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Comparing the primary energy and phosphorus consumption of soybean and seaweed-based aquafeed proteins – A material and substance flow analysis

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ABSTRACT

This study compares the environmental performances of two protein sources for aquafeed production: Brazilian soy protein and Norwegian seaweed protein concentrates. The efficiency and sustainability of these two production systems are assessed using a comparative material and substance flow analysis accounting for the transfers of primary energy and phosphorus. The primary energy and phosphorus demand of 1 t of soy protein concentrate is compared to 2 t seaweed protein concentrate to assess commodities with similar protein contents. The primary energy consumption of the latter protein source (172,133 MJ) is found 11.68 times larger than for the soy-based concentrate (14,733 MJ). However, the seaweed protein energy requirement can be reduced to 34,010 MJ if secondary heat from a local waste incineration plant is used to dry the biomass during the late-spring harvest. The seaweed system outperformed the soy system regarding mineral phosphorus consumption since 1 t of soy protein requires 25.75 kg mineral phosphorus while 2 t of seaweed protein require as little as 0.008 kg input. These results indicate that substituting soy protein with seaweed protein in aquafeed leads to an environmental trade-off. The seaweed value chain produces proteins with near zero mineral phosphorus consumption by using naturally occurring marine phosphorus while the soy value-chain produces proteins for roughly 1/12th of the primary energy required by seaweed. Based on the current production technology, the seaweed value-chain will require extensive innovation and economies of scale to become energy competitive. Further research should investigate the predictive environmental impacts of a fully developed seaweed protein concentrate value-chain and account for the background emissions and multi-functionality in each system.

1. Introduction

Eradicating malnutrition and hunger is a critical task of the 21st century, and it is also the second target of the sustainable development goals adopted by the United Nations on September 25th, 2015 (United Nations, 2015). As the earth's population steadily marches towards 9 billion by 2050, the growing demand for fiber, food, and bio-energy, overflows earth's planetary boundaries (Steffen et al., 2015). Increase incomes in some of the most populated countries is expected to drive demand for protein-rich food, adding pressure on the biosphere (Wu et al., 2014). Erosion, deforestation and the extensive use of fertilizers in agriculture are leading to a steady decline of arable land (FAO, 2011), and significant disruptions of nitrogen and P cycles (Bouwman et al., 2009). This escalating discharge of nutrients from land to oceans leads to eutrophication of freshwater and marine ecosystems and depletes mineral Phosphorus (P) reserves (Cordell and White, 2011; Rabalais et al., 2009).

In Norway, intensive production of farmed salmon is facing multiple environmental challenges, including parasite and disease outbreaks, feed ingredient scarcity, nutrient discharge, and as a result, concerns about environmental impacts are strong (Cole

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Abbreviation

CPED	Cumulative Primary Energy Demand
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
SFA	Substance Flow Analysis
P	Phosphorus
SPC	Soy Protein Concentrate
SWPC	Seaweed Protein Concentrate

et al., 2009). Life Cycle Assessment (LCA) results show that salmon feed is driving the environmental impacts of salmon aquaculture (Hognes et al., 2014; Pelletier et al., 2009). Norwegian aquafeed manufacturers started substituting large percentage of fishmeal with Soy Protein Concentrate (SPC) extracted from *Glycine max* beans a little over a decade ago (Ytrestøyl et al., 2015). Today, 94% of the SPC used in Norway originate from Brazil (Lundeberg and Grønlund, 2017). The Brazilian soy industry is responsible for massive deforestation, ecosystem degradation, resource depletion and greenhouse gas emissions in one of the world's most biodiverse regions (Gibbs et al., 2015).

While environmental impacts associated to production are unavoidable, solutions exists to produce sustainable food using efficient and innovative supply-chains causing a minimum of environmental damages. Strategies suggested for mitigating climate change and reach sustainable food security are based on both supply and demand transformations. The supply-based strategy consists of reducing food waste and promoting the development of sustainable new food supply chains (Garnett, 2014). One such platform designed for optimized sustainability is the biorefinery, recently recognized by the Norwegian Research Council as a key transformation unit for promoting new feed and food value chains (The Research Council of Norway, 2013). Norway's extensive coastline, excellent mariculture conditions, and large-scale aquaculture industry provide an excellent starting point for macroalgae cultivation as a high-quality feedstock for new Norwegian biorefineries (Skjermo et al., 2014; Stévant et al., 2017).

Researchers are looking for sustainable alternatives to Brazilian SPC and seaweed is one of the alternative feedstock considered (Sørensen et al., 2011; Ytrestøyl et al., 2015). LCA research has already documented the environmental impacts of soy protein products (e.g., Dalgaard et al., 2008; Raucci et al., 2015) and Seaweed Protein Concentrate (SWPC) (Seghetta et al., 2016). However, these studies were performed separately. An in-depth, comparative environmental system analysis of these two value-chains is absent from the scientific literature.

The Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) methodology was successfully applied in various industrial sectors to measure crucial environmental efficiency indicators and to track critical substances in value-chains (Barles, 2009; Wang et al., 2016). It comprises studies tracking key nutrients in agriculture (Cooper and Carliell-Marquet, 2013) and aquaculture (Hamilton et al., 2015a) production systems. This study consequently applies the MFA/SFA methodology to compare the primary energy and P demand of SPC (derived from Brazilian *Glycine max*), and SWPC (extracted from Norwegian *Saccharina latissima*). This research aims to increase the understanding of the SPC and SWPC value chains, compare their environmental efficiencies across two key indicators (primary energy and P), and assess the potential of SWPC as an alternative aquafeed ingredient for the Norwegian aquaculture industry. Because our primary objective is to develop a deep comprehension of the flow dynamics of these two production systems, we purposely used the MFA/SFA methodology instead of a comparative LCA. This allows us to analyze in depth the processes of each foreground systems and focus on value-chain over product comparison. A comparative LCA will be performed under the PROMAC research project at a later stage to supplement this environmental assessment.

2. Methods

2.1. Material and substance flow analysis

MFA/SFA is an environmental accounting tool used to assess flows and stocks of material, energy, and substance in socio-economic systems. It uses the fundamental principle that neither matter nor energy can be created or destroyed in an isolated system. Their quantities remain constant in a system delimited by boundaries of space and time and follow the mass-balance principles (Brunner and Rechberger, 2003). In practice, the MFA/SFA involves consequential modeling of anthropogenic foreground systems and is particularly useful for improving resource management (Brunner, 2012). Primary modeling and flow calculations were performed in Microsoft Excel while secondary modeling was performed in eSankey.

2.2. The SPC and SWPC production systems

Both the SPC and SWPC systems integrate cradle-to-customer gate system boundaries. In the SPC system, the boundaries start with soybean cultivation in Brazilian farms and end upon delivery at the factory gates of Norwegian fish feed producers, before incorporation into compound aquafeed. The boundaries of the SWPC system start at a local seaweed farm located in Solund, on the west coast of Norway, and end with the delivery of SWPC to a Norwegian aquafeed producer. The processes of the SPC and SWPC systems were selected based on primary data sources, systems understanding, and modeling assumptions (Fig. 1).

2.3. Model construction

The life cycle inventory of Da Silva et al. (2010) was the primary data source used to model soybean cultivation in Brazil. The extraction of Brazilian soybeans into SPC was modeled after process data from the Agri-footprint LCA database used in Hognes et al. (2014). SPC manufacturers (Caramuru, Selecta, Imcopa) and aquafeed producers (EWOS, Biomar, Skretting) provided the logistics data necessary to model the import of SPC to Norway. Primary cultivation data (provided by the Dutch company Hortimare), was used to construct processes 1 to 3 in the seaweed system (Van Den Heuvel, F., Hortimare, Pers. Com., December 8th, 2016). Additional data describing the extraction of seaweed into SWPC was gathered from the life cycle inventory of Seghetta et al. (2016) and used to model biorefinery extraction. Finally, assumptions were made to build a transport scenario between the hypothetical SWPC biorefinery and a local aquafeed producer (additional data).

The production volume of the two systems were adjusted to reach protein equivalency. This adjustment ensures functional unit coherence and safeguards the comparative integrity of the system requirement needed to produce the desired output; protein. Protein equivalency was practically obtained by setting the functional unit of production at 1 t with 62% protein content for SPC (Hognes et al., 2014), and 2 t with 31% protein content for SWPC (Seghetta et al., 2016). Both functional unit contain 0.62 t of pure proteins. To respect the system's mass balance, each flow of primary energy has a corresponding outflow of energy emissions. Primary energy inflows and their corresponding emission outflows are equal.

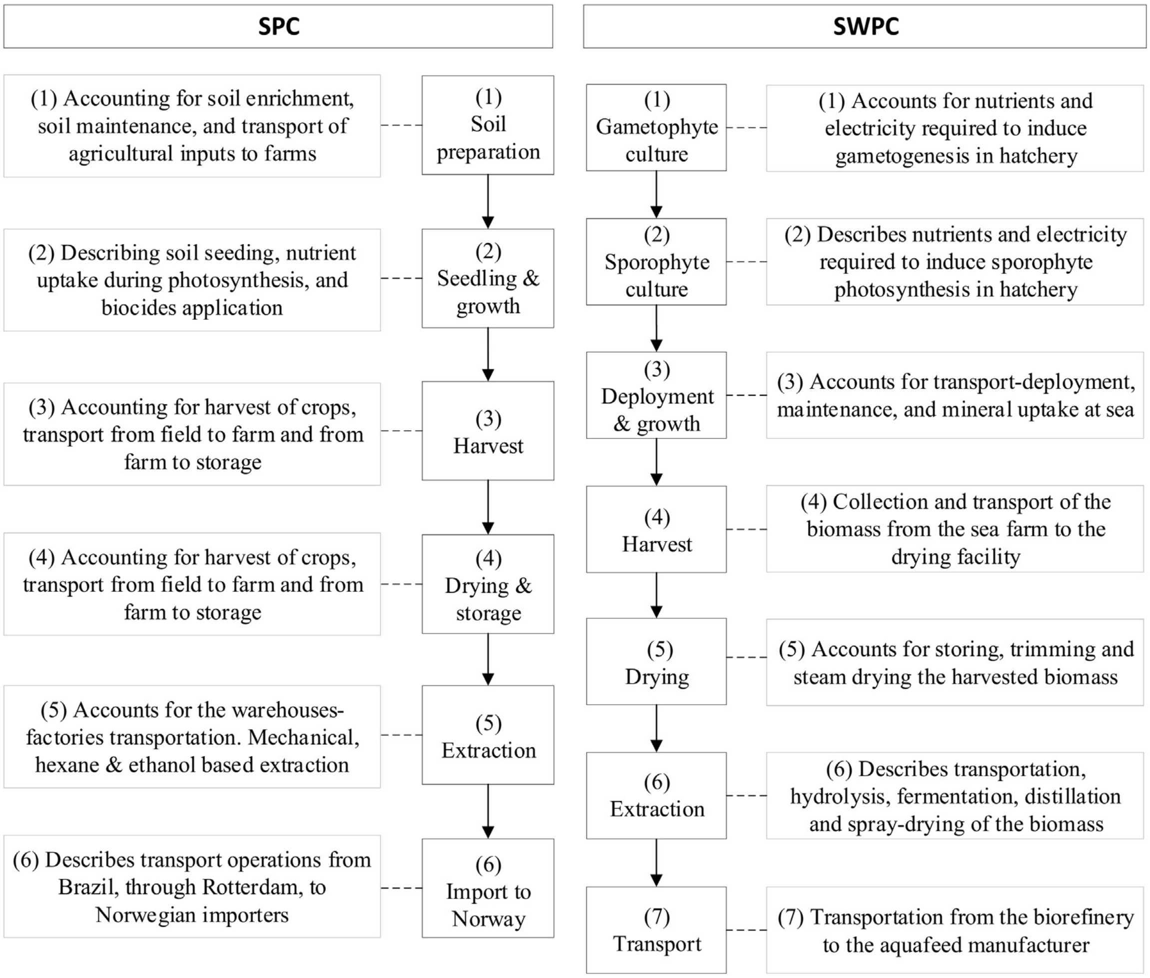

Fig. 1. Description of SPC and SWPC processes.

However, it should be noted that the energy is in different states. Energy emissions are either kinetic, chemical, or thermal. Tables 1 and 2 shows how the SPC and SWPC models were constructed by presenting each flow's mathematical formula and corresponding data sources. Energy emission flows formulas are not shown as they are identical to the primary energy inflows. The full list of assumptions made during modeling is available in the additional data.

3. Results

3.1. Current imports

In 2015, Norway imported 362,217 t of SPC from a resource base of 711,673 t of soybeans, generating 976,240 t of crop residues. For an average soybean yield of 2713 kg/ha (Da Silva et al., 2010), the 2015 SPC import to Norway required 1,970,247 ha of Brazilian land, corresponding to the occupation of 19,702 km^2 of arable land. This surface represent roughly ½ of the Netherlands. Norwegian SPC imports in 2015 required 5,336,705 GJ of energy, which is equivalent to 1.48 TWh of primary energy, mainly in the form of fossil fuels. The SPC production also required 86,626 t of mineral fertilizers, 154,675 t of manure, and 976,240 t of crop residues for soil enrichment. Mineral fertilizers are by far the most common P input to SPC production, totaling 3417 t of pure mineral P.

3.2. Primary energy comparative analysis

The Cumulative Primary Energy Demand (CPED), demonstrates significant differences between the two productions systems (Figs. 2 and 3). 1 t of SPC requires 14,733 MJ of primary energy while 2 t of SWPC requires 172,133 MJ of energy input. The SPC MFA/SFA model (Fig. 6) indicates that primary energy requirements concentrate around the extraction process (F0,5a; F0,5b) and the import to Norway (F0,6a; F0,6b; F0,6c), representing combined 71.99% of the system CPED (Fig. 2). For the SWPC system (Fig. 7), primary energy demand for drying the biomass eclipses all the other flows (F0,5a), representing alone 80.24% of the system CPED (Fig. 3).

The distribution of primary energy use based on the type of energy (fossil and non-fossil) shows that the SPC and the SWPC system have opposing energy profiles (Figs. 4 and 5). The SPC system relies mainly on energy from fossil origin while the SWPC value-chain requires mostly non-fossil electricity. For the SPC system, the ratio of fossil/non-fossil is 83/17%, while the corresponding ratio for the SWPC system is 9/92%.

3.3. Phosphorus comparative analysis

P inflows into the SPC system are dominated by mineral fertilizers (F0,1a) and crop residues (F0,1c) from the previous harvest (Fig. 6). Manure (F0,1c) provides only a marginal P input. Most of

Table 1
Flow description of the SPC system.

Flows	Equations & sources
Process 1 - Soil preparation	
F0,1a - [P] Mineral fertilizers	Mineral fertilizer P_2O_5 content PT1,3,5,6[a] × corresponding PT/region PR[a] × P_2O_5 P content[a]
F0,1b - [P] Manure	Manure P_2O_5 content PT2,4[a] × corresponding PT/region PR[a] × P_2O_5 P content[a]
F0,1c - [P] Crop residues	Leaves-stems-pods P_2O_5 uptake TP1,2,3,4,5,6[a] × corresponding PT/region PR[a] × P_2O_5 P content[a]
F0,1d - Diesel, maintenance	(Diesel ploughing & subsoiling PT1,2,5 + diesel tilling PT3,4,5 + diesel dethatching PT3,4,5 + diesel fertilizer application PT1,3,5,6 + diesel manure application PT2,4)[a] × corresponding PT/region PR[a]
F0,1e - Diesel, transport inputs	Load-distance ingredient PT1,2,3,4,5,6[a] × corresponding PT/region PR[a] × lorry diesel consumption[b]
F1,0a - [P] Drained by water	PO_4 to water PT1,2,3,4,5,6[a] × corresponding PT/region PR[a] × PO_4 P content[a]
F1,0b - [P] Fixation in soil	(P_2O_5 to soil PT1,2,3,4,5,6 − PO_4 to underground water)[a] × corresponding PT/region PR[a] × corresponding P_2O_5/PO_4 P content[a]
F1,2 - [P] Net primary production	P in leaves-stems-pods[a] + P in beans[a] − P in seeds[a]
Process 2 - Seedling & growth	
F0,2a - [P] Seeds	Seeds input PT1,2,3,4,5,6[a] × corresponding PT/region PR[a] × seed P content[a]
F0,2b - [P] Biocides	(Glyphosate input PT1,2,5 + methamidophos input PT1,2,3,4,5,6)[a] × corresponding PT/region PR[a] × corresponding glyphosate/methamidophos P content[a]
F0,2c - Diesel, seedling	Diesel seedling PT1,2,3,4,5,6[a] × corresponding PT/region PR[a]
F0,2d - Diesel, biocides	Diesel biocides applications PT1,2,3,4,5,6[a] × corresponding PT/region PR[a]
F2,0a - [P] Biocides dispersion	(Glyphosate input PT1,2,5 + methamidophos input PT1,2,3,4,5,6)[a] × corresponding PT/region PR[a] × corresponding glyphosate/methamidophos P content[a]
F2,3 - [P] Soy plants	P in leaves-stems-pods[a] + P in beans[a]
Process 3 - Harvest	
F0,3a - Diesel, harvesting	Diesel harvesting PT1,2,3,4,5,6[a] × corresponding PT/region PR[a]
F0,3b - Diesel, transport to farm	Diesel transport to farm PT1,2,3,4,5,6[a] × corresponding PT/region PR[a]
F0,3c - Diesel, transport to storage	Load-distance soybeans PT1,2,3,4,5,6[a] × corresponding PT/region PR[a] × lorry diesel consumption[b]
F3,0a - [P] Crop residues	Leaves-stems-pods P_2O_5 uptake TP1,2,3,4,5,6[a] × corresponding PT/region PR[a] × P_2O_5 P content[a]
F3,0b - [P] Seeds, next harvest	Seeds output PT1,2,3,4,5,6[a] × corresponding PT/region PR[a] × seed P content[a]
F3,4 - [P] Soybean, 18% water	(P_2O_5 uptake beans PT1,2,3,4,5,6 × corresponding PT/region PR × P_2O_5 P content)[a] − seeds P content[a]
Process 4 - Drying & storage	
F0,4 - Wood chips, drying	Woodchips energy for drying[a] + electricity energy cleaning & storage[a]
F4,0 - [P] Soybean, 13% water	P_2O_5 uptake beans PT1,2,3,4,5,6[a] × corresponding PT/region PR[a] × P_2O_5 P content[a]
Process 5 − Extraction	
F0,5a - Diesel, transport to factory	(Load-distance road × lorry diesel consumption)[c,b] + (load-distance railway × freight train diesel consumption)[c,d] + (load-distance waterway × barge freight diesel consumption)[c,d]
F0,5b - Energy, extraction	Diesel-energy input[c] + electricity-energy input[c] + natural gas-energy input[c]
F5,0a - [P] Soybean, hulls	Soybean hulls output[c] × soybean hulls P proportion[e]
F5,0b - [P] Soybean, crude oil	Soybean crude oil output[c] × soybean crude oil P proportion[f]
F5,0c - [P] Soybean, molasses	Soybean molasses output[c] × soybean molasses P proportion[g]
F5,6 - [P] SPC, 8% water	SPC output[c] × SPC P proportion[h]
Process 6 - Import to Norway	
F0,6a - Diesel, transport to port	((Load-distance road Sorriso to Porto de Santos/Porto de Imbituba[i,j] × corresponding port UR[i] × Caramuru MS) + (load-distance road Araucária to Porto de Paranaguá[k,j] × Imcopa MS) × lorry diesel consumption[b]) + (load-distance railway Araguari to Porto de Vitória[l,j] × Selecta MS × freight train diesel consumption[d])
F0,6b - Diesel, transport Rotterdam	((Load-distance shipping Porto de Santos/Porto de Imbituba to R[i,m] × corresponding port UR[i] × Caramuru MS) + (load-distance shipping Porto de Paranaguá to R[k,m] × Imcopa MS) + (load-distance shipping Porto de Vitória to R[l,m] × Selecta MS)) × freight shipping heavy fuel oil consumption[d]
F0,6c - Diesel, transport to Norway	((Load-distance shipping R to Myre/Karmøy[n,m] × corresponding factories UR[n] × Biomar MS[o]) + (load-distance shipping R to Florø/Halsa/Bergneset[p,m] × corresponding factories UR[p] × Ewos MS[o]) + (load-distance shipping R to Stavanger/Averøy/Stokmarknes[q,m] × corresponding factories UR[q] × Skretting MS[o])) × freight shipping diesel consumption[r]
F6,0d - [P] SPC, 8% water	SP output[c] × SPC P proportion[h]

Abbreviations: MS = Market Share; PT = Production Types; P = Phosphorus; PR = Production Ratios; R = Rotterdam; UR = Use Ratios.
Sources. [a](Da Silva et al., 2010), [b](Spielmann and Scholz, 2005), [c](Hognes et al., 2014), [d](Spielmann et al., 2007), [e](Barbosa et al., 2008), [f](Knoll and Life, 2007), [g](Hall et al., 2005), [h](Endres, 2001), [i](Caramuru, Pers. Com., November 15th, 2016), [j](Google Maps, 2016), [k](Imcopa, Pers. Com., November 14th, 2016), [l](Sugui, P.R., Selecta, Pers. Com., November 14th, 2016), [m](SeaRates, 2016), [n](Skansen, T., Biomar, Pers. Com., November 21st, 2016), [o](Rana et al., 2009), [p](Ewos, Pers. Com., November 22th, 2016), [q](Skretting, Pers. Com., November 21st, 2016), [r](Gabi Software, 2016).

the total P input is either captured by *Glycine max* or fixed in the soil (F0,1b). In the SWPC system, P flows are marginal until seaweed sporophytes begin to take up P from the marine environment (F0,3c). According to the assumptions and biorefinery extraction techniques of Seghetta et al. (2016), the P in the seaweed biomass is entirely transferred to the liquid fertilizer fraction. Consequently, 100% of the P input to the extraction process follows the liquid fertilizer fraction (F0,6d) while 0% ends up in the SWPC commodity (F6,7). The input analysis reveals that 30.4 kg of total P input is required to produce 1 t of SPC. In comparison, the total P input to SWPC is slightly lower, with a requirement of 25.05 kg for each 2 t SWPC produced. The classification of P input sources reveals significant differences (Figs. 8 and 9). 85% of the P input to the SPC system come in form of mineral P in fertilizer and 15% is captured from naturally occurring sources. The distribution is inverted in the SWPC system. Out of the total input, 99.97% and 0.03% come respectively from naturally occurring and mineral sources.

The SPC outflow analysis shows that each ton of SPC produced generate the emission of 15.46 kg (50.78%) of P to soil and water, while 14.99 kg (49.22%) is transferred to anthroposphere systems

Table 2
Flow description of the SWPC system.

Flow	Equations & sources
Process 1 - Gametophyte culture	
F0,1a - [P] Gametophyte, year −1	Gametophyte biomass inoculated[a,b,c] × *S. latissima* gametophyte P content
F0,1b - [P] Culture nutrients	F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration[d] × SW culture volume[c] × $NaH_2PO_4 \cdot 2H_2O$ P content
F0,1c - [P] Seawater	SW culture mass[c] × SW P content, July/August[e]
F0,1d - Electricity, hatchery	(White light power × HU × quantity)[c] + (red light power × HU × quantity)[c] + (air conditioning power × HU × quantity)[c] + (aeration pump power × HU × quantity)[c] + (autoclave power × HU × quantity)[c]
F1,0a - [P] Used enriched seawater	((SW culture mass × SW P content, July/August)[c,e] + (F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration × SW culture volume × $NaH_2PO_4 \cdot 2H_2O$ P content))[c,d] × gametophyte P non-uptake fraction
F1,0b - [P] Gametophyte, year +1	Gametophyte biomass inoculated[c] × *S. latissima* gametophyte P content
F1,0c - [P] Gametophyte, losses	NPP gametophyte biomass P content[c,d,e] × gametophyte loss ratio
F1,2 - [P] Gametophyte biomass	NPP gametophyte biomass P content[c,d,e] × gametophyte settlement ratio
Process 2 - Sporophyte culture	
F0,2a - Electricity, hatchery	(White light power × HU × quantity)[c] + (aeration pump power × HU × quantity)[c] + (UV treatment power × HU × quantity)[c] + (climatization power × HU × quantity)[c] + (filtration system power × HU × quantity)[c]
F0,2b - [P] Seawater	F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration[d] × SW tank volume[c] × $NaH_2PO_4 \cdot 2H_2O$ P content
F0,2c - [P] Culture nutrients	F/2 medium nutrient concentration[d] × SW tank volume[c] × nutrients inputs over time[c]
F2,0b - [P] Used enriched seawater	((SW tank mass × SW P content, September)[c,e] + (F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration × SW tank volume × $NaH_2PO_4 \cdot 2H_2O$ P content))[c,d] × sporophyte P non-uptake fraction
F2,3 - [P] Sporophyte biomass	Quantity of P in gametophyte biomass[c,c,f,g] + NPP sporophyte biomass P content[c,d,e]
Process 3 - Deployment & growth	
F0,3a - Fuels, transport to farm	(((Distance H–H × RM × FT diesel consumption)[c] + (distance H–F × RM × SB diesel consumption)[c] + (distance H–F × RM × MB petrol consumption)) × number of trips)[c] + (deployment distance × MB petrol consumption)[c]
F0,3b - Fuels, maintenance	((Distance H–H × RM × FT diesel consumption)[c] + ((distance H–F × RM) + maintenance distance) × MB petrol consumption)[c] × number of trips[c]
F0,3c - [P] Uptake, open seawater	Quantity of P in seaweed biomass[c,h,i,j] − quantity of P in sporophyte biomass[c,d,e,f,g]
F3,4 - [P] Seaweed biomass	Quantity of seaweed biomass[c] × *S. latissima* DM content[h] × *S. latissima* P content[j]
Process 4 - Harvest	
F0,4 - Fuels, transportation	Load-distance, pontoon deployment × RM × NabCat diesel consumption)[c,k] + ((distance H–H × RM × FT diesel consumption)[c] + ((distance H–F × RM + maneuvering distance) × MB petrol consumption)[c] + (harvest hours × generator diesel consumption)[c] + (load-distance F–H × RM × NabCat diesel consumption)[c,k] + (load-distance H-DF × RM × refrigerated lorry diesel consumption))[c,l] × harvest days
F4,5 - [P] Seaweed, 85% H_2O	Quantity of seaweed biomass[c] × *S. latissima* DM content[h] × *S. latissima* P content[j]
Process 5 - Drying	
F0,5a - Steam heat, drying	Convective dryer steam requirement[m] × quantity of seaweed biomass[c] × seaweed shrinkage ratio[h]
F0,5b - Electricity, drying facility	(Transverse slicer power × HU × quantity)[n] + (convective dryer power × HU × quantity)[m] + (climatization power × HU × quantity)[o]
F5,6 - [P] Seaweed, 20% H_2O	Quantity of seaweed, 85% H_2O[c] × *S. latissima* DM content[h] × *S. latissima* P content[j]
Process 6 - Extraction	
F0,6a - Diesel, transportation	Load-distance DF-BR × lorry diesel consumption[p]
F0,6b - Heat, extraction	Heat-energy hydrolysis & fermentation[h] + heat-energy distillation[h]
F0,6c - Electricity, extraction	Energy feedstock handling[h] + energy enzyme production[h] + energy storages & utilities[h]
F0,6d - [P] Liquid fertilizer	Seaweed, 20% H_2O P content[c,h,j] × liquid fertilizer P TC[h]
F6,7 - [P] SWPC	Seaweed, 20% H_2O P content[c,h,j] × SWPC P TC[h]
Process 7 - Transportation	
F0,7 - Diesel, transportation	(Load-distance BR-H × lorry diesel consumption)[p] + (load-distance H-FFF × ship diesel consumption)[q]
F7,0b - [P] SWPC	Seaweed, 20% H_2O P content[c,h,j] × SWPC P TC[h]

Abbreviation: SW = Sea Water; HU = Hours Used; NPP = Net Primary Production; H–H = Hatchery-Harbor; H–F = Harbor-Farm; RM = Roundtrip Multiplier; SB = "Snekke" Boat; MB = Maneuvering Boat; DM = Dry Matter; F–H = Farm-Harbor; H-DF = Harbor-Drying Facility; DF-BR = Drying Facility-BioRefinery; TC = Transfer Coefficient; BR-H = BioRefinery-Harbor; H-FFF = Harbor-Fish Feed Factory.

Sources. [a](Zhang et al., 2007), [b](Xu et al., 2009), [c](Van Den Heuvel, F., Hortimare, Pers. Com., December 8th, 2016), [d](Guillard and Ryther, 1962), [e](Moy et al., 2016), [f](Skjermo, J., Sintef, Pers. Com., December 16th, 2016), [g](Horntje, 2014), [h](Seghetta et al., 2016), [i](Vilg et al., 2015), [j](Manns et al., 2014), [k](Hansvik, T., Moen Marin, Pers. Com., December 22nd, 2016), [l](Keller, 2010), [m](Sandvik Process Systems, 2016), [n](FAM, 2016), [o](Kide, 2016), [p](Spielmann and Scholz, 2005), [q](Gabi Software, 2016), [r].

(Fig. 10). The largest contributors of P transfer to the anthroposphere are the crop residues (F0,3a) and the SPC fraction (F6,0d), while those generating the most substantial emissions to the environment are P fixation in soil (F1,0b) and P drained by water (F1,0a). For each 2 t produced in the SWPC system, 25.04 kg (99.97%) P is transferred to the anthroposphere while only 0.0071 kg (0.03%) is emitted to soil and water. The only significant outflow is the liquid fertilizer fraction (F6,0c) which transfers the phosphorus back to the anthroposphere (see Fig. 11).

4. Discussion

4.1. Implications of the primary energy consumptions

4.1.1. Energy sources and production

For similar crude protein content, producing Norwegian SWPC requires 11.68 times more primary energy than producing and importing Brazilian SPC to Norway. This considerable difference in CPED could prove to be a limitation for the SWPC commodity. Larger primary energy demand in a system often leads to greater

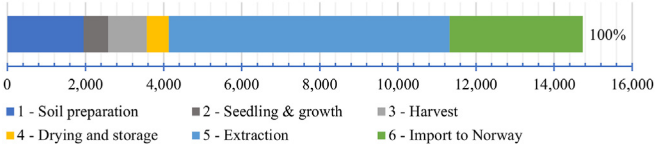

Fig. 2. Process CPED of the SPC system (MJ).

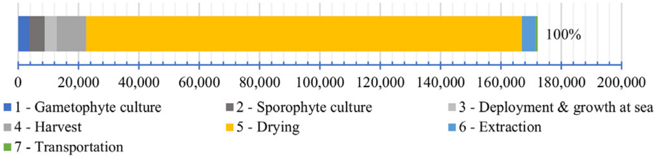

Fig. 3. Process CPED of the SWPC system (MJ).

global warming potential and higher production costs (Sorrell, 2015). It is critical to analyze the nature of the energy mix and energy production to measure the environmental impacts associated with primary energy use. With current technology, the fossil-fuel requirements of the SPC and SWPC systems are approximately equivalent (12,179 and 14,661 MJ respectively) and come in form of diesel, heavy oil, and natural gas. This means that similar environmental impacts can be expected from these inputs. However, the large quantity of electricity required for drying the seaweed biomass in Norway could generate relatively little environmental impacts. The Norwegian electricity mix can be supplied by nearly 100% renewable hydropower generating overall low environmental burden (Itten et al., 2012). The MFA/SFA methodology is not adapted to compare energy productions since it focuses on the foreground system. A comparative LCA could take this analysis further and investigate the sensitivity of each system to different energy mixes and their contributions to the overall environmental impacts.

4.1.2. Seaweed preservation

Seaweed is highly sensitive to microbial activity due to its high water content (85%) and must be preserved shortly after harvest. Drying is an efficient way to stabilize the biomass and is a conventional method to reduce weight during transportation (Keshani et al., 2010). Nevertheless, current drying methods available in Norway are energy intensive and remain a significant bottleneck for the SWPC system. On the other hand, these results demonstrate a massive system-wide improvement potential if the preservation step can be improved. For example, ensiling the macroalgae biomass is a promising alternative to drying. The ensiling process typically utilizes acids to lower the pH of a fodder crop below 5, either with or without a lactic acid bacterial inoculant (Herrmann et al., 2015). However, large-scale ensiling processes introduce food safety concerns and may lead to new infrastructure requirements to accommodate large volumes of raw material with much higher water content. The cost-benefit of replacing drying with fermentation will require a life cycle analysis to sort out the trade-offs between these two preservations methods.

Optimizing the drying process by utilizing the waste heat produced by Norwegian industry is another option. In this paper, a waste incineration heat and power plant is used as a case study. This facility located in Ålesund on the west coast of Norway and generates 22.5 GWh of surplus energy mainly during the summer months of June and July (Tafjord, K.A., Tafjord AS, Pers. Com., December 22nd, 2016). Macroalgae biomass is typically harvested in Norway between April and May. June overlaps slightly with harvesting times, but in most areas, it is late with respect to biofouling, which reduces the quality of the biomass (Stévant et al., 2017). One option is to harvest late and utilize the waste heat from waste incineration plants, sacrificing some quality for efficiency. If this option is applied, producing SWPC will then require 2.3 times more primary energy than producing SPC instead of the 11.68 original factor. An alternative scenario is to ensile the biomass during peak harvesting times and dry the fermented material when waste heat is primarily available.

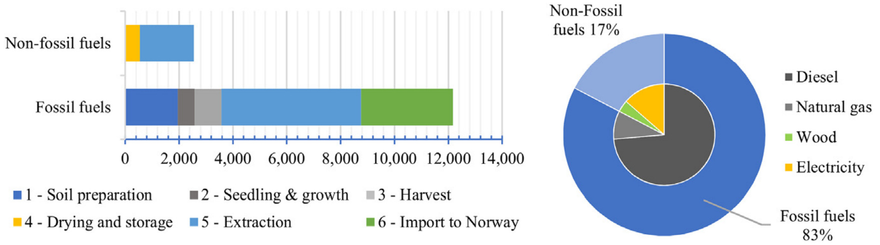

Fig. 4. Process CPED of the SPC system, displayed per energy types (MJ).

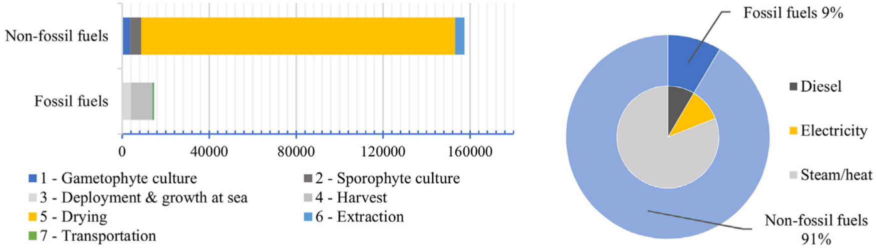

Fig. 5. Process CPED of the SWPC system, displayed per energy types (MJ).

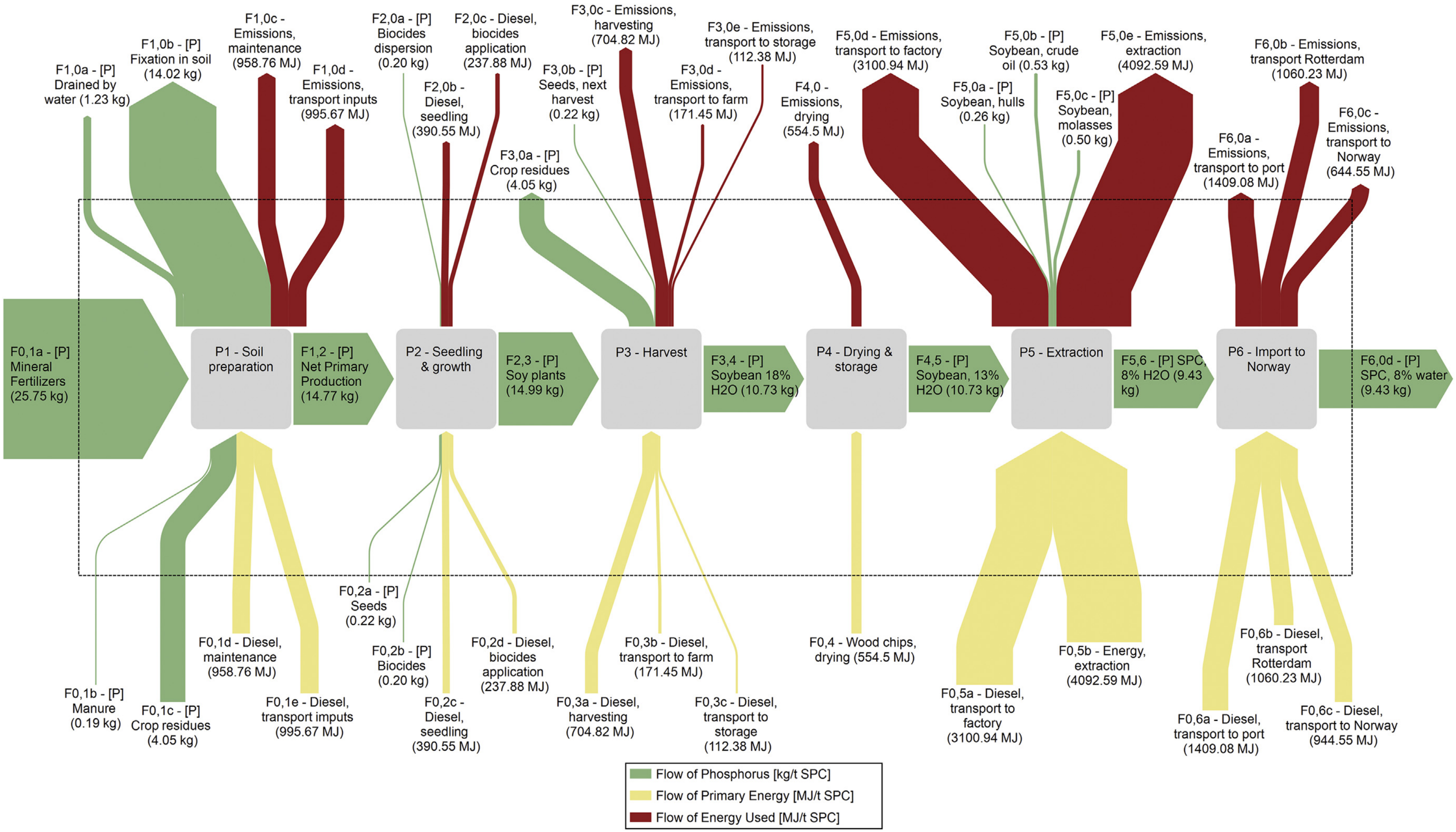

Fig. 6. MFA/SFA Sankey diagram of the SPC production system.

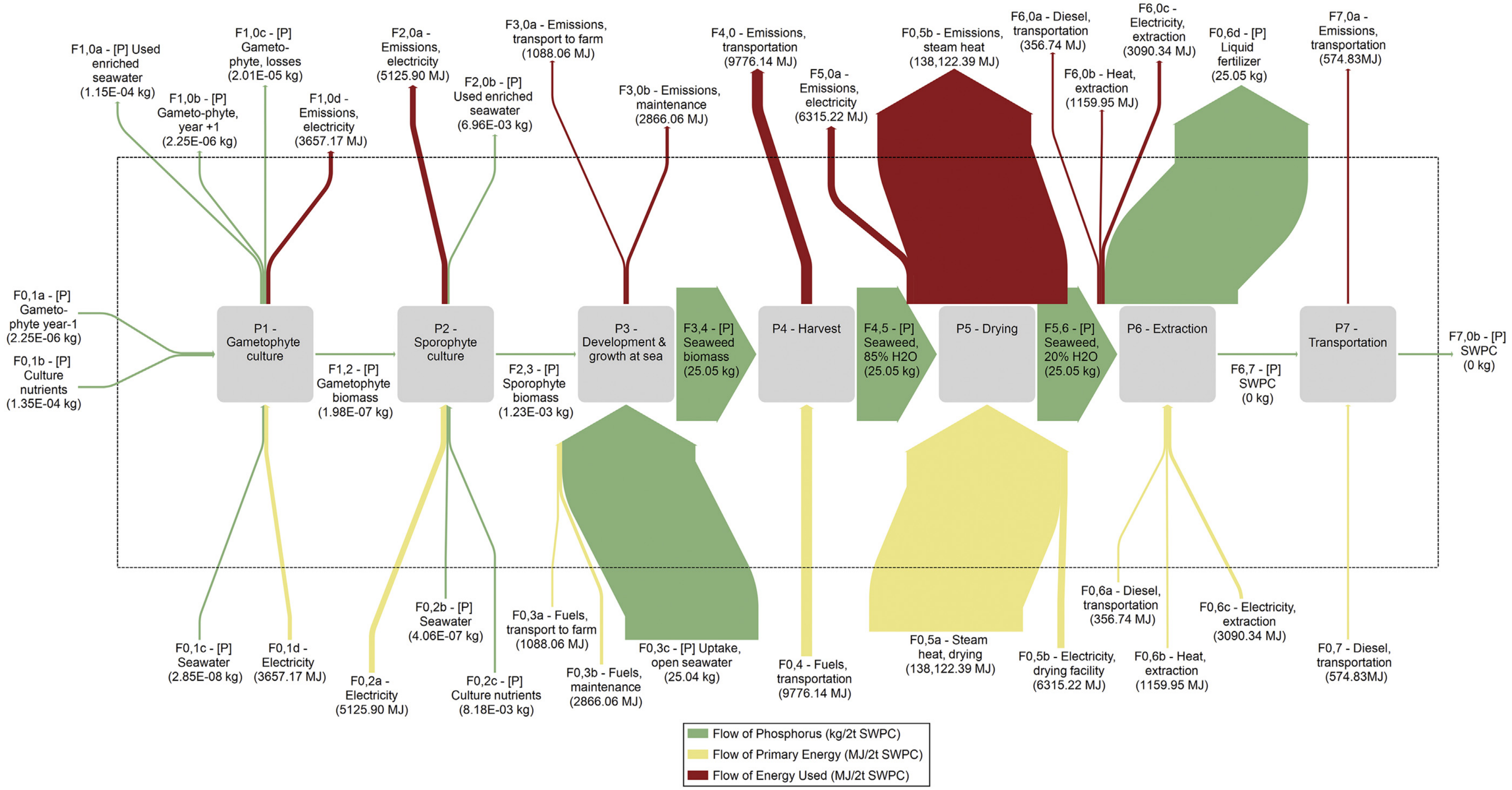

Fig. 7. MFA/SFA Sankey diagram of the SWPC production system.

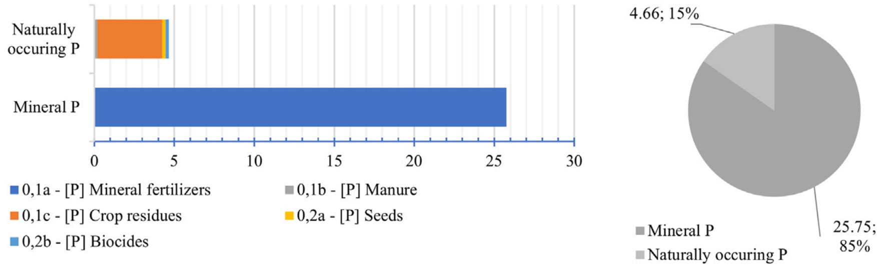

Fig. 8. Origin of the P flowing in the SPC system (kg).

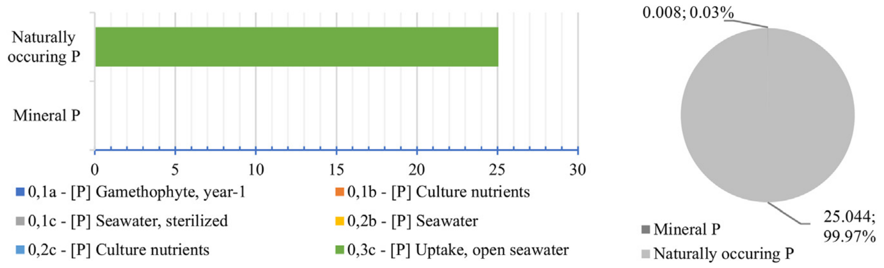

Fig. 9. Origin of the P flowing in the SWPC system (kg).

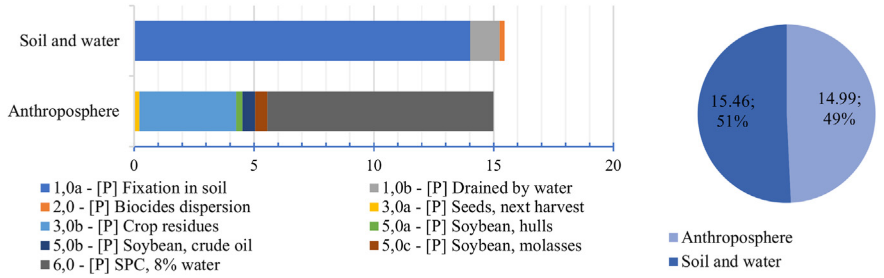

Fig. 10. Initial fate of phosphorus outflow in the SPC system (kg).

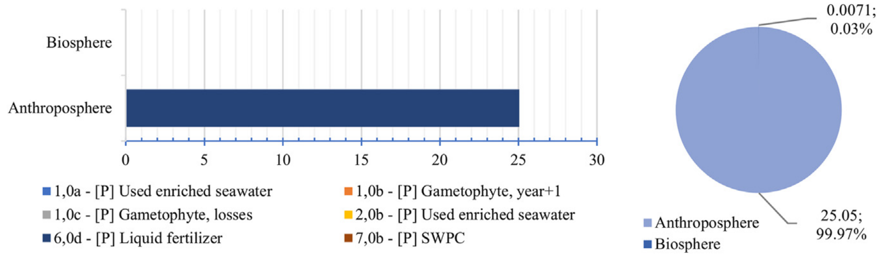

Fig. 11. Initial fate of phosphorus outflow in the SWPC system (kg).

4.1.3. Selection and domestication

A multitude of factors influences the primary energy demand of each system. In this study, maturity and scale had a real impact on the outcome results. The SPC value chain has been optimized over decades. Selective breeding of soy varieties increased protein content and yields (Koester et al., 2014). Over the last 20 years, the Brazilian government has created ideal conditions for improving the capacity of SPC production processes and supply chain organization (Goldsmith, 2008). The SWPC system does not benefit from a similar industrial maturity. The seaweed cultivation industry has only recently selected species for domestication, and is currently working on optimizing cultivation processes; transformation to feed and food products has yet to be developed at an industrial scale (Skjermo et al., 2014).

4.2. Implications of the phosphorus demand

4.2.1. Intensive agriculture

Brazilian soybeans are cultivated using intensive mono-agricultural methods. The inefficiency of the soil preparation process is one of the most significant P management issues in the SPC system. The MFA/SFA shows that 50.9% of the P applied for soil enrichment is not transferred to *Glycine max* in the year of harvest. Instead, this P is bound to soils (F1,0b) and partly drained by leaching, erosion, and surface run-off (F1,0a) (Fig. 6). Assuming continuity in cultivation methods, and stable production yields, this means that farmers are overloading soils with P year after year (Li et al., 2015). The high rainfall in these regions (De Freitas and Landers, 2014) provides the right conditions for transport of excess P from the fields to fresh and marine water bodies. For each ton of SPC produced, 84.68% of the P input comes directly from rock phosphate sources, primarily from China, the United-States, and the northern Sahara. Input of P through manure (F0,1b) is marginal, representing only 0.64% of the cumulative P input to process 1 (Fig. 6). All P sources are not equal. Mineral fertilizers are primary sources of P; they are non-renewable stocks that cannot be regenerated. Although high doses of mineral fertilizer increase crops yield, the over-concentration of P in agricultural soils is the single largest P loss occurring throughout the SPC system (Fig. 6). It is urgent to optimize soil enrichment processes and develop alternatives to intensive monocultures to mitigate this threat. Research shows that it is possible to recycle primary P sources through careful management of secondary P rich co-products and wastes (Hamilton et al., 2015b). Recent Brazilian research suggests that local secondary P sources could cover up to 20% of the P demand of the country by 2050 (Withers et al., 2018). This means that ambitious actions are needed at the policy level to incentivize the use of manure, crop residues, and a new generation of bio-fertilizers.

4.2.2. P management performances

The total P consumption of the SPC system is equal to 30.4 kg/t, whereas the SWPC system consumes 25.05 kg/2t. Comparing mineral P content, the SPC mineral P demand is 25.75 kg/t while the SWPC system's consumption drops to 0.0083 kg/2t. Furthermore, Seghetta et al. (2016) calculated a 95% substitution ratio for the seaweed fertilizer compared to mineral fertilizer. In other words, the 25.05 kg of P (F0,6c) embedded in the seaweed fertilizer fraction could theoretically substitute up to 23.8 kg of mineral P. Capturing P from the marine environment for growth, and recycling it back to the anthroposphere in the form of a liquid bio-fertilizer has clear advantages compared to relying on fossil P reserves from mining operations. The potential of recycling the P stocked in the oceans to the anthroposphere is one of the most important findings of this paper and deserves more attention. A fair comparison between ocean-based P and mineral P should include a full assessment of products and by-products of the two systems. Furthermore, Seghetta et al. (2016) assumes that 100% of the P follow the liquid fertilizer fraction. If confirmed, this means that SWPC would be deficient in P, a mineral required by salmons for optimal growth and naturally present in SPC (9.43 kg/t). In this scenario, fish farmers would have to add mineral P to compensate this deficiency. Analyzing the effect of different co-product environmental allocations and transfer ratios of P to the SWPC commodity are outside the scope of this study and should be addressed in future research.

4.3. Feasibility aspects

Cultivation area, available technology, and scale are other important considerations for assessing the feasibility of substituting SPC with ocean-based proteins. Replacing 10% of Norwegian SPC imports would require 72,443 t of SWPC, which corresponds to 1,362,436 t of *S. latissima* wet-weight. With current production technology and yields (60 t/ha), this would require approximately 227 km^2 dedicated to macroalgae cultivation, in addition to the hatchery facilities onshore. If we compare this number to the 1970 km^2 of land used for 10% of SPC production, SWPC requires only 11.5% of the equivalent land area at sea. Such cultivation efficiency could contribute to reducing the enormous pressure on terrestrial croplands (FAO, 2011) without occupying large areas in the marine space. Despite some potential environmental advantages, economic sustainability will be a key determinant of success for any innovative technologies, including the development of an SWPC industry in Norway. The small scale of production, high labor costs, and substantial primary energy demand are factors hindering SWPC from competing with SPC on price under current market conditions. If SWPC is to compete with SPC in the foreseeable future, the cost of production must be drastically reduced through process innovation and optimization.

4.4. Uncertainty and limitation

Mass-balance verification is used to measure the level of data coherence in the system. This verification show that the SPC model is balance consistent, except for the soil preparation process, which displays a deficit of -0.0438 kg of P. This imbalance represents 0.14% of the process inputs in absolute value and is well within the frame of inherent data uncertainty. The SWPC system is mass-balanced, indicating good data convergence.

MFA/SFA models are based on parameters from a wide variety of data sources. Each parameter contains uncertainty that adds up to an overall level of uncertainty in the final model. Evaluating uncertainty is critical to understanding the integrity of the system and results of system analysis. Ideally, a quantitative uncertainty analysis should have been performed in this study, but the extensive use of industry data with unknown uncertainty hampered this effort. However, inferences about model uncertainty can be made based on high impact flows. For instance, parameters such as the production methods, cultivation yields, and mineral fertilizer inputs are assumed to have a strong influence on the SPC system's results. Similarly, in the SWPC system, results are expected to be highly sensitive to cultivation yield, seaweed dry matter content, and biorefinery extraction ratios. In the SPC system, processes 1 to 4 were constructed with a high level of detail due to the good quality of Da Silva's dataset (Da Silva et al., 2010). Processes 5 and 6 include numerous assumptions and a broad diversity of data sources and are assumed to contain a higher degree of uncertainty. The SWPC system suffers from similar limitations. The youth of the seaweed industry is a challenge to the modeling. The whole cultivation process is based on the production of a single company. Although Hortimare is a leading actor in European macroalgae cultivation and uses industry-standard technology, this is perhaps the most significant limitation of this model.

Adjusting the two systems for protein equivalency is a controversial step and uncommon in MFA. A major limitation to the integrity of this technique is the quality of the protein. SPC from *Glycine max* is a highly digestible feed ingredient bred to limit anti-nutritional factors that could affect fish growth (Storebakken et al., 1998). SWPC has not been tested in fish nutrition, so very little can be said about the suitability of this protein, despite being equal to SPC in gross protein output once the systems are adjusted. Other important factors to consider is that 2 tons of 31% protein will mean that twice the amount of raw material will have to enter the feed mill. Unless the SWPC has a nutritional advantage over SPC, the added volume will create unwanted adjustments for manufacturer in logistics, storage, transport, and feed formulation to replace the ubiquitous SPC. Therefore, before one can truly begin to assess the viability of SWPC replacing SPC at the system's level, extensive studies must be performed to test the suitability of the raw material as a feed ingredient in finfish nutrition. Finally, biorefinery processes should focus on developing an SWPC product with similar protein content to SPC to lower the cost of adoption for feed producers.

5. Conclusion

This study is motivated by recent efforts highlighting the Norwegian aquaculture feed industry's reliance on imported agricultural commodities generating significant environmental impacts in other countries. Brazilian SPC is one of the most common protein-rich ingredients used in Norwegian compound feeds and is produced with high and inefficient use of fossil P fertilizers. With current technology, substituting SPC by SWPC is an environmental trade-off. Such a substitution would largely increase the primary energy consumption of protein-rich feed ingredients, but would likely reduce eutrophication, mineral P depletion, as well as land and freshwater use. P management efficiency in food and feed production systems is vital for current and future food security. It is also where lays the sustainable advantage of seaweed feedstock compared to land-based crops. This study was performed at an advantageous time to identify potential system enhancements in the emerging Norwegian macroalgae-based bioeconomy. The 11.68 times high primary energy of the SWPC system vs. the SPC system is mainly a result of the drying process required to remove water from the macroalgae biomass. In addition to the benefits of upscaling and optimizing the production, sizeable primary energy demand reduction can be achieved utilizing secondary energy and/or ensiling. Several potential drawbacks and unresolved issues impede the adoption of SWPC by the aquafeed industry. SPC is a well-established ingredient in animal nutrition and became over the years a standard ingredient in many aquafeed. SWPC is untested for nutritional suitability, digestibility, and palatability in animal nutrition and is currently only available at 31% protein concentration, about half of SPC's standard 62%. Further research is also required to analyze in-depth the allocation of each system's co-products. In this perspective, a comparative LCA would allow the influence of indirect and direct emissions on a broader range of environmental impacts to be included in the analysis. Such a study would be a natural extension of this work.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.07.247.

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