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Comparative MFA of protein rich aquafeed ingredients: can Norwegian seaweed dethrone Brazilian soybean?

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Preface

This thesis was written from October 2016 to February 2017 and concluded my master of science in Industrial Ecology. It was written at the department of Industrial Economics and Technology Management (IØT) at the Norwegian University of Science and Technology (NTNU).

The thesis was written in collaboration with the PROMAC research project led by Møreforsking Ålesund. PROMAC is a multidisciplinary research project financed by The Research Council of Norway under the BIONÆR program. This project answers the call for a more circular bioeconomy by investigating the potential to develop innovative food and feed commodities from Norwegian macroalgae.

Due to my academic background in food science, I consider reaching food sustainability one of the most interesting and challenging issues to address today. Joining PROMAC during my specialization project sparked my interest and develop my enthusiasm for the environmental assessment of food production systems. Working for PROMAC gave me the possibility to write this thesis for work package six, in charge of the project life cycle assessment, an opportunity for which I am grateful for.

First, I would like to sincerely thank my supervisors, professor Annik Magerholm Fet and Erik Olav Gracey for their excellent guidance and pertinent advices. Their support has been constant throughout the semester and this study would not exist without them. I would like to express my gratitude to Jon Halfdanarson. I had the chance to share Jon’s office during the last five months and he was always available for academic questions and training challenges. Thank you, Nina Benedicte Aubert, for your everyday patience, your capacity to recharge my motivation, and your efficient proof-reading. I am also grateful to Eivind Lekve Bjelle. His advices on scientific writing and report structure helped me improve this study. Finally, I would like to thank Vamilson Prudêncio da Silva, Freek van den Heuvel (Hortimare), and the PROMAC partners for their data and friendly advices.

Abstract

Improving sustainability in agriculture and aquaculture production systems is paramount to global food security and maintaining healthy, diverse ecosystems. One way to reduce pressure on terrestrial food production systems is looking towards the ocean for food production. With its extensive coastline and intensive salmon aquaculture, Norway is experimenting with macroalgae as a new feedstock for a circular bio-economy. The PROMAC research project was launched in 2015 to assess the Norwegian capacity to produce efficiently macroalgal food and feed commodities. This thesis is a part of the environmental analysis performed in PROMAC, and contributes by comparing the environmental performances of two similar aquafeed ingredients: Brazilian Soy Protein Concentrate (SPC) and Norwegian Seaweed Protein Concentrate (SWPC). The efficiency and sustainability of these two production systems is assessed using a comparative Material and Substance Flow Analysis accounting for the transfers of primary energy and phosphorus. While a life cycle assessment study is used to model the cultivation of soybeans in Brazil, cultivation data from a single Norwegian seaweed farm is the primary data input to the seaweed cultivation model. Both systems were modelled with sets of assumptions and generic datasets. To compare commodities with similar protein contents, the primary energy and phosphorus footprints of one ton of SPC is compared to two tons SWPC. The primary energy footprint of SWPC (172,133 MJ) is 11.68 times larger than for SPC (14,733 MJ). However, the SWPC footprint can be reduced to 34,010 MJ by utilizing secondary heat from a waste incineration plant during the late spring harvest. The SWPC system outperformed the SPC system in terms of fossil P footprinting, since one ton of SPC requires 25.75 kg fossil P while two tons of SWPC require as little as 0.008 kg fossil P input. Furthermore, results indicate that, while soybean co-products reduce SPC environmental impacts, SWPC co-product biofertilizers can replace the production of mineral fertilizers at a ratio of nearly 1:1 and reduces the SWPC fossil P -into negative values, -26.36 kg. The overall conclusion of this study is that SWPC holds a competitive advantage based on P management performances, however, replacing SPC will be difficult and require serious innovation and optimization to become energy competitive.

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Abbreviations

CED	Cumulative Energy Demand
CPED	Cumulative Primary Energy Demand
CW	Center West
dwt	Deadweight Tonnage
GHG	Greenhouse Gas
IMTA	Integrated Multi-Trophic Aquaculture
LCA	Life Cycle Assessment
MJ	Mega Joule
MFA	Material Flow Analysis
P	Phosphorus
PER	Production Efficiency Ratio
SO	Southern
SPC	Soy Protein Concentrate
SPI	Soy Protein Isolate
SWPC	Seaweed Protein Concentrate
tkm	Ton-Kilometer
WW	Wet Weight

1 Introduction

1.1 Background and motivation[1]

Eradicating malnutrition and hunger is one of the critical tasks of the 21st century. It is also the second target of the Sustainable Development Goals adopted by the United Nations on September 25th 2015 (United Nations, 2015b). Although the undernourished part of the world's population has been reduced from 23.3% in the 1990s to 12.9% today, it was estimated in 2015 that 795 million people are still suffering from malnutrition and hunger worldwide (FAO et al., 2015). Adding to this current challenge, the world's population is rapidly increasing. Global population reached 7.3 billion in 2015 and according to the UN medium projection variant, it will reach 9.7 billion in 2050 (United Nations et al., 2015). Accordingly, there is a solid consensus among the scientific community that climate change and population growth will increase pressure on natural resources, particularly on land, water, and food commodities (Alexandratos et al., 2011, Herrero, 2013).

The biosphere is under pressure and the growing demand for fiber, food and bio-energy, overflows earth's planetary boundaries (Steffen et al., 2015). In the agricultural sector, strategies suggested for mitigating climate change and reach sustainable food security are based on both supply and demand transformations (Smith et al., 2014). The supply-based strategy includes reducing food waste and promoting the development of sustainable new food supply chains. A demand-based strategy, however, aim to change consumption patterns and consumers diets (Garnett, 2014). We know that to provide sustainable sources of food for all, we must reach reasonable levels of consumption and develop the world's key food production systems (Herrero, 2013). A shift of diets would also have a substantial mitigation leverage and could address the intensification of the demand for nutrient dense food commodities such as meat and dairy (Westhoek et al., 2014). Since a greater consumption of protein is linked to large fresh water, Greenhouse Gas (GHG), and nutrient footprints, it is urgent that societies develop sustainable production systems and take ambitious climate mitigation actions (Wu et al., 2014). It is also critical that every person gets access to protein for growth and health. Yet, the unbalance between populations is dramatic: today 2 billion people are obese, while approximately one billion of the world's population has deficiency in proteins (United Nations, 2015a, Wu et al., 2014).

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[1] This section is based on the literature review "The place of seaweed and its industry in tomorrow's food and feed production systems" (Philis, 2016).

Today, the Agriculture Forestry and Other Land Use (AFOLU) sector contribute to one fourth of all anthropogenic GHGs emissions (Smith et al., 2014). In the same time, approximately a third of anthropogenic GHGs atmospheric emissions are captured and stored in the earth's oceans (Doney et al., 2009). The carbon buffering capacity of the ocean leads to an increase concentration of hydrogen and a reduction of carbonate ions resulting in ocean acidification (ibid.). Erosion, deforestation, and extensive use of mineral fertilizers from agriculture and aquaculture systems are leading to a steady decline of arable land and to significant disruptions of nitrogen and Phosphorus (P) cycles (FAO, 2011, Vitousek et al., 1997, Tirado and Allsopp, 2012). The flux of nutrients from land to oceans generated by these systems, have deleterious effects on the biosphere. The intensive use of P and nitrogen from fertilizers, are drained from agricultural lands and eutrophy estuaries and coastal areas (Huang et al., 2003, Rabalais et al., 2009, Hamilton et al., 2015a). Wastes from finfish and crustacean aquaculture are directly released in the oceans which amplified concentration of nutrients in coastal waters (Wang et al., 2012).

Among the bio-based industries, the fisheries and the aquaculture sector are dominating marine biomass production. Worldwide, these productions accounted for approximately 160 million tons in 2012, with an annual growth rate of 3.2%. Since the 1990s, the capture production stagnated, and many scenarios predict a decreasing production from fisheries because of overfishing issues (FAO, 2014). Aquaculture, on the other hand, is driving the growth. China is by far the main producer of farmed finfish, crustaceans, and molluscs, generating alone 61.7% of the world's production. Norway is the only European country in the top 15 aquaculture producers, with an annual production of 1.332 million tons in 2014 (FAO, 2014, SSB, 2015). In Norway, like in several other countries, the development of aquaculture is facing extensive challenges including parasites, diseases, nutrient depletion, and concerns about environmental impacts are strong. During the last decade, the industry replaced a significant fraction of fish meals by vegetable land based products. Consequently, the lack of EPA and DHA marine omega-3 fatty acids became a serious concern for aquaculture companies (Gracey, 2014, Sørensen et al., 2011).

Life Cycle Assessment (LCA) results show that fish feed is driving environmental impacts of farmed salmons (Pelletier et al., 2009, Skontorp et al., 2012). Today, one of the ingredients replacing fish meals in Norwegian salmon feed is particularly raising concerns: the SPC. This product, extracted from *Glycine max* beans, is by far the largest protein source employed by the Norwegian aquaculture industry (Ytrestøyl et al., 2015). In 2013, Norway imported approximately 360,000 t of SPC to feed salmonids, from which approximately 80% originated from Brazil (Lindahl, 2014). This situation is problematic for Norway and its aquaculture industry, since intensive soybean cultivation in Brazil is directly associated to deforestation, ecosystem degradation, resource depletion and significant GHGs emissions (WWF, 2014, Raucci et al., 2015).

The structural linearity of the world's economy is certainly accountable for these environmental challenges. Because the world's industrial production systems use the environment as a waste reservoir, efficiency and circularity are neglected by design (Pearce and Turner, 1990). However, due to raising concerns and increasing consequences, the concept of circular economy is emerging in Europe and China. This concept is based on a simple but brilliant idea: how could industrial systems behave more like ecosystems? (Frosch and Gallopoulos, 1989). China is looking in this direction to address resource scarcity and growing environmental degradation, and in December 2015, the European Commission published an ambitious circular economy strategy (Geng et al., 2009, European Commission, 2016). Innovation is a key element to achieve the shift from a linear to a circular economy by enabling the emergence of new business models, technologies, processes, and value chains. Because some aspects of the economy are driven by consumption, the choices made every day by consumers have the potential to transform the economy.

Europe's strategy for the bioeconomy development answers many of the 2020 Strategic Development Goals. The term bioeconomy refers to a segment of industries using inputs from renewable living resources such as plants, animals, and micro-organisms to produce goods and services. By using renewable biological products, bio-based industries can meet many sustainability requirements along with solid social and economic perspectives (McCormick and Kautto, 2013). Under programs such as "A Resource Efficient Europe" and "Innovative Union", the emergence of a strong bioeconomy in Europe will be the key element for green and smart growth (European Commission, 2012). The European Commission identify sustainable practices in food production to be a societal challenge, and consider marine and bio-based industries as the key components for the solution (European Commission, 2014a). Among other commodities and services, bio-based industries could provide sustainable sources of food, fiber, water and energy (OECD, 2009). They are characterized as products with high innovative potential, particularly within a circular economy perspective (European Commission, 2015). Research and innovation applied on biomass and bio-based products are already happening and many projects are financed under Horizon 2020 (European Commission, 2014a).

The growing attention to seaweeds is a welcomed development. In the last decades, macroalgae products have started to appear in Europe. The western consumer, driven by underlying trends of healthy food and environmentalism, start to consider macroalgae as a sustainable food with potential health benefits (Chapman et al., 2015, Mouritsen et al., 2013). The macro biochemical composition of macroalgae shows a high water and mineral content, an important concentration of polysaccharides, and significant proteins and amino-acids proportions. In a context where energy intensive food products bring environmental and health concerns, brown, green, and red algae could be part of a remedy. Seaweeds are low in calories and lipids, but rich in fibers and minerals. Quantitative and qualitative analysis reveals that the protein content of brown seaweed such as *Saccharina latissima* and *Alaria esculenta* range from 3% to 15% of the dry weight and contains six out of nine essential amino acids (Harnedy and FitzGerald, 2011).

Adding to these benefits, seaweed applications are vast and promising. This biomass can be used wet or dried, raw or transformed, for human consumption or animal feed, holds potential for biofuel production, and could be an effective feedstock for biorefineries (Wei et al., 2013, Mazarrasa et al., 2014, Skjermo et al., 2014). The increasing pressure on land, water, and fertilizers, is driving the interest for seaweed to feed domestic animals. Indeed, the carbon, nitrogen, and P biosphere disequilibrium gives seaweed a competitive advantage compared to land based crops. Macroalgae are fast growing plants without land or freshwater footprints (Skjermo et al., 2014). These species belong to the lowest marine trophic level, meaning that they can grow solely by using the basic nutrients found in seawater and the energy from the sun. Because these plants use carbon, P, and nitrogen to build molecules, and sunlight is harvested through photosynthesis, cultivation and growth of macroalgae on coastal areas has a significant bioremediation potential. Such characteristics imply that seaweed can be cultivated with a minimum maintenance and without use of pesticides and fertilizers (ibid.).

In Norway, the growing interest to develop a strong and innovating Norwegian bioeconomy is meeting the need to improve the sustainability of salmon farming. Researchers and authorities identified bioindustries as one of the cornerstone to improve aquaculture sustainability and develop new food and feed value chains based on biorefineries (The Research Council of Norway, n.d.). The characteristics of seaweed coupled to Norway's extensive coastline and excellent mariculture conditions, demonstrate that seaweed could be an excellent feedstock for new Norwegian biorefineries (Skjermo et al., 2014). Today, several research projects are developing industrial cultivation methods (Forskningsrådet, 2016) and bio-extraction processes to generate innovative food and feed commodities from the seaweed biomass (Møreforsking, 2015).

1.2 Goal and scope

Because of the significant impacts of SPC imports from the Norwegian aquaculture industry, researchers are looking for alternative protein rich ingredients (Sørensen et al., 2011). One of the PROMAC project objectives is to determine if a SWPC commodity could be produced from Norwegian seaweed biomass, and if this production would be sustainable (Møreforsking, 2015). To evaluate the feasibility and the environmental performances of commodities and value chains develop under this project, one of the work packages is performing an LCA. This thesis is taking part to this research and intend to facilitate this environmental analysis.

An essential task of environmental assessment studies is to ensure that new processes and new commodities developed have improved environmental performances compared to the one produced before. Based on this idea, this thesis intends to compare two aquafeed ingredients: the imported Brazilian SPC and the Norwegian SWPC. Through an environmental product comparison, this study aim to increase the understanding of the SPC and SWPC value chains and to compare their respective efficiencies. Such a comparison is performed using the Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) tools. Like LCA, this method is adapted for environmental product comparisons and because it enables a systematic modelling of each foreground system, it increases the knowledge and the understanding of supply chains studied. Through calculation and analysis of biomass, primary energy and P flows, this study means to compare the environmental efficiencies of the two production systems. Primary energy footprint and biomass transfers are essential efficiencies indicators. The MFA models are mapping these two types of flows. To complete the analysis, SFA layers track the P embedded in the MFA biomass flows. Transfers of P show how each production system manage this limited nutrient and highlight the eutrophication potential of these two value chains.

To reach the goals of such environmental assessment, the following research questions were formulated:

1. What are the main differences and similarities between the SPC and SWPC production systems?
2. How large is the primary energy footprint of SWPC compare to the SPC one today? What are the implications for the SWPC and SPC value chains?

3. How is the phosphorus resource managed in the SPC and SWPC production systems? Is there one of the systems handling phosphorus more efficiently than the other?

1.3 Thesis structure

This report is divided in six sections, section one being the present introduction. The second section consists of a literature review analysing which environmental assessment have been performed on the SPC and SWPC value chains. This review specifically investigates the energy consumption and the P emissions reported for these two production systems in the scientific literature. The third section presents the methods used to perform this environmental analysis. The MFA/SFA tool is presented as well as the main data sources used to construct the models. Furthermore, the most significant assumptions are listed and described, and a thorough explanation of the processes, flows, equations, and sources is given. Table 3.4 gather the flows and the equations used to build the SPC system, while Table 3.5 shows the flows and equations used in the SWPC system.

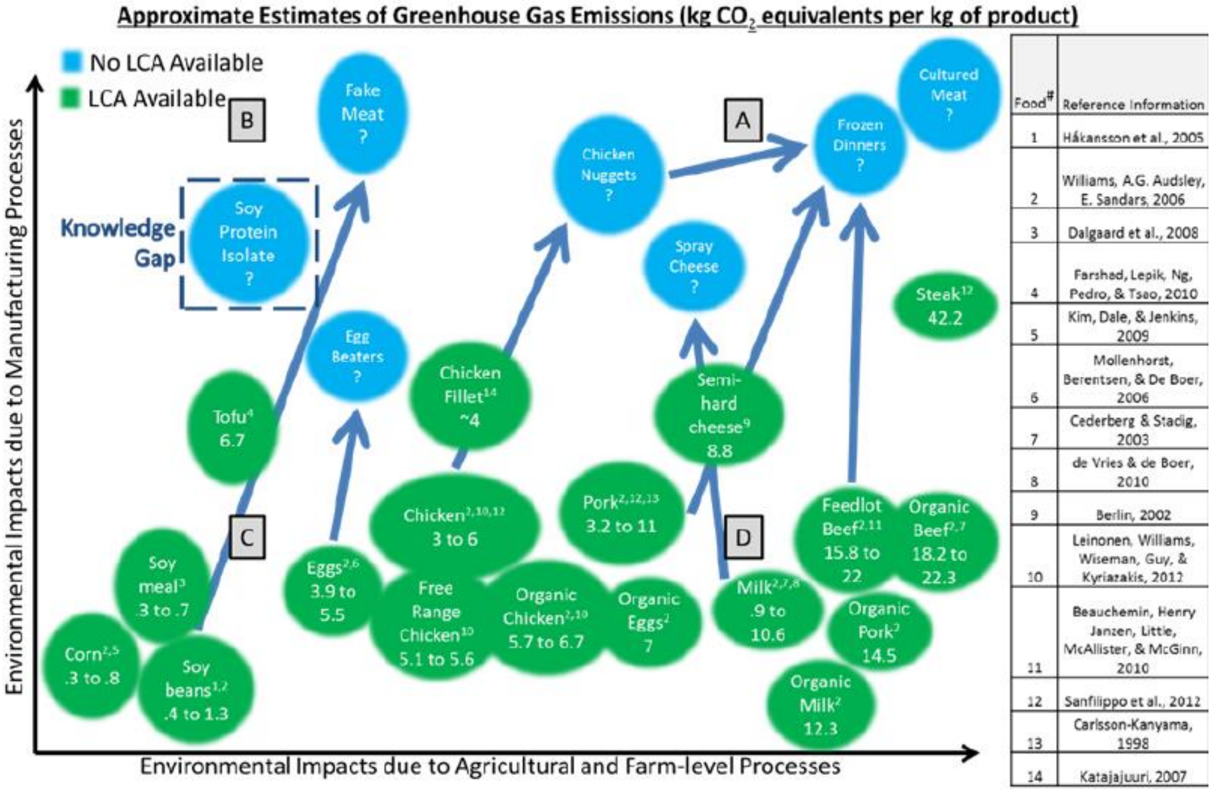
In section four, the results are compiled. This section is divided in three sub-sections. Sub-section one and two gather the results of the soy MFA/SFA base models and includes figures of these four models constructed to perform this analysis. The soy MFA/SFA base models are represented by Figure 4.3 and Figure 4.4 while the seaweed MFA/SFA based models are shown in Figure 4.9 and Figure 4.10. In sub-section three, one MFA/SFA scenario of each system are presented for comparison and the corresponding MFA/SFA figures are presented in Appendix A to Appendix C. Section five is the discussion of the report. In the first part, implications of the results and feasibility are discussed while the second part focuses on the models limitations and uncertainties. Section six is concluding this study by presenting the main findings connected to the research questions and by suggesting further research on this thesis topic.

2 Literature review

This section reviews environmental assessment performed on the SPC and SWPC value chains. It does not intend to provide a complete overview of environmental studies performed on each production system, but to highlight results relevant for this report. Since the author did not find environmental assessment using the MFA/SFA methodology on either system, a review of LCA studies was performed. However, a thorough examination of the literature showed that none of the LCA reviewed had a scope completely identical to this thesis. This is a significant review limitation. In addition, since this study is specifically accounting for primary energy demand and examine P transfers, it was estimated consistent to focus on the energy use and the freshwater eutrophication impact categories. Due to the mismatch of scope and methods, most of the LCAs performed on the SPC value chain (Rocha et al., 2014, Raucci et al., 2015, Dalgaard et al., 2008) and on the SWPC value chain (Taelman et al., 2015a, Aitken et al., 2014) were excluded from the review.

2.1 SPC

The lack of environmental studies specifically measuring the environmental impacts of Brazilian SPC is a knowledge gap that should be addressed. As Figure 2.1 below shows, this data deficiency was already pointed out by Berardy in 2015.



Food#	Reference Information
1	Håkansson et al., 2005
2	Williams, A.G. Audsley, E. Sandars, 2006
3	Dalgaard et al., 2008
4	Farshad, Lepik, Ng, Pedro, & Tsao, 2010
5	Kim, Dale, & Jenkins, 2009
6	Mollenhorst, Berentsen, & De Boer, 2006
7	Cederberg & Stadig, 2003
8	de Vries & de Boer, 2010
9	Berlin, 2002
10	Leinonen, Williams, Wiseman, Guy, & Kyriazakis, 2012
11	Beauchemin, Henry Janzen, Little, McAllister, & McGinn, 2010
12	Sanfilippo et al., 2012
13	Carlsson-Kanyama, 1998
14	Katajajuuri, 2007

Figure 2.1: Food commodities rank based on their supply chain environmental impacts and LCA availability (Berardy et al., 2015)

The results of two LCAs are reviewed in this sub-section. Each of these LCAs have different scopes. The paper written by Da Silva et al. (2010) focuses exclusively on Brazilian soybean cultivation, while the study done by Berardy et al. (2015) includes both cultivation and transformation stages. Results of da Silva et al. (2010) are calculated for 1000 kg of soybeans dried to 13% humidity and imported to Rotterdam. Because this study compares the impacts of soybean production in the Center West (CW) and the Southern (SO) regions of Brazil, it highlights the differences of cultivation methods and environmental performances. On the other hand, Berardy et al. (2015) assess the production of 1 kg of Soy Protein Isolate (SPI) using the soybean meal dataset developed by Dalgaard et al. (2008). In Dalgaard study, the soybean meal is cultivated and transformed in Argentina, while the remaining modelling of the SPI value chain performed by Berardy is occurring in the United States. The LCA performed by Dalgaard et al. (2008) and used by Berardy et al. (2015) avoided co-product allocation through system expansion. This means that the soybean oil produced simultaneously to the soybean meal was accounted for, by including the avoided production of palm and rapeseed oils inside the boundaries of the LCA. This explains the excellent environmental performances of the soybean meal commodity in these two studies.

2.1.1 Energy use

The Cumulative Energy Demand (CED) to produce, dry and import Brazilian soybeans to Rotterdam is equal to 12,634 Mega Joules (MJ) for the CW region and 6,999 MJ for the SO region (da Silva et al., 2010). The contribution of the different processes and inputs show that fertilizers, diesel, and ocean transport account for similar energy demand in both regions (Figure 2.2). In region CW, they represent respectively 1,931 MJ, 1,597 MJ, and 1,591 MJ, while in the SO region, these processes and inputs are accountable for 1,186 MJ, 1,478 MJ, and 1,813 MJ. However, there are also significant differences of energy requirements between the CW and SO regions regarding deforestation and road transportation. While 2,631 MJ and 3,078 MJ are allocated to these two categories in the CW region, 1,035 MJ and 0 MJ can be attributed to road transportation and deforestation in the SO region (da Silva et al., 2010: Table 3). Based on these CED results, the author assesses the energy demand of road, rail, and river transport to be equal to 1.990 MJ, 0.765 MJ and, 0.657 MJ per km. The author concludes that the most urgent mitigation actions consist to stop deforestation in the CW region and to prioritize transport by river and by train instead of road transport. Since the production ratios of CW and SO are respectively equal to 70% and 30%, the overall CED of this LCA is equal to 10,943 MJ (da Silva et al., 2010).

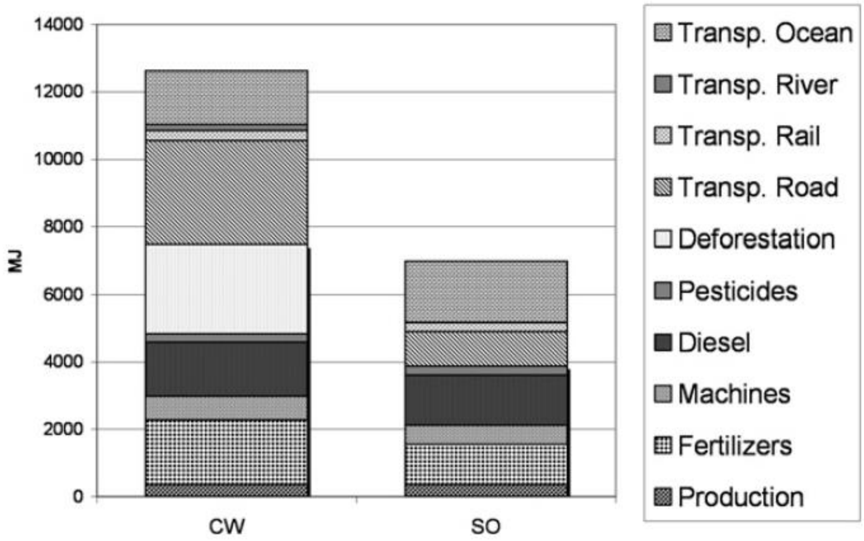


Figure 2.2: CED of Brazilian soybeans imported to Rotterdam (da Silva et al., 2010)

The environmental assessment of Berardy et al. (2015) calculated that cultivation and extraction of soybean meal require an energy input of 2.36 MJ per kg SPI produced (Figure 2.3). This means that a production of 1000 kg of SPI from soybean meal entail an energy use of 2,360 MJ. The analysis highlights that the two main contributors of this production system are sodium hydroxide and the avoided soy animal feed. Because of the co-product allocation by system expansion, soybean meal improves the SPI energy profile by a negative requirement of -6.35 MJ/kg.

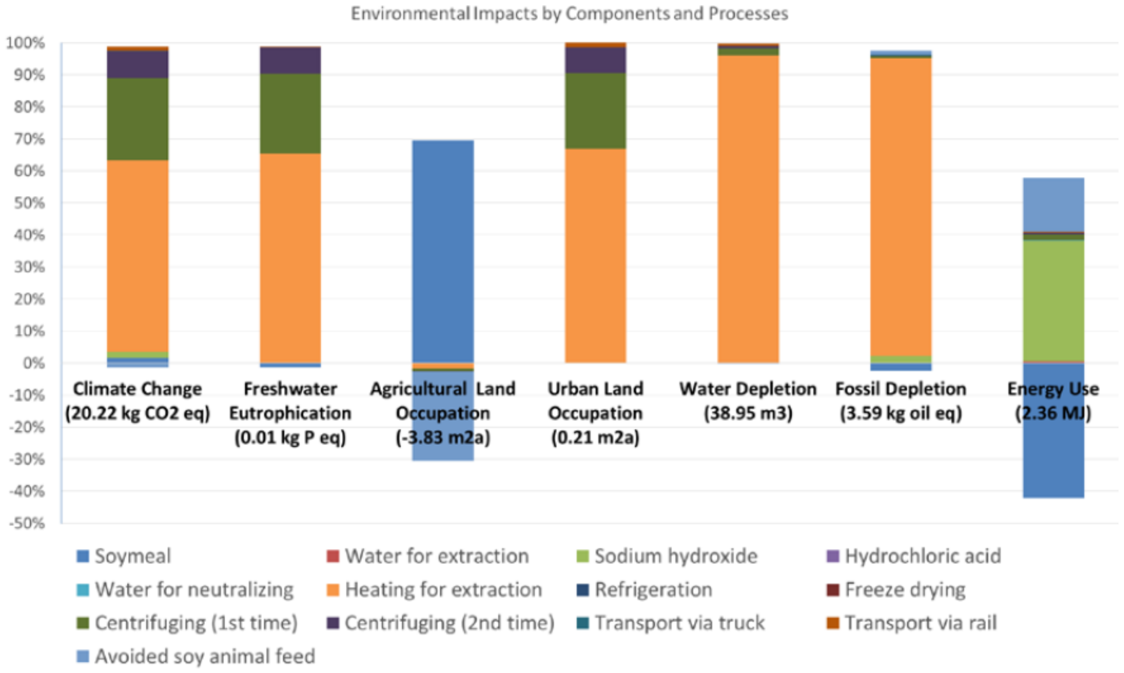


Figure 2.3: Environmental impacts generated by the production of SPI from soybean meal (Berardy et al., 2015)

2.1.2 Eutrophication

In the study of da Silva et al. (2010), the eutrophication impact category account for the emissions of PO_4, NO_3, NO_x and NH_3 and is expressed in PO_4-equivalents. The emissions of PO_4 alone are slightly larger in CW than in the SO region. The author estimate the phosphate lost during erosion to be the largest contribution to eutrophication. Larger emission in the CW region is due to the more intensive use of mineral fertilizers. In CW 1.73 kg and 1.36 kg of PO_4 emissions per ton soybeans produced were attributed to crop production and to fertilizers respectively. In the SO region, crop production emits 1.54 kg of PO_4 while emissions from fertilizers goes down to 0.96 kg. Overall, emissions of PO_4 represent 3.1 kg in CW and 2.51 kg in SO. For the whole country, this means that the production of 1 t soybeans generates the emission of 2.92 kg of PO_4. Consequently, the emissions of phosphate from the system represent 43.02% of the 6.80 kg PO_4-equivalents accounted for in the eutrophication impact category.

In Berardy's LCA, the freshwater eutrophication impacts generated by the production of 1 kg SPI, represent 0.01 kg of P-equivalents. This means that each ton of SPI produced generate the emission of 10 kg of P-equivalent in the environment. The main contributors to these emissions are the heating for extraction, the centrifugation, and the use of hydrochloric acid (Figure 2.3). The author highlights that the soymeal commodity has a positive impact on freshwater eutrophication due to the displacement of rapeseed or palm oil, resulting in -0.001 to -0.02 kg P emitted per kg of soymeal produced (Berardy et al., 2015).

2.2 SWPC

Due to a lack of environmental assessment performed on the SWPC value chain and to scope mismatches, only the LCA from Seghetta et al. (2016) is reviewed in this sub-section. In this environmental assessment, the cultivation and the bio-extraction of several seaweed species is thoroughly assessed through the entire value chain. This includes the cultivation stage, the dehydration, the transportation, and the biorefinery processes leading to the production of a protein rich fish feed fraction, bioethanol, and liquid fertilizer. This study models the cultivation of 208 km^2 of seaweed fields grown in the Danish marine waters. For each of the scenarios performed, the results are expressed per hectare of cultivated seaweed. This review focuses on the results of scenario A3, investigating the environmental impacts generated by the cultivation and transformation of *S. latissima* (Seghetta et al., 2016).

2.2.1 Energy use

The CED analysis of Seghetta account for the total energy used throughout the production process minus the energy contained in the bioethanol produced. Results from scenario A3 show that 62,000 MJ of energy was required to produce and transform 1 ha of *S. latissima.* Since the study report a cultivation yield of 10 t/ha, this value also corresponds to the processing of 10 t Wet Weight (WW) *S. latissima*. Out of this 62,000 MJ, 17,000 MJ are estimated to come directly from fossil fuels. This represents 27.41% of the total energy input. Results from the CED analysis clearly identify the drying process to be the largest contributor, accounting for 63% of the base case scenario’s CED. In the A3 scenario, the situation is identical, as drying is accounting for approximately 50,000 MJ. The results presented in Figure 2.4 show that the cultivation is the second largest CED contributor, while substituted protein and substituted mineral fertilizer reduce the CED by approximately 8,000 MJ.

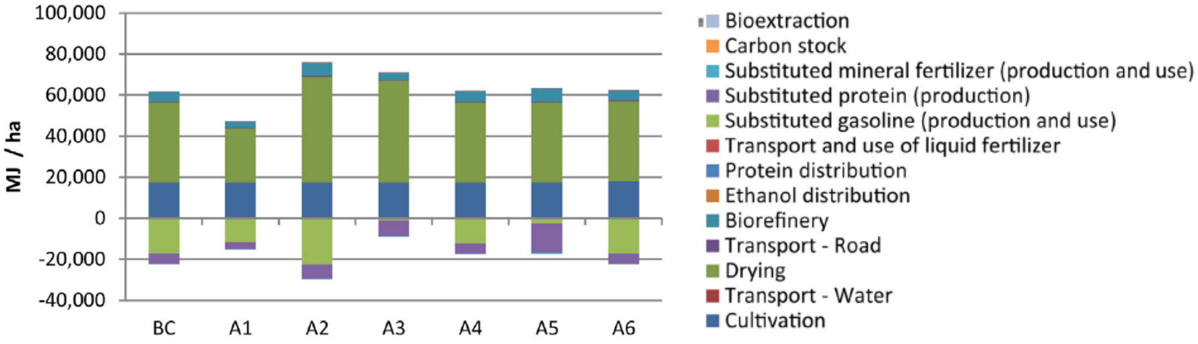


Figure 2.4: CED of each production scenarios (Seghetta et al., 2016)

2.2.2 Eutrophication

In this study, the eutrophication impact category is divided into Nitrogen-limited and P-limited marine eutrophication. The P-limited impact category is expressed in P-equivalents per hectare. Because of the bio-extraction capacity of seaweed biomass, all the scenarios display negative eutrophication potential. Across scenarios, the bio-extraction occurring during seaweed growth contributes from 74% to 94% of the overall values. Results of the A3 scenario display the second-best P-limited marine eutrophication score with a value of -6.3 kg of P-equivalents. The only scenario outscoring this one is A5, with a score of -10.4 kg of P-equivalents, in which *Laminaria digitata* is harvested in the spring instead of the summer. In scenario A3, Figure 2.5 show that the transport and use of liquid fertilizer is the largest P-limited marine eutrophication contributor (Seghetta et al., 2016).

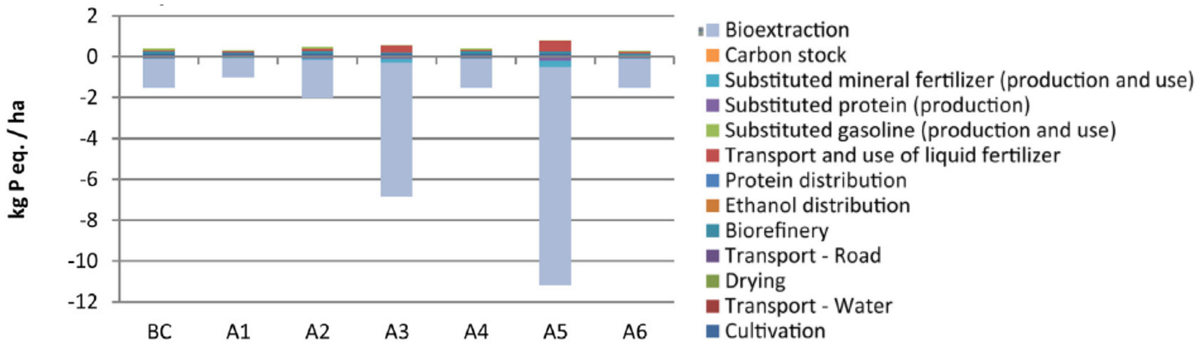


Figure 2.5: P-limited marine eutrophication of each scenarios (Seghetta et al., 2016)

3 Methods

3.1 Material/Substance Flow Analysis (MFA/SFA)

MFA is an environmental accounting tool used in the field of Industrial Ecology to assess material and energy flows and stocks in socio-economic systems. The MFA method is particularly effective at improving resource management (Stanisavljevic and Brunner, 2014) and is often used for decision support in environmental management (Brunner and Rechberger, 2004). In practice, the MFA tool involves consequential modelling of anthropogenic systems defined in time and space. These systems can be modelled in a static or dynamic state within a system boundary defined by the practitioner. MFA is based on the fundamental principle that neither matter nor energy can be created or destroyed in an isolated system. Their quantities remain constant. This implies that outputs plus stock changes equal the system's inputs and can be calculated through mass-balance (ibid.).

MFA and LCA are complementary tools in environmental assessment. While LCA provide complete life-cycle environmental impacts of products, MFA allows the practitioner to develop a deep system understanding as well as generate a systematic description of processes, flows and stocks of the foreground system. SFA is a variant of MFA that focuses on the study of single chemical elements or compounds. The SFA tool is often used when the MFA methodology is useful to understand flows and stocks of critical substances or to monitor pollutants within socio-economic systems and the biosphere (Brunner, 2012).

Recent applications of MFA include tracking global metal cycles (Liu and Müller, 2013) and optimizing e-waste management (Hischier et al., 2005). MFA is also increasingly used to assess urban metabolism (Barles, 2009) and the sustainability of construction materials (Wang et al., 2016). The classic application of SFA is to monitor environmental toxins involved in chemical pollutions (Mao and Graedel, 2009), however recently the fate of key nutrients in food production systems have been modelled using SFA. These include key nutrients in agriculture (Chen et al., 2008, Senthilkumar et al., 2012, Cooper and Carliell-Marquet, 2013) and aquaculture (Hamilton et al., 2015a, Gracey, 2014).

Both the language and modelling codes are strictly defined in the MFA methodology. The objective of such standardisation is to generate a common language to investigate anthropogenic systems and to increase a practitioner's precision (Brunner and Rechberger, 2004). Figure 3.1 illustrates the MFA/SFA modelling language. A colour caption highlights the differences between flows of material/substance and energy. The colour code is specific to this study.

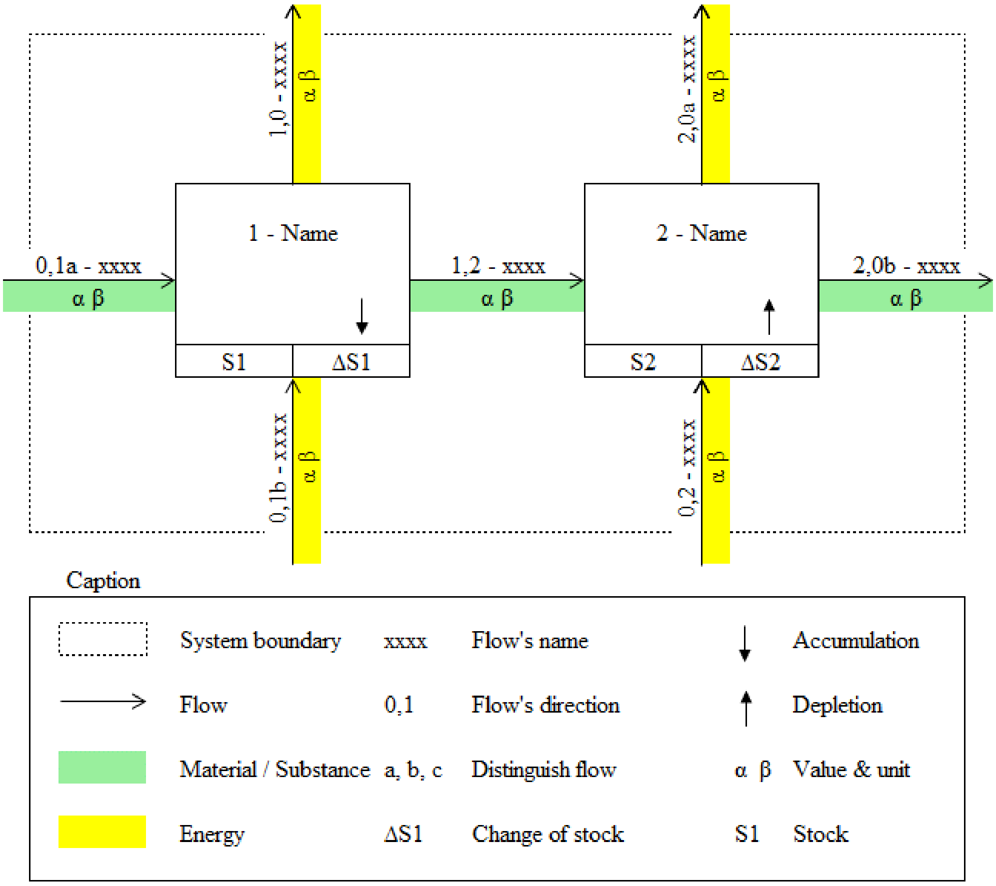


Figure 3.1: Generic system displaying the MFA/SFA modelling rules and principles

3.2 System boundaries

Defining system boundaries is an essential task in MFA/SFA. These boundaries should reflect the goal and scope of a study. The processes, flows and stocks inside the system are integrated parts of the environmental analysis while the rest of the biosphere and technosphere outside a system is neither modelled, quantified nor analysed. In this study, because the objective is to perform a comparative environmental analysis using MFA and SFA, the boundaries are relatively similar for both systems. However, because these production systems are fundamentally different in terms of scale, maturity, and data availability, these variances are reflected in their system boundaries.

3.2.1 SPC

The models developed for the SPC study are constructed per cradle-to-customer gate system boundaries. This means that the boundary starts with soybean cultivation in Brazil and ends with the delivery of Brazilian SPC to the factory gates of Norwegian fish feed producers. The

SPC system is based on an optimized and well-developed Brazilian industry. Consequently, most of the processes and flows are modelled at the national scale.

3.2.2 SWPC

The boundaries used for the SWPC models are also cradle-to-customer gate types. They start at a local seaweed farm near Solund on the west coast of Norway and end with the delivery of SWPC to a Norwegian aquafeed producer. Seaweed cultivation is a very young industry and due the lack of data availability on a national scale, the system was modelled at a local scale using significant assumptions.

3.3 Main data sources

3.3.1 SPC

The cultivation stage of the SPC system is extensively based on the LCA performed by Vamilson Prudêncio da Silva, published in 2010. This research provided high-resolution data of soybean production in Brazil by accounting for the substantial cultivation differences between the CW and the SO regions of the country. The life cycle inventory of this study was employed in both the MFA and SFA models and was the main source of data to build processes one to four. In 2015, this dataset was used to compare Brazilian soybean import to microalgae production in the Netherlands (Taelman et al., 2015b). The SO region comprises the states of Minas Gerais, Espírito Santos, Rio de Janeiro, Sao Paulo, Paraná, Santa Catarina, and Rio Grande do Sul. However, Minas Gerais and Paraná dominate soybean production in this region. In CW, soybean culture is concentrated in Mato Grosso and Goiás and to a lesser extent in Mato Grosso do Sul (da Silva et al., 2010). Figure 3.2 shows the location of each state in their respective regions and the geographic position of the SO and CW regions in Brazil.

Figure 3.2: Map of Brazil with highlighted CW and SO regions & states (modified from IBGE, 2017)

In da Silva’s study, six different production types were combined to generate LCA data more representative of the complexity of Brazilian production methods. Figure 3.3 shows how the six production types are distributed and how they generate together a detailed image of Brazilian soybean production. Production types one to four are used in the SO region while types five and six are applied in the CW region. Differences between the six production types concern soil preparation techniques and the application of either mineral or organic fertilizers. Agricultural soils are either tilled or directly drilled and either pig manure or mineral fertilizers are applied for soil enrichment (Figure 3.3).

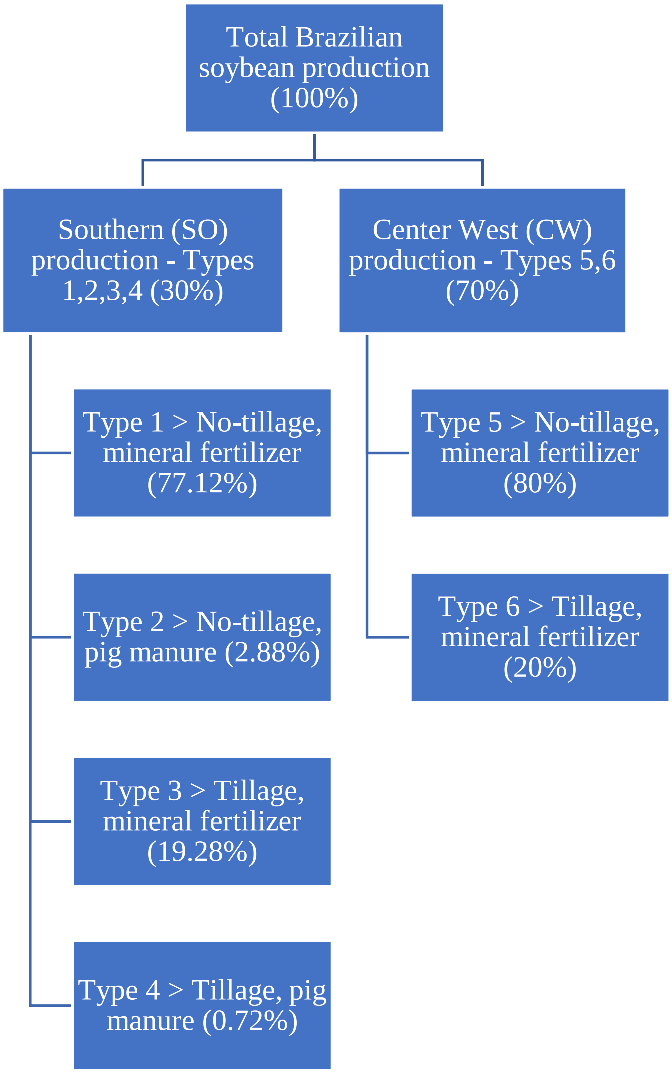


Figure 3.3: Brazilian soybean production modelled by da Silva et al. (2010)

Various other data sources completed the value chain. Data from an LCA assessing Norwegian salmon production was used to model the extraction process (Skontorp et al., 2012).

In this study, the SPC extraction occurring in Brazil was based on the database Agri-footprint. The import of Brazilian SPC to Norway was modelled with various data sources. Transportation to Brazilian harbours and to Rotterdam were largely based on personal communication with Caramuru, Selecta, and Imcopa, the three main SPC producers exporting to Norway. Similarly, transportation from Rotterdam to Norway was built on data from the three main Norwegian fish feed manufacturers: EWOS, Biomar, and Skretting.

3.3.2 SWPC

The Dutch seaweed farming company Hortimare provided the cultivation data. This company operates in Norway and is an industrial research partner in the PROMAC project. The cultivation data used in the SWPC system correspond to the latest production methods employed in Hortimare's seaweed farm located near Solund in Norway. This data comprises the hatchery processes, cultivation at sea, and different types of transport required for maintenance and harvest of the biomass. The seaweed industry in Norway is a young, small, and rapidly changing sector. Production processes are therefore evolving quickly and data is only available for small scale pilot production (Philis, 2016). For this reason, cultivation processes were modelled with a culture yield of 60-tons WW *S. latissima*, a large harvest in Norwegian standards.

Due to the absence of data spanning the complete value chain of the Norwegian seaweed industry, various assumptions were required to model the transformation stage. In addition, because extraction and biorefinery processes are still researched and unpublished in the PROMAC project, the bio-extraction suggested by Michele Seghetta was used to model seaweed transformation (Seghetta et al., 2016). This Danish study demonstrates how *S. latissima* can be extracted through successive hydrolysis, fermentation, and distillation stages and produce outputs of CO_2, ethanol, liquid fertilizer, and SWPC. To simplify transportation assumptions and to impart a sense of industrial realism, macroalgae production was assumed to occur near Ålesund, one of Norway's most important ports for marine resources and a prime location for a future biorefinery. Similarly, assumptions were made to model the drying process, transportations, and the location of an aquafeed producer to facilitate integration of the biorefinery scenario into the system.

3.4 Assumptions

3.4.1 SPC

Due to the large scale and maturity of the soybean industry in Brazil, an important amount of reliable data was available to model this system. Yet, assumptions were still required to complete the value chain (Table 3.1).

3.4.2 SWPC

Unlike the Brazilian SPC industry, the Norwegian seaweed industry is scattered and undeveloped (Philis, 2016). To model cultivation, transportation, and the transformation of seaweed into SWPC, it was necessary to establish several significant assumptions (Table 3.2).

Table 3.1: Description of assumptions made in the SPC system

SPC MFA/SFA assumptions description
1. Production yield is constant over time Constant production yield allows for simplifying calculations involving crop residues and seeds inputs and outputs.
2. Soybean seeds and crop residues are direct outputs of the system from the third process Soybean seeds and crop residues are treated as outputs of the system although they can be considered as short term stocks. This assumption facilitates mass-balance calculations.
3. 100% of the biocides are dispersed into the biosphere Accounting for biocides settlement on crops implied complex calculation whereas it is estimated that quantities of chemical deposits on crops are neglectable.
4. Caramuru, Imcopa, and Selecta hold 100% of the Brazilian SPC market share, and weight respectively 33.33% each This assumption reduces the complexity of logistical modelling. It is based on Biomar supplier network (Biomar, T. Skansen, personal communication, October 20th 2016).
5. All SPC imports transit through Rotterdam The transition of the SPC cargo through Rotterdam is based on Biomar logistics (Biomar, T. Skansen, personal communication, October 20th 2016). Assuming all cargo follow the same route reduces the process complexity.
6. EWOS, Biomar, and Skretting hold 100% of the Norwegian aquafeed market share These three main aquafeed producers are by far the main Brazilian SPC importers in Norway (Lindahl, 2014).
7. All imported Brazilian SPC contains 62% protein The SPC produced by IMCOPA contain minimum 62% protein (Skontorp et al., 2012). To simplify the system, it is assumed that all SPC imported to Norway has the same protein content.
8. 100% of the SPC imported by Norway come from Brazil In reality, approximately 80% of the SPC imported by to Norway come from Brazil (Lindahl, 2014). This assumption narrows the scope of this study on Brazilian SPC.
8. The input and output of P from crop residues flow in a closed loop and does not affect other flows of the system The input and output of P from crop residues are not accounted for in the LCA by da Silva et al. (2010). This set of assumptions simplifies the system without compromising the P cycle (the growing plants capture 100% of the P in crop residues from the previous harvest; this P is entirely transferred to the crop straws; at harvest the crop straws become crop residues again and this P fraction leave the system).
9. 100% of the P in biocides is dispersed in the biosphere The quantity of P in the chemical deposits of biocides is estimated to be negligible.
10. Drying does not affect the P content of food/feed commodities Drying processes do not affect quantities of minerals like P. Reducing the water fraction concentrates minerals but does not affect the absolute quantity (Adepoju and Adefila, 2015).
11. The P content in waste water is negligible Absence of data

Table 3.2: Description of assumptions made in the SWPC system

SWPC MFA/SFA assumptions description
1. Gametophytes and sporophytes use 15% of the F/2 medium nutrients (added nutrients + seawater nutrients) Data scarcity was a serious limitation for modelling gametophyte and sporophyte culture. It was assumed that gametophytes and sporophytes grow in a large excess of nutrients (Hortimare BV, F.V.D. Heuvel, personal communication, December 8th 2016; CEVA, H. Marfaing, personal communication, January 5th 2017) and only use a fraction of the nutrients available.
2. All gametophyte losses occur during the settlement of gametophyte on twines Gametophytes, sporophytes, and seaweed plants fall from the culture support as a natural part of the seaweed lifecycle. This phenomenon is not adapted to modelling.
3. The chemical composition of *S. latissima* reflects the nutrient absorption occurring at sea; Consequently, uptake calculations are based on ash content Determining nutrient uptake from seawater under experimental conditions is outside of the scope of this study. Using published chemical composition is more adapted to this environmental assessment.
4. Hatchery production, sea farming and harvest occur near Ålesund, Norway This assumption is essential to integrate the cultivation and transformation sections of the supply chain. Land-based transformation cannot realistically occur in Solund and large-scale transport of the biomass from Solund to Ålesund is not desirable from an operations standpoint. Ålesund is a major port with excellent characteristics to establish biorefineries (PROMAC, n.d.).
5. The biomass is transported to a drying facility near the company Tafjord Kraftvarme Tafjord Kraftvarme is an industrial partner in PROMAC producing district heating and electricity from a waste incineration facility near Ålesund. This assumption provides the possibility to use Tafjord's excess heat during summer months.
6. The biomass is processed with a transverse slicer and a convective belt dryer Industrial seaweed drying processes are not currently in operation in Norway (Philis, 2016). The drying process was therefore modelled using a convective belt dryer adapted to the biomass that enables the use of secondary steam heat (SINTEF, T. Nordvedt, personal communication, December 22th 2016).
7. The steam heat required for drying is produced from the Norwegian electricity mix. In Norway, electricity is easily accessible and overwhelmingly based on renewable hydropower sources (Government.no, 2016). Electricity is therefore the most likely energy source used in these conditions.
8. The bio-extraction of *S. latissima* described in Seghetta et al. (2016) can be utilized in a biorefinery near Ålesund, Norway. Industrial seaweed biorefineries are not currently available in Norway (Philis, 2016). The modelling of the extraction process is entirely based the high resolution data from the recent Seghetta study (Seghetta et al., 2016).
9. The drying facility is located 20 km away from the harbour. The biorefinery is within a 30 km range from the drying facility and 20 km from the closest harbour. The biorefinery is located 20 km away from the closest harbour. The closest fish feed factory is located at 100 km by boat. The logistics system was modelled based on realistic assumptions focusing on limiting distances between raw material landing, drying and processing.
10. 2t of SWPC provides the same functional unit as 1t of SPC. The protein content of SWPC produced according to Seghetta et al. (2016) contain 31.34% crude protein while SPC contains a minimum of 62% (Skontorp et al., 2012). Consequently, twice the amount of SWPC is necessary to obtain the same quantity of crude protein.

3.5 MFA/SFA models organisation

In this master's thesis, the term "system" designates each environmental assessment performed on the SPC and the SWPC value chains. Henceforth, two systems are described in this report, the SPC and the SWPC systems. The term "model" describes the mathematical organization of the MFA and SFA systems in excel and their representation as figures in the report. The models are organized using parameter sheets that form the basis for all system flows. Each MFA/SFA model consists of three excel sheets linked together, "parameters" to "flows" to "figures". This link parameters-flows-figures insure the study's overall flexibility and evolving capacity. Because each system contains several models, this term is often use in the plural form.

The SPC system is named Soy_MFA/SFA_modelling in excel and is comprised of four different models. The MFA and SFA models are always built in tandem and are either marked as "base" or with a scenario number. The SWPC system is identically organized. Table 3.3 presents the base and scenario models built for each system.

Table 3.3: List of soy and seaweed MFA/SFA models built in Excel

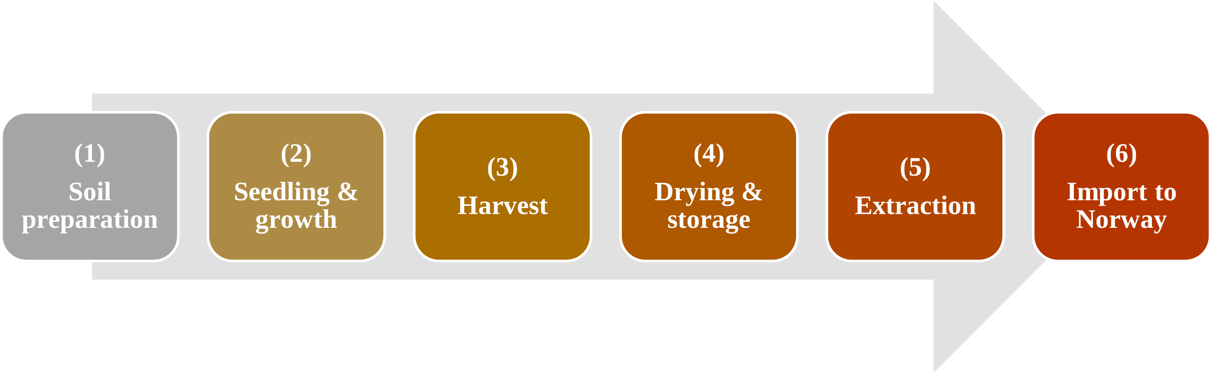
Soy_MFA_base	Flows of biomass and energy in the Brazilian SPC value chain; values expressed for one year of imports (2015).
Soy_SFA_base	Flows of P embedded in the biomass in the Brazilian SPC value chain; values expressed for one year of imports (2015).
Soy_MFA_S1	Flows of biomass and energy generated by production and import of Brazilian SPC to Norway; values expressed per ton imported.
Soy_SFA_S1	Flows of P embedded in the biomass generated by production and import of Brazilian SPC to Norway; values expressed per ton imported.
Seaweed_MFA_base	Flows of biomass and energy generated by production and transport of Norwegian SWPC; values expressed per batch of 60t WW *S. latissima*.
Seaweed_SFA_base	Flows of P embedded in the biomass generated by production and transport of Norwegian SWPC; values expressed per batch of 60t WW *S. latissima*.
Seaweed_MFA_S1	Flows of biomass and energy generated by production and transport of Norwegian SWPC; values expressed per ton SWPC.
Seaweed_SFA_S1	Flows of P embedded in the biomass generated by production and transport of Norwegian SWPC; values expressed per ton SWPC.
Seaweed_MFA_S2	Flows of biomass and energy generated by production and transport of Norwegian SWPC; values expressed for 2 tons SWPC.
Seaweed_SFA_S2	Flows of P embedded in the biomass generated by production and transport of Norwegian SWPC; values expressed for 2 tons SWPC.

3.6 Processes & flows

This section elaborates on the selection, construction, and organisation of processes and flows used to create each system.

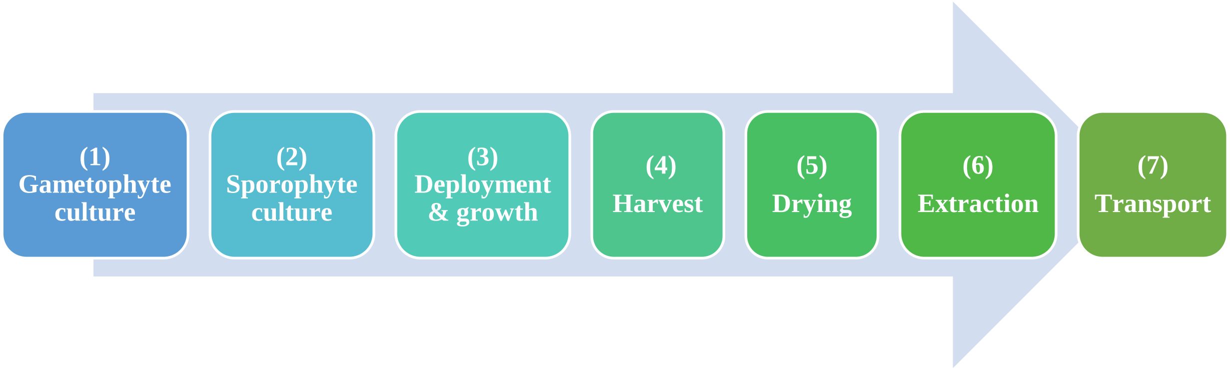
3.6.1 Processes

Because this study compares commodities with similar functional units, both systems were built with a compatible structure. In addition, SPC and SWPC production systems have similar value chains, each consisting of cultivation and transformation stages facilitating this comparison. Process construction is an iterative procedure that evolves over multiple steps of revision along with the practitioner's system understanding. For both the SPC and SWPC systems, the main cultivation data sources strongly influenced and shaped process selection and construction. The life cycle inventory data from da Silva et al. (2010) and process data from Hortimare were the modelling starting points of each system and directly impacted the systems scales, scopes, and boundaries. An illustration and description of each system's processes is presented in Figure 3.4 and Figure 3.5.



(1) Accounting for soil enrichment, soil maintenance, and transport of agricultural inputs to farms
(2) Describing soil seeding, nutrient uptake during photosynthesis, and biocides application
(3) Accounting for harvest of crops, transport from field to farm and from farm to storage
(4) Woodchip based drying and soybean storage conditions
(5) Accounts for the warehouses-factories transportation. Mechanical, hexane & ethanol based extraction
(6) Describes transport operations from Brazil, through Rotterdam, to Norwegian importers

Figure 3.4: Description of SPC processes



(1) Accounts for nutrients and electricity required to induce gametogenesis in hatchery
(2) Describes nutrients and electricity required to induce sporophyte photosynthesis in hatchery
(3) Accounts for transport-deployment, maintenance, and mineral uptake at sea
(4) Collection and transport of the biomass from the sea farm to the drying facility
(5) Accounts for storing, trimming and steam drying the harvested biomass
(6) Describes transportation, hydrolysis, fermentation, distillation and spray-drying of the biomass
(7) Transportation from the biorefinery to the aquafeed manufacturer

Figure 3.5: Description of SWPC processes

3.6.2 Flows

Table 3.4 and Table 3.5 provide a comprehensive documentation of each system's construction. Table 3.4 is for the SPC system while Table 3.5 is for SWPC. The flows list under each process always starts with MFA flows followed by SFA ones. SFA flows can be easily identified by the symbol [P], standing for "Phosphorus", which is placed between the flows direction and name.

Table 3.4: Flow description of the SPC system

Flow direction & name	Flow description	Equations & sources	Additional data
1 - Soil preparation MFA/SFA			
0,1a - Mineral fertilizers	Quantity of mineral fertilizer applied on soil before cultivation	Mineral fertilizer input PT1,3,5,6[1] × corresponding PT/region PR[1]	CH_4N_2O, P_2O_5, and KCL
0,1b - Manure	Quantity of manure applied on soil before cultivation	Manure input PT2,4[1] × corresponding PT/region PR[1]	Represent 3.6% of SO PR
0,1c - Crop residue	Quantity of crop residues applied on soils after last harvest	Straw input TP1,2,3,4,5,6[1] × corresponding PT/region PR[1]	Constant cultivation yield assumed
0,1d - Diesel, maintenance	Amount of diesel-energy required for soil 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)[1] × corresponding PT/region PR[1,a]	20% of soils are subsoiled each year
0,1e - Diesel, transport inputs	Amount of diesel-energy required to transport ingredients to farms	Load-distance ingredient PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × lorry diesel consumption[2,a]	SO: 250km / CW: 350km; lorry 7.5-16t
1,0a - Emission, maintenance	Amount of emission-energy produced by tractors engines operation	(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)[1] × corresponding PT/region PR[1,a]	Thermal, chemical, and kinetic energies
1,0b - Emission, transport inputs	Amount of emission-energy produced by trucks engines operation	Load-distance ingredient PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × lorry diesel consumption[2,a]	Thermal, chemical, and kinetic energies
1,0c - Nutrients, fixation in soil	Quantity of nutrients dispersed in agricultural soil	(Nutrients to soil TP1,2,3,4,5,6[1] – nutrients to underground water TP1,2,3,4,5,6)[1,b] × corresponding PT/region PR[1]	N, P_2O_5, and K_2O
1,0d - Nutrients, drained by water	Quantity of nutrients drained by underground and surface water	Nutrients to water TP1,2,3,4,5,6[1] × corresponding PT/region PR[1]	N-NO_3 and P_2O_5
1,2 - Net primary production	Quantity of biomass generated through photosynthesis	Quantity of soybeans[1] + quantity of crop residues[1] – quantity of seeds[1]	Mass-balance calculations
0,1a - [P] Mineral fertilizers	Quantity of P embedded in mineral fertilizers applied on soil	Mineral fertilizer P_2O_5 content PT1,3,5,6[1] × corresponding PT/region PR[1] × P_2O_5 P content[1]	SO: 0-20-20 / CW: 02-20-20
0,1b - [P] Manure	Quantity of P embedded in pig manure applied on soil	Manure P_2O_5 content PT2,4[1] × corresponding PT/region PR[1] × P_2O_5 P content[1]	Pig manure has low P concentration
0,1c - [P] Crop residues	Quantity of P embedded in previously harvested crop residues	Leaves-stems-pods P_2O_5 uptake TP1,2,3,4,5,6[1] × corresponding PT/region PR[1] × P_2O_5 P content[1]	Based on *Glycine max* P distribution
1,0a - [P] Fixation in soil	Quantity of P dispersed in soil and not absorbed by plants	(P_2O_5 to soil PT1,2,3,4,5,6 – PO_4 to underground water)[1,b] × corresponding PT/region PR[1] × corresponding P_2O_5 / PO_4 P content[1]	
1,0b - [P] Drained by water	Quantity of P drained by underground and surface water	PO_4 to water PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × PO_4 P content[1]	Leaching, erosion, surface runoff
1,2 - [P] Net primary production	Quantity of P used by the plant during growth	P in leaves-stems-pods[1] + P in beans[1] – P in seeds[1]	Mass-balance calculations
2 - Seedling & growth MFA/SFA			
0,2a - Seeds	Quantity of seeds applied on soil to start a new culture	Seeds input PT1,2,3,4,5,6[1] × corresponding PT/region PR[1]	Seeds treated with biocides
0,2b - Biocides	Quantity of active biocides molecules applied on seeds and crops	Biocides products input PT1,2,3,4,5,6[1] × corresponding PT/region PR[1]	Herbicide, insecticide, fungicide
0,2c - Diesel, seedling	Amount of diesel-energy required for seedling	Diesel seedling PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	
0,2d - Diesel, biocides	Amount of diesel-energy required for biocides application	Diesel biocides applications PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	
2,0a - Biocide, dispersion	Quantity of active biocides molecules dispersed in the biosphere	Biocides products input PT1,2,3,4,5,6[1] × corresponding PT/region PR[1]	Assumed total dispersion (simplification)
2,0b - Emissions, seedling	Amount of emission-energy produced by tractors engines during seedling	Diesel seedling PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	Thermal, chemical, and kinetic energies
2,0c - Emissions, biocides	Amount of emission-energy produced by tractors engines during spraying	Diesel biocides applications PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	Thermal, chemical, and kinetic energies
2,3 - Soy plants	Quantity of whole Glycine max on field before harvest	Quantity of soybeans[1] + quantity of crop residues[1]	Mass-balance calculations
0,2a - [P] Seeds	Quantity of P embedded in the seeds used for seedling	Seeds input PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × seed P content[1]	Based on P soybean (18% H_2O) content
0,2b - [P] Biocides	Quantity of P in some of the biocides molecules applied	(Glyphosate input PT1,2,5 + methamidophos input PT1,2,3,4,5,6)[1] × corresponding PT/region PR[1] × corresponding glyphosate / methamidophos P content[1]	P settling on the biomass is neglected
2,0 - [P] Biocides dispersion	Quantity of P embedded in biocides dispersed in the biosphere	(Glyphosate input PT1,2,5 + methamidophos input PT1,2,3,4,5,6)[1] × corresponding PT/region PR[1] × corresponding glyphosate / methamidophos P content[1]	Assumed total dispersion (simplification)
2,3 - [P] Soy plants	Quantity of P embedded in whole glycine max plants before harvest	P in leaves-stems-pods[1] + P in beans[1]	Mass-balance calculations
3 - Harvest MFA/SFA			
0,3a - Diesel, harvesting	Amount of diesel-energy required for harvesting	Diesel harvesting PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	
0,3b - Diesel, transport to farm	Amount of diesel-energy required for transport from fields to farms	Diesel transport to farm PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	
0,3c - Diesel, transport to storage	Amount of diesel-energy required for transport from farms to storage	Load-distance soybeans PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × lorry diesel consumption[3,a]	Lorry 28 tons
3,0a - Emissions, harvesting	Amount of emission-energy produced by combine harvester engines	Diesel harvesting PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	Thermal, chemical, and kinetic energies
3,0b - Emissions, transport to farm	Amount of emission-energy produced by tractors/trucks engines	Diesel transport to farm PT1,2,3,4,5,6[1] × corresponding PT/region PR[1,a]	Thermal, chemical, and kinetic energies
3,0c - Emissions, transport to storage	Amount of emission-energy produced by trucks engines	Load-distance soybeans PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × lorry diesel consumption[3,a]	Thermal, chemical, and kinetic energies
3,0d - Seeds, next harvest	Quantity of seeds stored for next harvest	Seeds output PT1,2,3,4,5,6[1] × corresponding PT/region PR[1]	Constant cultivation yield assumed
3,0e - Crop residues	Quantity of crop residues applied on soils for next harvest soil preparation	Straw output TP1,2,3,4,5,6[1] × corresponding PT/region PR[1]	Constant cultivation yield assumed
3,4 - Soybeans, 18% water	Quantity of soybeans produced	(Soybean cultivation yield TP1,2,3,4,5,6 – seeds output PT1,2,3,4,5,6)[1] × corresponding PT/region PR[1]	Harvest humidity: 18%
3,0a - [P] Seeds, next harvest	Quantity of P embedded in seeds stored for next harvest	Seeds output PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × seed P content[1]	Constant cultivation yield assumed
3,0b - [P] Crop residues	Quantity of P embedded in the crop residues spread on soils	Leaves-stems-pods P_2O_5 uptake TP1,2,3,4,5,6[1] × corresponding PT/region PR[1] × P_2O_5 P content[1]	Constant cultivation yield assumed
3,4 - [P] Soybean, 18% water	Quantity of P embedded in the soybeans produced	(P_2O_5 uptake beans PT1,2,3,4,5,6 × corresponding PT/region PR × P_2O_5 P content)[1] – seeds P content[1]	
1st system adjustment	**All the flows of processes 1, 2, and 3 are multiplied by a coefficient factor to adjust the production output of Soybeans, 18% water from 980.29kg to 1000kg**		
4 - Drying & storage MFA/SFA			
0,4 - Wood chips, drying	Amount of woodchips-energy required to dry soybeans before storage	Woodchips energy for drying[1] + electricity energy cleaning & storage[1]	Aggregation of electricity because marginal
4,0a - Emissions, drying	Amount of emission-energy produced during combustion	Woodchips energy for drying[1] + electricity energy cleaning & storage[1]	Thermal, chemical, and kinetic energies
4,0b - Water evaporation	Quantity of water removed from harvested soybeans	Soybean cultivation yield TP1,2,3,4,5,6[1] × corresponding PT/region PR[1] × beans shrinkage ratio[1]	Original yield = adjusted bean output (1000kg)

Table 3.4 - Continued

Flow direction & name	Flow description	Equations & sources	Additional data
4,5 - Soybeans, 13% water	Quantity of soybeans produced dried to 13% humidity	Soybeans, 18% water[1] – water evaporation[1]	Mass-balance calculations
4,5 - [P] Soybean, 13% water	Quantity of P embedded in the soybeans produced and dried	P_2O_5 uptake beans PT1,2,3,4,5,6[1] × corresponding PT/region PR[1] × P_2O_5 P content[1]	Drying do not affect P content
2nd system adjustment	**All the flows of processes 1, 2, 3, and 4 are multiplied by a coefficient factor to adjust the production output of Soybeans, 13% water from 942.53kg to 1000kg**		
5 – Extraction MFA/SFA			
0,5a - Diesel, transport to factory	Amount of diesel-energy required to transport soybeans to factories	(Load-distance road × lorry diesel consumption)[4,3] + (load-distance railway × freight train diesel consumption)[4,5] + (load-distance waterway × barge freight diesel consumption)[4,6,a]	Lorry > 20t; train: bulk; barge 5500t: bulk
0,5b - Energy, extraction	Amount of fuels/electricity-energy required for the extraction process	Diesel-energy input[4] + electricity-energy input[4] + natural gas-energy input[4]	Data already in MJ
5,0a - Emissions, transport to factory	Amount of emission-energy produced by truck, train, and barge engines	(Load-distance road × lorry diesel consumption)[4,3] + (load-distance railway × freight train diesel consumption)[4,5] + (load-distance waterway × barge freight diesel consumption)[4,6,a]	Thermal, chemical, and kinetic energies
5,0b - Emissions, extraction	Amount of emission-energy produced during the extraction process	Diesel-energy input[4] + electricity-energy input[4] + natural gas-energy input[4]	Thermal, chemical, and kinetic energies
0,5c - Process water	Quantity of purified water required to produce SPC from soybeans	Process water input[4]	/t soybeans input
5,0c - Soybean, hulls	Quantity of soybean hulls mechanically extracted from the biomass	Soybean hulls output[4]	/t soybeans input
5,0d - Soybean, crude oil	Quantity of soybean crude oil produced by hexane extraction	Soybean crude oil output[4]	/t soybeans input
5,0e - Soybean, molasses	Quantity of soybean molasses produced by ethanol extraction	Soybean molasses output[4]	/t soybeans input
5,0f - Waste water	Quantity of waste water generated during the extraction of the biomass	Waste water output[4]	/t soybeans input
5,6 - SPC, 8% water	Quantity of SPC produced by mechanical, hexane and ethanol extraction	SPC output[4]	/t soybeans input
5,0a - [P] Soybean, hulls	Quantity of P embedded in extracted soybean hulls	Soybean hulls output[4] × soybean hulls P proportion[7]	
5,0b - [P] Soybean, crude oil	Quantity of P embedded in extracted soybean crude oil	Soybean crude oil output[4] × soybean crude oil P proportion[8]	
5,0c - [P] Soybean, molasses	Quantity of P embedded in extracted soybean molasses	Soybean molasses output[4] × soybean molasses P proportion[9]	
5,6 - [P] SPC, 8% water	Quantity of P embedded in extracted SPC	SPC output[4] × SPC P proportion[10]	
3rd system adjustment	**All the flows of processes 1, 2, 3, 4, and 5 are multiplied by a coefficient factor to adjust the production output of SPC from 540kg to 1000kg**		
6 - Import to Norway MFA/SFA			
0,6a - Diesel, transport to port	Amount of diesel-energy required to transport SPC from factories to ports	((Load-distance road Sorriso to Porto de Santos/Porto de Imbituba[11,12,13] × corresponding port UR[11] × Caramuru MS) + (load-distance road Araucária to Porto de Paranaguá[14,15] × Imcopa MS) × lorry diesel consumption[3]) + (load-distance railway Araguari to Porto de Vitória[16,17] × Selecta MS × freight train diesel consumption[5,a])	3 SPC producers considered: Caramuru, Imcopa, Selecta; Assumption: 1/3 market share each; Lorry 16-32t
0,6b - Diesel, transport Rotterdam	Amount of heavy fuel oil-energy required to transport SPC from Brazilian ports to Rotterdam	((Load-distance shipping Porto de Santos/Porto de Imbituba to R[11,18,19] × corresponding port UR[11] × Caramuru MS) + (load-distance shipping Porto de Paranaguá to R[14,20] × Imcopa MS) + (load-distance shipping Porto de Vitória to R[16,21] × Selecta MS)) × freight shipping heavy fuel oil consumption[22,a]	50,000 dwt ships, transported in bulk
0,6c - Diesel, transport to Norway	Amount of diesel-energy required to transport SPC from Rotterdam to fish feed manufacturers in Norway	((Load-distance shipping R to Myre/Karmøy[23,24,25] × corresponding factories UR[23] × Biomar MS[26]) + (load-distance shipping R to Florø/Halsa/Bergneset[27,28,29,30] × corresponding factories UR[27] × Ewos MS[26]) + (load-distance shipping R to Stavanger/Averøy/Stokmarknes[31,32,33,34] × corresponding factories UR[31] × Skretting MS[26])) × freight shipping diesel consumption[35,a]	3 Norwegian fish feed producers considered: Biomar, Ewos, and Skretting; 3,000dwt ships used for transportation
6,0a - Emissions, transport to port	Amount of emission-energy produced by trucks and trains	((Load-distance road Sorriso to Porto de Santos/Porto de Imbituba[11,12,13] × corresponding port UR[11] × Caramuru MS) + (load-distance road Araucária to Porto de Paranaguá[14,15] × Imcopa MS) × lorry diesel consumption[3]) + (load-distance railway Araguari to Porto de Vitória[16,17] × Selecta MS × freight train diesel consumption[5,a])	Thermal, chemical, and kinetic energies released
6,0b - Emissions, transport Rotterdam	Amount of emission-energy produced by transatlantic tanker ships	((Load-distance shipping Porto de Santos/Porto de Imbituba to R[11,18,19] × corresponding port UR[11] × Caramuru MS) + (load-distance shipping Porto de Paranaguá to R[14,20] × Imcopa MS) + (load-distance shipping Porto de Vitória to R[16,21] × Selecta MS)) × freight shipping heavy fuel oil consumption[22,a]	Thermal, chemical, and kinetic energies released
6,0c - Emissions, transport to Norway	Amount of emission-energy produced by freight ships	((Load-distance shipping R to Myre/Karmøy[23,24,25] × corresponding factories UR[23] × Biomar MS[26]) + (load-distance shipping R to Florø/Halsa/Bergneset[27,28,29,30] × corresponding factories UR[27] × Ewos MS[26]) + (load-distance shipping R to Stavanger/Averøy/Stokmarknes[31,32,33,34] × corresponding factories UR[31] × Skretting MS[26])) × freight shipping diesel consumption[35,a]	Thermal, chemical, and kinetic energies released
6,0 - SPC, 8% water	Quantity of SPC produced and imported from Brazil to Norway	SPC output[4] × 3rd system adjustment	Assumed no losses during transport
6,0 - [P] SPC, 8% water	Quantity of P embedded in the imported SPC from Brazil to Norway	SP output[4] × SPC P proportion[10] × 3rd system adjustment	Assumed no losses during transport

Table's abbreviations: PT = Production Types; P = Phosphorus; PR = Production Ratios; R = Rotterdam; UR = Use Ratios; MS = Market Share.

Indications: [a]Fuels inputs are systematically converted in megajoules by multiplying quantities by corresponding fuel energy content / [b]Nutrients drained by underground water are subtracted from nutrients fixed in soil to avoid double accounting.

Sources: [1](da Silva et al., 2010); [2](Spielmann and Scholz, 2005b); [3](Spielmann and Scholz, 2005a); [4](Skontorp et al., 2012; based on Blonk Agri-footprint BV); [5](Spielmann et al., 2007a); [6](Spielmann et al., 2007b); [7](Barbosa et al., 2008); [8](Knoll and Life, 2007); [9](Hall et al., 2005); [10](Endres, 2001); [11](Caramuru, personal communication, November 15th 2016), ; [12](Google, n.d.-d); [13](Google, n.d.-c); [14](Imcopa, personal communication, November 14th 2016); [15](Google, n.d.-b); [16](Selecta, P. Sugui, personal communication, November 14th 2016); [17](Google, n.d.-a); [18](SeaRates, n.d.-c); [19](SeaRates, n.d.-a); [20](SeaRates, n.d.-b); [21](SeaRates, n.d.-d); (Spielmann et al., 2007c); [23](Biomar, T. Skansen, personal communication, November 21st 2016); [24](SeaRates, n.d.-j); [25](SeaRates, n.d.-i); [26](Rana et al., 2009); [27](EWOS Norge, n.d.); [28](SeaRates, n.d.-g); [29](SeaRates, n.d.-h) [30](SeaRates, n.d.-f); [31](Skretting, personal communication, November 21st 2016); [32](SeaRates, n.d.-k) [33](SeaRates, n.d.-e) [34](SeaRates, n.d.-l); [35](Gabi software).

Table 3.5: Flow description in the SWPC system

Flow direction & name	Flow description	Equations & sources	Additional data
1 - Gametophyte culture MFA/SFA			
0,1a - Gametophyte, year (-1)	Quantity of gametophyte biomass used to inoculate the new culture	Gametophyte culture density[1,2] × SW culture volume[3] × inoculation ratio[3]	10% of the production is stored for inoculation
0,1b - Culture nutrients	Quantity of nutrients added to seawater to produce the F/2 medium	F/2 medium nutrient concentration[4] × SW culture volume[3] × nutrients inputs over time[3]	Based on standardized F/2 medium composition
0,1c - Electricity	Amount of electricity-energy required for gametophyte production	(White light power × HU × quantity)[3] + (red light power × HU × quantity)[3] + (climatization power × HU × quantity)[3] + (aeration pump power × HU × quantity)[3] + (autoclave power × HU × quantity)[3,a]	
0,1d - Seawater	Quantity of seawater added to nutrients to produce the F/2 medium	SW culture volume[3] × SW density[5]	Seawater 30-50m deep, near Solund, Norway
1,0a - Emissions, electricity	Amount of emission-energy produced by lamps and machinery	(White light power × HU × quantity)[3] + (red light power × HU × quantity)[3] + (climatization power × HU × quantity)[3] + (aeration pump power × HU × quantity)[3] + (autoclave power × HU × quantity)[3,a]	Thermal and kinetic energies released
1,0b - Used enriched seawater	Quantity of seawater and F/2 medium nutrients left after cultivation	Quantity of SW[3,5] – (quantity of SW × SW mineral content, July/August/September × gametophyte nutrients uptake fraction)[3,5,6,7] + (culture nutrients × gametophyte nutrients non-uptake fraction)[3]	Partial mass-balance calculations; Gametophyte nutrients non-uptake = 85% (assumption)
1,1 - Net Primary Production	Quantity of biomass generated through photosynthesis	(Gametophyte culture density × SW culture volume)[1,2,3] – (gametophyte culture density × SW culture volume × inoculation ratio)[1,2,3]	Total biomass – inoculation biomass
1,0c - Gametophyte, year (+1)	Quantity of gametophyte biomass stored for next year's culture	Gametophyte culture density[1,2] × SW culture volume[3] × inoculation ratio[3]	Constant cultivation yield assumed
1,0d - Gametophyte, losses	Quantity of gametophyte biomass falling from cultivation supports	NPP gametophyte biomass[1,2,3] – gametophyte [3]	Mass-balance calculations; loss ratio = 99.025%
1,2 – Gametophyte biomass	Quantity of gametophyte biomass settled and growing on twines	(Gametophyte population settlement on twine × twine length)[3,8] / (gametophyte biomass population × gametophyte biomass density)[9]	The gametophyte biomass density is based on assumptions; settlement ratio = 0.975%
0,1a - [P] Gametophyte, year (-1)	Quantity of P embedded in the gametophyte biomass inoculated	Gametophyte biomass inoculated[1,2,3] × *S. latissima* gametophyte P content	Gametophyte P uptake = 15% (assumption)
0,1b - [P] Culture nutrients	Quantity of P contained in the F/2 medium nutrients added to seawater	F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration[4] × SW culture volume[3] × $NaH_2PO_4 \cdot 2H_2O$ P content	P final concentration = 69.54 µmol/L F/2 medium
0,1c - [P] Seawater	Quantity of P naturally in seawater in July-August	SW culture mass[3,5] × SW P content, July/August[6,7]	
1,0a - [P] Used enriched seawater	Quantity of P left in the F/2 medium after cultivation	((SW culture mass × SW P content, July/August)[3,5,6,7] + (F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration × SW culture volume × $NaH_2PO_4 \cdot 2H_2O$ P content))[3,4] × gametophyte P non-uptake fraction	Gametophyte P non-uptake = 85% (assumption)
1,1 - [P] Net Primary Production	Quantity of P used by gametophyte during growth	((SW culture mass × SW P content, July/August)[3,5,6,7] + (F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration × SW culture volume × $NaH_2PO_4 \cdot 2H_2O$ P content))[3,4] × gametophyte P uptake fraction	Gametophyte P uptake = 15% (assumption
1,0b - [P] Gametophyte, year (+1)	Quantity of P embedded in the gametophyte stored for next inoculation	Gametophyte biomass inoculated[3] × *S. latissima* gametophyte P content	Gametophyte P uptake = 15% (assumption)
1,0c - [P] Gametophyte, losses	Quantity of P embedded in the non-settling biomass fraction	NPP gametophyte biomass P content[3,4,6,7] × gametophyte loss ratio	Loss ratio = 99.025%
1,2 - [P] Gametophyte biomass	Quantity of P embedded in the settling biomass	NPP gametophyte biomass P content[3,4,6,7] × gametophyte settlement ratio	Settlement ratio = 0.975%
2 - Sporophyte culture MFA/SFA			
0,2a - Electricity	Amount of electricity-energy required for sporophyte development	(White light power × HU × quantity)[3] + (aeration pump power × HU × quantity)[3] + (UV treatment power × HU × quantity)[3] + (climatization power × HU × quantity)[3] + (filtration system power × HU × quantity)[3,a,b]	
0,2b - Seawater	Quantity of seawater required for land cultivation in tanks	SW tank volume[3] × SW density[5,b]	Seawater 30-50m deep, near Solund, Norway
0,2c - Culture nutrients	Quantity of nutrients added to seawater to produce the F/2 medium	F/2 medium nutrient concentration[4] × SW tank volume[3] × nutrients inputs over time[3,b]	Based on standardized F/2 medium composition
2,0a - Emissions, electricity	Amount of emission-energy produced by lamps and machinery	(White light power × HU × quantity)[3] + (aeration pump power × HU × quantity)[3] + (UV treatment power × HU × quantity)[3] + (climatization power × HU × quantity)[3] + (filtration system power × HU × quantity)[3,a,b]	Thermal and kinetic energies released
2,0b - Used enriched seawater	Quantity of seawater and F/2 medium nutrients left after cultivation	Quantity of SW[3,5] – (quantity of SW × SW mineral content, July/August/September × sporophyte nutrients uptake fraction)[3,5,6,7] + (culture nutrients × sporophyte nutrients non-uptake fraction)[3,b]	Partial mass-balance calculations; Sporophyte nutrients non-uptake = 85% (assumption)
2,2 - Net Primary Production	Quantity of biomass produced through photosynthesis	Quantity sporophyte biomass[3] – quantity gametophyte biomass[3,8,9,b]	Mass-balance calculations
2,3 – Sporophyte biomass	Quantity of sporophyte biomass settled on twine and coiled on ropes	Sporophyte biomass, end process, per meter twine[3] × twine length[3,b]	
0,2a - [P] Seawater	Quantity of P naturally in seawater in September	SW tank mass[3,5] × SW P content, September[6,7,b]	
0,2b - [P] Culture nutrients	Quantity of P contained in the F/2 medium nutrients added to seawater	F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration[4] × SW tank volume[3] × $NaH_2PO_4 \cdot 2H_2O$ P content[b]	
2,0 - [P] Used enriched seawater	Quantity of P left in the F/2 medium after cultivation	((SW tank mass × SW P content, September)[3,5,6,7] + (F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration × SW tank volume × $NaH_2PO_4 \cdot 2H_2O$ P content))[3,4] × sporophyte P non-uptake fraction[b]	Sporophyte P non-uptake = 85% (assumption)
2,2 - [P] Net Primary Production	Quantity of P used by sporophyte during growth	((SW tank mass × SW P content, September)[3,5,6,7] + (F/2 medium $NaH_2PO_4 \cdot 2H_2O$ concentration × SW tank volume × $NaH_2PO_4 \cdot 2H_2O$ P content))[3,4] × sporophyte P uptake fraction[b]	Sporophyte P uptake = 15% (assumption)
2,3 - [P] Sporophyte biomass	Quantity of P embedded in the sporophyte biomass	Quantity of P in gametophyte biomass[3,4,8,9] + NPP sporophyte biomass P content[3,4,5,6,7,b]	Mass-balance calculations
3 - Deployment & growth at sea MFA/SFA			
0,3a - Fuels, transport to farm	Amount of fuels-energy required to deploy the sporophyte at sea	(((Distance H-H × RM × FT diesel consumption)[3,10] + (distance H-F × RM × SB diesel consumption)[3] + (distance H-F × RM × MB petrol consumption)) × number of trips)[3] + (deployment distance × MB petrol consumption)[3,c]	Data scaled up to a 60t WW production; deployment distance is proportional to production yield
0,3b - Fuels, maintenance	Amount of fuels-energy required to maintain the seaweed field	((Distance H-H × RM × FT diesel consumption)[3,10] + ((distance H-F × RM) + maintenance distance) × MB petrol consumption) × number of trips[3,c]	Data scaled up to a 60t WW production; 6 maintenance trips from November to April
3,0a - Emissions, transport to farm	Amount of emission-energy produced by van and boat engines	(((Distance H-H × RM × FT diesel consumption)[3,10] + (distance H-F × RM × SB diesel consumption)[3] + (distance H-F × RM × MB petrol consumption)) × number of trips)[3] + (deployment distance × MB petrol consumption)[3,c]	Thermal, chemical, and kinetic energies released
3,0b - Emissions, maintenance	Amount of emission-energy produced by van and boat engines	((Distance H-H × RM × FT diesel consumption)[3,10] + ((distance H-F × RM) + maintenance distance) × MB petrol consumption) × number of trips[3,c]	Thermal, chemical, and kinetic energies released
0,3c - Minerals uptake	Quantity of minerals uptake from seawater by biomass during growth	(Quantity of seaweed biomass × *S. latissima* DM content × *S. latissima* ash content)[3,11,12] – (quantity of sporophyte biomass × *S. latissima* DM content × *S. latissima* ash content)[3,11,12]	Based on the chemical composition of *S. latissima*
3,3 - Net Primary Production	Quantity of biomass generated through photosynthesis	Quantity of seaweed biomass[3] – quantity of sporophyte biomass[3,b]	

Table 3.5 - Continued

Flow direction & name	Flow description	Equations & sources	Additional data
3,4 – Seaweed biomass	Quantity of seaweed biomass cultivated at sea and ready for harvest	Cultivation yield, *S. latissima*[3] × cultivation surface[3]	Culture conditions: near Solund, Norway
0,3 - [P] Uptake, open seawater	Quantity of P uptake from the seawater by the biomass during growth	Quantity of P in seaweed biomass[3,11,13] – quantity of P in sporophyte biomass[3,4,5,6,7,8,9,b]	Mass-balance calculations
3,3 - [P] Net Primary Production	Quantity of P used by seaweed during growth	Quantity of P in seaweed biomass[3,11,13] – quantity of P in sporophyte biomass[3,4,5,6,7,8,9,b]	Mass-balance calculations
3,4 - [P] Seaweed biomass	Quantity of P embedded in the seaweed biomass	Quantity of seaweed biomass[3] × *S. latissima* DM content[11] × *S. latissima* P content[13]	
4 - Harvest			
0,4 - Fuels, transportation	Amount of fuels-energy required to harvest and transport the biomass	(Load-distance, pontoon deployment × RM × NabCat diesel consumption)[3,14] + ((distance H-H × RM × FT diesel consumption)[3,10] + ((distance H-F × RM + manoeuvring distance) × MB petrol consumption)[3] + (harvest hours × generator diesel consumption)[3] + (load-distance F-H × RM × NabCat diesel consumption)[3,14] + (load-distance H-DF × RM × refrigerated lorry diesel consumption))[3,15] × harvest days[c]	Manoeuvring distance proportional to yield; NabCat and lorry load-distance values account for the absence of load during H-F and DF-H transportation; 4 days to harvest 60t WW with current tech. (assumption)
4,0 - Emissions, transportation	Amount of emission-energy produced by van, boats, and truck engines	(Load-distance, pontoon deployment × RM × NabCat diesel consumption)[3,14] + ((distance H-H × RM × FT diesel consumption)[3,10] + ((distance H-F × RM + manoeuvring distance) × MB petrol consumption)[3] + (harvest hours × generator diesel consumption)[3] + (load-distance F-H × RM × NabCat diesel consumption)[3,14] + (load-distance H-DF × RM × refrigerated lorry diesel consumption))[3,15] × harvest days[c]	Thermal, chemical, and kinetic energies released
4,5 - Seaweed, 85% H_2O	Quantity of seaweed biomass harvested	Cultivation yield, *S. latissima*[3] × cultivation surface[3]	It is assumed no losses during harvest
4,5 - [P] Seaweed, 85% H_2O	Quantity of P embedded in the harvest seaweed biomass	Quantity of seaweed biomass[3] × *S. latissima* DM content[11] × *S. latissima* P content[13]	It is assumed no losses during harvest
Process 1, 2, 3, and 4 are directly based on Hortimare's seaweed farm data and logistic, near Solund. For coherence between cultivation and transformation it is assumed cultivation occur under the same conditions near Ålesund			
5 - Drying			
0,5a - Steam heat, drying	Amount of steam-heat-energy required to dry the harvest biomass	Convective dryer steam requirement[16] × quantity of seaweed biomass[3] × seaweed shrinkage ratio[11]	Requirement expressed /kg H_2O evaporated
0,5b - Electricity, drying facility	Amount of electricity-energy required to power the machinery	(Transverse slicer power × HU × quantity)[17] + (convective dryer power × HU × quantity)[16] + (climatization power × HU × quantity)[18,a,c]	HU correlated to productivity and batch size
5,0a - Emissions, steam heat	Amount of emission-energy generated using steam heat	Convective dryer steam requirement[16] × quantity of seaweed biomass[3] × seaweed shrinkage ratio[11]	Thermal and chemical energies released
5,0b - Emissions, electricity	Amount of emission-energy produced by the machinery	(Transverse slicer power × HU × quantity)[17] + (convective dryer power × HU × quantity)[16] + (climatization power × HU × quantity)[18,a,c]	Thermal and kinetic energies released
5,0c - Water evaporation	Quantity of water removed from the harvest biomass	Quantity of seaweed biomass[3] × seaweed shrinkage ratio[11]	Biomass dried from 85% to 20% humidity
5,6 - Seaweed, 20% H_2O	Quantity of seaweed biomass dried at 20% humidity level	Quantity of seaweed biomass[3] – quantity of water evaporated[3,11]	Mass-balance calculations
5,6 - [P] Seaweed, 20% H_2O	Quantity of P embedded in the dried biomass	Quantity of seaweed, 85% H_2O[3] × *S. latissima* DM content[11] × *S. latissima* P content[13]	Drying do not alter P content (assumption)
6 - Extraction			
0,6a - Diesel, transportation	Amount of diesel-energy required for dried biomass transportation	Load-distance DF-BR × lorry diesel consumption[19,c]	DF-BR = 30km (assumption)
0,6b - Heat, extraction	Amount of heat-energy required for the extraction process	Heat-energy hydrolysis & fermentation[11] + heat-energy distillation[11,d]	
0,6c - Electricity, extraction	Amount of electricity-energy required for the extraction process	Energy feedstock handling[11] + energy enzyme production[11] + energy storages & utilities[11,a,d]	
0,6d - Process water	Quantity of process water added to the biomass during extraction	Quantity process water[11,d]	
6,0a - Emissions, transportation	Amount of emission-energy produced by truck engine	Load-distance DF-BR × lorry diesel consumption[19,c]	
6,0b - Emissions, heat	Amount of emission-energy produced generated by the use of heat	Heat-energy hydrolysis & fermentation[11] + heat-energy distillation[11,d]	
6,0c - Emissions, electricity	Amount of emission-energy produced by diverse electrical machinery	Energy feedstock handling[11] + energy enzyme production[11] + energy storages & utilities[11,a,d]	
6,0d - CO_2	Quantity of CO_2 produced by fermentation	(Quantity of seaweed, 20% H_2O[3,11] + quantity process water[11]) × CO_2 production TC[11,d]	
6,0e - Ethanol	Quantity of ethanol produced by distillation	(Quantity of seaweed, 20% H_2O[3,11] + quantity process water[11]) × ethanol production TC[11,d]	
6,0f - Liquid fertilizer	Quantity of liquid fertilizer produced by extraction	(Quantity of seaweed, 20% H_2O[3,11] + quantity process water[11]) × liquid fertilizer production TC[11,d]	
6,7 - SWPC	Quantity of SWPC produced by extraction	(Quantity of seaweed, 20% H_2O[3,11] + quantity process water[11]) × SWPC production TC[11,d]	90% DM and 31.34% protein content
6,0 - [P] Liquid fertilizer	Quantity of P embedded in the extracted liquid fertilizer	Seaweed, 20% H_2O P content[3,11,13] × liquid fertilizer P TC[11]	Seghetta assumed 100% P transfer
6,7 - [P] SWPC	Quantity of P embedded in the extracted SWPC	Seaweed, 20% H_2O P content[3,11,13] × SWPC P TC[11]	Seghetta assumed 0% P transfer
7 - Transportation			
0,7 - Diesel, transportation	Amount of diesel-energy required for transportation to fish feed factory	(Load-distance BR-H × lorry diesel consumption)[20] + (load-distance H-FFF × ship diesel consumption)[21,c]	BR-H = 20km (assumption) H-FFF = 100km (assumption)
7,0a - Emissions, transportation	Amount of emission-energy produced by truck and boat engines	(Load-distance BR-H × lorry diesel consumption)[20] + (load-distance H-FFF × ship diesel consumption)[21,c]	Thermal, chemical, and kinetic energies released
7,0b - SWPC	Quantity of SWPC delivered to a fish feed producer	(Quantity of seaweed, 20% H_2O[3,11] + quantity process water[11]) × SWPC production TC[11,d]	
7,0 - [P] SWPC	Quantity of P embedded in the SPWC produced	Seaweed, 20% H_2O P content[3,11,13] × SWPC P TC[11]	Seghetta assumed 0% P transfer

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

Indications: [a]Electricity-energy flows in kilowatt-hour are systematically converted in megajoules / [b]Each flows of process 2 are multiplied by the number of tanks used simultaneously to produce a batch of 60t WW *S. latissima* / [c]Fuels were converted from volume to mass and multiplied by the corresponding fuel energy content / [d]Data from Seghetta et al. (2016) was adjusted to the smaller biomass cultivation output of this system (60t WW).

Sources: [1](Zhang et al., 2007); [2](Xu et al., 2009); [3](Hortimare BV); [4](Guillard and Ryther, 1962); [5](Encyclopædia Britannica, n.d.); [6,7](Miljødirektoratet and Havforskningssinstituttet, 2015); [8](SINTEF, J. Skjermo, personal communication, December 16th 2016); [9](Horntje, 2014); [10](Ford, 2014); [11](Seghetta et al., 2016); [12](Vilg et al., 2015); [13](Manns et al., 2014); [14](Moen Marin, n.d.); [15](Keller, 2010b); [16](Sandvik, n.d.); [17](FAM, n.d.); [18](Kide, 2016); [19](Spielmann and Scholz, 2005b); [20](Keller, 2010a); [21](Gabi software).

4 Results

The results are organized in three different sections. The first one presents the results from the SPC system generated by the MFA and SFA base models. All system flows for the base case are calculated using the import of Brazilian SPC into Norway for 2015 (Statistics Norway SSB, 2015). This choice allows for a depicting of the SPC value chain in real scale and to generate results at the macro level. The second section presents the seaweed base models. Seaweed base layer flows are calculated with a production batch of 60 t WW *S. latissima*. Although this production level does not represent the actual volume of Norwegian cultivated seaweed over a year period, it still provides a picture of a large production per today's standards (Skjermo et al., 2014). The SPC and SWPC base model results are presented in separate sections to highlight the significant differences in production levels and industry maturity. Comparative analysis of the base layers is not entirely meaningful, hence the inclusion of scenarios for comparative purposes. The third and last result section is the core of this environmental assessment. In this section, the first SPC scenario is presented and compared to scenario two in the seaweed system. The crude protein content of SPC is 62% (Skontorp et al., 2012), while the crude protein content of SWPC is roughly equal to 31% (Seghetta et al., 2016). In order to facilitate comparison, the production volumes of the two systems have been adjusted to reach protein equivalency. Accordingly, scenario one for the SPC system is based on a production of one ton of SPC imported to the feed factory gate in Norway. SWPC scenario two is based on a two-ton production transported to the feed factory gate.

MFA flows are comprised of biomass and energy while SFA flows are in units of P embedded in the MFA biomass flows. In the MFA models biomass flows are coded in green, while energy flows are presented in yellow. In the SFA models, flows of P are also displayed in green. Units are indicated in the figure captions. Finally, mass-balance verification tables are presented with each model. Energy balances were not displayed in this report as inputs are equal to outputs by design. In the SPC and SWPC MFA models certain inflows and outflows we kept out of mass-balance verifications. Because these biocomponents contains P, they are part of the SFA layer mass-balances, however, it was not possible to integrate them in an MFA mass-balance accounting for crude weight. For instance, in the soy_MFA_base model, the mineral fertilizer input (flow 0,1a) was excluded because there is no mass-balance relation between the mass of mineral fertilizer input and the quantity of *Glycine max* tissues produced.

4.1 SPC base models

4.1.1 Soy_MFA_base (Figure 4.3)

4.1.1.1 Mass flows analysis

In 2015, Norway imported 362,217 t of SPC (flow 6,0d). This production required 711,673 t (flow 3,4) of soybeans grains and 14,312 t (flow 3,0d) of soybean seeds, and generated 976,240 t (flow 3,0e) of crop residues. Each of this flows represent respectively 41,8 %, 0.84 % and 57.35 % of the total 1,702,226 t of *Glycine max* (flow 2,3) full plants cultivated for this purpose. This implies that producing 1 t of SPC requires 4.69 t of *Glycine max*, leading to a Production Efficiency Ratio (PER) of 21.28%. Harvest and extraction have the strongest adverse impact on the system PER due to the large quantities of co-products they generate. While the biomass is reduced by 57.35% after harvest, the remaining biomass is reduced again by 46% during the extraction of dried soybeans into SPC.

With an average soybean yield of 2,713 kg/ha in CW and SO Brazil, the 2015 SPC import to Norway required 1,970,247 ha of Brazilian land. This area is equivalent to 19,702 km^2, which is slightly larger than the 18,856 km2 surface area of Sør-Trøndelag county (Sør-Trøndelag fylkeskommune, 2016). Soil enrichment is a significant source of environmental impacts in agriculture (Tilman et al., 2002). The 2015 SPC production for Norway utilized 86,626 t (flow 0,1a) of mineral fertilizer, 154,675 t (flow 0,1b) of manure, and 976,240 t (flow 0,1c) of crop residues. Although brut quantities of manure and crop residues are much larger than the amount of mineral fertilizer applied, the concentration of P and nitrogen in the mineral fertilizer fraction is significantly higher than in manure and in crop residues. On average, depending on the production types and regions in Brazil, 301 kg/ha of mineral fertilizers, 50,000 kg/ha of manure, and 3,603 kg/ha of crop residues are applied to enrich soils for SPC production. Overall, the production of each SPC ton require the inputs of 0.24 t of mineral fertilizer, 0.43 t of manure, and 2.7 t of crop residues.

4.1.1.2 Primary energy analysis

The 2015 SPC imports consumed 5,336,705 GJ of primary energy. This quantity of energy represents 1.48 TWh, an amount roughly equivalent to the overall energy consumption of Trondheim’s 87,000 households in 2007 (Trondheim SmartCity, 2007). 14.73 GJ of primary energy is consumed for every ton of SPC produced. Results from the Cumulative Primary Energy Demand (CPED) analysis displayed in Figure 4.1 provide an overview of the energy requirement of each process and their proportions regarding the overall system CPED. Extraction and transport from Brazil to Norway are the two largest contributors to the CPED, requiring respectively 2,605,628 GJ (48.82%) and 1,236,564 GJ (23.17%) of energy. The energy requirements for extraction are evenly distributed between diesel for transportation and factory process energy. In Figure 4.3, these flows are respectively equal to 1,123,217 GJ (flow 0,5a) and 1,482,410 GJ (flow 0,5b). Results from the import process show that land transportation from factories to harbours is larger than the energy required to transport SPC from Brazilian harbours to Rotterdam. Land transport intra Brazil represents 510,395 GJ (flow 0,6a), mostly due to lorry transportation, while the international nautical transport requires 384,034 GJ (flow 0,6b) of energy.

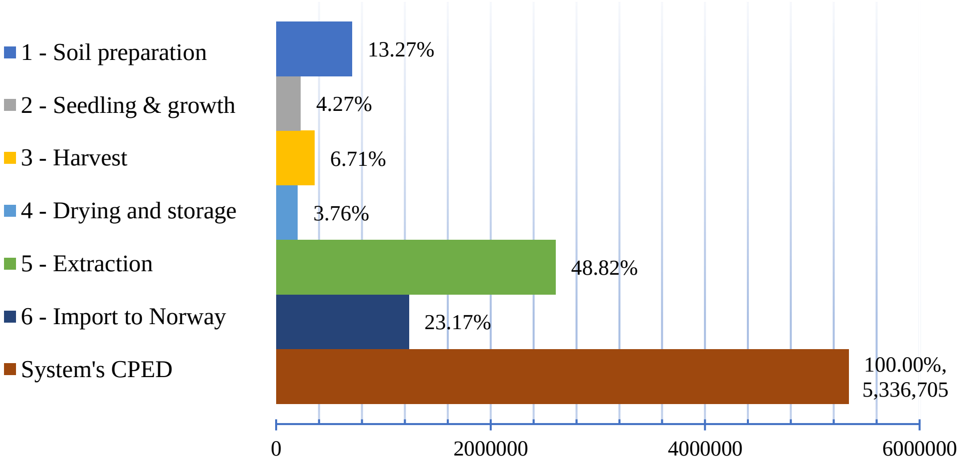


Figure 4.1: Process CPED of the soy_MFA_base model (GJ)

As shown in Figure 4.2, the SPC system relies heavily on fossil fuels. The category fossil fuel regroups oil, natural gas, and coal while non-fossil describes all other types of energy sources. Results show that 82.66% of the energy inputs are from fossil origin while 17.34% are based on non-fossil sources. These proportions represent respectively 4,411,419 GJ and 925,285 GJ of the system’s CPED. Finally, Figure 4.2 also shows that drying and extraction of soybeans are the only processes not relying partially or totally on fossil fuels.

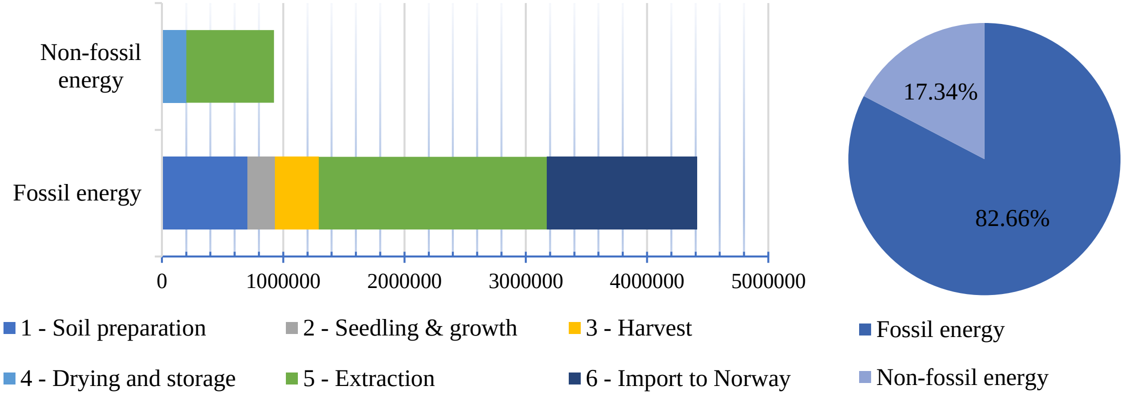


Figure 4.2: Process CPED displayed per input type; soy_MFA_base model (GJ)

The biomass-balance verification values presented in Table 4.1 all equal to zero. This means that all the soy based biomass inflows and outflows of processes two to six follow the principle of mass-conservation established in the MFA methodology.

Figure 4.3: Soy_MFA_base model

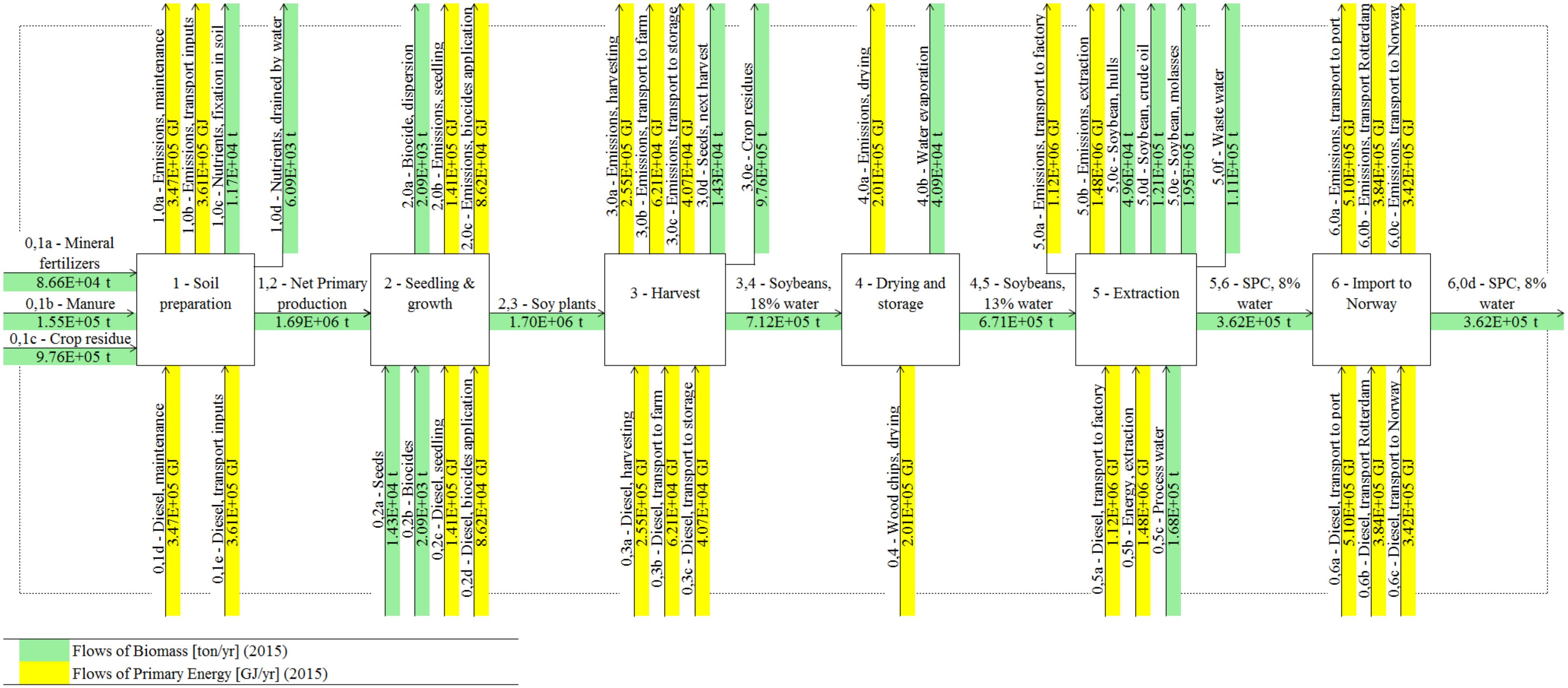


Table 4.1: Soy_MFA_base biomass-balance verification

Process	Value	Biomass-balance equation
2 - Seedling & growth	0.00E+00	(1,2 - Net Primary production) + (0,2a - Seeds) – (2,3 - Soy plants)
3 - Harvest	0.00E+00	(2,3 - Soy plants) – (3,0d - Seeds, next harvest) – (3,0e - Crop residues) – (3,4 - Soybeans, 18% water)
4 - Drying and storage	0.00E+00	(3,4 - Soybeans, 18% water) – (4,0b - Water evaporation) – (4,5 - Soybeans, 13% water)
5 - Extraction	0.00E+00	(4,5 - Soybeans, 13% water) + (0,5c - Process water) – (5,0c - Soybean, hulls) – (5,0d - Soybean, crude oil) – (5,0e - Soybean, molasses) – (5,0f - Waste water) – (5,6 - SPC, 8% water)
6 - Import to Norway	0.00E+00	(5,6 - SPC, 8% water) – (6,0d - SPC, 8% water)

Figure 4.4: Soy_SFA_base model

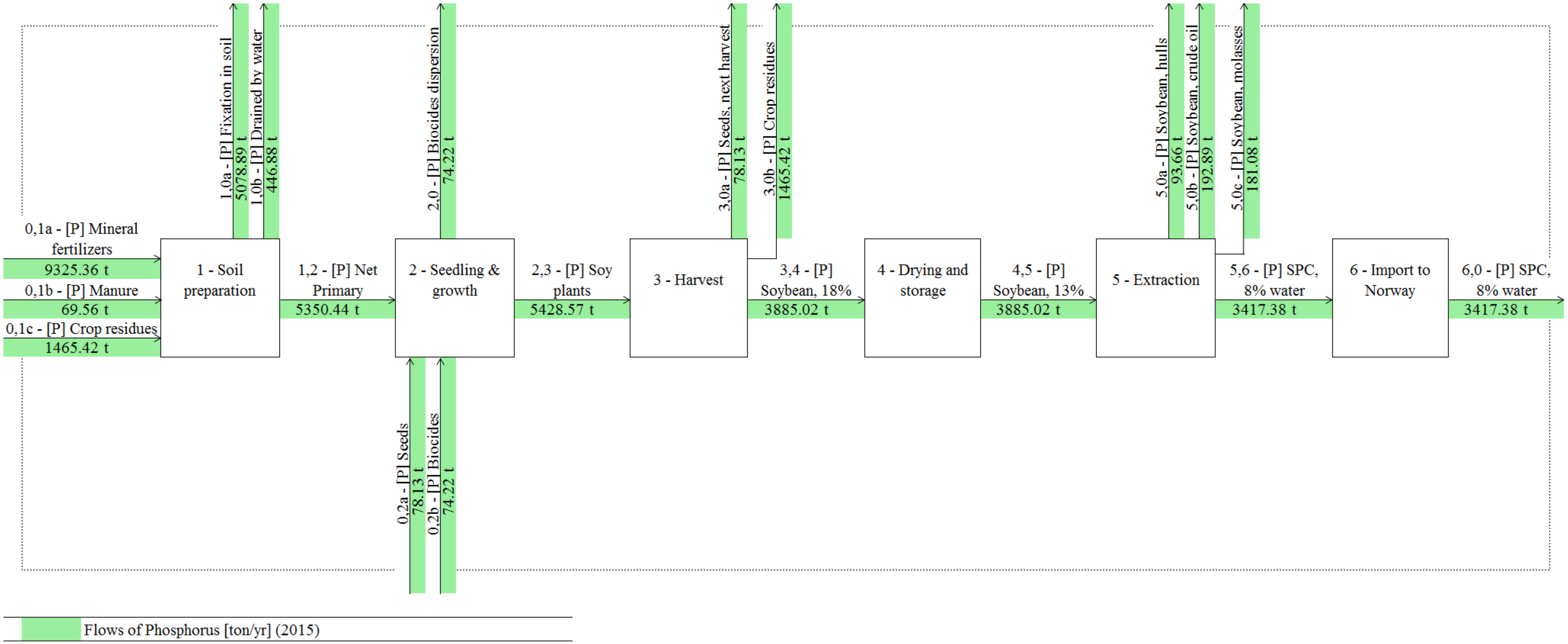


Table 4.2: Soy_SFA_base mass-balance verification

Process	Value	Mass-balance equation
1 - Soil preparation	-1.59E+01	(0,1a - [P] - Mineral fertilizer) + (0,1b - [P] Manure) + (0,1c - [P] Crop residues) – (1,0a - [P] Fixation in soil) – (1,0b - [P] drained by water) – (1,2 - [P] Net Primary Production)
2 - Seedling & growth	0.00E+00	(1,2 - [P] Net Primary Production) + (0,2a - [P] Seeds) + (0,2b - [P] Biocides) – (2,0 - [P] Biocides dispersion) - (2,3 - [P] Soy plants)
3 - Harvest	0.00E+00	(2,3 - [P] Soy plants) – (3,0a - [P] Seeds harvest) - (3,0b - [P] Crop residues) – (3,4 - [P] Soybean, 18% water)
4 - Drying and storage	0.00E+00	(3,4 - [P] Soybean, 18% water) – (4,5 - [P] Soybean, 13% water)
5 - Extraction	0.00E+00	(4,5 - [P] Soybean, 13% water) – (5,0a - [P] Soybean, hulls) – (5,0b - [P] Soybean, crude oil) - (5,0c - [P] Soybean, molasses) – (5,6 - [P] SPC, 8% water)
6 - Import to Norway	0.00E+00	(5,6 - [P] SPC, 8% water) – (6,0 - [P] SPC, 8% water)

4.1.2 Soy_SFA_base (Figure 4.4)

4.1.2.1 Phosphorus analysis

At first glance, Figure 4.4 shows that 3,417 t (flow 0.6 - [P]) of pure P were embedded in the 362,217 t (flow 0,6d) of SPC imported to Norway in 2015. In other words, there are 9.43 kg of pure P in each ton of SPC. Results from Figure 4.4 confirm that mineral fertilizers are significantly more concentrated P sources than manure and crop residues. The material inputs of 86,626 t (flow 0,1a), 154,675 t (flow 0,1b), and 976,240 t (flow 0,1c) of mineral fertilizer, manure and crop residues accounted for P inputs of respectively 9,325 t (flow 0,1a - [P]), 69 t (flow 0,1b - [P]), and 1,465 t (flow 0,1c - [P]). The Net Primary Production (NPP) flow indicates that *Glycine max* physically incorporates 5,350 t (flow 1,2 - [P]) of P while 5,078 t (flow 1,0a - [P]) ends up chemically bound in soils. The remaining 446 t (flow 1,0b - [P]) is drained by water to water bodies. Of the 5,078 t (flow 1,0a - [P]) captured by the plants, 63.87% of the P follows the SPC, while 27.38% is eventually recycled back into the soil as crop residues.

All P sources are not created equal. Mineral fertilizers are primary sources of P; they are non-renewable stocks that cannot be regenerated. However, primary P sources can be recycled through careful management of P containing co-products. These P containing co-products are known as secondary P sources. Dependence on primary P reserves is a major threat to global food production. New research is focusing on improving secondary P utilization in the technosphere, typically in the form of wastes or by-products (Cordell et al., 2009, Hamilton et al., 2015b). Figure 4.5 shows that the SPC system strongly relies on fossil P, largely because of mineral fertilizer application. This flow alone accounts for 9,325 t (flow 0,1a - [P]) of P and represent 84.68% of the total P input of 11,012 t. On the non-fossil side, crop residues alone account for 86.84% whereas the input of manure is as low as 4.12% of the total of 1,687 t of this P fraction.

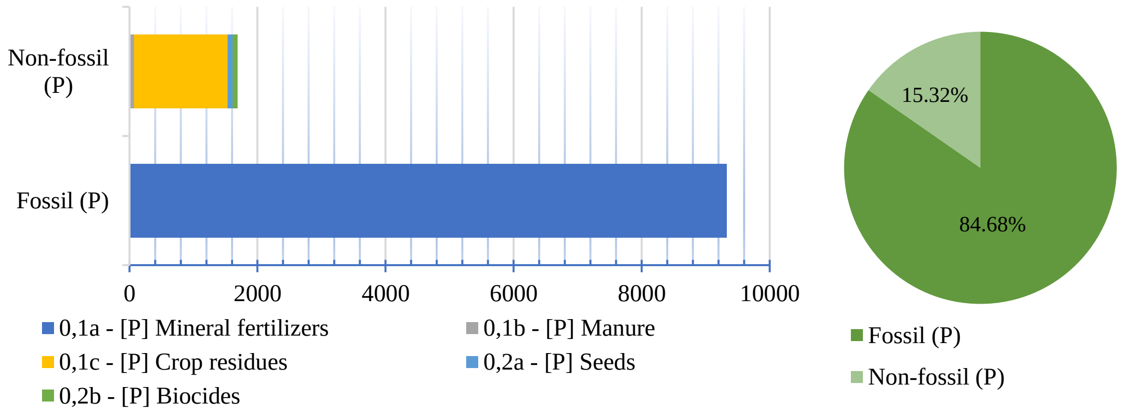


Figure 4.5: Origin of phosphorus inflow; soy_MFA_base model (t)

Analysing outflows highlight system management efficiencies and inefficiencies. The idea is to categorize each outflow based on the fate of the P inside. It is assumed that P outflows are either emitted to the biosphere where it can act as pollutant or it is emitted to the anthroposphere where it become a resource used for human, animal or plant growth. Figure 4.6 show a relative even distribution between reservoirs. Overall, 2015 SPC import generated the direct release of 5,599 t of P to the biosphere, either bounded to agricultural soils, emitted to water bodies, or spread embedded in biocides. This represent 50.78% of the total P required for this production. Furthermore, 49.22% of the P flowed in diverse form to the anthroposphere, mostly bounded to the SPC fraction or to the crop residues. This means that for each ton of SPC imported to Norway in 2015, 15.46 kg of P flowed to the anthroposphere while 14.98 kg were emitted to the biosphere.

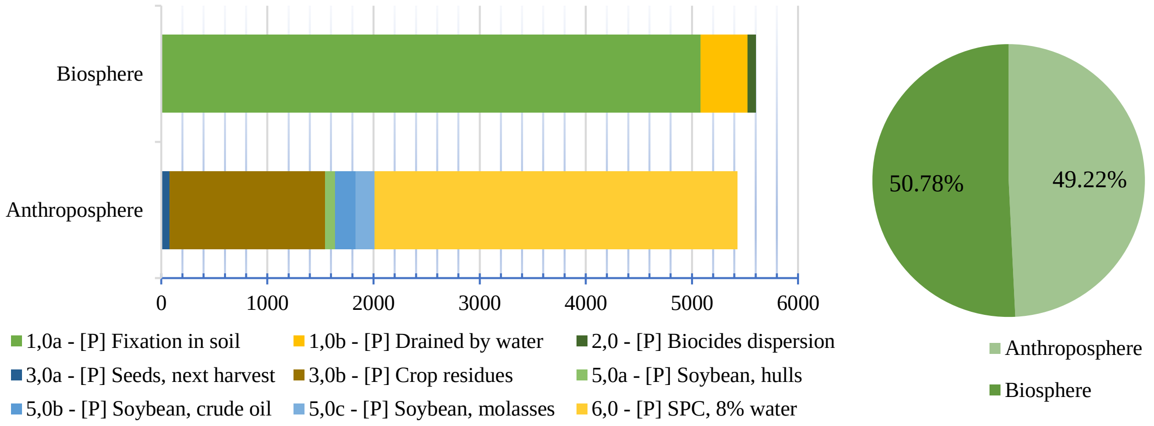


Figure 4.6: Fate of phosphorus outflow; soy_SFA_base model (t)

The soy_SFA_base model is mass balance consistent, except for soil preparation which shows a deficit of to -15.9 t of P (Table 4.2). In absolute value, this unbalance represents 0.14% of the process inputs. The impact of this error is estimated to be negligible and within the range of acceptability inherent to all data uncertainty.

4.2 SWPC base models

4.2.1 Seaweed_MFA_base (Figure 4.9)

4.2.1.1 Mass flows analysis

Primary results show that 60,000 kg (flow 4,5) WW of *S. latissima* can be transformed into 3,190 kg (flow 7,0b). During production of SWPC, 48,750 kg (flow 5,0c) of water was evaporated from the biomass and several by-products were formed during extraction. This outflow of water corresponds to the reduction of the biomass water content from 85 to 20%. 23,491 kg (flow 6,0f) of liquid fertilizer co-product was generated during extraction. However, a significant fraction of the 15,881 kg (flow 0.6d) process water are transferred during extraction to this co-product. In terms of percentages, drying alone reduces the biomass by 81.25%, while the remaining dried seaweed is further reduced and concentrated during extraction by an additional 71.64%. Consequently, the PER of the SWPC transformation stage is 5.31%. This means that 18,8 kg of WW raw material is required to produce 1 kg of SWPC. Because seawater nutrient uptake from seaweed is a very complex and volatile process, this flow was calculated based on S. latissima ash content available in the literature (Vilg et al., 2015). Consequently, 59,940 kg (flow 3,3) of *S. latissima* capture 2,427 kg (flow 0,3c) of diverse minerals from seawater. This means that the plants used 0.04 kg of minerals for each kg generated through photosynthesis. Finally, it can be highlighted that the 3,190 kg (flow 7,0b) of SWPC produce require a cultivation surface of 1 ha, which correspond to a cultivation yield of 60 t/ha, WW *S. latissima*.

4.2.1.2 Primary energy analysis

274,577 MJ of energy are required to produce 3,190 kg (flow 7,0b) of SWPC. That is equivalent to an input of 86 MJ/kg of commodity. Results clearly show that drying is the largest CPED process contributor by requiring 230,399 MJ (flow 0,5a) of steam heat and 10,073 MJ (0,5b) of electricity. The sum of these two inflows constitute 83.91% of the system CPED (Figure 4.7). Although the CPED of the other processes are relatively low compared to drying, there are several inputs that warrant closer inspection. For instance, harvesting requires as much as 15,594 MJ (flow 0,4) of various fuels, while 5,833 MJ (flow 0,1c) and 8,176 MJ (flow 0,2a) of electricity are required for gametophyte and sporophyte culture in the hatchery.

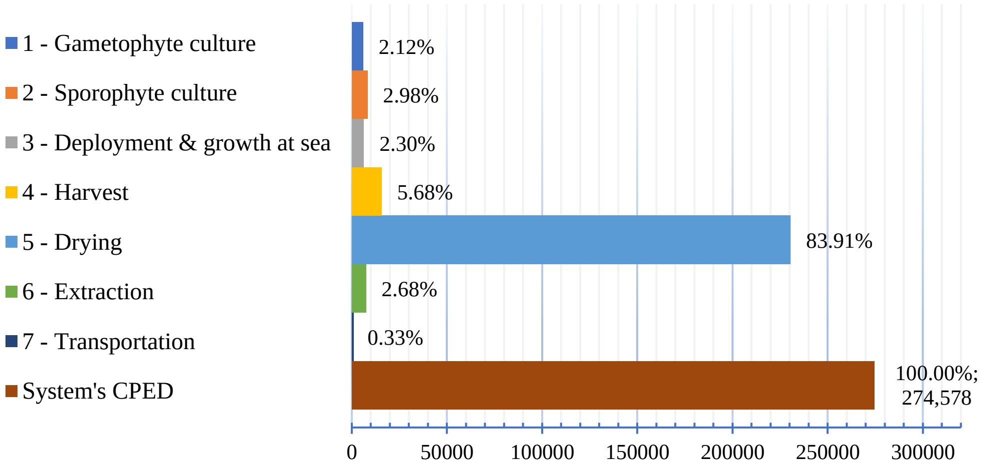


Figure 4.7: Process CPED of the seaweed_MFA_base model (MJ)

In this system, 23,387 MJ (8.52%) of energy is from fossil fuels, mostly for transportation, while 251,189 MJ (91.48%) of the energy input is non-fossil. The high percentage of non-fossil energy is largely due to the 230,399 MJ (flow 0,5a) of steam heat required for drying. This energy flow is considered to be non-fossil due to the assumption that the steam heat was generated using a Norwegian electricity mix heavily supplied by hydropower. For more information on this assumption, please see the "methods" chapter, section "assumptions", in "Table 3.2". The other energy inflows categorized as non-fossil are also inflows of electricity (Figure 4.8). Gametophyte & sporophyte culture, as well as extraction are processes relying mostly on electricity. On the other hand, transportation processes rely on fossil fuels such as diesel and petroleum (MacKenzie and Walsh, 1990). In this category, the harvest process accounts for 15,594 MJ (flow 0,4) of the 23,387 MJ, corresponding to 66.68% of the system fossil fuel consumption.

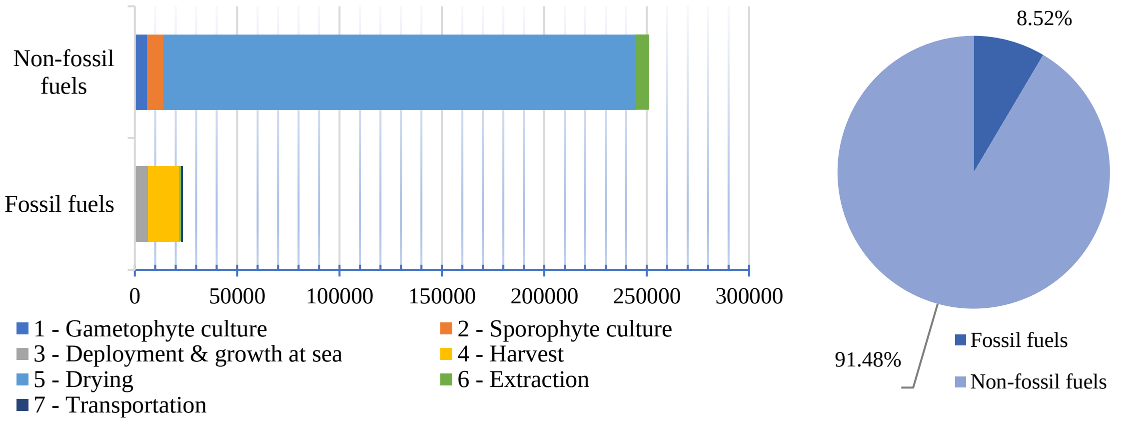


Figure 4.8: Process CPED displayed per input type; seaweed_MFA_base model (MJ)

Mass-balance consistency is verified in processes two to seven (Table 4.3). There is a slight unbalance in the gametophyte culture process. The unbalance of process one is equal to 3.12E-17 kg which means that the sum of the inflows is slightly larger than the sum of the outflows. This difference only represents 1.30E-14% of the inputs subject to mass-balance calculations. The impact of this error is estimated to be negligible and within the range of acceptability inherent to all data uncertainty.

Figure 4.9: Seaweed_MFA_base model

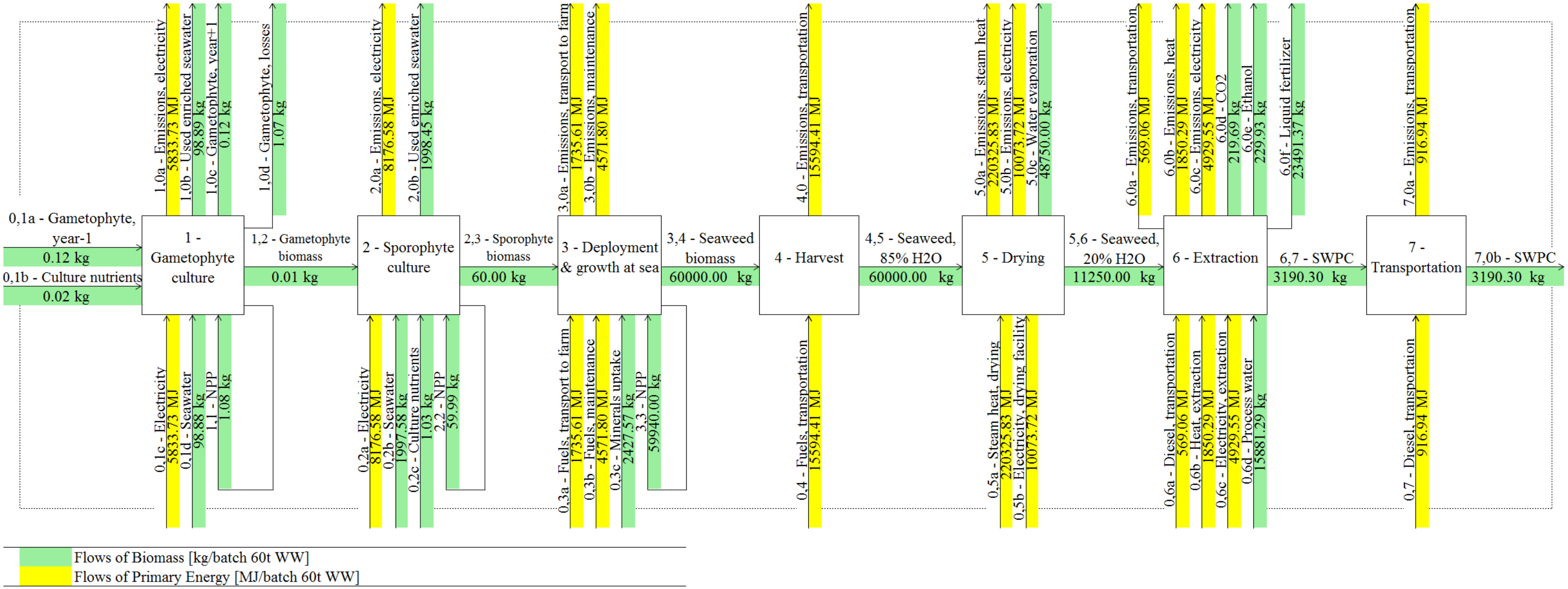


Table 4.3: Seaweed_MFA_base biomass-balance verifications

Process	Value	Biomass-balance equations
1 - Gametophyte culture	3.12E-17	(0,1a - Gametophyte, year-1) + (1,1 - NPP) – (1,0c - Gametophyte, year+1) – (1,0d - Gametophyte, losses) – (1,2 - Gametophyte biomass)
2 - Sporophyte culture	0.00E+00	(1,2 - Gametophyte biomass) + (2,2 - NPP) – (2,3 - Sporophyte biomass)
3 - Deployment & growth at sea	0.00E+00	(2,3 - Sporophyte biomass) + (3,3 - NPP) – (3,4 - Seaweed biomass)
4 - Harvest	0.00E+00	(3,4 - Seaweed biomass) – (4,5 - Seaweed, 85% H_2O)
5 - Drying	0.00E+00	(4,5 - Seaweed, 85% H_2O) – (5,0c - Water evaporation) – (5,6 - Seaweed, 20% H_2O)
6 - Extraction	0.00E+00	(5,6 - Seaweed, 20% H2O) + (0,6d - Process water) – (6,0d - CO2) – (6,0e - Ethanol) – (6,0f - Liquid fertilizer) – (6,7 - SWPC)
7 - Transportation	0.00E+00	(6,7 - SWPC) – (7,0b - SWPC)

Figure 4.10: Seaweed_SFA_base model

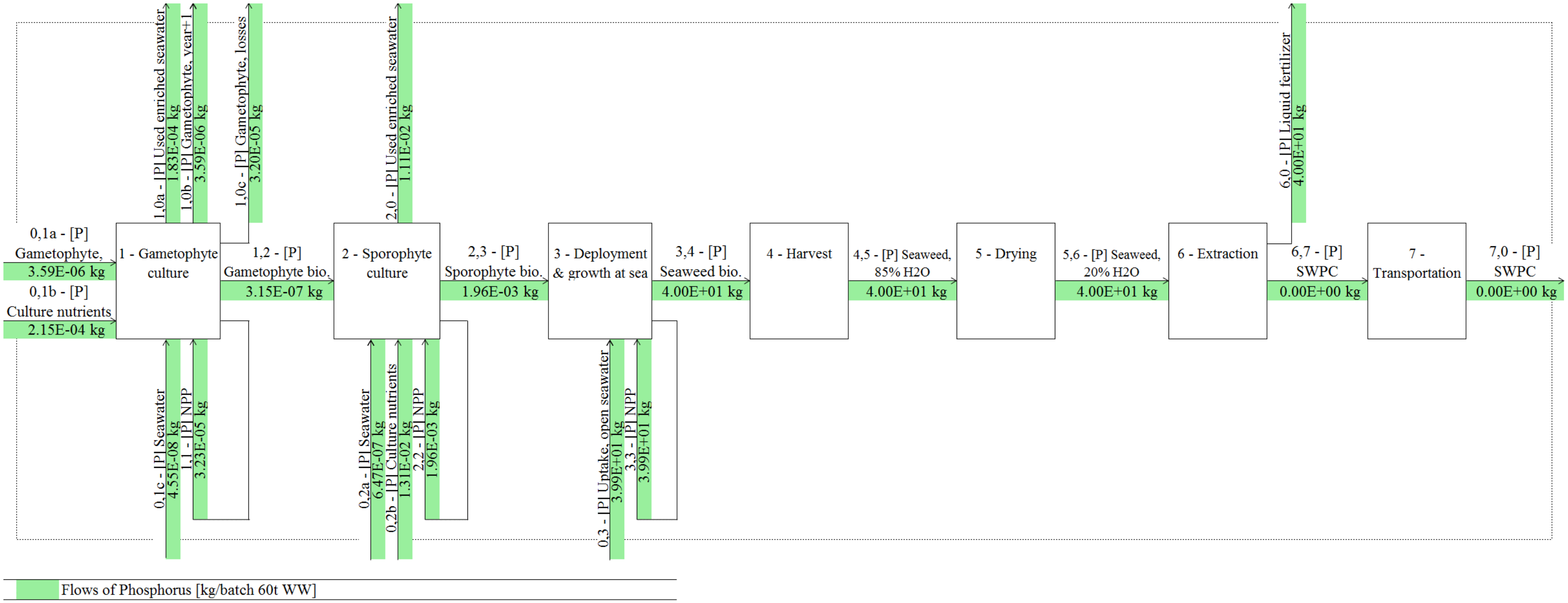


Table 4.4: Seaweed_SFA_base mass-balance verifications

Process	Value	Mass-balance equations
1 - Gametophyte culture	2.17E-20	(0,1a - [P] Gametophyte, year-1) + (0,1b - [P] Culture nutrients) + (0,1c - [P] Seawater) – (1,0a - [P] Used enriched seawater) – (1,0b - [P] Gametophyte, year+1) – (1,0c - [P] Gametophyte, losses) – (1,2 - [P] Gametophyte biomass)
2 - Sporophyte culture	0.00E+00	(1,2 - [P] Gametophyte biomass) + (0,2a - [P] Seawater) + (0,2b - [P] Culture nutrients) – (2,0 - [P] Used enriched seawater) – (2,3 - [P] Sporophyte biomass)
3 - Deployment & growth at sea	0.00E+00	(2,3 - [P] Sporophyte biomass) + (0,3 - [P] Uptake, open seawater) – (3,4 - [P] Seaweed biomass)
4 - Harvest	0.00E+00	(3,4 - [P] Seaweed biomass) – (4,5 - [P] Seaweed, 85% H_2O)
5 - Drying	0.00E+00	(4,5 - [P] Seaweed, 85% H_2O) – (5,6 - [P] Seaweed, 20% H_2O)
6 - Extraction	0.00E+00	(5,6 - [P] Seaweed, 20% H_2O) – (6,0 - [P] Liquid fertilizer) – (6,7 - [P] SWPC)
7 - Transportation	0.00E+00	(6,7 - [P] SWPC) – (7,0 - [P] SWPC)

4.2.2 Seaweed_SFA_base (Figure 4.10)

4.2.2.1 Phosphorus analysis

According to the assumptions and biorefinery extraction techniques of Seghetta et al. (2016), the P in seaweed biomass is entirely transferred to the liquid fertilizer fraction. Consequently, 100% of the P input to the extraction process follow the liquid fertilizer fraction (flow 6,0 - [P]) while 0% ends up in the SWPC commodity (flow 7,0 - [P]). 60,000 kg of *S. latissima* (flow 4,5) contains only 39.95 kg (flow 3,4 - [P]) of pure P nearly all derived from the seawater. In other words, 1.5 t tons of cultivated *S. latissima* contains 1 kg of P. Results show that P inflows and outflow related to the hatchery process have minor effects on the overall production of 60 t WW *S. latissima*. For instance, inflows of P required for gametophyte cultivation only account for 0.0002 kg (flow 0,1a - [P] + 0,1b - [P] + 0,1c - [P]) while outflows generated during sporophyte culture represent as little as 0.013 kg (flow 2,0 - [P] + 2,3 - [P]) of P. On the other hand, the uptake of P by the plants during growth at sea is by far the most significant input of the system with 39.94 kg (flow 3,3 - [P]) of P captured over a growth cycle spanning approximately 7 months.

The analysis of the model inflows (Figure 4.11) clearly demonstrates that the SWPC value chain does not rely on fossil P. From the overall model input of 39.96 kg of P, only 0.013 kg is of fossil origin while 39.94 kg are inputs from non-fossil sources. These values represent respectively 0.03% and 99.97% of the total inputs. Mariculture, such as this system with *S. latissima* does not require mineral fertilizer or biocides. The only source of fossil P employed in this production system originates from nutrients added to seawater during gametophyte and sporophyte culture. Each of these flows represent respectively 0.0002 kg (flow 0,1b - [P]) and 0.013 kg (flow 0,2b - [P]).

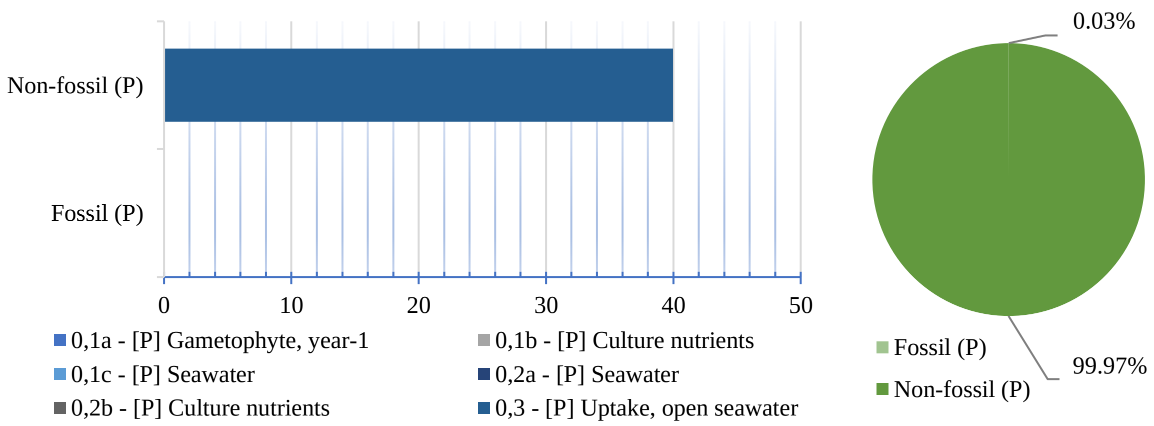


Figure 4.11: Origin of phosphorus inflows; seaweed_SFA_base (kg)

The output analysis show that as much as 99.97% of the P of this system is emitted to the anthroposphere while only 0.03% flows out to the biosphere (Figure 4.12). Values from the input and output analysis are corresponding. In fact, the fossil P inputs to the system (flows 0,1b - [P] + 0,2b - [P]) corresponds to biosphere outflows (flows 1,0a - [P] + 2,0 - [P]) while the outflow to the anthroposphere (flow 6,0 - [P]) can be tracked down to a non-fossil P origin (flow 0,3 - [P]). This illustrate the key capacity of seaweed to transfer P from the biosphere to the anthroposphere. This transfer occurs when the plant capture P during photosynthesis (flow 0,3 - [P]) and when this P is recovered through extraction of the biomass into liquid fertilizers (flow 6,0 - [P]). Through this commodity, the P can re-enter the anthroposphere and be employed for food or feed production again.

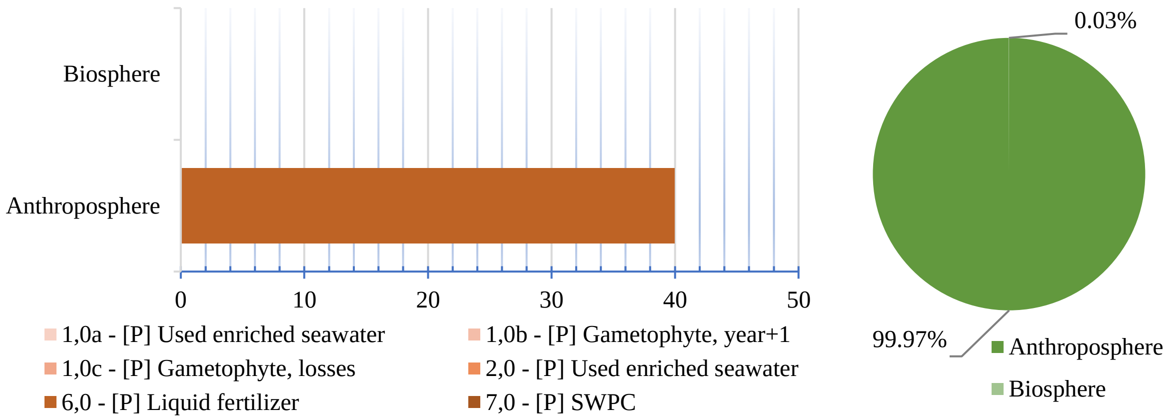


Figure 4.12: Fate of phosphorus outflows; seaweed_SFA_base (kg)

The seaweed_SFA_base P mass-balance verification shows that processes 2 to 7 are balanced while process one is slightly off (Table 4.4). This imbalance was inherited from the seaweed_MFA_base model and the conclusion is similar: an imbalance of 2.17E-20 kg represents only 9.91E-15% of the process P inputs and can therefore be neglected.

4.3 SPC vs SWPC

One of the main goal of this thesis is to compare specific environmental impacts of SPC and SWPC. In this section, the soy scenario 1 models are presented and compared to the seaweed scenario 2 models. Because the main function of the SPC and SWPC commodities is to provide crude protein for animal nutrition, 1 t of SPC at 62% CPC is compared to 2 t SWPC at 31.34% CPC. This insure crude protein equivalency between the two products. Each of the MFA/SFA scenarios are derived from the base models with identical flows and processes. Due to the similar structure of the models and to avoid over presenting similar figures in this report, the S1 SPC and S2 SWPC models are displayed in the appendix section. Appendix A and Appendix

B contain models soy_MFA_S1 and soy_SFA_S1 while Appendix C and Appendix D contains models seaweed_MFA_S2 and seaweed_SFA_S2.

4.3.1 MFA models: S1 vs S2

4.3.1.1 Mass-flow analysis

Results from the MFA models showed that 1,000 kg of SPC (flow 6,0d) can be produced from 4,699 kg of *Glycine max* (flow 2,3) while 2,000 kg of SWPC (flow 7,0b) requires an input of 37,614 kg of *S. latissima* WW. The transformation of *Glycine max* into SPC generates a PER of 0.21, while the transformation of *S. latissima* to SWPC demonstrates a PER as low as 0.0531. In other words, protein concentrate produced through the SPC value chain is approximately four times more efficient than the current SWPC value chain. To calculate the transformation PER of each system, the production efficiency of harvesting, drying and extraction were summed up. Results show that although *S. latissima* displays a superior harvesting efficiency than *Glycine max* (respectively of 100% and 42.03%), soybeans exhibit much higher efficiencies through the drying and extraction processes. This difference of PER is largely due to the difference of water content in the respective biomasses. During the drying process, the humidity in soybeans is reduced from 18% (flow 3,4) to 13% (flow 4,5) while seaweed is dried from 85% (flow 4,5) to 20% (flow 5,6). In addition, extraction between the two raw materials is very different. While 1,851 kg dried soybeans (flow 4,5) input to extraction allows a production of1 t SPC, as much as 7,052 kg of dried seaweed (flow 5,6) is required to produce 2 t SWPC. On the other hand, each of these plants have remarkably different cultivation yields.

In Brazil, the average yield of *Glycine max* cultivated in the SO and CW regions is equal to 6,360 kg/ha while in Solund, the seaweed farm yield reach an output of 60,000 kg/ha. Adjusted to the dry matter content, the respective cultivation yields become 3,985 kg/ha and 5,642 kg/ha. Consequently, *S. latissima* has a cultivation yield 1.41 times larger than *Glycine max*. Finally, a comparison of cultivation inflows shows that 1 t of SPC requires 239 kg of mineral fertilizer (flow 0,1a), 427 kg of manure (flow 0,1b), and 2,695 kg of crop residues (flow 0,1c), while 2 t of SWPC require 0.65 kg of F/2 medium nutrients (flow 0,1b + 0,2c) and 1521 kg of seawater minerals (flow 0,3c).

4.3.1.2 Primary energy analysis

The primary energy results show major differences between the two production systems. Figure 4.13 and Figure 4.14 highlight that 1 t of SPC require 14,733 MJ of primary energy while 2 t of SWPC require a tremendous 172,133 MJ input. This means that to produce the same functional unit from different sources, the SWPC commodity requires 11.68 times more primary energy than producing SPC.

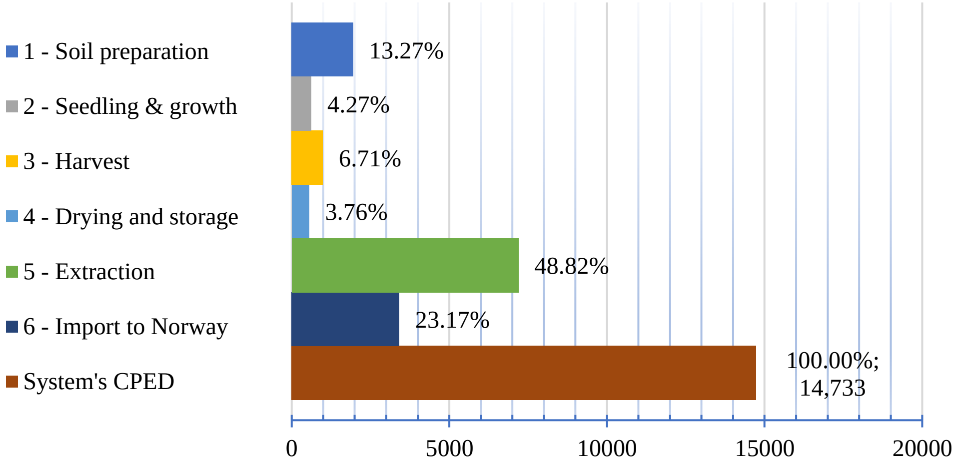


Figure 4.13: Process CPED of the soy_MFA_S1 model (MJ)

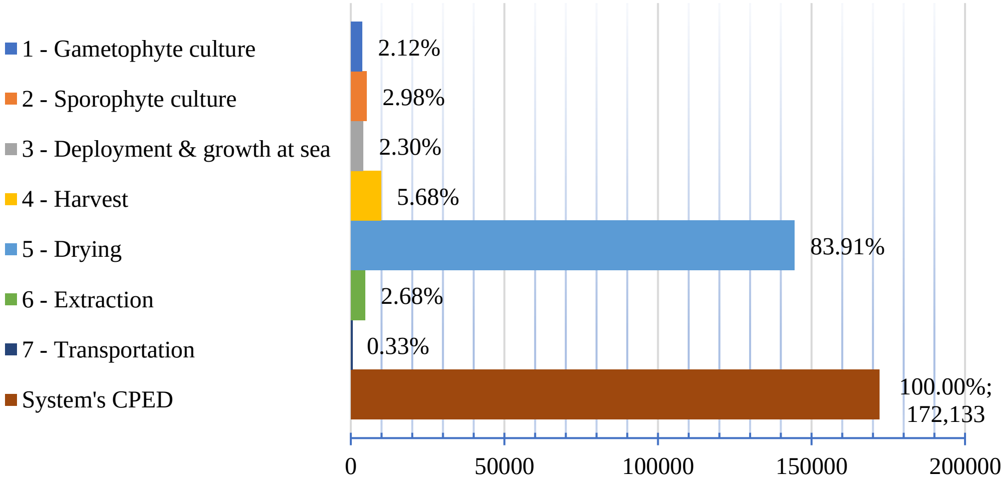


Figure 4.14: Process CPED of the seaweed_MFA_S2 model (MJ)

The distribution of the CPED per process based on the energy source type show that the SPC and the SWPC system have opposite energy profiles (Figure 4.15 and Figure 4.16). The results clearly show that the SPC system relies mainly on primary energy from fossil origin while the SWPC value chain require mostly non-fossil primary energy, especially from electricity. For the SPC system the ratio of fossil/non-fossil is 82.66%/17.34%, while the corresponding ratio for the SWPC system is 8.52%/91.48%. However, taking into consideration the large difference in total energy demand between the two commodities, the 14,661 MJ (8.52%) fossil fuel required to produce 2 t SWPC equals approximately the 14,733 MJ total primary energy required for manufacturing 1 t of SPC. In the soy S1 system, soil preparation, extraction, and import to Norway are the processes requiring most fossil fuels. In the seaweed S2 system, deployment at sea and harvest are the biggest consumers of fossil energy. These results indicate that logistics and transport processes requiring tractors, trucks, ships, or trains are drivers of fossil fuel consumption in both systems, while processes not involving transportation can more easily rely on non-fossil energy sources such as electricity and bioenergy.

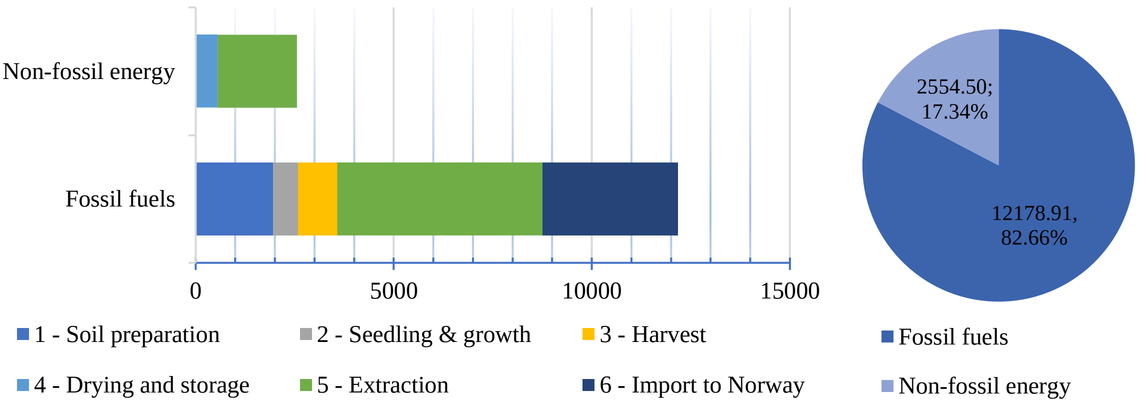


Figure 4.15: Process CPED displayed per input type; soy_MFA_S1 model (MJ)

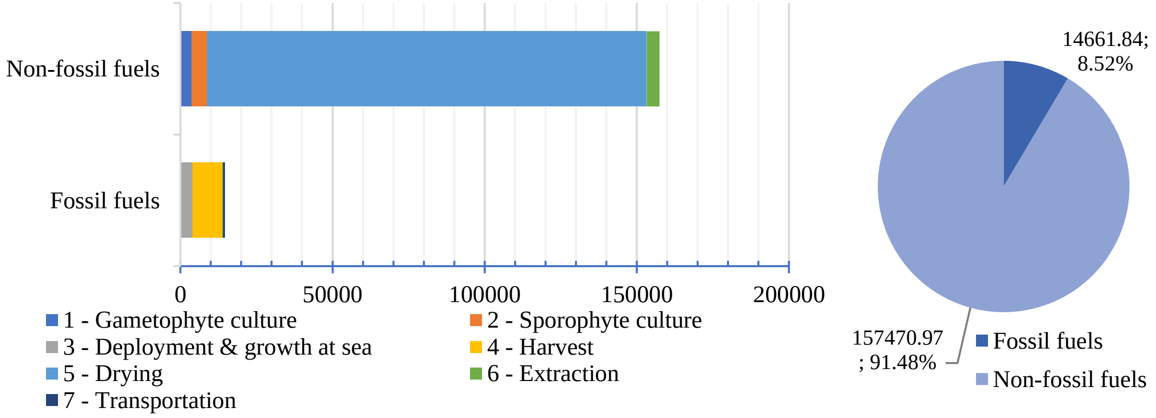


Figure 4.16: Process CPED displayed per input type; seaweed_MFA_S2 (MJ)

The soy_MFA_S1 model is mass-balance consistent (Appendix A). Results indicates imbalances in process 1 and 6 of the seaweed_MFA_S2 model (Appendix B) representing respectively 1.39E-17 kg and 2.05E-12 kg. Because these values are so small compared to the system flows, the impact of this error is estimated to be negligible and within the range of acceptability inherent to all data uncertainty.

4.3.2 SFA models: S1 vs S2

4.3.2.1 Phosphorus analysis

Results highlight that a significant fraction of the P in the SPC value chain follows the SPC fraction, while the totality of the P in the *S. latissima* ends up in a co-product. Consequently, the outflow of SWPC (flow 6,7 - [P] and 7,0 - [P]) does not contain any P. The liquid fertilizer co-product from SWPC production contains 25.05 kg (flow 6,0 - [P]) of pure P for every 2 t SWPC manufactured while SPC concentrate contains 9.43 kg (flow 6,0 - [P]) of P for each ton of SPC produced (Appendix C & Appendix D). Although not entirely meaningful to compare primary products to co-products, the comparison does reveal a valuable by-product stream (liquid fertilizer) that provides a net P flow to agricultural land by transferring non-primary P from a marine environment to terrestrial crop production.

The input analysis reveals that, 30.4 kg of total P inputs are 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. A quick look at Figure 4.17 & Figure 4.18 show that, the SPC and SWPC system have an opposite P input profile. In the SPC model, 84.68% come from fossil P sources while only 15.32% come from non-fossil ones. In the SWPC model, the distribution is reversed. Out of the total input 99.97% and 0.008 kg 0.03% come respectively from non-fossil and fossil sources.

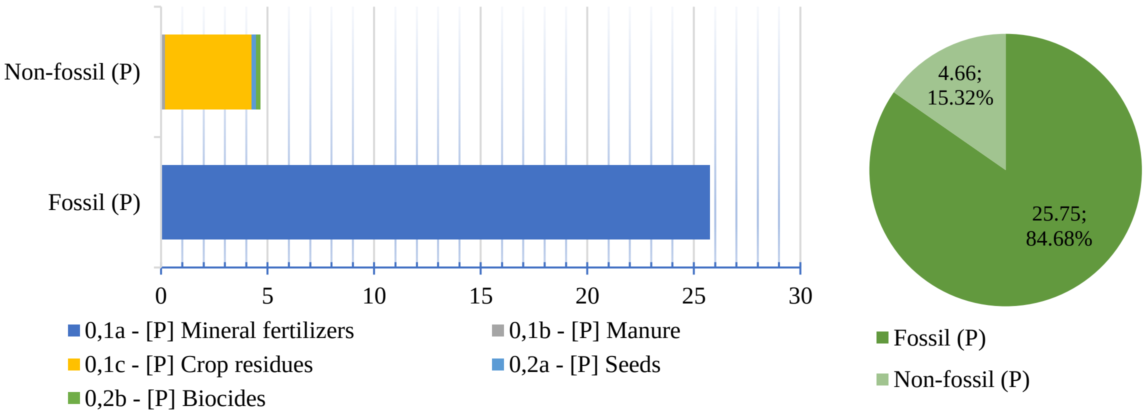


Figure 4.17: Origin of phosphorus inflow; Soy_SFA_S1 (kg)

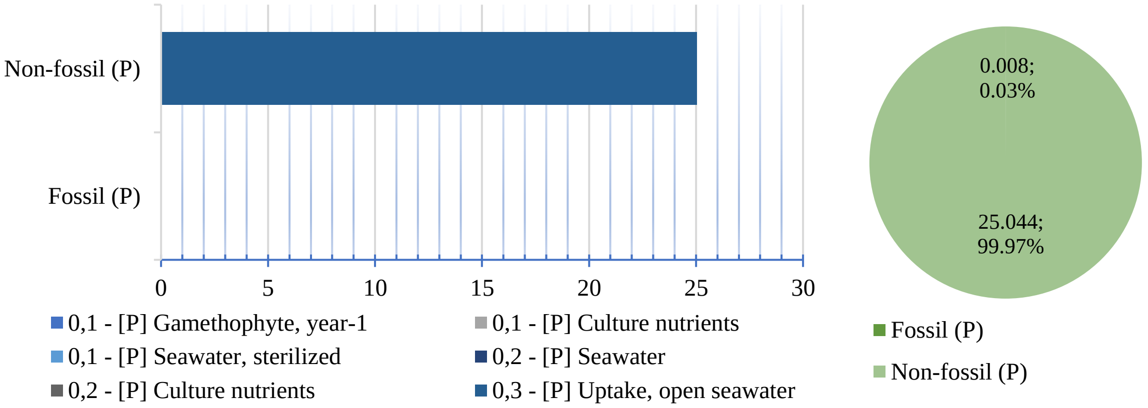


Figure 4.18: Origin of phosphorus inflow; Seaweed_SFA_S2 (kg)

P output analysis classifies P outflows of each system based on the assessed destination of the corresponding P fraction. The SPC analysis show that 50.78% of the P is emitted to the biosphere while 49.22% reach the anthroposphere (Figure 4.19). This means that the production of 1 t of SPC imply the displacement of 15.46 kg of P to the biosphere while 14.99 kg will be recovered in different forms in anthroposphere systems. The SWPC system output analysis show a different profile (Figure 4.20). In this system, the output to the anthroposphere is as high as 99.97%, while as low as 0.03% are emitted to the biosphere throughout the production process. This means that for each 2 t SWPC produced, 25.04 kg are transferred to the anthroposphere while only 0.00014 kg are emitted to the biosphere. Detailed analysis show that in the SPC system the outflows accounting for most emissions to the anthroposphere are the crop residues (flow 3,0b - [P]) and the SPC fraction (flow 6,0 - [P]) while those generating the largest emissions to the biosphere are P fixation in soil (flow 1,0a - [P]) and P drained by water (flow 1,0b - [P]). In comparison, in the SWPC system, the only significant outflow is the liquid fertilizer fraction (flow 6,0 - P) transferring P to the anthroposphere.

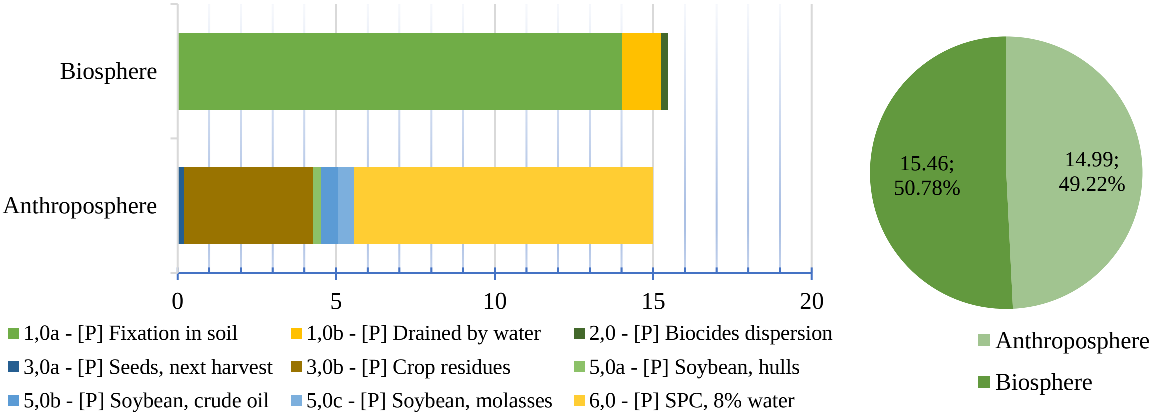


Figure 4.19: Fate of phosphorus outflow; soy_SFA_S1 model (kg)

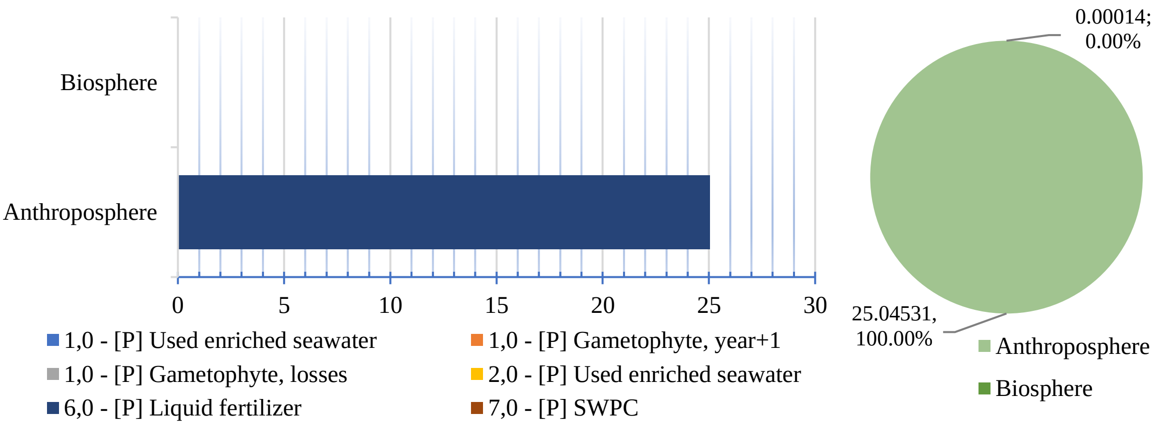


Figure 4.20: Fate of phosphorus outflow; seaweed_SFA_S2 model (kg)

Results show one inconsistency equal to -4.38E-02 kg in the soil preparation process of the soy_SFA_S1 model (Appendix C). This deficit is inherited from the soy_SFA_base model (Table 4.2) and represent only 1.30E-14% of the inputs subject to mass-balance calculations. In the seaweed_SFA_S2 model two inconsistencies equal to -4.98E-21 kg and 1.73E-18 kg can be respectively found in process 1 & 2 (Appendix D). They represent 3.62E-15% and 2.12E-14% of their respective process cumulative inputs. In both systems, the impacts of these errors are estimated to be neglectable and within the range of acceptability inherent to data uncertainty.

5 Discussion

5.1 Implications of primary energy footprints

5.1.1 Actual performances

The results show that for similar CPC, producing Norwegian SWPC requires 11.68 times more primary energy than importing Brazilian SPC to Norway. This considerable difference in CPED is a serious competitive limitation for the SWPC commodity. A higher primary energy footprint between two competing products generally leads to a poorer sustainability profile and also likely higher production costs (Science for Environment Policy, 2015).

5.1.2 Influences of value chains

A multitude of factors influence the primary energy footprint results of each commodity. In this study, maturity and scale had a real impact on the outcome results. Cultivation methods for SPC production have been optimized over decades. Selective breeding of soy varieties increased protein content and yields (Mahmoud et al., 2006, Koester et al., 2014). Over the last 20 years, the Brazilian food industry enhanced SPC production processes and supply chain organization (Goldsmith, 2008). The SWPC system does not benefit from a similar industrial maturity. The introduction section demonstrated that the seaweed cultivation industry is young, species selection is just starting, process optimization is still undergoing, and transformation has yet to be developed at an industrial scale (Skjermo et al., 2014). Large scale cultivation enables economies of scale for both transportation and transformation processes. For instance, a 50,000 Deadweight Tonnage (dwt) transatlantic ship consumes as little as 0.003 kg of fuel per Ton-Kilometer (tkm) while the 40-dwt NabCat workboat used by Hortimare for seaweed harvest consumes 0.45 kg/tkm of diesel. Consequently, the NabCat boat consumes 150 times more fuel than the transatlantic ship for each ton-kilometres transported. Similar effects can be observed in the industry. Like most young industries with growth potential, the seaweed industry is expected to eventually reduce energy consumption through economies of scale and process optimization in correlation with increasing production capacities (Rasmussen, 2013).

5.1.3 Structural improvement perspectives

Although the current fossil fuel footprint of the SWPC system is higher in than for the SPC value chain, when broken down into relative inputs, SWPC appears more sustainable. As a fraction of total energy use, the primary energy demand profile of SWPC is based on 91.48% non-fossil fuels while SPC production has an 82.68% reliance on fossil fuels. This means that a much larger fraction of processes in the SWPC system can utilize non-fossil energy inputs such as electricity. Processes capable of utilizing electricity over fossil fuels can improve a system's environmental performance when renewable and low-carbon energy sources are a major part of the electricity mix, as is the case in Norway with hydropower. 68.45% of the primary energy in the SPC system is allocated to transportation, while this proportion goes down to 6.85% in the SWPC system. The main advantage of the SPC system, its maturity, becomes a challenge to sustainable improvement opportunities due to the longstanding system structure, specifically a dependence on fossil based engines for powering tractors, trucks, trains, and ships. Although, Brazilian authorities promote the use of biofuels in tractors and trucks, global transportation systems are still highly dependent on diesel and heavy fuels (Zilio et al., 2015). Because new fossil-fuel free technology replacing thermal engines is not part of the IPCC suggested mitigations actions, these transport processes are not likely to be converted to clean energy anytime soon (Sims R. and Lah, 2014). Perhaps the lowest hanging fruit in the SPC value chain is reducing lorry transport (0.04 kg/tkm) with railway and waterway transports (0.01 kg/tkm).

5.1.4 Enhancing the SWPC system

Seaweed is highly sensitive to microbial activity due to its very high water content (85%) and must be preserved in some manner shortly after harvest. In terms of logistics and fuel consumption, transporting biomass with 85% water is not desirable over long distances with large quantities. Drying is an excellent way to quickly stabilize the biomass and is a common method to reduce weight during transport. For instance, fruit juices from concentrate are dehydrated before transoceanic passage and are rehydrated once the product reaches its destination (Keshani et al., 2010). Nevertheless, the primary energy demand of macroalgae dehydration is tremendous. The amount of steam required to dry the wet seaweed biomass is by far the major driver of the SWPC primary energy footprint. Drying the 37,614 kg (flow 4,5) of macroalgae required to produce 2 t of SWPC necessitates as much as 138,122 MJ (flow 0,5a) of steam energy (Appendix B). This flow alone represents 80.24% of the system CPED. Improving or replacing the drying process represents a major opportunity to reduce the SWPC primary energy footprint.

Silage is an interesting alternative to drying that utilizes anaerobic lactic fermentation to chemically stabilize the biomass by reducing the pH. Primary energy demand is expected to be very low for the fermentation portion of this process. However, as mentioned previously, transporting wet biomass over large distances will lead to an unknown amount of emissions from fossil fuels that must be considered as a trade-off. The second uncertainty of this method is the unknown impact on biomass nutrient composition. Though ensiling has been used in agriculture since antiquity, its application to seaweed and effect on nutritional profile is not represented in the available literature. Ensiling is a cheap, effective technique for preventing spoilage and can be performed in large, almost continuous batches (Hortimare BV, F.V.D. Heuvel, personal communication, December 8th 2016). More research and optimization protocols are needed before ensiling becomes a standard conservation treatment for seaweed, however the method show considerable promises.

Compacting is another method that warrants consideration. By compressing the biomass just after harvest, a fraction of the water can be removed from the biomass using very little energy. This method could also be performed before ensiling or just before drying to improve transport and logistics. However, compression will also alter the structure of the biomass, and may produce a stream of soluble by-products in the wastewater

Optimizing the drying process is another alternative. For instance, the convective belt dryer used in the SWPC models was selected based on feasibility characteristics more than efficiency and optimization. These dryers are commonly used in the food industry for fruit and vegetable dehydration. One advantage is their capacity to use waste heat via steam as a direct input, however the strengths and weaknesses of this technology compared to others has not been systematically assessed. There are, for instance technologies such as freeze-drying and microwave drying that might be better adapted and more efficient to use on seaweed biomass. Another possibility is drying the seaweed biomass just after harvest on specially designed ships. Such a process has major logistical advantages, but until a prototype is created, it will be hard to assess trade-offs between land and sea based drying.

Secondary or waste heat is produced in large quantities in Norwegian industry (Enova, 2009), especially on the Western coast of Norway. Utilizing waste or secondary heat improves the environmental profile of the utilizing process and overall system by replacing primary heat through an LCA method called allocation (ISO 14040, 2006) In PROMAC, a waste incineration combined heat and power plant is used as a case study. The Tafjord facility in Ålesund in Western Norway has 22.5 GWh of surplus energy that could effectively recovered and used to dry seaweed biomass during the summer months of June and July (SINTEF Ocean, Tom Nordtvedt, personal communication, December 22nd 2016). This means that during this two-month period, the 22,058 t of seaweed needed to produce 1,172 t of SWPC could be dried with secondary heat from the waste incineration plant. If the synergy between waste incineration and seaweed drying can be established, it could potential reduce the SWPC system primary energy footprint by 138,122 MJ, bringing the system CPED down to 34,010 MJ to produce 2 t of protein concentrate. This is a tremendous reduction of 80.24%. which means that producing SWPC will then require 2.3 times more primary energy instead of the 11.68 times more originally. Such industrial synergies are real world example of how circular bioeconomy can be accomplished in Europe and in Norway (European Commission, 2014b, The Research Council of Norway, n.d.).

Some seaweed producers choose to bypass the sporophyte culture process and significantly reduce the energy use in the hatchery through direct seeding. Instead of wrapping twine around sea ropes, gametophytes are glued directly onto the culture ropes. Unformal description of Japanese seaweed cultivation methods indicates that direct seeding is commonly used in this country (Millard, n.d.). This method reduces the primary energy footprint by 5,125 MJ (flow 0,2a) (Appendix B).

5.1.5 Future competitiveness

Assuming the primary energy demand of SPC remain equivalent (or slightly decreases) and the SWPC value chain utilizes waste heat drying and direct seeding, the primary energy footprint could become competitive against the SPC one. These two measures combined reduce the primary energy demand of 2 t SWPC down to 28,884 MJ, which represent 1.96 times the energy required to produce 1 t SPC. These two measures are however not sufficient alone and realistically, a significant upscaling of SWPC production will quickly expand the energy demand beyond readily available waste heat. To reach competitiveness, the SWPC system would have to evolve and generate an additional 50% primary energy reduction through economies of scale, optimization, and innovation.

5.2 Implications of phosphorus footprints

5.2.1 Phosphorus management in the SPC system

Because soybeans are cultivated using intensive agricultural methods, several P management issues were highlighted by the SFA analysis.

The inefficiency of the soil preparation process is one of the most significant issues facing P management in the SPC system. The SFA of this process shows that 50.9% of the P applied for soil enrichment does not reach *Glycine max* in the year of harvest. Instead, this P is bound to soil and partly drained by leaching, erosion, and surface run-off (flow 1,0a and 1,0b) (Appendix C). Assuming continuity in cultivation methods stable production yields, this means that farmers are overloading soils with P year after year (Li et al., 2015). Due to this practice, the flow “soil fixation” (flow 1,0a) is considered an outflow from the agricultural system to the biosphere. Moreover, the natural P cycle is heavily dependent on the hydrodynamics of water for transport from one ecosystem to another. Considering the considerable rainfall in both of these regions (de Freitas and Landers, 2014), most of the excess P in fields likely drained overtime into water bodies where its effects could be benign or could generate negative environmental impacts on fresh and marine water ecosystems (Hamilton et al., 2015a, Rabalais et al., 2009).

Results showed that like most monoculture, *Glycine max* relies heavily on fossil P provided through mineral fertilizers. For each ton of SPC produced, 84.68% of the P input comes directly from fossil sources. This fossil P has been accumulated in the earth’s crust over millions of years. The high consumption rate of fossil P by intensive agriculture is not sustainable and raise concerns about P depletion (Steffen et al., 2015, Cordell and White, 2011). The SFA layer shows that the input of P through manure is marginal (flow 0,1a), representing only 0.64% of the cumulative P input to process 1 (Appendix C). However, the size of this flow is not representative of the use rates of individual Brazilian farmers. Large quantities of manure are used to replace mineral fertilizers in certain farms, but only a very small fraction of Brazilian farmers are using this enrichment method. According to da Silva et al. (2010) study, only 3.6% of SO Brazilian soybeans are produced using manure.

These results show a real need and a real potential to optimize the soil enrichment process. Although high doses of mineral fertilizer increase crop yields, the overconcentration of P in agricultural soils is the single largest P loss occurring throughout the system. This calls for a significant reduction of fertilizer application. Beyond mineral P management, urgent action is needed to incentivize the use of manure, crop residues, and a new generation non-fossil P products, such as food waste fertilizers or liquid seaweed fractions.

5.2.2 Phosphorus management in the SWPC system

Macroalgae, being low trophic level marine organisms, have entirely different P resource requirements compared to soybeans (Skjermo et al., 2014). Throughout the SWPC value chain, the inputs of fossil P (flow 0,1b [P] + 0,2b [P]) are marginal and represent as little as 0.03% while the non-fossil P uptake from seawater (flow 0,3 - [P]) represents 99.97% of the total input (Appendix D). Taking into consideration risks of fossil P scarcity (Cordell and White, 2011) and the growing pressure on global food supply (Godfray et al., 2010), the cultivation of seaweed reveals a double advantage. First, it is a very efficient method to produce large quantities of edible plants without fossil P footprint and second, it recycles secondary P stocked at the end of the P cycle back into the anthroposphere.

One production system seeking to take full advantage of nutrient uptake capacity of seaweed is Integrated Multi-Trophic Aquaculture (IMTA). The goal of an IMTA system is agro-industrial symbiosis. In this system, primary producers, such as macroalgae, mollusc, and shell capture the excess of inorganic and organic nutrients from high trophic species such as finfishes. In Norway, IMTA systems have utilized macroalgae and blue mussels to capture excess inorganic and organic nutrients from Atlantic Salmon. In this system, nutrients contained in salmon feed pellets are recycled through several trophic cascades, promoting growth of the filtering species (Chopin et al., 2010, Wang et al., 2012). Considering that Norwegian salmon are fed nutrients with a high degree of fossil origin, including fossil P (Ytrestøyl et al., 2015), IMTA is an attractive option for theoretically recycling nutrients of mineral origin. However, in recent studies, only a fraction of the fossil P emitted by farmed fishes can be recovered by seaweed cultivated in IMTA (Broch et al., 2013). Among other factors, Norwegian researchers attribute this low uptake rate to seasonal growth mismatches between salmonids and macroalgae (Handa et al., 2013). Although IMTA systems do not drastically enhance the nutrient recycling capacity of macroalgae, there is strong evidence that IMTA systems significantly increase macroalgae yields and health (Silva Marinho, 2016, Wang et al., 2013).

5.2.3 SPC vs SWPC

The total P footprint of the SPC system is equal to 30.4 kg/t, whereas the SWPC system consumes 25.05 kg/2t. However, if global footprints take only into account primary fossil P content, then the SPC fossil P footprint score drops to 25.75 kg/t while the SWPC is reduced to 0.008 kg/2t. Furthermore, the SWPC production system also generates a liquid fertilizer containing P, which can be logically argued to generates a new positive P balance for terrestrial P resource management. Seghetta et al. (2016) calculated a 95% substitution ratio for the seaweed fertilizer compared to mineral fertilizer. This means that the 25.05 kg of P (flow 6,0 - [P]) embedded in 14,726 kg (flow 6,0f) of seaweed fertilizer can substitute up to 26.36 kg of fossil P usually applied through mineral fertilizers. Reducing the fossil P footprint of the SWPC system by the quantity of fossil P avoided generates a negative score equal to -26.36kg/2t. In EA methods, such as LCA and MFA, a negative footprint score indicates a positive impact. In this situation, the production of SWPC reduces fossil fuel depletion by recycling secondary P into biofertilizers. However, this last results cannot be compared to the 25.75 kg/t fossil P footprint of the SPC system. A fair comparison with this value must consider the avoided productions of all the co-products produced in each of the system. Results from the literature review show that in Berardy et al. (2015), the environmental impacts associated to soybean meal were significantly reduced by accounting for the avoided production of vegetable oils resulting of the co-production of soybean oil.

5.3 Feasibility aspects

An important question to consider before aiming to replace SPC with SWPC is cultivation area. For example, how much coastal water surface area would be required for Norway to replace as little as 10% of SPC production? The Norwegian aquaculture industry required 19,702 km^2 of land in Brazil to satisfy import demand for SPC in 2015. After adjusting for CPC, replacing 10% of the SPC import would require 72,443 t of SWPC. Based on the results of the seaweed MFA models, this translates to 1,362,436 t of *S. latissima* WW cultivated to reach this production level. With a cultivation yield of 60 t/ha, replacing 10% of the SPC import with SWPC would require approximately 227 km^2 at sea. If we compare this number to the 1,970 km^2 of land used for 10% of SPC production, SWPC requires only 11,5% of the equivalent land mass at sea. In addition to little or no demand for fossil P, the efficiency of production per unit area is another strong argument for the potential of mariculture, especially considering the enormous pressure on terrestrial crop lands (FAO, 2011).

Economic sustainability is today the most important determinant of success for new technologies. The small size, high cost of labour, and high primary energy are all factors that will likely hinder SWPC from competing with SPC on price without some major changes to the market. However, such changes are not unthinkable in the near future. For instance, if a stiff carbon tax is implemented (Metcalf and Weisbach, 2009) or if the price of rock phosphate appreciates significantly (Cordell and White, 2011), then the price of SPC and other terrestrial protein sources will rise accordingly, lowering the price gap with mariculture ingredients. Since price is usually the ultimate baseline for market acceptancy, the next few years will be crucial for the seaweed industry. Will seaweed farmers, policymakers, and researchers succeed at transforming this young value chain into a full scale, effective and innovative industry?

5.4 Models limitations and uncertainties

This section will discuss limitations, uncertainties, and errors of each system. Differences between the systems with respect to scale and maturity were already discussed in section 4.1.1.2, “influences of value chains” and will not be discussed again here.

5.4.1 The environmental assessment

The absence of similar environmental assessment in the literature was a significant limitation for results comparison. Since MFA/SFA studies of similar value chains were not found in the literature, LCA studies were reviewed in section two. These LCAs are relevant for this study, but their results are not comparable to the primary energy and P footprints calculated in this thesis. Energy use and eutrophication impact categories were assessed in da Silva et al. (2010) and Berardy et al. (2015) for soybean cultivation and transportation, and in (Seghetta et al., 2016), for seaweed. However, because LCA includes indirect environmental impacts of background processes, their results were systematically larger than the ones calculated with the MFA/SFA tools. For instance, da Silva et al. (2010) accounts for the indirect energy use generated by deforestation and mineral fertilizer production. The same is true for the Seghetta et al. (2016) study, which accounts for indirect P emissions during transport and use of biofertilizers, and includes energy consumption during seaweed farm construction in its analysis. These indirect impacts are outside the scope of this MFA/SFA analysis. Although it looks like a structural limitation of the MFA/SFA methodology, the difference is in the details. MFA/SFA is a methodology best suited for developing a deep system understanding, whereas LCA is limited in its resolution due to the large data requirements and background processes One of the goals of this study is to increase the understanding of the SPC and SWPC foreground systems and to transfer this knowledge support to the LCA in the PROMAC project.

5.4.2 The SPC system

The level of detail used to model processes one to four is excellent due to the large scope, high quality, and reliability of da Silva's data. However, the processes "Extraction" and "Import to Norway" are modelled from generic databases and assumptions, and thus presents more uncertainties and flaws than the cultivation stage. For instance, based on the Agri-footprint database process, it was estimated that average transportation of dried soybeans from farms to SPC factories requires 867 tkm by road, 416 tkm by railway, and 101 tkm by waterway, for each ton of SPC produced. In reality, the purchasing patterns of SPC producers are more complex and dynamic. For instance, certain producers report purchasing soybeans only within close range of the processing unit, others select their suppliers based on market prices (Caramuru, personal communication, November 15th 2016; Imcopa, personal communication, November 14th 2016). Similarly, process 6 "import to Norway" was considerably simplified. Modelling was restricted to trade between the three main producers and three main importers, and the number of import routes was reduced. For example, it was assumed that Rotterdam was the exclusive transit port between Brazil and Europe, whereas in reality, transit ports fluctuate according to logistics requirements.

In the SFA models, three limitations are significant. The first one is the processing of crop residues. To simplify complex nutrient interactions and because da Silva's LCA did not account for the P embedded in crop residues, this P was assumed to be completely transferred to *Glycine max* straws. The reality is more complex. Instead of being only stored by the soybean straws, the P from crop residues is transferred to every fraction of the plant (the straw, the leaves, the pods, and the beans). The second limitation concerns the fixation of P in soil (flow 0,1a - [P]) (Appendix C). According to the MFA/SFA methodology, this flow should be a stock. However, as discussed in section 4.1.2.1, "P management of the SPC system", this P fraction is considered to be a loss to the agricultural production system and is consequently modelled as an outflow leaving the system. Finally, significant uncertainty comes from calculating P content in the different soy fractions (hulls, crude oil, molasses and SPC). These calculations are based on P content value from biochemical analysis in scientific literature, but the quality is not optimal.

5.4.3 The SWPC system

At the system scale, one of the main limitations of the seaweed models is its high dependency on assumptions. The transformation stage does not exist today in Norway (Skjermo et al., 2014), so processes five and six were necessarily modelled from assumptions. In addition, due to the lack of organized and published data from seaweed farmers, the whole cultivation process was modelled based on one company's operations. This is perhaps the biggest limitation to the SWPC model. To become representative of the whole Norwegian seaweed cultivation industry, data from several additional seaweed farmers should have been included in this model. The absence of industrial transformation of *S. latissima* or other seaweed species into feed ingredients also raises many questions. For instance, how digestible is the SWPC produced by Seghetta's biorefinery for salmonids? Does the SWPC have any functional effects beyond providing dietary protein? Research into these questions is ongoing, however there is an urgent need for documented answers (Norambuena et al., 2015). Among the many assumptions made to model processes five and six, some were dictated more by necessity than by accuracy. A good example is the assumption establishing that seaweed cultivation occurs exactly as in Hortimare's farm, but geographically close to Ålesund. Although this assumption is essential to connect the cultivation stage to the transformation stage, it is not scientifically correct to assume the same yield or growth conditions. Research shows that local conditions at seaweed farms have significant impacts on growth rates, yields, maintenance, transport, and logistics (Taelman et al., 2015a, Peteiro and Freire, 2012).

In the SFA layers of this system, most limitations come from data scarcity and from simplification of complex processes. For example, due to the lack of biochemical studies on *S. latissima* gametophytes and sporophytes, the quality of P content calculation for these development stages was poor. In process three, the capture of seawater P by seaweed (flow 0,3 - [P]) was simplified, assuming that the average P content of *S. latissima* corresponds to its uptake during the outgrowing at sea. Such an assumption reduces the accuracy of the process, but is nevertheless necessary. Assessing seaweed P uptake from the seawater from a specific seaweed farm at a specific time would require tremendous research due to the vast range of dynamic parameters involved (Broch et al., 2013).

5.4.4 Sensitivity analysis

Building MFA and SFA models of two production systems requires an extensive use of parameters. Each of these parameters have a certain amount of uncertainty that add up to an overall level of model uncertainty. One very efficient method to allocate the global model uncertainty is to assign each parameter an uncertainty by using sensitivity analysis. A common method used by MFA/SFA practitioners consists of testing the sensitivity of all parameters simultaneously by using Monte Carlo Simulations (Doubilet et al., 1985).

No sensitivity analysis was performed in this study, however in the SPC system, parameters such as the production types, the cultivation yield, and mineral fertilizer inputs are assumed to have a strong influence on the results. Similarly, in the SWPC system, results are expected to be highly sensitive to cultivation yield, seaweed dry matter content, and the dehydration ratio.

6 Conclusion

By performing a comparative environmental analysis on the SPC and SWPC aquafeed ingredients, this study's intent is to determine if the SWPC value chain could be more sustainable and efficient than the SPC currently used by Norwegian compound feed manufacturers. This study specifically accounts for primary energy and phosphorus footprints, as it assesses the performances of two crucial sustainability indicators related to production efficiencies and resource depletion levels. Although not fully comprehensive, these two indicators evaluate the environmental key performances where food and feed production must excel to be part of tomorrow's sustainable value chains.

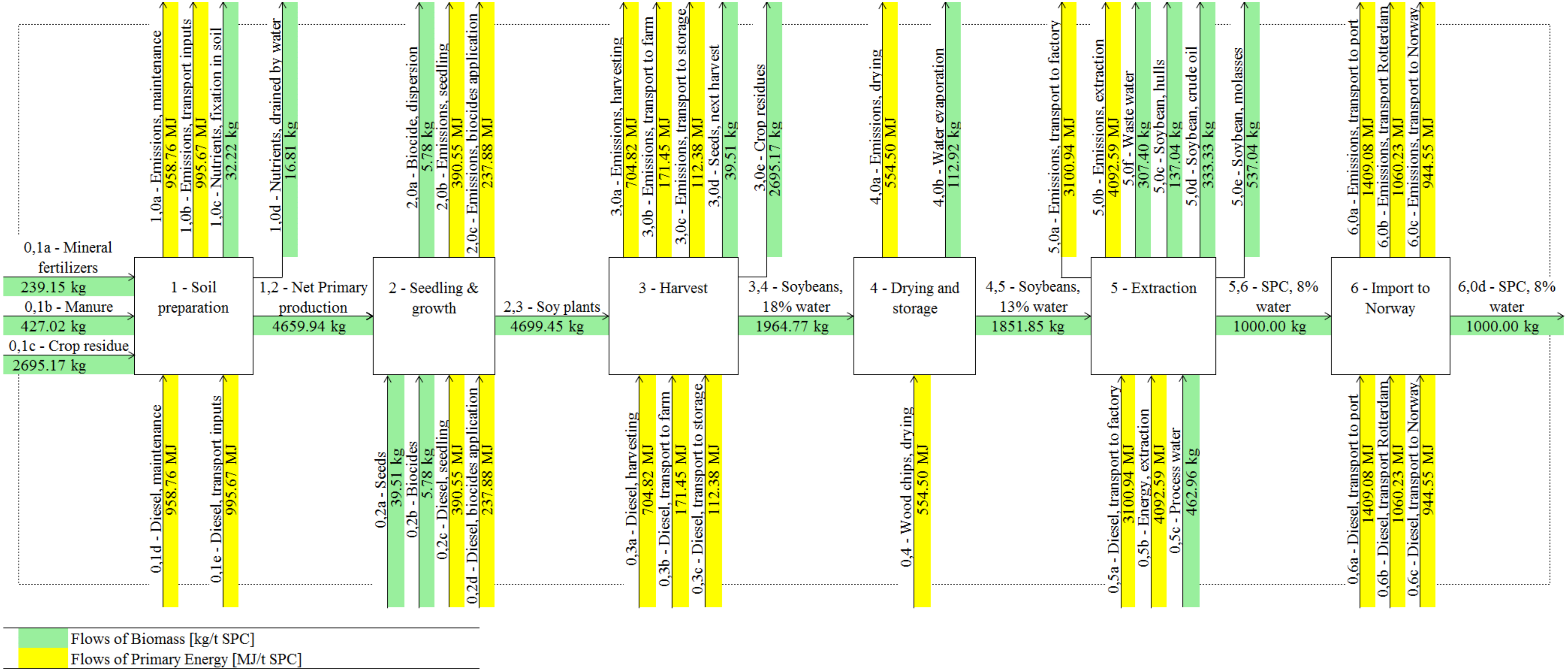
Results show that with today's technology, substituting SPC by SWPC is an environmental trade-off. Such substitution would dramatically increase the primary energy footprint of protein rich feed ingredients, while also likely reduce freshwater and marine eutrophication, mitigate fossil P depletion impacts, and decrease pressure on arable lands. While enhancement opportunities exist in each system, their potential for improvement is not comparable. The inefficient P management of the SPC system is primarily structural, while the inefficient energy use of the SWPC system is mostly due to its small size and youth. In fact, although SPC is a dominant ingredient today, when considering the innovation potential for SWPC, including upscaling and process optimization, the environmental trade-offs appear to favour the SWPC system.

To leverage the environmental trade-offs completely in its favour, the SWPC value chain must undertake two transformations. The first transformation lies in process innovation and industrial synergy implementation and holds most of the potential to reduce SWPC's high primary energy footprint. Using secondary energy for seaweed dehydration and developing macroalgae silage protocols are examples of such actions, and show excellent promise. Although it is totally unrealistic to replace the entire SPC import based on this raw material alone, the SWPC system shows promise as a supplementary product, especially when utilizing secondary heat from Norwegian industries. The second transformation lays on upscaling and optimization. If the small and young Norwegian seaweed industry evolves into a large and effective industry, the primary energy footprint of SWPC could be further reduced to competitive levels.

Although the importance of primary energy is undeniable, the efficiency of P management in food and feed production systems is vital for current and future food security. This is where the real competitive advantage of SWPC becomes obvious. Like all intensive monoculture, soybean production contributes to steady depletion of the global fossil P resources. The SWPC value chain is fossil P free, and holds the potential to mitigate fossil P depletion by recycling non-fossil P from the ocean back into the anthroposphere in the form of biofertilizers.

The need for comprehensive environmental assessment of new food production systems, including blue value-chains is crucial to sustainable development. This task is vast and the scientific knowledge gap between the SPC and SWPC value chains is wide. One interesting lead to complete this study will consist of strengthening the data in the SWPC model and to develop additional SFA layers. For instance, accounting for the nitrogen footprint of each system would complete the nutrient efficiency analysis. Because MFA/SFA studies are characterized by a specific scope and a large degree of details, there is a strong need to perform comprehensive LCAs including all stages of the SPC and SWPC value chains. As results showed, an LCA accounting for the avoided emissions of each system's co-products would precisely calculate the fossil P mitigation potential of the SWPC system, as well as account for environmental impact reductions due to the co-production of soybean oil and other co-products in the SPC system.

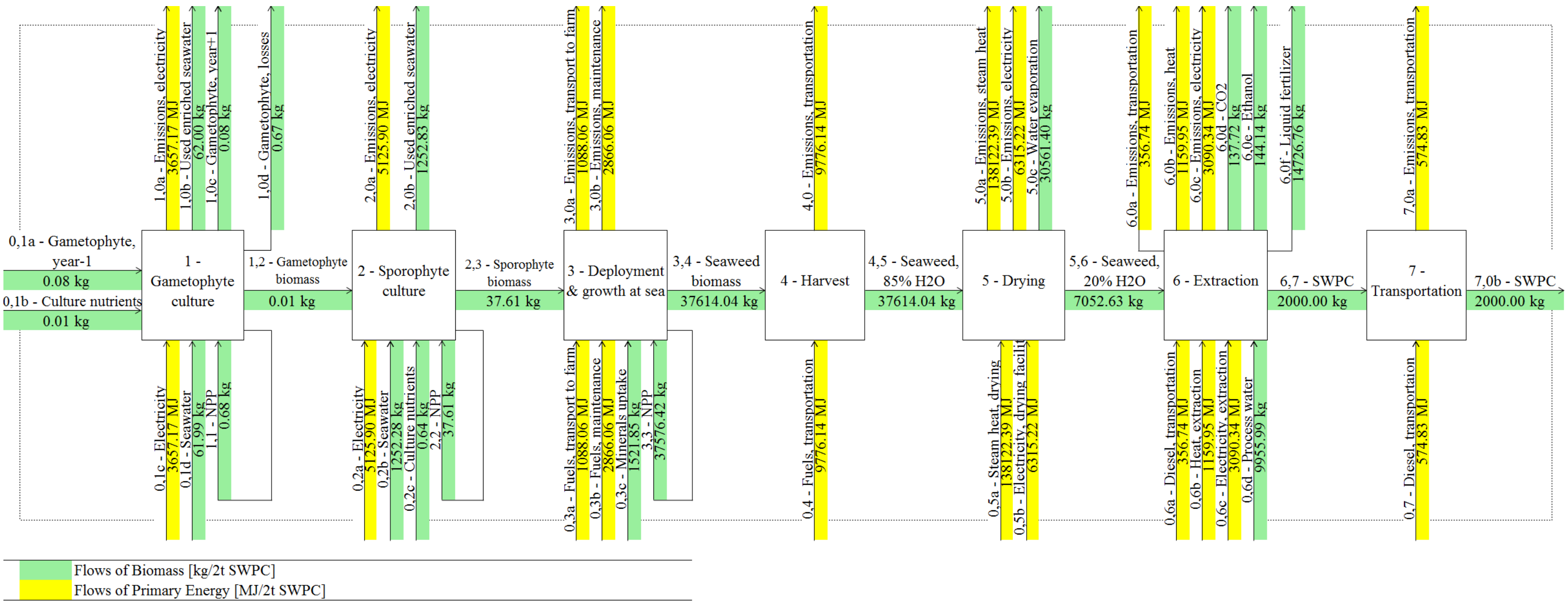
Appendix A: Soy_MFA_S1 model



Soy_MFA_S1 mass-balance verification

Process	Value	Biomass-balance equation
2 - Seedling & growth	0.00E+00	(1,2 - Net Primary production) + (0,2a - Seeds) – (2,3 - Soy plants)
3 - Harvest	0.00E+00	(2,3 - Soy plants) – (3,0d - Seeds, next harvest) – (3,0e - Crop residues) – (3,4 - Soybeans, 18% water)
4 - Drying and storage	0.00E+00	(3,4 - Soybeans, 18% water) – (4,0b - Water evaporation) – (4,5 - Soybeans, 13% water)
5 - Extraction	0.00E+00	(4,5 - Soybeans, 13% water) + (0,5c - Process water) – (5,0c - Soybean, hulls) – (5,0d - Soybean, crude oil) – (5,0e - Soybean, molasses) – (5,0f - Waste water) – (5,6 - SPC, 8% water)
6 - Import to Norway	0.00E+00	(5,6 - SPC, 8% water) – (6,0d - SPC, 8% water)

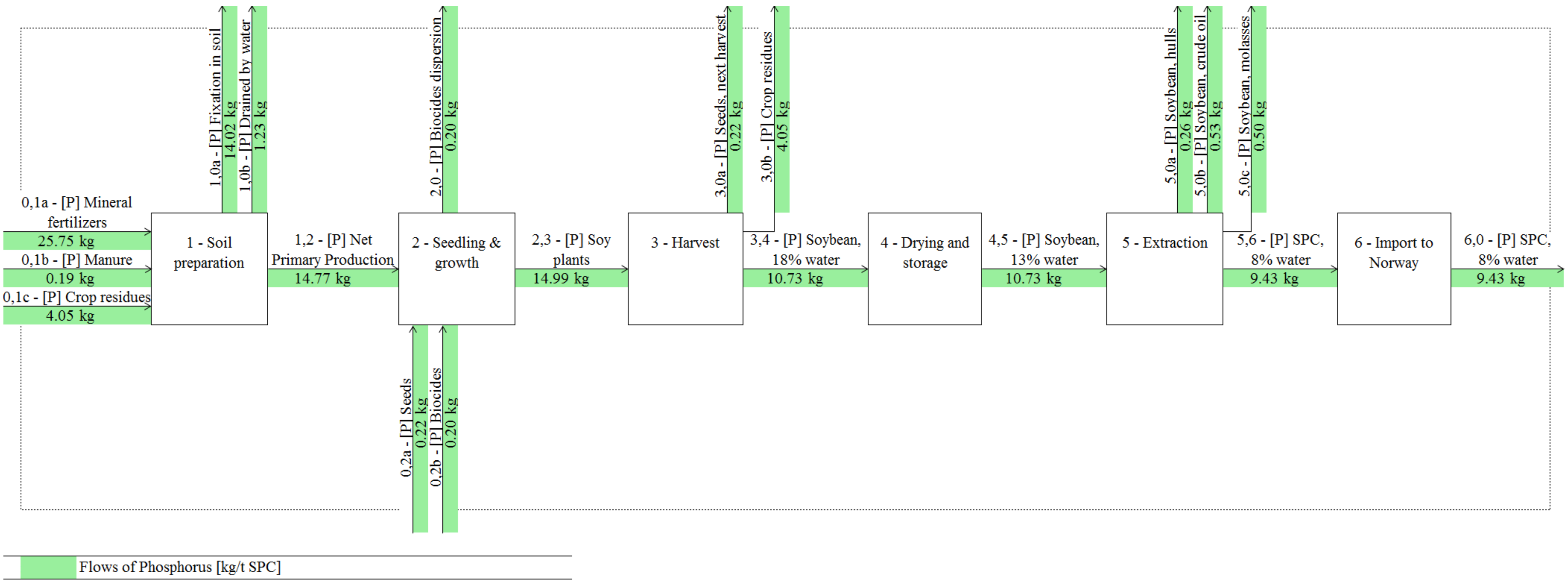
Appendix B: Seaweed_MFA_S2 model



Seaweed_MFA_S2 mass-balance verification

Process	Value	Biomass-balance equations
1 - Gametophyte culture	1.39E-17	(0,1a - Gametophyte, year-1) + (1,1 - NPP) – (1,0c - Gametophyte, year+1) – (1,0d - Gametophyte, losses) – (1,2 - Gametophyte biomass)
2 - Sporophyte culture	0.00E+00	(1,2 - Gametophyte biomass) + (2,2 - NPP) – (2,3 - Sporophyte biomass)
3 - Deployment & growth at sea	0.00E+00	(2,3 - Sporophyte biomass) + (3,3 - NPP) – (3,4 - Seaweed biomass)
4 - Harvest	0.00E+00	(3,4 - Seaweed biomass) – (4,5 - Seaweed, 85% H_2O)
5 - Drying	0.00E+00	(4,5 - Seaweed, 85% H_2O) – (5,0c - Water evaporation) – (5,6 - Seaweed, 20% H_2O)
6 - Extraction	2.05E-12	(5,6 - Seaweed, 20% H2O) + (0,6d - Process water) – (6,0d - CO2) – (6,0e - Ethanol) – (6,0f - Liquid fertilizer) – (6,7 - SWPC)
7 - Transportation	0.00E+00	(6,7 - SWPC) – (7,0b - SWPC)

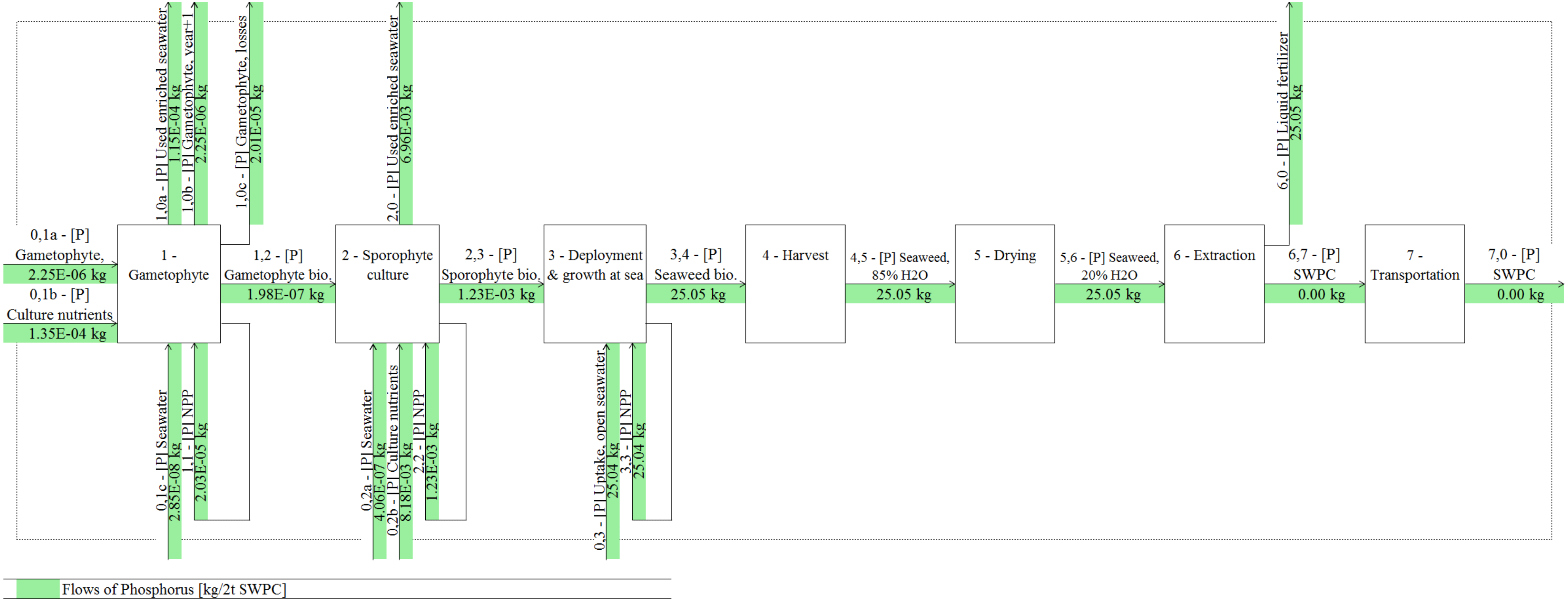
Appendix C: Soy_SFA_S1 model



Soy_SFA_S1 mass-balance verification

Process	Value	Mass-balance equation
1 - Soil preparation	-4.38E-02	(0,1a - [P] - Mineral fertilizer) + (0,1b - [P] Manure) + (0,1c - [P] Crop residues) – (1,0a - [P] Fixation in soil) – (1,0b - [P] drained by water) – (1,2 - [P] Net Primary Production)
2 - Seedling & growth	0.00E+00	(1,2 - [P] Net Primary Production) + (0,2a - [P] Seeds) + (0,2b - [P] Biocides) – (2,0 - [P] Biocides dispersion) - (2,3 - [P] Soy plants)
3 - Harvest	0.00E+00	(2,3 - [P] Soy plants) – (3,0a - [P] Seeds harvest) - (3,0b - [P] Crop residues) – (3,4 - [P] Soybean, 18% water)
4 - Drying and storage	0.00E+00	(3,4 - [P] Soybean, 18% water) – (4,5 - [P] Soybean, 13% water)
5 - Extraction	0.00E+00	(4,5 - [P] Soybean, 13% water) – (5,0a - [P] Soybean, hulls) – (5,0b - [P] Soybean, crude oil) - (5,0c - [P] Soybean, molasses) – (5,6 - [P] SPC, 8% water)
6 - Import to Norway	0.00E+00	(5,6 - [P] SPC, 8% water) – (6,0 - [P] SPC, 8% water)

Appendix D: Seaweed_SFA_S2 model



Seaweed_SFA_S2 mass-balance verification

Process	Value	Mass-balance equations
1 - Gametophyte culture	-4.98E-21	(0,1a - [P] Gametophyte, year-1) + (0,1b - [P] Culture nutrients) + (0,1c - [P] Seawater) – (1,0a - [P] Used enriched seawater) – (1,0b - [P] Gametophyte, year+1) – (1,0c - [P] Gametophyte, losses) – (1,2 - [P] Gametophyte biomass)
2 - Sporophyte culture	1.73E-18	(1,2 - [P] Gametophyte biomass) + (0,2a - [P] Seawater) + (0,2b - [P] Culture nutrients) – (2,0 - [P] Used enriched seawater) – (2,3 - [P] Sporophyte biomass)
3 - Deployment & growth at sea	0.00E+00	(2,3 - [P] Sporophyte biomass) + (0,3 - [P] Uptake, open seawater) – (3,4 - [P] Seaweed biomass)
4 - Harvest	0.00E+00	(3,4 - [P] Seaweed biomass) – (4,5 - [P] Seaweed, 85% H_2O)
5 - Drying	0.00E+00	(4,5 - [P] Seaweed, 85% H_2O) – (5,6 - [P] Seaweed, 20% H_2O)
6 - Extraction	0.00E+00	(5,6 - [P] Seaweed, 20% H_2O) – (6,0 - [P] Liquid fertilizer) – (6,7 - [P] SWPC)
7 - Transportation	0.00E+00	(6,7 - [P] SWPC) – (7,0 - [P] SWPC)

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