN>
- European Commission. (2012b). *Innovating for sustainable growth: A bioeconomy for Europe – Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions*. https://ec.europa.eu/research/bioeconomy/pdf/201202_innovating_sustainable_growth_en.pdf
- Filgueira, R., Strohmeier, T., & Strand, Ø. (2019). Regulating services of bivalve molluscs in the context of the carbon cycle and implications for ecosystem valuation. In A. C. Smaal, J. G. Ferreira, J. Grant, J. K. Petersen, & Ø. Strand (Eds.), *Goods and services of marine bivalves* (pp. 231–251). Springer International Publishing.
- Forbord, S., Matsson, S., Brodahl, G. E., Bluhm, B. A., Broch, O. J., Handå, A., Metaxas, A., Skjermo, J., Steinhovden, K. B., & Olsen, Y. (2020). Latitudinal, seasonal and depth-dependent variation in growth, chemical composition and biofouling of cultivated *Saccharina latissima* (Phaeophyceae) along the Norwegian coast. *Journal of Applied Phycology*, 32, 2215–2232. <https://doi.org/10.1007/s10811-020-02038-y>
- Franzén, D., Infantes, E., & Gröndahl, F. (2019). Beach-cast as biofertiliser in the Baltic Sea region-potential limitations due to cadmium-content. *Ocean & Coastal Management*, 169, 20–26. <https://doi.org/10.1016/j.ocecoaman.2018.11.015>
- Frischknecht, R., Jungbluth, N., Althaus, H., Bauer, C., Doka, G., Dones, R., Hirschler R., Hellweg S., Humbert S., Köllner T., Loerincik Y., Margni M., & Köllner, T. (2007). *Implementation of life cycle impact assessment methods*.
- Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- GHK, & BioIS. (2006). *Costs and benefits of the ELV directive. Annex 5 – Environmental impacts analysed and characterisation factors*. <https://ec.europa.eu/environment/waste/elv/study.htm>
- Gillerblad, J. (2018). [Personal communication about the harvest of common reed in the Stockholm-Uppsala region, with the CEO of Sala Vassklipping AB, December 12, 2018].
- Granhed, A. (2018). [Personal communication about mussel farming on the Swedish west coast, November 30, 2018].
- Gren, I.-M., Lindahl, O., & Lindqvist, M. (2009). Values of mussel farming for combating eutrophication: An application to the Baltic Sea. *Ecological Engineering*, 35(5), 935–945. <https://doi.org/10.1016/j.ecoleng.2008.12.033>
- Gröndahl, F., Brandt, N., Karlsson, S., & Malmström, M. E. (2009). Sustainable use of Baltic Sea natural resources based on ecological engineering and biogas production. Paper presented at the Ecosystems and Sustainable Development VII-the Proceeding of the Seventh International Conference on Ecosystems and Sustainable Development (ECOSUD). <https://doi.org/10.2495/ECO090151>
- Gröndahl, F., Edlund, U., Welander, U., Pavia, H., Albers, E., & Undeland, I. (2013). *Seaweeds for a biobased society? Farming, biorefining and energy production (Seafarm). Project application to the Formas strategic call "a bio-based economy"*.

- Gruber, N., & Galloway, J. N. (2008). An Earth-system perspective of the global nitrogen cycle. *Nature*, 451(7176), 293–296. <https://doi.org/10.1038/nature06592>
- Guinée, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The International Journal of Life Cycle Assessment*, 7(5), 311–313.
- Hackl, R., Hansson, J., Norén, F., Stenberg, O., & Olshammar, M. (2018). Cultivating *Ciona intestinalis* to counteract marine eutrophication: Environmental assessment of a marine biomass based bioenergy and biofertilizer production system. *Renewable Energy*, 124, 103–113. <https://doi.org/10.1016/j.renene.2017.07.053>
- Hahlin, T. (2018). [Personal communication about the harvest of common reed using amphibious Truxor harvestors, November 15, 2018].
- Hansson, K., Ejhed, H., Widén-Nilsson, E., Johnsson, H., Brunell, J. T., Gustavsson, H., Hytteborn, J., & Åkerblom, S. (2019). *Näringsbelastningen på Östersjön och Västerhavet 2017: Sveriges underlag till HELCOM:s sjunde Pollution Load Compilation*. <https://urn.kb.se/resolve?urn=urn:nbn:se:havochvatten:diva-255>
- Hansson, P.-A., & Fredriksson, H. (2004). Use of summer harvested common reed (*Phragmites australis*) as nutrient source for organic crop production in Sweden. *Agriculture, Ecosystems & Environment*, 102(3), 365–375. <https://doi.org/10.1016/j.agee.2003.08.005>
- Hasselström, L., Thomas, J.-B. E., Nordström, J., Cervin, G., Nylund, G. M., Pavia, H., & Gröndahl, F. (2020). Socioeconomic prospects of a seaweed bioeconomy in Sweden. *Scientific Reports*, 10(1), 1610. <https://doi.org/10.1038/s41598-020-58389-6>
- Hedberg, N., Kautsky, N., Kumbal, L., & Wikström, S. (2018). Limitations of using blue mussel farms as a nutrient reduction measure in the Baltic Sea. *Report from Baltic Sea Centre*, 2, 2018.
- Hishamunda, N., Ridler, N., & Martone, E. (2014). Policy and governance in aquaculture: lessons learned and way forward. *FAO Fisheries and aquaculture technical paper*(577), 1. <http://www.fao.org/documents/card/en/c/a6c20b4f-7b92-5da6-b5f8-83bbde723eb6/>
- Hrůzová, K., Matsakas, L., Karnaouri, A., Norén, F., Rova, U., & Christakopoulos, P. (2020). Second-generation biofuel production from the marine filter feeder *Ciona intestinalis*. *ACS Sustainable Chemistry & Engineering*, 8(22), 8373–8380. <https://doi.org/10.1021/acssuschemeng.0c02417>
- ISO 14044. (2006). Environmental management - Life cycle assessment - Requirements and guidelines. ISO/TC 207/SC 5. *European Committee for Standardization*.
- Jordbruksverket. (2012). *Handlingsplan för utveckling av svenskt vattenbruk - Konkretisering av Strategi 2012–2020 (Action plan for the development of Swedish aquaculture - Concretization of Strategy 2012–2020)*. <https://webbutiken.jordbruksverket.se/sv/artiklar/ra151.html>
- Kamermand, P., & Capelle, J. J. (2019). Provisioning of mussel seed and its efficient use in culture. In A. C. Smaal, J. G. Ferreira, J. Grant, J. K. Petersen, & Ø. Strand (Eds.), *Goods and services of marine bivalves* (pp. 27–49). Springer International Publishing.
- Kellogg, M. L., Cornwell, J. C., Owens, M. S., & Paynter, K. T. (2013). Denitrification and nutrient assimilation on a restored oyster reef. *Marine Ecology Progress Series*, 480, 1–19.
- Kiessling, A., & Rustas, B.-O. (2020). Vass - framtidens nyttogröda. <https://www.slu.se/fakulteter/vh/forskning/forskningsprojekt/vilt-och-fisk/vass-framtidens-nyttogröda/>
- Kilén, M. (2019). *Aquaculture in Sweden in 2018. SCB statistiska meddelanden JO 60 SM 1901*. https://www.scb.se/contentassets/cef2fb103630496bb532e76c98f747e6/jo1201_2018a01_sm_jo60sm1901.pdf
- Köbbing, J. F., Thevs, N., & Zerbe, S. (2013). The utilisation of reed (*Phragmites australis*): A review. *Mires & Peat*, 13, 1–14.
- Kotta, J., Futter, M., Kaasik, A., Liversage, K., Rätsep, M., Barboza, F. R., Bergström, L., Bergström, P., Bobsien, I., Díaz, E., Herkül, K., Jonsson, P. R., Korpinen, S., Kraufvelin, P., Krost, P., Lindahl, O., Lindegård, M., Lyngsgaard, M. M., Mühl, M., Sandman, A. N., Orav-Kotta, H., Orlova, M., Skov, H., Rissanen, J., Šiaulyš, A., Vidakovic, A., & Virtanen, E. (2020). Cleaning up seas using blue growth initiatives: Mussel farming for eutrophication control in the Baltic Sea. *Science of The Total Environment*, 709, 136144. <https://doi.org/10.1016/j.scitotenv.2019.136144>
- Krause, G., Brugere, C., Diedrich, A., Ebeling, M. W., Ferse, S. C. A., Mikkelsen, E., Pérez Agúndez, J. A., Stead, S. M., Stybel, N., & Troell, M. (2015). A revolution without people? Closing the people–policy gap in aquaculture development. *Aquaculture*, 447, 44–55. <https://doi.org/10.1016/j.aquaculture.2015.02.009>
- Langlet, D., & Mahmoudi, S. (2016). *EU environmental law and policy*. Oxford University Press.
- Laugen, A. T., Hollander, J., Obst, M., & Strand, Å. (2015). 10. The pacific oyster (*Crassostrea gigas*) invasion in Scandinavian coastal waters: Impact on local ecosystem services. In J. Canning-Clode (Ed.), *Biological invasions in changing ecosystems* (pp. 230–252), Warsaw, Poland: De Gruyter Open Poland. <https://doi.org/10.1515/9783110438666-015>
- Limburg, K. E., Breitbart, D., Swaney, D. P., & Jacinto, G. (2020). Ocean deoxygenation: A primer. *One Earth*, 2(1), 24–29. <https://doi.org/10.1016/j.oneear.2020.01.001>
- Lindahl, O., Hart, R., Hernroth, B., Kollberg, S., Loo, L.-O., Olrog, L., Rehnstam-Holm, A. S., Svensson, J., Svensson, S., & Syversen, U. (2005). Improving marine water quality by mussel farming: A profitable solution for Swedish society. *AMBIO: A Journal of the Human Environment*, 34(2), 131–138. <https://doi.org/10.1579/0044-7447-34.2.131>
- Linnæus, C. (1755). 1745. Öländska och Gotländska Resa på rikens höglovliga ständers befallning förrättad år 1741. von Sydow, C. O. (red.) *Stockholm*. <https://lib.ugent.be/catalog/rug01:001667415>
- Liu, S., Trevathan-Tackett, S. M., Lewis Ewers, C. J., Ollivier, Q. R., Jiang, Z., Huang, X., & Macreadie, P. I. (2019). Beach-cast seagrass wrack contributes substantially to global greenhouse gas emissions. *Journal of Environmental Management*, 231, 329–335. <https://doi.org/10.1016/j.jenvman.2018.10.047>
- Macreadie, P. I., Trevathan-Tackett, S. M., Baldock, J. A., & Kelleway, J. J. (2017). Converting beach-cast seagrass wrack into biochar: A climate-friendly solution to a coastal problem. *Science of The Total Environment*, 574, 90–94. <https://doi.org/10.1016/j.scitotenv.2016.09.021>
- McCrackin, M. L., Muller-Karulis, B., Gustafsson, B. G., Howarth, R. W., Humborg, C., Svanbäck, A., & Swaney, D. P. (2018). A century of legacy phosphorus dynamics in a large drainage basin. *Global Biogeochemical Cycles*, 32(7), 1107–1122. <https://doi.org/10.1029/2018gb005914>
- Mihelcic, J. R., Fry, L. M., & Shaw, R. (2011). Global potential of phosphorus recovery from human urine and feces. *Chemosphere*, 84(6), 832–839. <https://doi.org/10.1016/j.chemosphere.2011.02.046>
- Mortensen, S., Strand, Å., Dolmer, P., Laugen, A. T., & Naustvoll, L. - J. (2019). *Høsting av stillehavssøsters*. Copenhagen: Nordisk Ministerråd. <http://norden.diva-portal.org/smash/record.jsf?pid=diva2%3A1375473&dsid=-2829>
- Murray, C. J., Müller-Karulis, B., Carstensen, J., Conley, D. J., Gustafsson, B. G., & Andersen, J. H. (2019). Past, present and future eutrophication status of the baltic sea. *Frontiers in Marine Science*, 6(2). <https://doi.org/10.3389/fmars.2019.00002>
- Nesme, T., Colomb, B., Hinsinger, P., & Watson, C. A. (2014). Soil phosphorus management in organic cropping systems: From current practices to avenues for a more efficient use of p resources. In S. Bellon & S. Penvern (Eds.), *Organic farming Prototype for sustainable agricultures* (pp. 23–45). Springer Netherlands.
- Norén, F. (2018). [Personal communication about ascidian mariculture on the Swedish west coast, October 4, 2018].

- Östberg, K., Hasselström, L., & Håkansson, C. (2012). Non-market valuation of the coastal environment – Uniting political aims, ecological and economic knowledge. *Journal of environmental management*, 110, 166–178. <https://doi.org/10.1016/j.jenvman.2012.06.012>
- Pechsiri, J. S., Thomas, J.-B. E., Risén, E., Ribeiro, M. S., Malmström, M. E., Nylund, G. M., Jansson, A., Welander, U., Pavia, H., & Gröndahl, F. (2016). Energy performance and greenhouse gas emissions of kelp cultivation for biogas and fertilizer recovery in Sweden. *Science of The Total Environment*, 573, 347–355. <https://doi.org/10.1016/j.scitotenv.2016.07.220>
- Petersen, J. K., Hasler, B., Timmermann, K., Nielsen, P., Tørring, D. B., Larsen, M. M., & Holmer, M. (2014). Mussels as a tool for mitigation of nutrients in the marine environment. *Marine Pollution Bulletin*, 82(1), 137–143. <https://doi.org/10.1016/j.marpolbul.2014.03.006>
- Petersen, J. K., Taylor, D., Bergström, P., Buer, A. - L., Darecki, M., Filippelli, R., Gren, I.-M., Hasler, B., Holbach, A., Nielsen, P., Petersen, L. K., Lindegarth, M., Lund, I., Maar, M., Ritzenhofen, L., Sagan, S., Saurel, C., Schernewski, G., Stybel, N., & Timmermann, K. (2020). *Policy guidelines for implementation of mussel cultivation as a mitigation measure for coastal eutrophication in the Western Baltic Sea*. DTU Aqua: <https://doi.org/10.11581/dtu:00000079>
- Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., & Wagener, T. (2016). Sensitivity analysis of environmental models: A systematic review with practical workflow. *Environmental Modelling & Software*, 79, 214–232. <https://doi.org/10.1016/j.envsoft.2016.02.008>
- Quilliam, R. S., van Niekerk, M. A., Chadwick, D. R., Cross, P., Hanley, N., Jones, D. L., Vinten, A. J., Willby, N., & Oliver, D. M. (2015). Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land? *Journal of Environmental Management*, 152, 210–217. <https://doi.org/10.1016/j.jenvman.2015.01.046>
- Ray, N. E., O'Meara, T., Williamson, T., Izursa, J. - L., & Kangas, P. C. (2018). Consideration of carbon dioxide release during shell production in LCA of bivalves. *The International Journal of Life Cycle Assessment*, 23(5), 1042–1048. <https://doi.org/10.1007/s11367-017-1394-8>
- Risén, E., Nordström, J., Malmström, M. E., & Gröndahl, F. (2017). Non-market values of algae beach-cast management – Study site Trelleborg, Sweden. *Ocean & Coastal Management*, 140, 59–67. <https://doi.org/10.1016/j.ocecoaman.2017.02.009>
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., & Foley, J. A. (2009). A safe operating space for humanity. *Nature*, 461, 472–475. <https://doi.org/10.1038/461472a>
- Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2015). The seasonal variation in the chemical composition of the kelp species *Laminaria digitata*, *Laminaria hyperborea*, *Saccharina latissima* and *Alaria esculenta*. *Journal of Applied Phycology*, 27(1), 363–373. <https://doi.org/10.1007/s10811-014-0327-1>
- Schoumans, O. F., Chardon, W. J., Bechmann, M. E., Gascuel-Oudou, C., Hofman, G., Kronvang, B., Rubæk, G. H., Ulén, B., & Dorioz, J. M. (2014). Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. *Science of The Total Environment*, 468–469, 1255–1266. <https://doi.org/10.1016/j.scitotenv.2013.08.061>
- Seghetta, M., Romeo, D., D'Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni, S., & Thomsen, M. (2017). Seaweed as innovative feedstock for energy and feed – Evaluating the impacts through a Life Cycle Assessment. *Journal of Cleaner Production*, 150, 1–15. <https://doi.org/10.1016/j.jclepro.2017.02.022>
- Seghetta, M., Tørring, D., Bruhn, A., & Thomsen, M. (2016). Bioextraction potential of seaweed in Denmark – An instrument for circular nutrient management. *Science of The Total Environment*, 563–564, 513–529. <https://doi.org/10.1016/j.scitotenv.2016.04.010>
- Sinha, R., Thomas, J.-B. E., Strand, Å., Söderqvist, T., Stadmark, J., Franzén, F., Ingmannson, I., Gröndahl, F., & Hasselström, L. (2021). Exploring plausible contributions to N and P loop closure in Sweden by harvesting and utilising marine biomass. Manuscript submitted for publication.
- SMED. (2016). *Overview of total nitrogen and phosphorus loads to marine environments*. Swedish Environmental Emissions Data. <https://tbv20.smhi.se/tbv/overview/>
- Smedberg, U. (2018). [Personal communication about beachcast harvest and utilisation in Gotland, December 3, 2018].
- Smil, V. (2000). Phosphorus in the environment: Natural flows and human interferences. *Annual Review of Energy and the Environment*, 25(1), 53–88. <https://doi.org/10.1146/annurev.energy.25.1.53>
- Söderqvist, T., Eggert, H., Olsson, B., & Soutukorva, Å. (2005). Economic valuation for sustainable development in the Swedish Coastal Zone. *Ambio*, 34(2), 169–175. <https://www.jstor.org/stable/4315577>
- Soetaert, K., Hoffmann, M., Meire, P., Starink, M., van Oevelen, D., Regenmortel, S. V., & Cox, T. (2004). Modeling growth and carbon allocation in two reed beds (*Phragmites australis*) in the Scheldt estuary. *Aquatic Botany*, 79(3), 211–234. <https://doi.org/10.1016/j.aquabot.2004.02.001>
- Soininen, N., Belinskij, A., Similä, J., & Kortet, R. (2019). Too important to fail? Evaluating legal adaptive capacity for increasing coastal and marine aquaculture production in EU-Finland. *Marine Policy*, 110, 103498. <https://doi.org/10.1016/j.marpol.2019.04.002>
- Spångberg, J., Jönsson, H., & Tidåker, P. (2013). Bringing nutrients from sea to land – Mussels as fertiliser from a life cycle perspective. *Journal of Cleaner Production*, 51, 234–244. <https://doi.org/10.1016/j.jclepro.2013.01.011>
- Spöndly, R. (2020). [Personal Communication on the biological potential of common reed (*Phragmites australis*) and plausible futures for the harvest of common reed in 2030 and 2050, April 23, 2020].
- Stadmark, J., & Conley, D. J. (2011). Mussel farming as a nutrient reduction measure in the Baltic Sea: Consideration of nutrient biogeochemical cycles. *Marine Pollution Bulletin*, 62(7), 1385–1388. <https://doi.org/10.1016/j.marpolbul.2011.05.001>
- Stead, S. M. (2019). Using systems thinking and open innovation to strengthen aquaculture policy for the United Nations Sustainable Development Goals. *Journal of Fish Biology*, 94(6), 837–844. <https://doi.org/10.1111/jfb.13970>
- Steen, I. (1998). Phosphorus availability in the 21st century: management of a non-renewable resource. *Phosphorus Potassium*, 217, 25–31.
- Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, 347(6223), 1259855. <https://doi.org/10.1126/science.1259855>
- Strand, Å. (2019). [Personal communication about the composition of blue mussels and pacific oysters sampled at the west coast, January 23, 2020].
- SwAM. (2015). *God Havsmiljö 2020. Marin strategi för Nordsjön och Östersjön. Del 4: Åtgärdsprogram för havsmiljön*. <https://www.havochvatten.se/download/18.45ea34fb151f3b238d8d1217/1452867739810/rapport-2015-30-atgardsprogram-for-havsmiljon.pdf>
- Thomas, J.-B. E., Ribeiro, M. S., Pottting, J., Cervin, G., Visch, W., Nylund, G. M., Olsson, J., Albers, E., Undeland, I., Pavia, H., & Gröndahl, F. (2020). A comparative environmental life cycle assessment of hatchery, cultivation and preservation of the kelp *Saccharina latissima*. *ICES Journal of Marine Science*, 78, 451–467. <https://doi.org/10.1093/icesjms/fsaa112>
- Trimmer, J. T., & Guest, J. S. (2018). Recirculation of human-derived nutrients from cities to agriculture across six continents. *Nature Sustainability*, 1(8), 427–435. <https://doi.org/10.1038/s41893-018-0118-9>

- Vaccari, D. A. (2009). Phosphorus: A looming crisis. *Scientific American*, 300(6), 54–59. <https://www.jstor.org/stable/26001380>
- Van Der Plasse, A. (2018). [Personal communication about the harvest of the invasive Pacific Oyster on the Swedish west coast, November 30, 2018].
- Verbyla, M. E., Oakley, S. M., & Mihelcic, J. R. (2013). Wastewater infrastructure for small cities in an urbanizing world: Integrating protection of human health and the environment with resource recovery and food security. *Environmental Science & Technology*, 47(8), 3598–3605. <https://doi.org/10.1021/es3050955>
- Walker, A. (2019). Prince Edward Island official vows to promote aquaculture industry. *Aquaculture North America*. <https://www.aquaculturenorthamerica.com/prince-edward-island-official-vows-to-promote-aquaculture-industry/>
- Wilhelmsson, S., Yngvesson, J., Jönsson, L., Gunnarsson, S., & Wallenbeck, A. (2019). Welfare Quality® assessment of a fast-growing and a slower-growing broiler hybrid, reared until 10 weeks and fed a low-protein, high-protein or mussel-meal diet. *Livestock Science*, 219, 71–79. <https://doi.org/10.1016/j.livsci.2018.11.010>
- Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Sibanda, L. M., Afshin, A., Chaudhary, A., Herrero, M., Augustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindhal, T., Singh, S., Cornell, S. E., Reddy, K. S., Narain, S., & Murray, C. J. L. (2019). Food in the Anthropocene: The EAT Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, 393(10170), 447–492. [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4)
- Withers, P. J. A. (2019). Closing the phosphorus cycle. *Nature Sustainability*, 2(11), 1001–1002. <https://doi.org/10.1038/s41893-019-0428-6>
- Wrange, A.-L., Valero, J., Harkestad, L. S., Strand, Ø., Lindegarth, S., Christensen, H. T., Dolmer P., Kristensen P. S., & Mortensen, S. (2010). Massive settlements of the Pacific oyster, *Crassostrea gigas*, in Scandinavia. *Biological Invasions*, 12(5), 1145–1152. <https://doi.org/10.1007/s10530-009-9535-z>
- Wu, J., Franzén, D., & Malmström, M. E. (2016). Anthropogenic phosphorus flows under different scenarios for the city of Stockholm, Sweden. *Science of The Total Environment*, 542, 1094–1105. <https://doi.org/10.1016/j.scitotenv.2015.09.024>
- Xiao, X., Agusti, S., Lin, F., Li, K., Pan, Y., Yu, Y., Zheng, Y., Wu, J., & Duarte, C. M. (2017). Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Scientific Reports*, 7, 46613. <https://doi.org/10.1038/srep46613>
- Zhou, Y., Yang, H., Liu, S., He, Y., & Zhang, F. (2002). Chemical composition and net organic production of cultivated and fouling organisms in Sishili Bay and their ecological effects. *Fisheries*, 26(1), 21–27.
- Ziegler, F., Hornborg, S., Green, B. S., Eigaard, O. R., Farmery, A. K., Hammar, L., Hartmann K., Molander S., Parker R. W. R., Hognes E. S., Vázquez-Rowe I., & Smith, A. D. M. (2016). Expanding the concept of sustainable seafood using Life Cycle Assessment. *Fish and Fisheries*, 17(4), 1073–1093. <https://doi.org/10.1111/faf.12159>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Thomas J-BE, Sinha R, Strand Å, et al. Marine biomass for a circular blue-green bioeconomy? A life cycle perspective on closing nitrogen and phosphorus land–marine loops. *J Ind Ecol*. 2021;1–18. <https://doi.org/10.1111/jiec.13177>