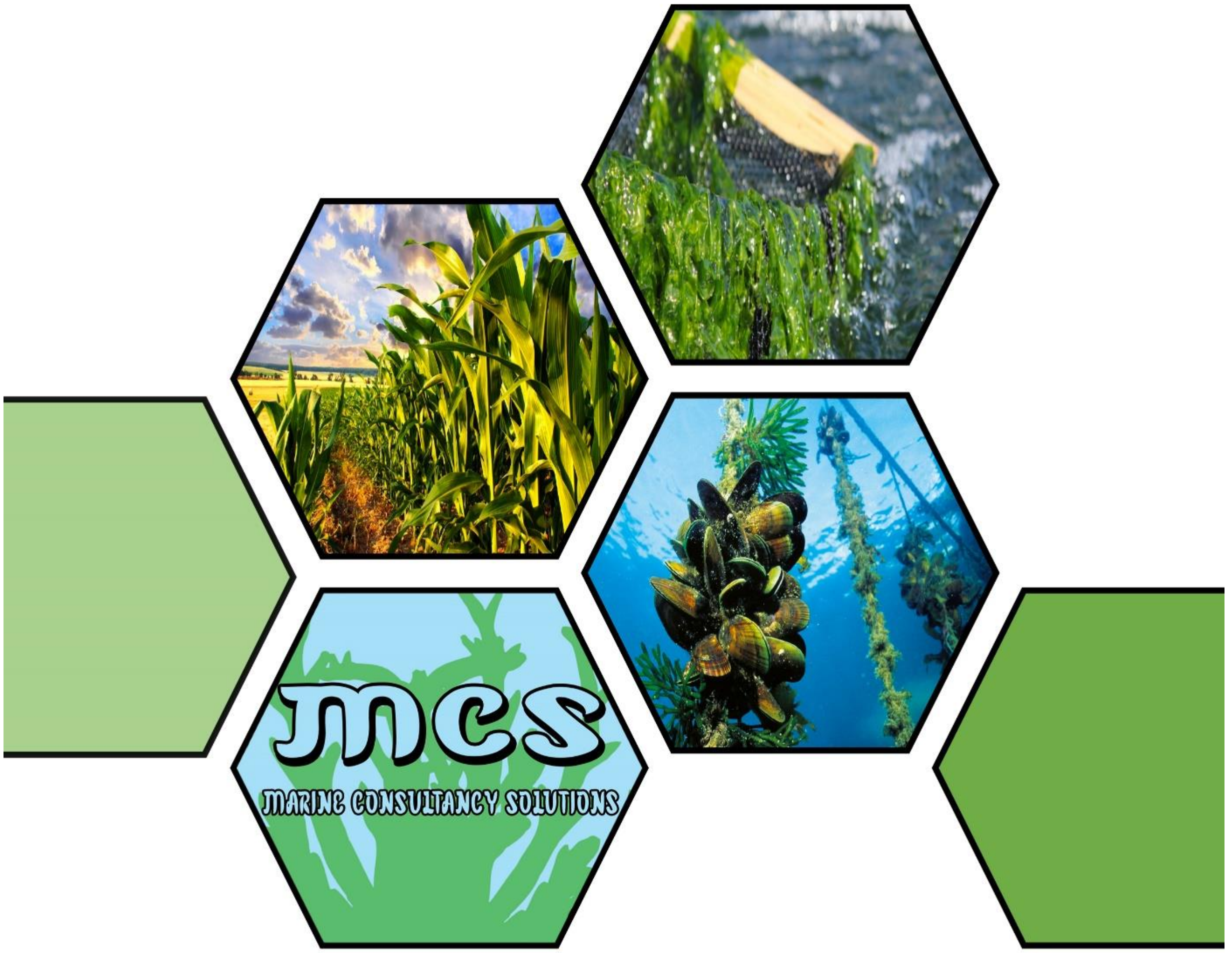
Comparing Land and Marine-based Food Production: Framework Development and Integration Opportunities



Project 2453 'On land or sea'

Final Product, 1st May 2020

Members: Herman de Munnik, Ghalia Nassar, Matthias Hof, Evelien van den Berg, Kyra Pikaar, Elliot Martin, Kim Tiebie

Commisioner: Marnix Poelman, Wageningen Marine Research

Contact details

Commissioner
Ing. Marnix Poelman, project manager aquaculture
Email: marnix.poelman@wur.nl
Telephone: +31 317 487 035

Secretary
Ghalia Nassar
Email: ghalia.nassar@wur.nl
Telephone: +31 655 986 867

Summary

With the Earth's population growing, an increased food production is required. Current agricultural practices have been deemed as environmentally damaging and unsustainable through the heavy use of fertilizers, land clearing, and habitat destruction. As an alternative to the environmental damaging agriculture practices, intensification of marine-based production is proposed. Whilst the oceans cover 71% of the earth's surface, their contribution to the total global food supply leaves much to be desired. An opportunity that has yet to be explored is expansion of aquaculture in the North Sea. Cultivation of low trophic aquaculture species such as bivalves and seaweed have been proposed as species which have high biological and economical potential in the North Sea.

Whilst the opportunity for cultivation is promising, there are still knowledge gaps that need answers. Methodologies for assessing and comparing marine-based production systems with land-based production systems are currently lacking, whilst potential integration opportunities also exist between the two systems. To tackle this issue, a framework for integration of land-based and marine-based systems was developed using a literature review. The CASSIS framework: a framework for Circular Alternative Sustainable Solutions for Integrated Systems, consists of three steps; 1) identification and analysis of the current food production system; 2) identification and analysis of the alternative production system; and 3) the integration of the current and the alternative system. To assess indicators based on the three pillars of sustainability -environmental, economic and social-, the framework uses various tools, which are environmental life cycle assessment, life cycle costing, social life cycle assessment, and the CMW index for biodiversity.

The framework was applied to a case study in which soybean in animal feed was partially substituted (1.6%) by seaweed (Saccharina latissima). The integration of these two production systems resulted in an increase of energy demand and fossil fuel use, and heavy metal content of the feed. For the other environmental indicators included, a slight decrease was shown. The economic analysis of the integrated system showed an increase in production and processing costs, resulting in 39% higher total costs. The assessment of the qualitative indicators showed a positive effect of the integrated system on land use, biodiversity, labour conditions, license to produce and pesticide use. There was no effect on consumer drivers and barriers, subsidies and employment opportunities. The integrated system had a negative effect on disease and pest susceptibility.

Through the application of the framework in the case study, strengths and weaknesses of the framework are identified. The main weakness is the dependence on data availability and the time-consuming nature of the framework. The main strength is the integral approach of the framework, taking all three pillars of sustainability into account. Even though the framework is not designed for general comparisons between land-based and marine-based production, opportunities for integration can be identified. These opportunities are likely to address real and wanted solutions by the industry by involving stakeholders in determining indicators and/or strengths and weaknesses.

Table of Contents

Summary **2**
Table of contents **3**
1. Introduction **4**
2. Methodology **8**
2.1. Research Methods 8
2.2. An Overview of the Framework 8
2.3. Step-by-step Explanation of the Framework 10
2.4. Indicators of the Framework 18
3. Case study **23**
3.1. Step 1: Characterizing status quo 23
3.1A. Identify the current food production system 23
3.1B. Determine relevant indicators 24
3.1C. Data analysis with the use of tools 27
3.1D. Identify strengths and weaknesses of the current food production system 35
3.2. Step 2: The alternative 36
3.2A. Identify alternative food production system 36
3.2B. Data analysis with the use of tools 36
3.2C. Identify strengths and weaknesses of the alternative food production system 44
3.3. Step 3: Integration 46
3.3A. Define integrated food production system 46
3.3B. Integrate data of original and alternative system to develop a new integrated system 46
3.3C. Compare integrated production system to original target production system 50
4. Discussion on Framework **52**
5. Conclusion and Recommendations **54**
References **56**
Appendices **69**
Appendix 1. Search Engines and Keywords 69
Appendix 2. Data Collection for Case Study - Soybean 70
Appendix 3. Data Collection for Case Study - Saccharina latissima 74
Appendix 4. LCC Comparison Graphs for the Case Study 76

Table of Figures

Figure 1. The CASSIS Framework: A framework for Circular Alternative Sustainable Solutions for Integrated Systems. 10

Figure 2. Depiction of the components of a life cycle (source from Philips, 2015) 13

Figure 3. Strategies for improving circularity within a production system (source from PBL, 2018). 17

Figure 4. Location of Mato Grosso, Brazil (source from Wikipedia, 2020). 24

Figure 5. Potential freshwater ecotoxicity impacts per kg harvested crop (source from Norberg et al., 2017). 30

Figure 6. Matta Grosso's agricultural regions derived from Richards et al. (2015). 34

Figure 7. Spatial distribution of human activity in the Dutch part of the North Sea (source from UNESCO, n.d.). 43

Table of Tables

Table 1. Values of environmental indicators for the baseline scenario (only soy included in animal feed) and the integration scenario (1.6% seaweed replacement in the animal feed). 47

Table 2. Values of economic indicators for the baseline scenario (only soy included in animal feed) and the integration scenario (1.6% seaweed replacement in the animal feed). 48

Table 3. Assessment of qualitative indicators of the integrated system (1.6% seaweed replacement) compared to the baseline (soybean only). 49

1. Introduction

With the population on earth continuing to grow, it is necessary for global food production to increase in order to meet growing demands. Whilst production can be increased through intensifying current use of cropland or through clearing land for further production, there remain environmental impacts and trade-offs that need consideration (Godfray et al., 2010). Current agricultural practices have been deemed as environmentally damaging and unsustainable through the heavy use of fertilizers, land clearing, and habitat destruction as a result of intensification (Burney, David, & Lobell, 2010). Heavy fertilizer use has led to eutrophication of marine, freshwater and terrestrial ecosystems which has had profound impacts on these ecosystems (Vitousek, Mooney, Lubchenco, & Melillo, 1997). It is important that in meeting future food demands, there is a shift from nutrient inefficient and environmentally taxing agriculture towards food systems with an emphasis on sustainability, resource efficiency, and circularity when possible. With the need to produce 50% more food by 2050, present agriculture practices cannot meet these demands due to lack of resources and current environmental burdens will only increase as a result (Duarte et al., 2009; FAO, 2017).

An alternative to land-based production is through strengthening use of marine resources. Marine-based food production systems are a promising alternative to agricultural production systems. Cultivation does not require land conversion like agricultural systems and production is not limited by scarce land and water resources (Costello et al., 2019). Whilst the oceans cover 71% of the earth’s surface, their contribution to the total global food supply leaves much to be desired (Schubel & Thompson, 2019). In this regard, there is a need to look towards marine-based solutions in addressing the growing food demand. An opportunity that has yet to be explored is expansion of aquaculture in the North Sea. Whilst the North Sea is an area thriving with human activity, offshore aquaculture is notably absent despite the North Sea being classified as highly productive (McGlade, 2002). Currently, cultivation of low trophic aquaculture species such as bivalves and seaweed have been proposed as species which have high biological and economical potential in the North Sea (Jansen et al., 2016). Furthermore, seaweed and bivalves are also able to provide ecosystem services such as carbon sequestration, stabilizing shorelines, and bioremediation (Alleway et al., 2019).

Whilst the opportunity for cultivation is promising, there are still knowledge gaps that need answers. The North Sea is a crowded space which is also used for other maritime activities with areas reserved for nature conservation objectives (Jansen et al., 2016). Offshore cultivation thus needs to be done in a sustainable manner that takes into consideration other stakeholders, assesses ecosystem impacts, and finds the right balance between marine and land production in terms of viability and sustainability. Methodologies for assessing and comparing marine-based production systems with land-based production systems are currently lacking, whilst potential integration opportunities also exist between the two systems through the use of seaweed in animal feed (Makkar et al., 2016; Rajauria, 2015) or seaweed extract as an alternative to fertilizers (Selvam & Sivakumar, 2014; Sivasankari, Venkatesalu, Anantharaj, & Chandrasekaran, 2006). Therefore, there is the need for innovative and circular solutions that are able to evaluate land and marine-based productions and identify areas for integration between the two systems. In doing so, the North Sea can be developed into an integrated food system that connects nutrients from sea to land.

The objective of this report is to address one of the many challenges that humanity is currently facing, that is moving from traditional towards circular and sustainable production and consumption practices. This involves the identification of viable and sustainable options or alternatives whilst taking into consideration various aspects regarding the environment, economy, and society (Azapagic, Stamford, Youds, & Barteczko-Hibbert, 2016). However, each aspect has abundant sets of criteria that vary for land and marine-based production system alternatives, thereby hindering the process for consolidation. Furthermore, the three facets include a number of qualitative and quantitative data that is often subjective, difficult to integrate, and largely context specific. The report aims to settle these dilemmas by tackling the following central research question:

How do land and marine-based food production systems compare in an integrated food system?

Alongside the central question, the current report aims to investigate the following sub-questions:

- *What factors are essential for characterizing integrative, circular food production systems?*
- *Which indicators can be used to quantify these factors?*
- *What relationships exist between indicators?*
- *What data can be compared and what is a suitable method to compare systems with each other?*
- *How can the framework be used in practice to compare land and marine-based food production systems?*

To support Wageningen Marine Research (WMR) objectives for circular and sustainable integration between marine and land production, this report proposes an approach for tackling this issue. The report adopts a systems approach in which all three components of sustainability – environmental, economic, and social – are integrated and evaluated in a life cycle assessment. The Systems Approach enables a multidisciplinary and trans-disciplinary perspective with stakeholder participation throughout the process (Azapagic et al., 2016). An advantage of a systems approach is situated in its ability to recognize the complexity and interrelationships of systems (i.e. food production systems), whilst acknowledging sustainability issues as multifaceted. This leads to accomplishing technical and methodological solutions on all sustainability fronts.

The prominence of the report lies in the framework. Food production systems are analyzed from a systems and life cycle approach in order to find opportunities for integrative and circular food production that include marine production. The proposed framework aims to enhance the effectiveness of decision-making processes primarily for WMR in regard to incorporating sea and agriculture systems. The framework can be applied in scientific research aimed to pursue the feasibility of integration methods between land and marine-based food production systems. Finally, the framework can be used as an effective step-by-step methodological guide that encompasses a handful of the components for integrative management. The outcome of the framework can serve as a basis to advocate local and national governmental bodies along with policy makers to form more sustainable and circular solutions to minimize agricultural intensifications at a national and global level. In order to achieve responsible production and consumption, a better comprehension of the integration processes and trade-offs behind new innovative production systems is beneficial, if not crucial.

The outline of the report will proceed with chapter two on the methodology used in the report and the proposed framework. This will include research methods, an overview of the framework with a step-by-step elaboration, and a description of general indicators involved in the framework. The third chapter will discuss the application of the framework with a case study. This will be followed with a fourth chapter where strengths and weaknesses of the framework are discussed. Lastly, chapter five provides a conclusion of the report with limitations and further recommendations discussed.

2. Methodology

The succeeding section will begin by discussing research methods utilized in the report in section A, followed by an overview of the framework in section B, where the overall methodological approach is elaborated upon. Next, a step-by-step explanation of the framework is demonstrated in section C. Lastly, in section D, the proposed framework is applied to a case study and a general description of relevant criteria is provided.

2.1. Research Methods

Throughout discussions around sustainable food systems exists a call for innovative and circular solutions aimed at uniting land with sea. Thus, the core essence of this report is to develop a framework for characterizing land and marine-based food production systems. The report uses two research methods to develop the aforementioned framework. An analysis of the literature is administered as the primary research method to assimilate scientific findings and relevant criteria. Secondary, an interview[1] with Roel Helmes, seaweed LCA researcher, is conducted to discuss specific concepts and elements, exchange literature, and validate outcomes regarding the development of the framework. These two methods are used as a guidance to gain valuable insight on existing and potential avenues capable of fulfilling the addressed research questions.

The primary research method, a literature review, is recognized as the most appropriate method to adopt as it would allow identification and synthesization of relevant material in line with the research scope. The collected information facilitated in creating and validating the proposed framework. The literature review is performed online using search engines and defined keywords found in Appendix 1. The obtained literature is organized into an excel file where each scientific article is categorized and defined using the following designed protocol; 1) outline of main topic(s) found in the article; 2) description of main findings in the article. As for the secondary research method, notes are documented during the interview and digitized in the excel file containing synthesized notes, discussion of main topics, and provided literature.

2.2. An Overview of the Framework

The framework, outlined in Figure 1, is developed to answer the research questions tackled in this report. The concept of a framework is valued to be the most suitable in achieving the stated objective. The methodological approach used to design the framework is mainly inspired by the knowledge obtained from the literature review formerly described in section A. By using the gathered information, a comprehensive

---

[1] Various researchers (n=5) have been contacted from Wageningen University and Research (WUR) and associated research centers (WMR, WPR, & WER). However, due to unprecedented circumstances caused by the COVID-19, only one interview was able to be achieved.

understanding of which elements are essential for establishing such a framework were identified. The three sustainability aspects – environmental, economic, and social – were recognized to be important components to consider when evaluating circular and integrative food production systems. Additionally, due to the novelty of the subject, the framework certainly had to take into consideration the different perspectives of the involved stakeholders. Hence, the acknowledgement of these two characteristics sharpened the vision set for the framework and narrowed the focus on how to proceed with the development phase.

During the development phase, several articles (Cottrell et al. 2017; Finnveden & Moberg, 2005; Jurgilevich et al. 2016; Niero & Rivera, 2018; Seghetta, Hou, Bastianoni, Bjerre, & Thomsen, 2016; Withers, Doody, & Sylvester-Bradley, 2018) containing a diverse set of concepts were used as inspiration. An article by Azapagic et al. (2016) proved the most resourceful by providing an in-depth outlook into decision-making frameworks. The paper investigated the notion of integrating the aforementioned sustainability aspects into a framework aimed at sustainable production and consumption. Further articles (Jeswani, Azapagic, Schepelmann, & Ritthoff, 2010; Petrillo et al., 2016; Rönnlund et al., 2016; van der Werf & Petit, 2002; ISO, 2006) identify indicator-based methods and approaches such as life cycle assessments (LCA) to be commonly performed in integrated sustainability assessments throughout literature. Consequently, the framework is developed and implemented through a case study in this report. The methodology for the case study consisted of defining a geographical location and collecting desirable data through literature. If any data collection was unavailable in the given geographical location due to scarce literature, complementary data is collected from other geographical sources.

The framework is divided into three steps, with each step involving several actions. In the first step, a food production system is described and analyzed in light of economic, environmental and social indicators relating to sustainability and circular production. This should be performed by taking the whole life cycle into account as much as possible. After the data has been sufficiently collected, the strengths and weaknesses of the production system are identified. This will help highlight opportunities for improvement.

In the second step, an alternative partial production system is described. An alternative partial production system can relate to any or multiple production steps within the complete production system, such as alternative feed, fertilizer, and biofuel. Indicators need to be chosen on the basis of comparability and compliance to both systems. Additionally, strengths and weaknesses are identified based on literature. Furthermore, through comparing these strengths and weaknesses with the strengths and weaknesses of the production system analyzed in step one; opportunities for integration can be found. It is important to note that step one and two can and should be performed in parallel in an iterative fashion in order to find a food production system and alternative (partial) system that complement one another.

Lastly, step three concerns integrating the alternative partial production system with the original production system. Based on the chosen indicators relating to sustainability and circular production, a comparison of the new integrated production system and original production system is accomplished. Based on this comparison, a conclusion can be drawn on the feasibility of the alternative production systems, and whether it improves upon the original production system.

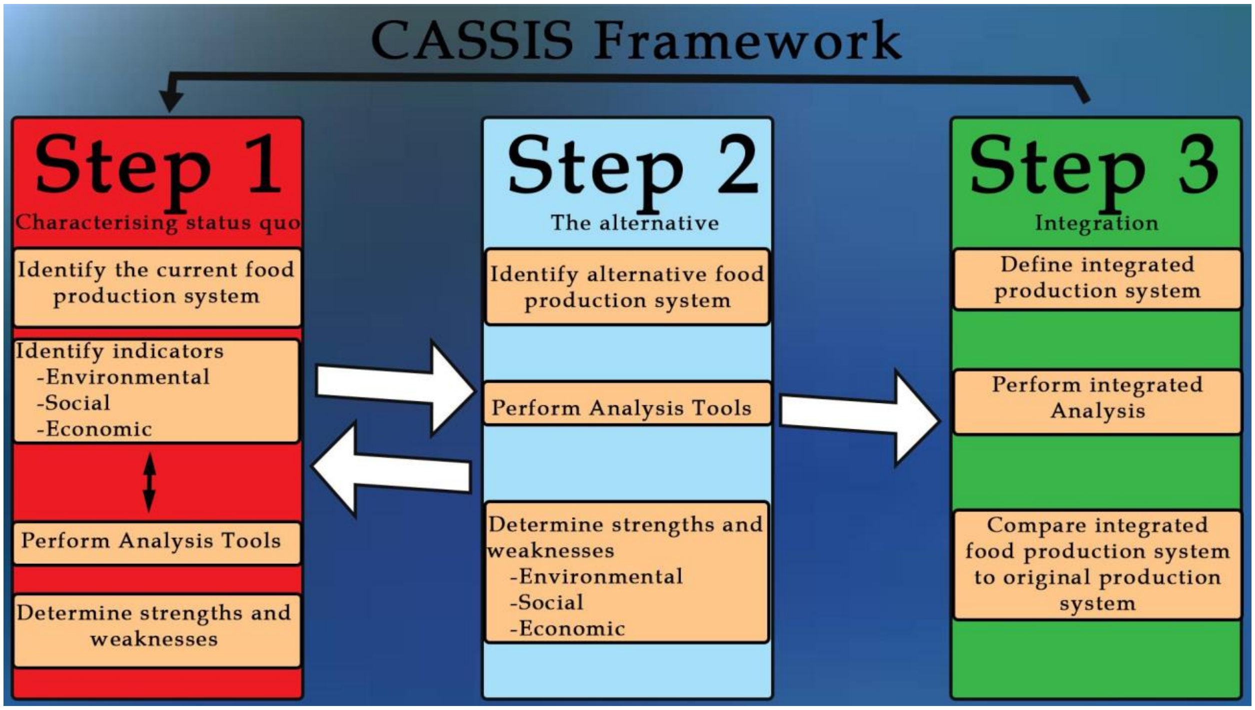


Figure 1. The CASSIS Framework: A framework for Circular Alternative Sustainable Solutions for Integrated Systems. The white arrows show the iterative process between step 1 and 2 in finding an opportunity for integration, and their input into step 3. The black arrow represents the final comparison between the new integrated production system and the original one.

2.3. Step-by-step Explanation of the Framework

Step 1: Identifying and characterizing current food production system

A. Identify current food production system

In the first action, the current food production system should be described, and its boundaries clearly defined. The term food production system incorporates a chain of processes and infrastructure involved in feeding the growing world population (van Berkum & Dengerink, 2019). This includes inputs, production, processing, marketing, distribution, consumption, and waste. The food production system connects three dimensions: (i) environmental: living processes associated in food production and their impacts, (ii) economic: power of different actors on various facets of the system, (iii) social: society values and dietary patterns that affect food usage (Gamboa et al., 2016). A food production system should have a clear comprehension of the interdependencies between the associated stakeholders (from producers, processors, retailers, consumers, and policy makers) in order to ascertain how finite resources and labor inputs can translate into desired outcomes, such as food security and human nutrition (Chase & Grubinger, 2014; Gamboa et al., 2016; van Berkum & Dengerink, 2019). Understanding the food production system and employing systems thinking is crucial to identifying causes of system fragility and formulating durable strategies.

A food production system consists of an array of subsystems, including but not limited to farming systems, input supply systems, economic as well as social systems (Chase & Grubinger, 2014). For every subsystem, system boundaries (i.e. species level, farm level, or region level) are acknowledged and defined to identify possible limitations and solutions, and their impact on the overarching food production system. This can reveal leverage points for change and formulate resolutions that fulfil the desired outcomes. The choice of subsystem(s) is dependent on the targeted changes that are required. Lastly, based on the current standpoint, relevant indicators can be discussed and evaluated to achieve an integrative and circular food production system.

B. Determine relevant indicators

When the current state of the food production system has been determined, it is important to find a way to critically analyze this state and how it relates to other alternatives. With the current focus on integrative and circular food systems, various indicators ranging from environmental, social, and economic should be defined in order to compare a more integrative system with a less integrative one. In defining these indicators, stakeholders play an important role. These stakeholders have a different interest in the issue, and all interests will have to be taken into account to ensure all sides of the issue are well-represented and the measurement of criteria will be as objective as possible. This also enhances transparency, thereby benefiting stakeholder discussions. However, the number of indicators should not exceed a certain limit, as this may result in confusion among the stakeholders. It is therefore important to summarize the indicators into a small selection of important and well-phrased indicators. A life cycle assessment (LCA) can provide guidance in which environmental indicators are relevant for different steps in the production process. Other useful tools are life cycle costing (LCC) and social life cycle assessment (S-LCA). Life cycle costing (LCC) is used to identify the economic indicators involved throughout the system. As for the social aspect, a social life cycle assessment (S-LCA) is used to classify applicable social indicators. These methods will be elaborated shortly. Hence, the relevant indicators for comparing integrative with non-integrative food systems can have a focus on the differences in environmental, economical, and social impacts in the production systems observed. Examples of this can be the difference in impact between using synthetic fertilizer and fertilizer based on seaweed, or the difference in impact between commonly used cattle feed and cattle feed based on seaweed. Therefore, action B includes a breakdown of all indicators deemed important for circular food production.

C. Data analysis with the use of tools

In this action, literature or field research should be performed to acquire data for each defined indicator. The framework proposes the following tools for this: Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA), and Community Weighted Mean (CWM) trait value analysis. Performing your own research to acquire data is preferred over analyzing data from literature, as this allows for setting system boundaries and functional units fitting to the production system of interest. This will lead to less assumptions needed to be made in the comparison phase of the framework. However, this approach can be quite time and resource intensive. As step 1 and 2 of the framework should be performed in an iterative way, literature study can still be supplemented in earlier, explorative stages of the study, or in cases where time and resources are limited.

When comparing food systems, it is important to look at the whole life cycle of products. As LCA is unique in this regard (Finnveden, 2000), it is highly beneficial to incorporate this approach into the framework. Figure 2.1 shows all the stages of a product's life; from raw material extraction to materials processing, manufacture, distribution, and use. However, an LCA usually does not cover all relevant aspects (Finnveden, 2000), and large variations for the same product are often visible (Curran, 2014; Finnveden et al., 2009). Therefore, an LCA is often unable to indicate a clear choice between alternatives (Finnveden, 2000). Because of this, it is recommended to look at other tools as well (Curran, 2014). An LCA can, however, shed some light on factors concerning the environmental performance of a product, depending on the specific objective of the research performed. For this, careful selection of data to ensure a high quality of this is important to solve the limitations on this account (Finnveden, 2000). An LCA’s comprehensiveness ensures the recognition of important and less important stages of the life cycle, as well as the identification of areas of improvement (Finnveden, 2000; ISO, 2006). Besides this, trade-offs can become visible (Curran, 2014). The clear overview it provides can be useful for stimulating discourse on the subject (Curran, 2014; Finnveden, 2000; ISO, 2006). Therefore, the conclusion is that regardless of the limitations, an LCA can still be useful as part of a larger framework. Efforts will have to be taken, however, to ensure the question asked can actually be answered by the LCA and to ensure a high quality of the data.

Figure 2. Depiction of the components of a life cycle (source from Philips, 2015)

Tools

<u>Environmental life cycle assessment</u>

A life cycle assessment (LCA) is ‘a technique for assessing the environmental aspects and potential impacts associated with a product’ (ISO, 2006). Following the ISO guidelines, the LCA consists of 4 steps: 1) Goal and scope definition; 2) Inventory analysis; 3) Impact assessment; and 4) Interpretation (ISO, 2006).

I. Goal and scope definition

In defining the goal, the reasons for carrying out the assessment and the target audience are identified (ISO, 2006).

Scope definition consists of multiple components. A description of the production system and its system boundary are given. The system boundary indicates along which part of the life cycle the product is assessed (ISO, 2006). This can be along the entire life cycle, from cradle to grave, or for example on farm level only, from gate to gate (Li, Zhang, Liu, Ke, & Alting, 2014). A functional unit is defined as a quantification of what is being studied, for example one kilogram of that product. The functional unit is necessary to compare outputs of LCA studies. The environmental impacts associated with a product are identified as the impact categories (ISO, 2006). These impact categories may include global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP) (ISO, 2006; Pelletier et al., 2007; Stranddorf, Hoffman, & Schmidt, 2005).

When the impact categories are identified, the method of allocation must be determined. Many agricultural processes yield multiple products (ISO, 2006). Dairy cattle, for example, provide milk and meat. When assessing the milk, only part of the emissions is allocated to the milk as the meat is responsible for emissions as well (Vellinga, Gerber, Opio, 2010). Allocation can be done by three methods: 1) Main product allocation, where impacts from main products and by-products are distinguished; 2) Physical allocation, based on physical characteristics of the product such as energy content or mass; and 3) Economic allocation, based on monetary value of products (Dolezal, Spitzbart, & Mötzl, 2014).

When performing a life cycle assessment, assumptions made and limitations of the LCA study must be mentioned in the scope (ISO, 2006).

II. Inventory analysis

The inventory analysis of the LCA consists of the collection of relevant data and the calculation of environmental impacts of the product within the system boundary. In this step the allocation method is implemented (ISO, 2006).

III. Impact assessment

The impact assessment of the LCA is an evaluation step in which the significance of the inventory analysis outputs and associated environmental impacts is assessed. In this step, it is determined whether the objectives of the life cycle assessment have been met or the goal and scope must be modified (ISO, 2006).

IV. Interpretation

In the last step, the interpretation, inventory analysis results and impact assessment are considered together. This should result in conclusions that are in line with the goal and the scope, and recommendations for future research or policymakers (ISO, 2006).

Life cycle costing

The LCA described above only considers the environmental pillar of sustainable production. For the assessment of the economic and social pillars different methods must be applied. For the economic pillar, this method is life cycle costing (LCC). This method assesses the total costs of a product along its life cycle (Azapagic et al., 2016; Swarr et al., 2011).

The concept LCC is not yet often used in literature but is used in this framework because of its compatibility with LCA. Furthemore, while LCC itself is not commonly used, it can be constructed from more widespread economic indicators such as: return on investment, investment cost, net present value, break-even point, production costs, revenues. LCC also closely resembles the often-used total annualised cost (Azapagic et al., 2016).

Social life cycle assessment

For the social pillar, a social life cycle assessment (SLCA) can be used. This SLCA follows the approach of an environmental LCA, but the impact categories consist of social aspects. It assesses the negative and positive social impacts of a product in a life cycle perspective, such as number of jobs provided, child labour and cultural heritage (Azapagic et al., 2016; Grießhammer et al., 2006). A SLCA can contain both quantitative and qualitative indicators. It is up to the user's discretion to convert qualitative indicators into quantitative data by using a scoring method, or to use them in a purely descriptive manner.

CWM Index for Biodiversity

Following the assumption that ecosystem functioning is determined by functional traits of organisms, functional diversity is the best measure of the benefits provided by biodiversity (Ricotta & Moretti, 2011). Functional diversity, defined as the distribution of traits across a community (Diaz & Cabido, 1997). Functional diversity is quantifiable and usable for comparing different ecosystems by using the CWM index. CWM is an index used to assess diversity and evenness of the distribution of a trait value across a species assemblage (Ricotta & Moretti, 2011). CWM values of a single trait are computed following equation 1.

$$\mathrm{CWM} = \sum_{i=1}^{S} p_i x_i \quad (1)$$

pi denotes relative abundance of species i (i = 1, 2, …, S) and xi denotes the trait value of species i. Functional diversity is assessed by computing CWM values for all identified trait values.

Apart from using the CWM index, it is important to relate biodiversity to a set desired ecosystem. What the desired ecosystem for an area is, is largely a policy decision based on: ecosystem integrity, the protection of endangered species and specific ecosystem services.

D. Identify strengths and weaknesses of the target food production system

In this step, the food production system is evaluated in order to determine strengths and weaknesses. These are based on the results from the life cycle assessment and vital to evaluate where improvements can be made in the life cycle. Assessments characterize how a system performs and determine strengths and weaknesses allowing for a comprehensive analysis of the system. This can be done through a strengths, weaknesses, opportunities, and threats (SWOT) analysis which allows for an analysis of potential opportunities for improvement in the food production system. During SWOT analysis, it is important that the three sustainability domains of a food system are considered (economic, environmental, and social). Assessment of all three domains is needed in order to accurately assess the food system. Indicators that were previously determined are used here to evaluate the life cycle and identify where improvements are needed from an economic, environmental and social aspect. This requires the use of good metrics that can distinguish and compartmentalize the different sections of the life cycle in order to understand and identify where improvements can be made. It's important that the SWOT analysis looks to seek the insight of all key stakeholders to the production system. This allows for a further examination into ongoing processes and what can be improved on.

Step 2: Identifying the alternative production system

A. Identify (part of) alternative food production system

In step 1D, the strengths and weaknesses of the target food production system were identified. In order to improve these weaknesses of the target food production system, the inclusion of an alternative production system can be considered. This alternative could consist of an entire food production system addressing the entire original system, or be a partial system addressing a specific part of the original system. This alternative system must be identified depending on the nature of the possible improvements in the target system (e.g. negative environmental impact) and the overall goal of the target system (e.g. plant protein inclusion in animal feed).

B. *Data analysis with the use of tools*

In this step, the same tools as in step 1.C are used to acquire data on the (partial) alternative food production system.

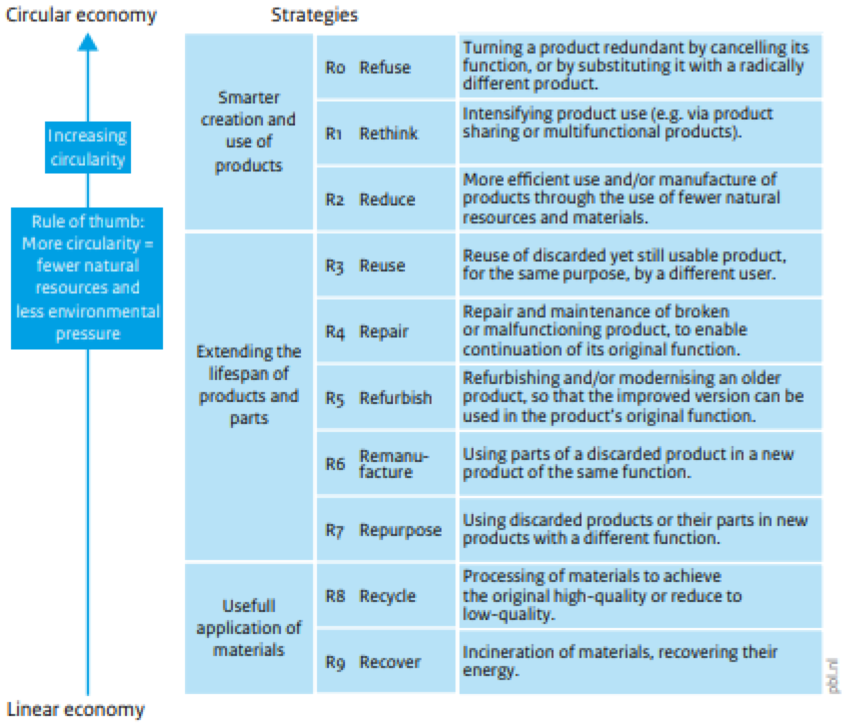
C. Identify strengths and weaknesses of the partial alternative production system

To integrate the alternative system into the target system (step 3 of the framework), the alternative system must be analyzed first. For the analysis of the alternative system, the same indicators and methods as described in step 1 can be used. After the analysis, an overview of the strengths and weaknesses of the alternative production system must be created. For this, the same methods as described in step 1D can be used. The overview allows for comparison to the strengths and weaknesses of the target food production system so opportunities of change can be identified.

Step 3: Integrate alternative system in current food production system

A. Define integrated production system

After exploring the strengths and weaknesses of the original production system and a potential alternative, they should be compared in order to find an opportunity for improvement of the new production system. In this step the newly integrated production system should be defined. This definition should take into account which stage of the original life cycle is addressed by the alternative, and by which method. After defining an integrated production system, it is beneficial to reflect on this system from the perspective of a circular economy. How does the new system address the old one? Is a product being reused or recycled? Is a product added onto the market or does it completely replace something else? Strategies shown in Figure 3 can help in increasing circularity within the system by utilizing fewer natural resources and reducing environmental burdens created by the original production system.



Strategies		
Smarter creation and use of products	R0 Refuse	Turning a product redundant by cancelling its function, or by substituting it with a radically different product.
	R1 Rethink	Intensifying product use (e.g. via product sharing or multifunctional products).
	R2 Reduce	More efficient use and/or manufacture of products through the use of fewer natural resources and materials.
Extending the lifespan of products and parts	R3 Reuse	Reuse of discarded yet still usable product, for the same purpose, by a different user.
	R4 Repair	Repair and maintenance of broken or malfunctioning product, to enable continuation of its original function.
	R5 Refurbish	Refurbishing and/or modernising an older product, so that the improved version can be used in the product's original function.
	R6 Remanufacture	Using parts of a discarded product in a new product of the same function.
	R7 Repurpose	Using discarded products or their parts in new products with a different function.
Usefull application of materials	R8 Recycle	Processing of materials to achieve the original high-quality or reduce to low-quality.
	R9 Recover	Incineration of materials, recovering their energy.

Figure 3. Strategies for improving circularity within a production system (source from PBL, 2018).

B. Integrate data of original and alternative system to develop a new integrated system

In this step, the data of the original and alternative system identified in step 1 and 2 are integrated in order to quantify the new integration production system. This would represent what the new system would look like.

C. Compare integrated production system to original target production system.

The selected indicators are used to form a comparison between the new integrated production system and the original production system, according to the results of life cycle assessments - LCA, LCC, and S-LCA, and the CWM. In order to identify the most sustainable solution(s), the decision maker and involved stakeholders should attribute their preference for the selected indicators. This should be well discussed among the involved parties in order to achieve best results. The valuation would indicate where the integrated alternative system is successfully capable of replacing a component in the original target production system.

2.4. Indicators of the Framework

This section provides a general introduction to a few indicators that can be used to assess the three sustainability aspects - environmental, economic, and social - in the framework. The framework should not be restricted to the mentioned indicators. A selection of the included indicators will be used while applying the framework to a case study in the succeeding chapter.

Environmental Indicators

Net Nutrient Flow: phosphorus, nitrogen

Nutrient flow refers to the flow of nitrogen and phosphorus which possess a biogeochemical cycle and can be used to indicate the sustainability and environmental impact of a system. Human induced-changes to these cycles have occurred due to intensive agricultural practices, resulting in many environmental and socio-economic impacts through changes in rates, pathways and efficiency of nutrient cycling (Lavelle et al., 2005). International trade and export also result in major nutrient movements with negative nutrient balances in exporting countries and nutrient accumulation in importing countries (Miwa, 1990). In order for sustainable agriculture, nutrient balances should be close to zero (Lavelle et al., 2005). Negative nutrient balances deplete nutrient stocks resulting in the need for external supplementation of nutrients to maintain and build-up nutrient stocks (Magdoff, Lanyon, & Liebhardt, 1997). Whilst positive nutrient balances result in nutrient accumulation and undesired transfers of nutrients from terrestrial to aquatic ecosystems causing eutrophication (Howarth et al., 2000; Lavelle et al., 2005).

Greenhouse Gas Emission

Greenhouse gas (GHG) emission is a relevant indicator, because these emissions significantly contribute to climate change. Greenhouse gas emissions are typically expressed in kg CO_2-eq/kg of product.

Water Use

A water footprint (WF) is used to estimate water consumption usage of a production or consumption activity (m^3 per activity or product) (Lathuillière, Johnson, Galford, & Couto, 2014). LCA still does not account for water use, therefore, a WF approach is considered to be aligned with current LCA methodologies according to ISO 14040:2006 (Franzese, Cavalett, Hayha, & D'Angelo, 2013). It serves as an indicator for freshwater use. WF is explicit to geographical and temporal locations. Total WF is the sum of green water, gray water, and blue water (Lathuillière et al., 2014). Green water represents soil moisture from rainwater utilized by plants, whereas grey water is water required to adjust pollutant load to water quality standards by use of fertilizers, and lastly blue water is water supplied via irrigation. Pollutant sources that affect the grey water footprint are often N and P fertilizer applications. Therefore, WF is a volumetric measure of water pollution and consumption usage (Franzese et al., 2013).

WF accounts for how much water volume is appropriated for various processes in a food production system. This provides useful data for water resource management and improvements on responsible and sustainable water use. Water use can aid in understanding trade-offs related to the production system, thereby reducing other environmental impacts such as impacts on water quality (Flach et al. 2020). Additionally, WF can help to assess economic, environmental, and social impacts at various levels (e.g. catchment level, local level, and country level) (Franzese et al., 2013). Therefore, water use is an important environmental indicator to analyze especially in the current and unprecedented climate change influences.

Land Use

Land use is an important subject to address in a life-cycle assessment (LCA). Globally, land is recognized as a finite resource and many of our current environmental challenges are linked directly to land use. Several models characterize land use with impact on biodiversity, primary productivity, climate regulation, hydrological functioning of soil, and human health (Lathuillière, Miranda, Bulle, Couto, & Johnson, 2017; Ridoutt, Motoshita, & Pfister, 2019). Despite their large contribution to global GHG emissions, LUC is rarely accounted for in most LCA studies and to a lesser extent LU as well (Vidal-Legaz et al., 2016). The inclusion of land use is vital in an LCA as it can help identify impacts that are essential to be addressed in the system. These impacts can then be used to assess trade-offs between alternative production systems. Land use as an indicator is divided into two separate parts:

1. Direct – Land use (LU) often termed as "land occupation" in an LCA. Land occupation is measured as the area time of which the land has been in its current state. It concerns the maintenance of the land during a certain period (Vidal-Legaz et al., 2016).
2. Indirect – Land use change (LUC) or referred to as "land transformation" in an LCA. Land transformation is used to assess emissions caused by changing a specific piece of land from its previous use to a current use (e.g. change from forest or grasslands to crop land) (Hörtenhuber, Piringer, Zollitsch, Lindenthal, & Winiwarter, 2013; Ridoutt et al., 2019).

Energy Use

The agricultural sector has become increasingly dependent on energy sources, such as oil, electricity, and gas (Bekhet & Abdullah, 2010; Karkacier & Goktolga, 2005). This dependency started during the industrial revolution, where a switch from human and animal power to machine power increased economic productivity significantly (Conforti & Giampietro, 1997). This machine power is, up till today, still often powered by fossil fuels (Andrea, Romanelli, & Molin, 2016; Bekhet, 2010). Combustion of fossil fuels has a massive effect on the environment, as it is the main contributor to anthropogenic GHG emission, especially CO_2 (Andrea et al., 2016; Höök & Tang, 2013). Energy use is often assessed in an LCA as it influences not only

GHG emission, but also abiotic depletion (e.g. fossil fuel depletion) (Andrea et al., 2016).

Pesticide Use

The use of pesticides emerged after WWII (Ecobichon, 2000). Reliance on pesticides increased due to intensification of agricultural practices (Ecobichon, 2001). Pesticides are used to protect crops from pests and diseases, therefore increasing productivity. Pesticides can be subdivided into three categories, namely: herbicides, insecticides, and fungicides (Ecobichon, 2001). In the 1980's there was an extensive shift of man labor from agriculture to industrial practices, related to industrialization. This increased the reliance on pesticides (Ecobichon, 2001). As the use of pesticides became more widespread, so did concerns of its use for human health (Jallow, Awadh, Albaho, Devi, & Thomas, 2017). Several studies were computed on the use and effect of pesticide use. Pesticide use is considered an important indicator to account for in an LCA. Pesticides have a big impact on the environment, and it must be taken into account when looking at alternative production systems. Pesticide use can be compared by looking at the ecotoxicity impact they have, expressed in ecotoxicity impact equivalent per kg of product.

Heavy Metals

Heavy metals, which are elements with atomic densities higher than 4 g/cm3 (Onakpa, Njan, & Kalu, 2018), are among the trace elements that are potentially harmful to human health in high concentrations (Barker & Pilbeam, 2007; ATSDR, 2011). This is recognized by the European Union, which has set limits for the presence of some of these heavy metals in animal feed (EC, 2002). This concerns arsenic (As), cadmium (Cd), lead (Pb) and mercury (Hg), which are highly toxic and therefore pose the highest risk to human health (EFSA, 2014; EFSA CONTAM Panel, 2010, 2011; EFSA Scientific Committee, 2015; Tchounwou, Yedjou, Patlolla, & Sutton, 2012).

Biodiversity

Biodiversity is an important theme in the sustainability debate (Vitousek et al., 1997). It has been associated with enhancing ecosystem resilience (Loreau et al., 2001), providing ecosystem services (Balvanera et al., 2006), and contributing to human wellbeing (Balmford & Bond, 2005). Furthermore, biodiversity is a commonly used indicator in environmental LCA's (Schmidt, 2008).

Susceptibility to Diseases/Pests

The production of many crops is limited by diseases and pests, as these have the ability to damage the crops to the extent that large economic losses occur. These diseases and pests can to some extent be fought using e.g. pesticides, but this is not always possible and has negative consequences as well. Because of the risks diseases and pests pose, it is an important indicator to take into account when comparing different crops.

Economic Indicators

In order to assess total lifecycle costs, data on total costs along the products life cycle is required. In the case of food products, the main costs can be divided into three main steps: (i) production costs, (ii) processing costs, and (iii) shipping costs. Disposal costs/recovery benefits, opportunity costs of labour, and opportunity costs of capital, of are ideally included into the three steps. They represent a cost incurred by society, but don’t directly correspond to the product’s lifecycle.

Composing enterprise budgets for the different companies involved in the products lifecycle (e.g. farmers, processing plants, and shipping companies) allows for the identification of economic strengths and weaknesses. Additionally, it allows for the possibility of assessing economic feasibility for each step of the product’s lifecycle.

Social Indicators

Consumer Drivers and Barriers

When converting from a certain production system to another one, an important factor that must be taken into account is whether consumers who use the product consider this to be a positive change. To determine whether it is positive, all several drivers and barriers must be taken into account. Drivers are factors that will make the consumers want to convert from a certain product to another. On the other hand, there are barriers which may hold the consumers from converting. This will vary greatly per product but is a very important factor to consider. All drivers and barriers must be analyzed and combined so that a consumer can determine whether they want to shift or not. Each consumer can give a weight to the drivers and barriers themselves, as this will also differ per consumer, depending on their preferences and financial situation.

Employment Opportunities

Employment opportunity is a socioeconomic indicator that includes dimensions such as employment creation, employment status, and new businesses. It refers to the quantity of jobs, people employed, created by the production chain (ILO, 2018). Employment opportunities are necessary for the production supply to meet the increasing demand of the product.

Labor Conditions

Labor conditions can act as an indicator to assess the sustainability of a system. A sustainable food system takes into consideration not only the environment and consumer, but also the workers who are involved during the growth, harvest and processing stages. It is thus important when assessing the sustainability of a food production system that all three pillars are considered: environmental, economic, and social. Aspects to consider on labor conditions can be working hours, earnings, job security, and working conditions (i.e. whether they are exposed to unsafe conditions through exposure to dangerous chemicals, machinery, and climate).

Subsidies

Subsidies can act as an indicator for governmental support. Subsidies can help to direct farming practices in directions favored by the government, meaning there is a level of importance to the government. Subsidies can have different forms, such as a monetary contribution or the provision of equipment (Schrank & Wijkström, 2003).

Spatial Planning

Spatial planning is included as an indicator because it gives a very useful insight into other present actors and stakeholders in a given location. Furthermore, it gives an indication about whether there is space, either at sea or on land, to change or expand a production system.

License to Produce

A license to produce is a social license allowing farmers to produce based on public trust. It includes the belief of the public that farmers will produce based on their social expectations and values. This license can be affected by public opinion in a positive or negative manner (Sterling & Charlebois, 2017).

Willingness to Change

Willingness to change can act as a driver and barrier to innovation. Implementation of potential changes cannot be expected if there is resistance from stakeholders and actors. Receptiveness to change is important in driving and stimulating new innovations and practices. If actors and stakeholders are not interested in change, this will ultimately result in the failure of change, even if the benefits outweigh the negatives.

Alternative Applications

Alternative applications refer to whether a product can have different or multiple applications than what was primarily intended. A product can create by-products which can have further beneficial applications (i.e. rice bran, a by-product during rice milling which can serve as a protein source to feed animals). In this regard, alternative applications are important to consider as they can indicate how well a resource is being efficiently used.

Health Impacts

Health impacts are important to consider in characterizing a food system whether these impacts are positive or negative. Health and sustainability go hand-in-hand with foods that have high health benefits having generally lower environmental impacts and vice-versa (Lindgren et al., 2018). This is evident in red meat production which has the highest land requirements and greenhouse gas emissions per gram of protein (Tillman & Clark, 2014). Health impacts to consider can be related to fatty acid content (i.e. omega-3 in fish) or toxic compounds present. It is also important that health impacts on animals are considered i.e. heavy metal concentrations in an ingredient.

3. Case study

In this part, the framework is applied to a case study to investigate whether the chosen framework is applicable to a relevant case. The production system analyzed is soybean production, as the agricultural component. For the aquaculture component, seaweed is analyzed. The outline follows the steps of the framework. First, the current food production system is characterized, using the indicators defined in the framework. Then, the alternative is analyzed using the same indicators and lastly, the two systems are integrated into an alternative and circular system.

3.1. Step 1: Characterizing status quo

In this first step of the framework, the current food production system for the case study is identified and analyzed using the tools and indicators as described. Based on the analysis, strengths and weaknesses of the current food system are given.

3.1A. Identify the current food production system

One of the most important components of animal feed in the Netherlands is soybean. Soybean is mainly produced in North America, South America and Asia (FAO, 2018). The Netherlands imports almost all their soy from Brazil, which is the second biggest producer of soybean globally with a production that has doubled over the last 15 years (Lathuillière et al., 2017). One of the major production areas in Brazil is the state of Mato Grosso which produces 26MT each year (Lathuillière et al., 2017). Mato Grosso is a state that is situated in the Central-West of Brazil in Figure 4. It is 900000 km2 big and is mainly situated in the Amazon, which means that it is naturally covered by trees (Spera et al., 2014).

In order to analyze the impact of the soybean system through the three aspects (environmental, economic, and social) and to identify strengths and weaknesses of the system, data analysis is conducted from cradle to arrival at the livestock farm, using the tools described in the framework. This means that cultivation, processing, and transport are accounted for in the LCA. The functional unit used in the assessment is 1 kilogram of protein.

Figure 4. Location of Mato Grosso, Brazil (source from Wikipedia, 2020).

3.1B. Determine relevant indicators

For the case study, several relevant indicators were chosen. The indicators are based on the three pillars of sustainability: environmental, economic, and social. In the following section, the choice and relevance of the indicators to the case study are described.

Environmental Indicators

Net Nutrient Flow: phosphorus, nitrogen
Determining the nutrient flow of phosphorus and nitrogen is important in assessing the sustainability of soybean. Nutrient flows can tell you whether nutrients are being taken out of the system (negative flow) or whether accumulation of nutrients is occuring due to high amounts of nutrient inputs (i.e. fertilizer use). Brazil is one of the biggest soybean producing and exporting countries in the world (Cattelan & Dall'Agnol, 2018). In this regard, the nutrient inputs and outputs are vital in assessing the sustainability long term considering many nutrients are removed from the system through exportation of soybean to other countries.

Greenhouse Gas Emission
The production of soybean meal has the potential to release greenhouse gas emissions at several stages, such as during crop cultivation, land use changes, processing and transport (da Silva, van der Werf, Spies, & Soares, 2010). The latter might be especially relevant since soy is typically transported over large distances. The primary greenhouse gas emissions in soy meal production are CO_2, N_2O and CH_4 (da Silva et al., 2010).

Water Use

Agricultural production systems are large users of water, so the inclusion of water use as a suitable environmental indicator for this case study is deemed essential. Water is a valuable resource and water management has a significant function in increasing food production and food security (da Silva et al., 2016). Brazil is a large exporter of food commodities, therefore, acknowledging the allocation of its water resources is important especially since local water availability poses a problematic issue to many Brazilians (Flach et al., 2020). Additionally, for a more circular and sustainable food system, water usage should be taken into consideration in order to locate drawbacks of improvement. Lastly, this indicator will be assessed through the water footprint (WF).

Land Use

The inclusion of land use in this case study as an indicator is recognized to be important for two primary reasons. Firstly, in Brazil, land use is predominantly connected to the expansion of the soybean industry in various regions, such as the Amazon and Cerrado. It has to transform a large portion of its natural landscapes and forests to accommodate the rising production numbers (88Mtons in 2014) (Lathuillière et al., 2014). Due to land use intensification and deforestation related to land transformation, the Brazilian Amazon is one of the largest sources of GHG emissions. Although, deforestation allotted to soybean has decreased throughout the 2000s with initiatives such as the "Soybean Moratorium"; recent studies show that soybean is still being grown on recently deforested land (da Silva et al., 2010). Soybean Moratorium has been put in action to exclude producers, who have deforested land within a specific timeframe (2006 – 2009), as a method to reduce the environmental impacts of soybean production across the supply chain (da Silva et al., 2010). Secondly, soybean production is exponentially growing with cultivation areas growing by 209% during the period 1995 – 2011 (Castanheira & Freire, 2013). This caused an increase in concerns regarding land occupation and the type of arrangements and inputs used on the land.

Energy Use

Energy use is a relevant indicator as energy used for cultivation, processing and transport of soybeans is often generated by fossil fuels. The use of fossil energy sources is associated with several environmental impacts, such as oil reserve depletion and greenhouse gas emission (Andrea et al., 2016).

Pesticide Use

In this case study, pesticide use was included as an indicator because the use of pesticides is a major problem in agriculture. In aquaculture, production systems are quite different, so a different approach of pesticide use is needed. Therefore, this indicator is used to compare pesticide use in both soybean and seaweed production. Brazil has one of the biggest productions of soybean worldwide as well as a major consumer of pesticides (Almeida, Friedrich, Tygel, Melgarejo, & Carneiro, 2017). These pesticides have a negative impact on the environment. Therefore, pesticide use is compared using an ecotoxicity impact assessment.

Heavy Metals

Heavy metals can find their way into human bodies through the consumption of animal products that have in turn been fed with feed containing heavy metals. The threat heavy metals pose on human health makes this an important indicator to take into account.

Biodiversity

Soybean cultivation has been recognized as a considerable threat to tropical biodiversity of Brazil (Fearnside, 2001). Deforestation, with the purpose of converting tropical rainforest to agricultural land, and the construction of the supporting infrastructure have been the main drivers of biodiversity loss in this area (Fearnside, 2001). For the purpose of this case study, an attempt to draw conclusions based on a qualitative literature analysis is performed. Due to time and resource constriction, conducting an in-depth CWM analysis is not possible. Nonetheless, the value of assessing biodiversity using this method still adds value to the overall analysis.

Susceptibility to Diseases/Pests

Diseases in soybean crops can seriously hamper the profitability. Due to this, diseases pose a serious threat to soybean cultivation in Brazil, where the social and economic importance of this crop is high (Garcia et al., 2020).

Economic Indicators

In order to conduct the LCC analysis, production costs and revenues, processing margins, and shipping costs need to be considered. All values are expressed as both: cost/benefit per acre, cost/benefit per kg, and cost/benefit per kg of protein. In order to identify strengths and weaknesses, costs are also expressed as a percentage of total revenue.

Social Indicators

Consumer Drivers and Barriers

In this case study, another indicator that will be used is consumer drivers and barriers. In the case of soybean and seaweed consumption, the consumer is the farmer. This indicator is included because seaweed is not yet a common component of animal feed. To convert from soybean to seaweed, farmers encounter several drivers and barriers that determine whether the conversion will be successful for them.

Employment Opportunities

Systemically, soybean is Brazil’s main agricultural commodity. Hence, employment opportunity as a socioeconomic indicator is considered in this case study mainly due to soy being one of the largest sources of profitability for Brazil’s economic development.

Labor Conditions
Labor conditions are an important social indicator to consider in assessing the sustainability of a system. Brazil is one of the biggest exporters of soybean in the world in both scale and value (Cattelan & Dall'Agnol, 2018). However, there are questions raised about the social sustainability of this soy considering allegations of exploitation, poor working conditions, and child labor during the cultivation of soybean on farms. These are important to consider in determining soybean sustainability.

Subsidies
The indicator is included because subsidies can stimulate farmers to implement changes or innovations in their production system and can be used as a measure of governmental importance (Schrank & Wijkström, 2003).

Spatial Planning
Spatial planning is included as an indicator because space is limited. In soybean production, the increase in soybean farms has resulted in deforestation of the rainforest in order to increase available land for agriculture. Seaweed production, however, takes place in the North Sea in this case. The North Sea is an area that is used intensively with a lot of different uses overlapping. This makes an accurate spatial planning crucial.

License to Produce
This indicator is included as the public is becoming more involved in food production. The public opinion is thus becoming a more important factor influencing food production practices, also for soybean production (Sterling & Charlebois, 2017).

3.1C. Data analysis with the use of tools

Data collection on indicators for the target production system, soybean, are stated and elaborated upon in this section. An overview of the environmental data collected is available in Appendix 2 (table 1).

Environmental Indicators

Net Nutrient Flow: phosphorus and nitrogen
Fertilization data was collected using Brazilian fertilizer statistics and the quantity of N-P-K formulations that were supplied by FNP (2011). Biological nitrogen fixation by soybean plants was set as a fraction of nitrogen uptake by the crop at 70% (Castanheira, Grisoli, Coelho, da Silva, & Freire, 2015). Crop yields were determined at 2930 kg ha^{-1} as provided by FNP (2011). Based on the findings by Ziep, Wohlgemuth, Emmenegger, Reinhard, & Zah (2009), nitrogen uptake in soybean plants was set at 77.1 kg N tons^{-1}. Nitrogen uptake expressed in kg N ha^{-1} was determined at 225.9 kg N ha^{-1}. Nutrient inputs by fertilizers were calculated as 8 kg N ha^{-1} for N-fertilizers and 35 kg P ha^{-1} for P-fertilizers (Castanheira et al., 2015). Nutrient outputs due to water erosion and leaching were calculated based on the model described in Ziep et al. (2009) and were 86.08 kg NO_3 ha^{-1} (19.44 kg N ha^{-1}), 0.86 kg PO_4 ha^{-1} (0.28 kg P ha^{-1}) and 0.49 kg P ha^{-1} (Castanheira et al., 2015).

Nitrogen output in soybean harvest was calculated as 77.6 kg N ha^{-1} based on crop yields described in FNP (2011) and a 42.32% protein content on dry matter (DM) basis (2.65% N DM basis) (Grieshop & Fahey, 2001). Nitrogen outputs through air emissions were calculated as 0.39 kg NH_3 (0.32 kg N), 1.05 kg N_2O (0.67 kg N) and 0.09 kg NOx (0.03 kg N) (Castanheira et al., 2015). Phosphorus output due to soybean harvest was calculated as 23.15 kg P ha^{-1} based on a 0.7% phosphorus content on DM basis in soybean (Doppenberg, 2017). Nitrogen flow was thus estimated as +175.74 kg N ha^{-1}. Phosphorus flow was thus estimated as +11.08 kg P ha^{-1}.

The hotspot in nutrient flow can be found in the process of cultivating soybeans. Due to application of fertilizer and large-scale cultivation, there occurs a lot of leaching and emissions which are responsible for eutrophication of surrounding areas.

Greenhouse Gas Emissions

The brazillian soybean production system has greenhouse gas emissions ranging from 337 to 694 Kg CO_2 eq per 1000 kg of soybean (da Silva et al., 2010). Transportation to Rotterdam contributed strongly to these emissions in the form of CO_2. GHG emissions varied between production regions within brazil, mainly due to differences in transportation distance and land use change. Deforestation was also a significant source of CO_2 emissions. Furthermore, the crop production also contributed strongly to GHG emissions in the form of N_2O. Similar values for GHG emissions were found in other studies of soybean production. These studies also found crop cultivation to be a hotspot for emission within the production system, due to crop degradation causing N_2O emissions (Dalgaard et al., 2008; Lehuger, Gabrielle, Gagnaire, 2009).

Water Use

A study by Franzese et al. (2013) has quantified the WF for soybean cultivation in Toledo River basin, Brazil and results indicate that the total WF of soybean production is 1880 liters per kilogram of soybean. Due to soybean being rainfed, green water accounts for 99% (1860 l kg^{-1}) of the total WF indicator, whereas grey water is liable for only 1% (19.4 l kg^{-1}). Soybean as a plant, is able to assimilate nitrogen from the atmosphere, thus N synthetic fertilizer is not required in this precise production system. However, due to lack of available data on water bodies, a more accurate description with phosphorus, potassium, and other chemical residue levels could not be completed for grey water. The study concludes that green water is the most important water source for soybean cultivation and an increase in crop yields is correlated with an increase in green water. Another study by Lathuillière et al. (2014) assessed the water consumption in the region Mato Grosso in Brazil and found that a total average of 1908 m^3 yr^{-1} ton^{-1} (with green water dominating) is required for soybean cultivation during the period 2001-2010. Interestingly, water use linked to soybean production increased by 30% along with soybean intensification during that time frame. Soybean cropland expansion is therefore the predominant source for the increase in green water usage in Brazil and is viewed as a hotspot for water use (Flach et al., 2020).

Land Use

One of the inputs that soybean production is dependent on is land. Land use for soybean cultivation varies by geographical location. A study by da Silva et al. (2010) considered land occupation and land transformation to characterize the effect of deforestation in Central West (CW) and Southern (SO) Brazil. Greenhouse gas emissions from land transformation were not assessed in the study's LCA. However, soybean production expansion related to destruction of the Amazon rainforest and Cerrado biome, both majorly focused in Mato Grosso, was seen to be 14% during 2001-2005. As for land occupation, SO region showed higher results than CW, 2070 and 1890 m^2 yr^{-1}, respectively. This is largely dependent on variances in soybean yields with 2535 kg ha^{-1} in SO and 2791 kg ha^{-1} in CW. Additionally, the impacts of transport to Rotterdam affects land occupation by 3%. Another study investigated carbon emissions from land transformation in Mato Grosso (Lathuillière et al., 2014). It shows land use change (LUC) to be equal to 1250 Mtons yr^{-1} in 2005, implying that deforestation for soybean cultivation in Mato Grosso contributed 17% to total Brazilian LUC emissions. Therefore, the inclusion of LUC in measuring the carbon emissions of soybean crops is important.

The hotspots for land use in the life cycle assessment of soybean is largely based on cultivation. As results indicate, soybean crop land is a greenhouse gas (GHG) emissions hotspot on the South American continent. Focusing on global warming potential, land use is a big contributor to the impacts in the production affecting carbon and water cycles as well as biodiversity of the land (Lathuillière et al., 2017). Lastly, CO_2 from deforestation is a main source for climate change impact (da Silva et al., 2010).

Unfortunately, GHG emissions arising from land transformation are not taken into consideration in this report due to the large system boundary and the lack of concrete numerical figures available in literature. Nonetheless, for an all-inclusive LCA study, land transformation GHG emissions should be quantified and apportioned.

Energy Use

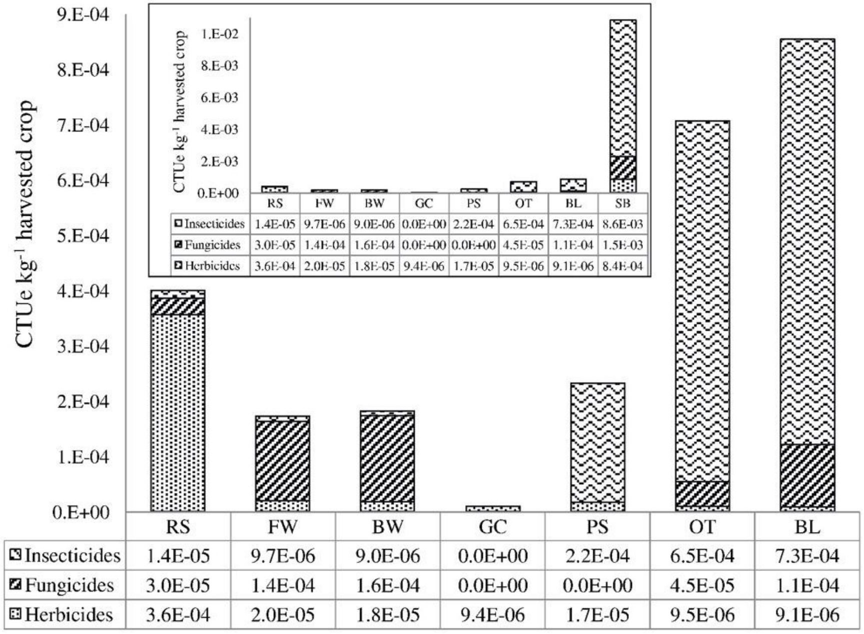
Brazil is one of the main soy producers globally and the cultivation of soy is ever increasing, accompanied by an increasing energy demand (Andrea et al., 2016). The study of Andrea et al. (2016) calculated that the energy use in the Mato Grosso region of Brazil comprises 7800 MJ per hectare. The yield of soy in this study is 2.8 tonnes per hectare resulting in an energy use of 2786 MJ per tonne of soy (Andrea *et al.*, 2016). The largest share (20%) is contributed by fossil fuel use (diesel). The diesel use is 41.7 litres per hectare, or 15.3 litres per tonne of soy (Andrea et al., 2016; Romanelli, Nardi, & Saad, 2012).

Soy cultivation provides multiple outputs which are soy oil as a main product, and soybean meal and hulls as co-products. The soybean meal is commonly used in livestock feed. Because of these multiple outputs, only part of the energy and fuel use above is allocated to the soybean meal (FAO, 2014). When mass balance allocation is used, 72.8% of the cultivation inputs are assigned to the soybean meal (FAO, 2014). The energy use is then 2028 MJ per tonne of soy and the fossil fuel use is 30.4 litres per hectare or 11.1 litres per tonne of soybean meal. As for the processing of the soybeans into soybean meal, it is done by crushing and the use of a solvent to extract the oil (FAO, 2014). This process uses 470.2 MJ per tonne of soybeans. The energy use of transport is lower than the value for processing at 180 MJ per tonne of soy. Fossil fuel use of transporting soy is 5 litres per tonne of soy (Dalgaard et al., 2008).

The hotspot for energy use in the life cycle of soybean is cultivation. The energy use of cultivation is 4.3 times higher than processing of soy and 11.3 times higher than the energy used in transport. Cultivation is also the hotspot for fossil fuel use.

Pesticide Use

Brazil is one of the biggest producers of soybean, but also one of the biggest consumers of pesticides (Almeida et al., 2017). In the period of 2000 until 2012, the use of pesticides per crop in tonnes has increased by over 200% (Almeida et al., 2017). These soybeans are imported from Brazil and used for chicken and pig feed. Norborg, Davis, Cederberg, & Woodhouse (2017) reviewed the effects the use of pesticides has on freshwater. They conducted research on animal products like chicken fillet and minced pork and the feed that is fed to the animals that produce these products. They compared rapeseed, feed wheat, bread wheat, grass/clover, peas, oats, barley, and soybean. They can be compared by expressing them in an ecotoxicity impact equivalent per kg of soybean meal. They found that soybean has a very high ecotoxicity impact compared to other crops because a lot of pesticides are needed to grow them as can be seen in Figure 5. The ecotoxicology impact of soybean is the highest of all crops with 1E-02. This is remarkably higher than the second highest crop, which is barley with 8.5E-04, and even more so compared to the crop with the lowest ecotoxicology impact, which is grass/clover with 9.4E-06



	RS	FW	BW	GC	PS	OT	BL	SB
▫ Insecticides	1.4E-05	9.7E-06	9.0E-06	0.0E+00	2.2E-04	6.5E-04	7.3E-04	8.6E-03
▨ Fungicides	3.0E-05	1.4E-04	1.6E-04	0.0E+00	0.0E+00	4.5E-05	1.1E-04	1.5E-03
▫ Herbicides	3.6E-04	2.0E-05	1.8E-05	9.4E-06	1.7E-05	9.5E-06	9.1E-06	8.4E-04

	RS	FW	BW	GC	PS	OT	BL
▫ Insecticides	1.4E-05	9.7E-06	9.0E-06	0.0E+00	2.2E-04	6.5E-04	7.3E-04
▨ Fungicides	3.0E-05	1.4E-04	1.6E-04	0.0E+00	0.0E+00	4.5E-05	1.1E-04
▫ Herbicides	3.6E-04	2.0E-05	1.8E-05	9.4E-06	1.7E-05	9.5E-06	9.1E-06

Figure 5. Potential freshwater ecotoxicity impacts per kg harvested crop (source from Norberg et al., 2017).

Furthermore, the effect of pesticide use in soybean production goes beyond environmental threats. It can also pose great threats to the farmers that use them (Bernieri, Rodrigues, Barbosa, Ardenghi, & da Silva, 2019). This will be elaborated on further in the social indicators.

Heavy Metals

The limits set by the European Union are: 40 mg/kg dry weight arsenic (As), 2 mg/kg dry weight inorganic arsenic (iAs), 1 mg/kg dry weight cadmium (Cd), 0.1 mg/kg dry weight mercury (Hg) and 10 mg/kg dry weight lead (Pb). Studies conducted by Corguinha et al. (2012, 2015) in Mato Grosso and Minas Gerais States in Brazil on the heavy metal content in grains of soybeans have found arsenic (As), cadmium (Cd) and Lead (Pb) levels below this threshold, with mean values of 0.065, 0.018 and 0.103 mg/kg dry weight respectively. A study conducted by Galhardi, Leles, de Mello & Wilkinson (2020) in Paraná State on the heavy metal content in grains of soybeans which are cultivated close to a coal mining area, found no values exceeding the European norms either, with arsenic (As) having a mean value of 0.02 mg/kg dry weight, cadmium (Cd) 0.04 mg/kg dry weight and lead (Pb) 4.70E-03 mg/kg dry weight. From this study can therefore be concluded that cultivating soybeans near coal mines does not pose additional risks in terms of heavy metal content for which EU limits exist. This study also monitored other heavy metals, such as zinc (Zn), chromium (Cr) and iron (Fe), but for these no European limits are set. Also note that values for inorganic arsenic (iAs) and mercury (Hg) were not measured in these studies. A summary of the data found is in table 2 in appendix 2.

From this it can be concluded that, concerning the heavy metals that are under EU legislation, arsenic (As), cadmium (Cd) and lead (Pb) are present in soybeans within these limits, even close to a coal mine. However, Olmedo et al. (2013) stated that industrial, agricultural and mining activities can increase levels of heavy metals, so more research into this may be necessary. More research will also have to be conducted in order to see if inorganic arsenic (iAs) and mercury (Hg) do not form any problems.

Biodiversity

The Mato Grosso area comprises three distinct biomes: tropical broadleaf rainforest, tropical savannas, and flooded grasslands and savannas (Junk et al., 2006; Millennium Ecosystem Assessment (MEA), 2001). Tropical rainforests and tropical savannas are the biomes with the highest species and family diversity in the world (MEA, 2001). Additionally, tropical rainforests support the highest amount of endemic species (MEA, 2001). Globally, the major opinion is that the tropical rainforests should be conserved (Pereira, Ferreira, de Santa Ribeiro, Carvalho, & de Barros Pereira, 2019). Arguments surrounding the indirect use values, in the form of climate change mitigation potential (Malhi et al., 2008), and non-use values, in the form of the existence value of the pristine rainforest (Rolfe, Bennett, & Louviere, 2000) dominate the debate. Locally, there’s more focus on the direct use value of land. Leaving behind most notions of conservation, but rather developing agriculture and supporting infrastructure (Pereira et al., 2019).

Large scale soy production, including soy designated for soy meal, has been associated with large scale deforestation in the Amazon area (Lehuger et al., 2009), and is said to be the main driver of biodiversity loss in the area (Kessler, Rood, Tekelenburg, & Bakkenes, 2007). Comparing biodiversity loss, standardized to mean national biodiversity, soy production in Brazil is the most damaging of all the export-oriented, plant-based, agricultural commodities (Kessler et al., 2007). Biodiversity loss can also occur during the shipping stage of the life cycle of the product. The use of ballast water in the shipping industry has put stress on coastal ecosystems by introducing harmful invasive species (Ruiz, Carlton, Grosholz, & Hines, 1997). Invasive species put stress on biodiversity by outcompeting native species (Butchart et al., 2010), often resulting in a less diverse community. Additionally, ballast water can transport harmful pathogens across ecosystems, increasing the risk of disease (Ruiz et al., 2000).

Recognition of this threat by the international community led to 'ballast water management convention', making high sea ballast water exchange mandatory (Dunstan & Bax, 2009). A modelled evaluation of this management solution shows that the risk of the settlement of an invasive species is halved, but species transfer between ecosystems is still a threat (Dunstan & Bax, 2009).

Susceptibility to Diseases/Pests

One of the main factors limiting soybean productivity is the occurence of diseases (Berger-Neto, Jaccoud-Filho, Wutzki, Tullio, Pierre, & Justino, 2017; Garcia, Machado Júnior, Bochnia, Weirich Neto, & Raetano, 2016; Weirich Neto, Fornari, Baeur, Justino, & Gracia, 2013). This concerns about 40 diseases, caused by fungi, bacteria, nematodes and viruses, with the ability to cause enormous losses (Embrapa, 2008; Ludwig et al., 2010; Santos et al., 2007). There are many types of fungi responsible for diseases in soybeans, such as rhizoctonia species causing leaf blight (Chavarro-Mesa et al., 2020), Sclerotinia sclerotiorum causing white mold (Berger-Neto et al., 2017), and Phakopsora pachyrhizi causing soybean rust (Childs, Buck, & Li, 2018; Yorinori et al., 2005). Soybean rust is one of the main threats to soybean production in Brazil and is associated with yield losses of over 80%, depending on the environmental conditions (Childs, Buck, & Li, 2018; Del Ponte, Godoy, Li, & Yang, 2006; Echeveste da Rosa, 2015; Yorinori et al., 2005).

Besides diseases, pests also occur on soybean farms. An example of this are stink bugs, which feed on pods and cause, among other things, shrivelled grains, and pod abortion (Sosa-Gómez et al., 2020).

Economic Indicators

Data on production costs and revenues are obtained from (Meade et al., 2016). Data on shipping and processing are obtained from (Goldsmith, 2008). The breakdown of costs and revenues associated with the life cycle of soybean meal, produced in Brazil and consumed in the Netherlands as part of a feed ingredient, can be found here. Shipping and processing costs are based on market prices, because a detailed breakdown of business operations is unavailable in literature.

Concluding from the accompanied LCC analysis, strengths of soy production are its relatively low production costs. The bulk of production costs can be attributed to fertilizer and other chemicals. All other costs are notably low, resulting in a total production cost of only 0.61-dollar cents per kg of soy protein. The main weakness of soy production is shipping costs, both from farm to processing plant, and overseas shipping to Europe. Overall, life cycle costs add up to 1.39 dollars per kg of soy meal.

Social Indicators

Consumer Drivers and Barriers

When farmers choose a certain feed, they have to take into account several factors. In this paragraph, the drivers and barriers for choosing a certain type of feed will be analysed. When choosing a type of feed, the biggest driver is the formulation that meets nutritional requirements at the least cost. Therefore, nutritional factors like protein content are a big driver. Another driver is the feasibility of importing soybean because it is imported on a very large scale. A barrier is that the costs need to remain as low as possible. Other barriers can be heavy metal residues and pesticide use as these can pose health threats for humans and animals.

Employment Opportunities

Richards, Pellegrina, VanWat & Spera (2015) looked at the impact of Mato Grosso's agriculture sector per 1 km^2 of soybean in 2002 – 2010. The authors concluded that soybean production has a strong and positive impact on its regional growth. Results show that nearly 45% of Mato Grosso's flourishment in non-agricultural GDP along with more than half of the non-agricultural employment and urban population growth was associated with Mato Grosso's agricultural sector. Another study by Rhoden, Costa, de Santana, Gabbi, & Janeque (2017) analyzed the generation of employment within the soybean production chain in the Rio Grande do Sul State, Brazil. Regarding the number of employers, a high growth from 3,865 to 7,660 in the period 2002 – 2015 signifying a 198% increase. Soybean production's association with economic relations signifies its considerable importance and reliance on the people and businesses who contribute to its flourishment and employment generation throughout the majority of Brazil.

Labor Conditions

Soybean production in Brazil has previously had problems regarding poor labor conditions on soybean farms with reports of forced and child labor, irregular workers and unsafe working conditions (Berkum, 2008). Despite installing a national plan in a bid to stop forced labor in 1995, there is still debate as to whether these rules are being enforced with NGOs continuing to classify working conditions as 'slavery'. A report by Bickel and Dros (2003) noted that poor labor conditions below international labor organization standards were notably related to activities involving deforestation, soil preparation for planting and the application of chemicals i.e. pesticides. However, issues regarding labor conditions in soybean cultivation have diminished over time due to advances in technological inputs requiring high quality laborers (Roessing & Lazzarotto, 2004). Workers are now more skillful than the average agricultural worker and thus, are less likely to be exploited or forced to work given that labor exploitation is related mainly to workers with low qualifications and skill sets (Berkum, 2008). Furthermore, labor conditions have improved through the national pact for the eradication of slave labor. This has allowed banks and governments to block financing available to farms who don't comply which has led to a reduction in the number of forced labor (Repórter Brasil, 2008).

Subsidies

Literature research shows no evidence for subsidies for soy cultivation and export provided by the Brazilian government. In the Netherlands, there also seems to be no subsidies provided by the government for inclusion of soy in livestock feed.

Spatial planning

Given that 58% of Brazil's soybean production comes from the Cerrado region (Mittermeier, 2004), there is a large focus on soybean cultivation in spatial planning in Matta Grosso (Figure 6). There are current legislations in place that must be considered in relation to development of properties and land which originate from Brazil's 1965 New Forestry Code. These include Áreas de Preservação Permanente (APP) and Área de Reserva Legal (LR). APP makes it forbidden to convert native vegetation that is found in these designated permanent preservation areas to build infrastructure or develop agricultural activity (Brancalion et al., 2016). LR ensures a sustainable management plan is employed by limiting allocation of farm area on a property to ensure sustainable economic use of natural resources on the land (Brancalion et al., 2016).

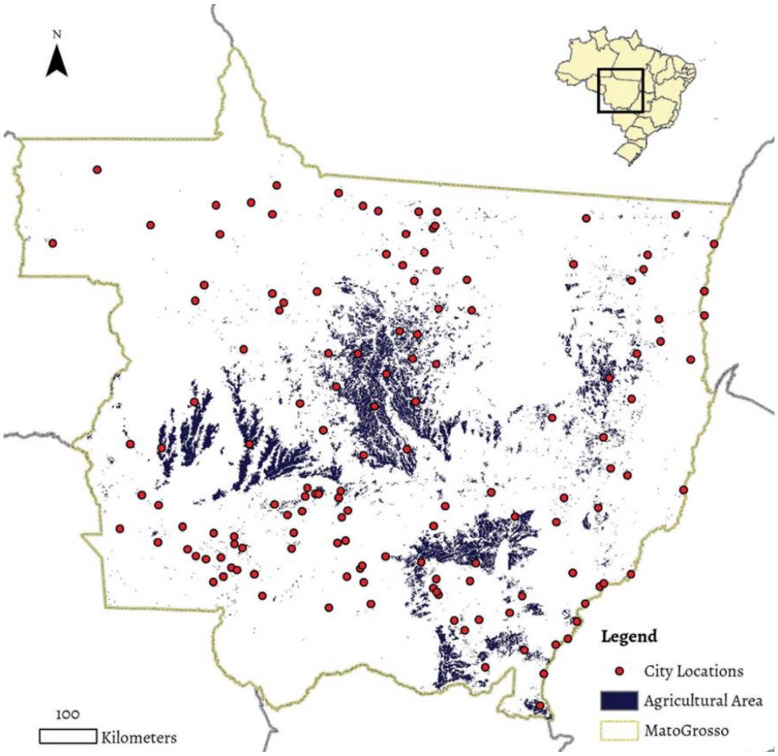


Figure 6. Matta Grosso's agricultural regions derived from Richards et al. (2015).

License to Produce
The social license to produce is affected by public opinion. This public opinion can, for example, be influenced by farming practices and environmental impacts of these practices (Sterling & Charlebois, 2017). Soybean cultivation is one of the main drivers of deforestation in Brazil (Gibbs et al., 2015; Kastens et al., 2017). Furthermore, the soy industry is associated with displacement of small farmers and indigenous peoples, and forced labour (Gibbs et al., 2015; Greco, Bindraban, & Stattman, 2009).

To decrease impacts of the soy industry, the soy moratorium (soyM) was implemented in 2006 and renewed indefinitely in 2016 (Gibbs et al., 2015). The moratorium is an agreement made by all major importers of Brazilian soy which states that no soy cultivated on newly deforested land will be purchased (Gibbs *et al.*, 2015; Kastens, Brown, Coutinho, Bishop, Esquerdo, 2017). After implementation of soyM (2007-2014), deforestation in the Mato Grosso region in Brazil has decreased 5.7-fold annually (Kastens et al., 2017).

3.1D. Identify strengths and weaknesses of the current food production system

In this section, the results of all analyzed indicators are used to determine the strengths and weaknesses of the soybean production system. From these strengths and weaknesses, certain opportunities and threats follow that can be used to identify an alternative production system.

When looking at soybean production, several strengths and weaknesses can be identified. The main threats appear to be in the cultivation step of its life cycle. Strengths of soybean are for example, that it contains a high amount of protein, which makes it suitable for animal feed. Also, it has already been widely accepted as a good component of animal feed. Furthermore, its production costs are relatively low. Lastly, soybean production in Brazil provides a big source of jobs. In these strengths, also lie opportunities. Due to its popularity as a component of feed, an opportunity of soybean is to produce it on a larger scale that would also provide even more jobs. However, the production also has its weaknesses. First of all, with the increasing demand for soybean, more land is needed. This has as a consequence that a great deal of deforestation takes place to make sure that production can expand. Also, pesticides and fertilizers are used on a large scale in Brazil. Furthermore, soy production has a high green water and energy requirement. From these weaknesses, certain threats follow. Deforestation poses a large environmental threat by causing biodiversity loss. From pesticide and fertilizer use, health threats to humans and the environment can result. Also, fertilizer use may lead to eutrophication. Another weakness is the high shipping costs. Soybean production in itself is rather low-cost. However, shipping costs add a big part to the final costs. Lastly, crop degradation can lead to N_2O emissions, which is a greenhouse gas.

From these weaknesses and threats, an alternative feed component may be chosen, which has strengths and opportunities that complement the shortcomings of soybean production. This alternative is analyzed in the next chapter.

3.2. Step 2: The alternative

In this second step of the framework, the alternative food production system for the case study is identified and analyzed using the tools and indicators as described. Based on the analysis, strengths and weaknesses of the alternative system are given.

3.2A. Identify alternative food production system

As was shown previously, the use of soybean in animal feed is damaging to the environment and therefore requires an alternative food production system. Ground-breaking offshore cultivation of seaweed is seen as an advantageous opportunity to decrease agricultural land use and associated environmental encumbrances (van Oirschot et al., 2017). By substituting soybean in animal feed by locally produced seaweed, the environmental impact of animal feed can be reduced significantly (Nordberg et al., 2017). Saccharina latissima is one of the most commonly produced species of seaweed in the North Sea, next to Ulva spp. Saccharina latissima was chosen for the case study because it has a rigid structure which is an advantageous trait for production. The production system used in the case study is single layer S. latissima cultivation.

In order to analyze the impact of the seaweed system in the three aspects (environmental, economic, and social) and to identify strengths and weaknesses of the system, the seaweed system is analyzed based on the same indicators and tools as the soybean system, from cradle to arrival at the livestock farm. This means that cultivation, processing and transport are accounted for. The functional unit used in the assessment is 1 kilogram of protein.

3.2B. Data analysis with the use of tools

Data collection on indicators for sugar kelp production is explained in the following section. An overview of the environmental data collected is available in Appendix 3 (table 1).

<u>Environmental Indicators</u>

Net nutrient flow: phosphorus, nitrogen

Saccharina latissima cultivation does not require addition of fertilizer in comparison to agriculture. In this regard nutrient inputs from fertilizer are negligible. Nitrogen uptake by S. latissima was estimated from the average protein content of *S. latissima* (7.1% of dry matter) determined by Schiener, Black, Stanley, & Green (2015) and yields from a single layer seaweed cultivation (1.2 tons fresh weight $100m^{-1}$) estimated by van Oirschot et al. (2017). The water content of S. latissima (85%) was determined by Schiener et al. (2015) resulting in an estimated yearly yield of 11 tons ha^{-1} yr^{-1} on dry matter basis (72 tons ha^{-1} yr^{-1} on wet-weight basis). Based on yields and nitrogen composition of *S. latissima* (1.5% of dry matter) determined by Schiener et al. (2015), nitrogen uptake was estimated as 0.165 tons N ha^{-1} yr^{-1}. Using estimated yields and the phosphorus content of *S. latissima* (0.29% of dry matter) determined by Seghetta et al. (2016), phosphorus uptake was estimated at 0.032 tons P ha^{-1} yr^{-1}.

Greenhouse Gas Emission

The study by van Oirschot et al. (2017) conducted a life cycle assessment for Saccharina latissima. The whole lifecycle was taken into account, including single layer cultivation, seed collection, processing, and transport. This assessment resulted in a greenhouse gas emission of 21.7 kg CO_2-eq per tonne dried protein. From the results it could be deduced that the drying of seaweed (processing) contributed approximately 74% to the total emissions. Infrastructure was included in the study, emitting 5.28 kg CO_2-eq per tonne dried protein (24% of the total). Cultivation itself, seed collection and transport together, contributed to approximately 2% of the total emissions. The study concluded that the processing of seaweed is the hotspot for greenhouse gas emissions.

Water Use

Unfortunately, the water footprint of green, grey, and blue water cannot fully apply for marine production systems, specifically offshore cultivation systems. New methodologies for water footprint (WF) need to be developed in order to have a well-defined representation on the water consumption of marine food production systems. It is an important indicator to factor for tradeoff viabilities that can improve linear food production systems. There is a possibility of including seawater loss into new methodologies and in the WF of the final product. This would include water loss during harvest, transport, and drying process (evaporation). However, such losses are still uncertain (Seghetta et al., 2016).

The available data on offshore Saccharina latissima cultivation in the Netherlands for protein production is quite limited as it is still in its infancy (van den Burg, Dagevos, & Helmes, 2019). Therefore, this case study resorted to using values from other studies in order to have a rounded insight on the position of seaweed cultivation. Seghetta et al. (2017) ran an LCA study on Saccharina latissima for protein production in Denmark. The authors revealed that the net water consumption for the process is equal to 61870 mg per year for a cultivation area of 208 km^2, which is quite insignificant. A general advantage of offshore seaweed cultivation is that it does not require heavy water consumption for production or harvest. Water consumption is highly linked to hydrolyzation of the seaweed biomass. However, extended literature does not provide information regarding on/off-site recyclable water or water treatment facilities.

Another study conducted by Taelman et al. (2015b) on multiple seaweed production scenarios concluded that seaweed production with 100% wind power supply accounts for the least water resource footprint in comparison to linear wastewater treatment plants, paddle wheels, and wastewater treatments coupled with microalgae. Furthermore, all scenarios have a general advantage in which they provide water quality restoration services.

Land Use

Land use is poorly accounted for in marine production system LCA studies due to difficulty and lack of methodological advances that account for the occupation of marine water surface area (Langlois et al., 2011; Taelman et al., 2015b). Unfortunately, in this case study, land use (including land use change) is not included in the analysis for offshore seaweed cultivation due to lack of standardized methodology to quantify land use in marine production systems hence leading to a lack of available data in literature (Seghetta et al., 2017). Piloted studies have run in Ireland and France on Saccharina latissima (Taelman, Champenois, Edwards, De Meester, & Dewulf, 2015a), but there are no figures for seaweed cultivation in the Netherlands due to its infant stage. First attempt to measure the impact of marine provincial occupation in an LCA study was completed by Taelman et al. (2014) using cumulative exergy extraction. It demonstrates spatially differentiated characterization factors to account for sea surface occupation based on the potential net primary production (NPP) available in the photic zone. This is due to the infrastructure for seaweed cultivation interfering with sunlight availability for NPP production. Further research on the inclusion of biorefinery infrastructure in land occupation impact in marine production systems LCA is required for an inclusive representation.

Two studies by Seghetta et al. (2016; 2017) in Denmark used 208 km^2 of water surface for Saccharina latissima cultivation. They concluded that during seaweed growth, bio-extraction of carbon has the ability to reduce atmospheric CO_2 due to the water surface's high exchange rate. This is contrary to the high amounts of CO_2 generated from land use change in soybean cultivation. Seaweed cultivation systems can be CO_2 neutral or feasibly negative providing climate mitigation through net reduction in atmospheric CO_2 (Seghetta et al., 2016). Therefore, sustainability issues such as land occupation can be mitigated. New methodologies need to take into account the water surface occupation at sea and related environmental impacts for a comprehensive and fair comparison between land and sea production.

Additionally, this innovative method can ease competition for land occupation of extensive soybean production that is producing aforementioned issues regarding land use change (i.e. deforestation) (Seghetta et al., 2017). Long term projections of soybean production foresee a 2.2% annual increase by 2030 generating even further rivalry for cropland with other agricultural crops (Seghetta et al., 2017).

Energy Use

The life cycle of seaweed is quite energy intensive. Seghetta et al. (2016) calculated the cumulative energy demand (CED) for the life cycle of Saccharina latissima. This CED is 62000 MJ per hectare of which 27% (17000 MJ/ha) originates from fossil fuel sources (Seghetta et al., 2016). Considering the energy value of diesel, this comes down to 472 litres of diesel per hectare. Saccharina latissima yields 11 tonnes dry matter per hectare, resulting in a CED of 5636 MJ per tonne dry matter and a fossil fuel use of 42.9 litres per tonne dry matter. These numbers include cultivation, processing and transport (van Oirschot et al., 2017).

The processing of seaweed often produces multiple products such as biofuel and fertilizer. An important processing step is the drying of seaweed (van den Burg et al., 2019). From the study of van Oirschot et al. (2017) it can be deduced that approximately 77% of the CED is caused by this drying process. In this study, the infrastructure for cultivation of seaweed, such as lines and buoys, has been accounted for as well. This infrastructure contributed to 21% of the CED. The other 2% is made up from harvest, transport and seed collection. In this paper, the authors concluded that drying (processing) is the hotspot for energy demand and fossil fuel use in the life cycle of seaweed (van Oirschot et al., 2017).

Pesticide Use

Not much research has been done yet on pesticide use in seaweed production. However, it seems that there is no pesticide use in the production of seaweed. Traces of pesticides have been found; however, this originates from agricultural residue (Banach, Hoek-van den Hil, & van der Fels-Klerx, 2020).

Heavy Metals

Seaweeds, and especially brown algae (Güven, Akyüz, & Yurdun, 1995), are efficient in improving water quality by taking up materials from the water. However, in doing this they also absorb and retain heavy metals present in that water (Kim, Kraemer, & Yarish, 2019). For the data below, when inorganic arsenic (iAs) has not been given in the paper, it has been calculated as 1.72% of total arsenic (As) as indicated by Almela, Jesús Clemente, Vélez, and Montoro (2006) and Díaz et al. (2012).

Compared to the EU limits (40 mg/kg DW arsenic (As), 2 mg/kg DW inorganic arsenic (iAs), 1 mg/kg DW cadmium (Cd), 0.1 mg/kg DW mercury (Hg) and 10 mg/kg DW lead (Pb), some heavy metal contents measured in S. *latissima* in locations comparable to the North Sea are too high. In the study conducted by Roleda et al. (2019) focusing on Norway and France, the minimum arsenic (As) value found already exceeded the EU limit, as well as the maximum value for mercury (Hg). The rest of the values for inorganic arsenic (iAs), cadmium (Cd), mercury (Hg) and lead (Pb) were below the EU limits. The study by Ometto et al. (2018) in Norway also found a mean and maximum arsenic (As) values above the EU limit, while the minimum value found did not exceed this EU limit. The same goes for cadmium (Cd). For inorganic arsenic (iAs), only the maximum value exceeded the EU limit by a small factor. Mercury (Hg) and lead (Pb) values did not exceed EU limits. A study by Schiener, Black, Stanley, and Green (2015) in Scotland only found a mean and maximum arsenic (As) value exceeding EU limits. However, this study did not look into cadmium (Cd) and mercury (Hg) values. Finally, a study by Maulvault et al., 2015 in a Norwegian site they considered contaminated, found only the mean arsenic (As) above the EU limit. The latter three studies also looked into other heavy metals, such as zinc (Zn), chromium (Cr) and iron (Fe), but for these no European limits are set. A summary of the data found is in table 2 in appendix 3.

It can be concluded that arsenic (As) is a problem in S. *latissima* in all locations. Inorganic arsenic (iAs), cadmium (Cd) and mercury (Hg) should be monitored, as the values for these heavy metals have exceeded EU limits depending on the location. Lead (Pb) was only found well below the EU limits. However, it should be noted that carryover of lead (Pb) (EFSA, 2004) and inorganic arsenic (iAs) (EFSA, 2009) to meat is low.

Biodiversity

The Dutch goal regarding biodiversity conservation falls in line with those formulated in the natura 2000 reports (Jak, Bos, & Lindeboom, 2009). Natura 2000 forms the basis of EU regulations surrounding biodiversity conservation. Conservation goals are realized through the implementation of protected areas. In the North Sea, species of high interest mainly comprises migratory birds and marine mammals (Jak et al., 2009). Therefore, it can be concluded that a desired ecosystem for the North Sea corresponds with an ecosystem that supports these species.

Due to the lack of empirical data the effect of offshore seaweed farms is not yet completely mapped out. Findings are mainly based on small scale experimental studies, and research from Asian countries, where offshore seaweed farms are more widespread. The effect of offshore seaweed farms on biodiversity is predicted to be largely positive. Seaweed farms are said to enhance biodiversity by:

- Providing invertebrates, such as bivalves and small crabs, with a suitable habitat (Jansen et al., 2018)
- Increasing food availability via an increase of primary production (Wood et al., 2017)
- Functioning as nursery habitats and shelter for fish species (Ingle et al., 2018)
- Attracting marine mammals and fish-eating birds due to the increased food supply (Wood et al., 2017)
- Serving as resting areas for migratory bird species

Offshore seaweed farms are hypothesized to contribute to the spread of invasive species, which negatively affects native biodiversity (Butchart et al., 2010). Rising water temperatures push nudged species towards the north. Species that would have no colonizing opportunities due to habitat fragmentation can use seaweed farms as a steppingstone towards northern waters (Khan, Levac, van Guelphen, Pohle, & Chmura 2018).

In some cases, marine mammals purposely avoid offshore aquaculture farms (Markowitz et al., 2004). If this is also the case for offshore aquaculture in the North Sea, extra care needs to be put in spatial planning. The impact is highest if aquaculture overlaps with important habitat, such as reproduction and feeding areas, or migration routes (Campbell et al., 2019a).

Susceptibility to Diseases/Pests

Seaweed farming decreases genetic diversity, which makes seaweeds more susceptible to diseases and pests (Valero et al., 2017; Campbell et al., 2019b). This is especially a problem in the aquatic environment, as the use of pesticides and fertilizers is not an option here (Campbell et al., 2019a). Aside from the large economic losses these diseases and pests can result in, they can also spread to nearby natural populations and cause problems there as well (Bernard, 2018; Loureiro, Gachon, & Rebours, 2015; Valero et al., 2017). Effective national and international policies on the prevention of diseases and pests are lacking, with as a result that these events hamper expansion of the seaweed sector (Campbell et al., 2019b). More research into diseases and pests in European seaweed cultivation will be necessary, as they have rarely been studied yet , and may become more frequent with climate change (Bernard, 2018; Loureiro et al. 2015).

Unfavorable environmental conditions e.g. temperature, salinity and light, as well as anthropogenic activities such as heavy metal pollution can result in diseases. However, in many cases these conditions leave the seaweeds stressed and weakened, resulting in a highly increased susceptibility to pathogens and pests. Infectious diseases in Laminaria species in the North Sea appear in the form of bacterial infections such as the rot disease and oomycete infections. Pests in European Laminaria aquaculture appear in the form of algal epiphytes, algal endophytes and epiphytic animals. Algal epiphytes cover seaweed surface, effectively blocking light uptake. If a seaweed manages to survive this, it will be weakened to the extent that it will be an easy prey for bacteria and oomycetes (Bernard, 2018). These epiphytic algae are regularly observed in European seaweed aquaculture (Peteiro & Freire 2013; Walls, Edwards, Firth, & Johnson, 2017) and are therefore one of the major concerns for this sector (Potin, Bouarab, Salaün, Pohnert, & Kloareg, 2002). Endophytes, present inside the seaweed, can result in various symptoms in Laminaria species, such as galls and severe thallus deformations. Lastly, epiphytic animals that feed on the seaweed or use it as a substrate can be regarded as a pest as they have the ability to damage the seaweed to a large extent (Bernard, 2018).

These diseases and pests are difficult to eliminate, as treatments such as the use of chemicals often have side effects on the seaweed itself as well as on the environment in the form of environmental pollution. Other disease management, such as exposing the culture ropes/nets to air in order to combat bacterial infections, is often very expensive. Therefore, prevention of diseases and pests is the best approach. However, for this it may be necessary to decrease the culture density (Bernard, 2018).

Economic Indicators

Data on production costs, shipping costs, and revenues are obtained from (van den Burg et al., 2016). Data on processing costs is missing, so the same margin of 12% is used. Differences in data availability of different production systems highlights one of the weaknesses of LCC in comparing two production systems. The detailed breakdown of costs and revenues associated with the production of seaweed meal can be found here.

Concluding from the LCC, seaweed production in its current form is not economically feasible. At current market price, a subsidy of 1.16 dollars per kg of seaweed is required for a farmer to break even. Due to the low protein content of the analyzed species, this number increases to 16.50 dollars per kg protein produced. The main perceived benefit of local protein production, the elimination of high shipping costs, is negated by the harvesting costs, incurred due to the offshore nature of production.

Social Indicators

Consumer Drivers and Barriers

One of the drivers for farmers to convert from the use of soybean in their feed to seaweed is that soybean production has a major impact on deforestation (Fehlenberg, 2017). Furthermore, no pesticides are used in seaweed cultivation (Banach et al., 2020), whereas soybean cultivation requires a high amount of pesticides and therefore has a big ecotoxicity impact (Nordberg et al., 2017). Another important driver is that seaweed is more suitable to be produced locally. While soybean can be cultivated in the Netherlands, there is not enough space and not the right climatic conditions to produce enough (Greendeals, 2018). However, there are also a few barriers for farmers to use seaweed in their feed. One of those barriers is the digestibility. Seaweed inclusion levels need to be monitored carefully since high inclusion levels can negatively affect growth (Makkar et al., 2016). Another barrier is the costs. Since seaweed is still an upcoming production system, it is not economically feasible yet to use it as a component of feed. As aqua-feed companies currently formulate on a least-cost basis, the high price of seaweed acts as a barrier to inclusion in feed.

Employment Opportunities

Currently, there are no findings that can represent this indicator in the European context, specifically The Netherlands. Seaweed production in the North Sea is still in a relatively new stage. Nonetheless, various discussion topics in respect to production and processing of seaweed in Europe such as employment opportunities for women or Asian migrants who have seaweed cultivation knowledge are discussed and evaluated within the sector (van den Burg et al., 2019). The Netherlands has great prospects for the seaweed sector to draw in large amounts of direct employment and new businesses.

Labor Conditions

With seaweed cultivation currently still in its infancy in the Netherlands, assessing labor conditions is difficult. However, given the labor-intensive nature of cultivation and the labor costs in Europe, technological innovations will be needed to reduce costs. Whilst there is no information on labor conditions, it is assumed that labor conditions will be high due to EU labor laws which set minimum standards for working and living conditions for European workers.

Subsidies

In the Netherlands, subsidies for seaweed cultivation are available and provided by the government (Ministry of Agriculture, Nature, and Food Quality). However, the government only provides these subsidies when certain requirements are met. These requirements are that the goal of seaweed cultivation must be research-related or in collaboration with a research institute. No subsidies are provided for up-scaling of production or market research (Stichting Noordzeeboerderij, 2018). There seem to be no subsidies provided by the Dutch government for the inclusion of seaweed in livestock feed.

Spatial Planning

In seaweed cultivation, spatial planning is a crucial indicator. The North Sea has a lot of different allocations which also frequently overlap as can be seen in Figure 7. To find a suitable production site, all other users of the North Sea must be taken into account. This makes the spatial planning of the North Sea a difficult task, especially since more uses like aquaculture and offshore wind parks keep arising.

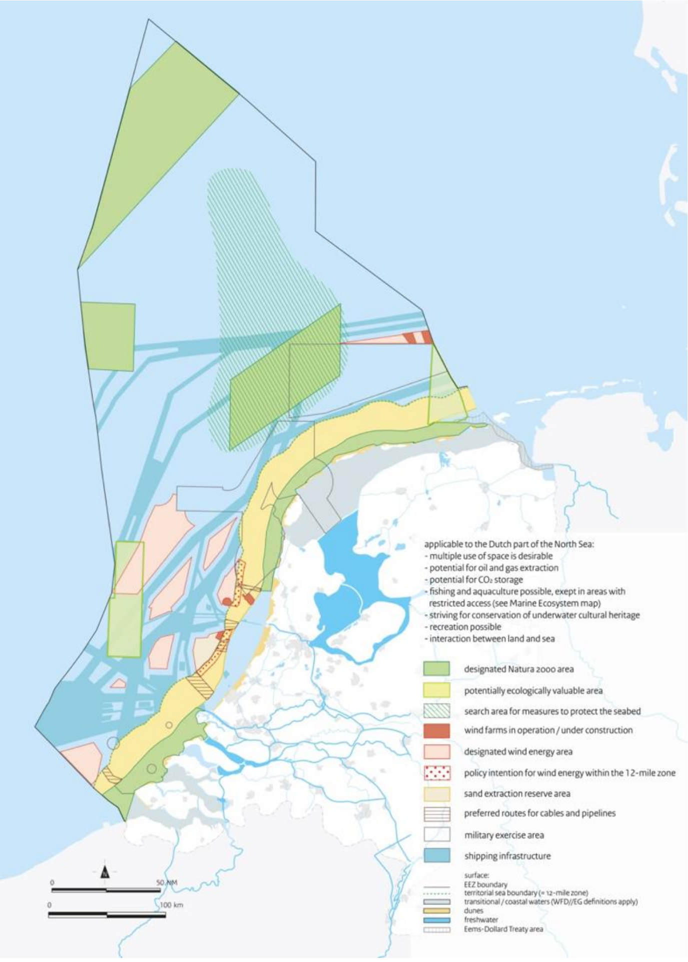


Figure 7. Spatial distribution of human activity in the Dutch part of the North Sea (source from UNESCO, n.d.).

License to Produce

As mentioned earlier, the license to produce is a social license which can be affected by public opinion (Sterling & Charlebois, 2017). The public opinion on seaweed cultivation may be influenced by the environmental impact of seaweed. Multiple studies have shown that seaweed can be beneficial for the ecosystem. First, seaweed farms provide a habitat for a range of organisms, creating a healthier ecosystem for marine life (Theuerkauf et al., 2019). Second, seaweed farms can increase ocean health by the reduction of nutrient pollution thereby improving water quality (Gentry et al., 2019; Theuerkauf et al., 2019). This is beneficial for the North Sea as well as the Central North Sea (off-shore) as they are at risk of eutrophication (Druon, Schrimpf, Dobricic, & Stips, 2004). Furthermore, seaweed is a low input system requiring little or no feed, freshwater and land (Theuerkauf et al., 2019). Whilst, seaweed also plays a role in carbon sequestration and could therefore potentially be a climate change mitigation strategy (Alleway et al., 2019; Gentry et al., 2019).

However, the magnitude of the benefits to the ecosystem provided by seaweed cultivation depend on environmental and socioeconomic conditions of the area. For example, benefits can be dependent on which species is farmed, farm management, the nutrient status of the ecosystem, and hydrodynamics (Theuerkauf et al., 2019). Overall, the environmental impact of seaweed might have a positive impact on public opinion and the license to produce.

3.2C. Identify strengths and weaknesses of the alternative food production system

From the data analysis, it can be concluded that the seaweed production cycle is associated with various strengths, weaknesses, opportunities, and threats. Strengths can be found in the aquatic nature of the production cycle, as this makes the use of fertilizer and freshwater supply redundant. Besides this, the seaweed can be produced locally, in the North Sea, where EU laws exist that ensure good labor conditions.

Opportunities of seaweed are found, among other things, in the great prospects for the seaweed sector to draw in employment and new businesses. Besides this, seaweed farms can increase biodiversity by providing habitats, shelter, resting areas, and food. They can be used as steppingstones for other species moving towards northern waters. Seaweed also plays a role in carbon sequestration, thereby mitigating climate change, and is able to improve water quality by taking up nitrogen (N) from the water.

However, this last opportunity is associated with a weakness as seaweeds also take up many heavy metals, such as arsenic (As), from the water. A second weakness is present in the high greenhouse gas emissions and energy and fossil fuel use associated with the processing of the seaweed. Thirdly, using much seaweed in feed is difficult as this may negatively affect growth. There are also economic weaknesses. It is not economically feasible yet for farmers to use seaweed as a feed component unless they receive a high subsidy. However, currently there are no subsidies for farmers to include seaweed in livestock feed.

Finally, some threats appear in the analysis of the seaweed production cycle. The combination of a low genetic diversity and unfavorable environmental conditions, which will appear more often with climate change, leads to a high susceptibility to diseases and pests, with substantial economic losses as a consequence. Seaweed farms can also spread invasive species. As a final threat, the spatial planning of the North Sea is becoming increasingly difficult, e.g. due to aquaculture and wind parks.

3.3. Step 3: Integration

In the third and final step of the framework, the alternative food production system, seaweed cultivation in the North Sea, is integrated with the original food production system, soybean cultivation in Brazil. The newly integrated food production system is defined then the data from both systems are merged in order to assess the functionality of the new integrated system. All indicators are assessed, and a comparison is made with the original target food production system.

3.3A. Define integrated food production system

Based on the data collected for both soybean and seaweed cultivation, two scenarios were created. One scenario acting as a baseline in which there was no integration of seaweed into animal feed and the second scenario in which seaweed was incorporated into animal feed. The seaweed replacement value was based on soybean protein consumption by the animal feed industry in the Netherlands and *S.latissima* protein yield based on an area of 145km^2 available for cultivation. This production area was based on nutrient availability for seaweed culture in the Dutch Exclusive Economic Zone in the North Sea (van den Boogaart et al., 2020). Soybean protein consumption was estimated using soybean protein content and yearly soy consumption by the animal feed industry determined by CBS (2014) of 720,000,000 kg. Seaweed protein yield was based on estimated yearly *S.latissima* yields of 11,324,500 kg protein for an area of 145km^2. Based on seaweed protein yields, it was determined that yearly seaweed yields would be able to replace 1.6% of soy use by the animal feed industry in the Netherlands. This resulted in two scenarios; 1) The baseline: the soybean production system described in step 1 (0% seaweed), and 2) The integrated system: 1.6% replacement of soy protein with *S.latissima* protein in animal feed. The previously discussed environmental impact indicators were used to facilitate comparison between the two scenarios with each indicator expressed in relation to kg protein. With this integrated production system, soy protein is being partly replaced by a potentially more sustainable product, *S. latissima protein,* in order to reduce environmental pressure. This strategy fits with the strategy "Refuse" for circular productions, which is the top strategy for increasing circularity previously shown in Figure 3.

3.3B. Integrate data of original and alternative system to develop a new integrated system

In order to assess the integrated system, it was important to combine data from the original and alternative system. These were based on indicators previously described in the environmental, economic and social domains. Results from the integrated system were divided into three categories: quantitative, qualitative, and economic. This was structured in this way rather than by the three domains as some environmental indicators contained qualitative data, i.e. biodiversity and pesticide use. Quantitative indicators were mainly composed of environmental indicators whereas qualitative indicators were composed of social indicators.

Quantitative Indicators

Results for the quantitative indicators from the scenarios tested can be found in Table 1. In general, replacement of soybean with seaweed resulted in a decrease in measured environmental indicators. Replacing 1.6% of soybean protein with seaweed decreased water consumption by 75.20 L kg protein. CED increased by 1.2 MJ kg protein to 8.12 MJ kg protein. Nitrogen and phosphorous input decreased to 0.007 kg N kg protein and 0.074 kg P kg protein respectively. GHG emissions decreased to 1.71 kg CO_2-eq kg protein. NH_3 and P leaching decreased to 0.076 kg NH_3 kg protein and 0.0004 kg P kg protein. Heavy metal concentrations per kg protein decreased with the exception of arsenic, cadmium and lead which increased by 0.07 mg kg protein, 0.001 mg kg protein and 0.00009 mg kg protein respectively.

Table 1. Values of environmental indicators for the baseline scenario (only soy included in animal feed) and the integration scenario (1.6% seaweed replacement in the animal feed). The numbers are based on 1 Kg of protein.

	Scenarios		
	Baseline	1.6% Seaweed replacement	% change
Indicator			
CED (MJ kg protein)	6.97	8.12	16.6
Diesel (L kg protein)	0.04	0.05	23.5
Water consumption (L kg protein)	4700.00	4624.80	-1.6
GHG (kg CO_2-eq kg protein)	1.74	1.71	-1.6
N input (kg N kg protein)	0.0071	0.0070	-1.6
P input (kg P kg protein)	0.075	0.074	-1.6
NH_3 leaching (kg NH_3 kg protein)	0.077	0.076	-1.6
P leaching (kg P kg protein)	0.00044	0.00043	-1.6
Arsenic (mg kg protein)	0.017	0.09	431.1
Cadmium (mg kg protein)	0.0116	0.013	9.7

Lead (mg kg protein)	0.02154	0.022	0.4
Zinc (mg kg protein)	17.6	17.35	-1.4
Chromium (mg kg protein)	0.48	0.47	-1.3
Copper (mg kg protein)	3.68	3.62	-1.5
Iron (mg kg protein)	32	31.79	-0.7
Nickel (mg kg protein)	0.88	0.87	-1.5
Cobalt (mg kg protein)	0.024	0.02	-1.4

Results of the economic indicators for the baseline scenario (0% seaweed protein) and integrative scenario (1.6% seaweed protein) are given in table 2. Calculations can be found here.

Table 2. Values of economic indicators for the baseline scenario (only soy included in animal feed) and the integration scenario (1.6% seaweed replacement in the animal feed).

	Scenarios		
	Baseline	1.6% Seaweed replacement	% change
Indicator			
Production costs soy protein ($)/(kg)	0,61	0,58	-5,20
Production costs seaweed protein ($)/(kg)	0,00	0,39	N/A
Total production costs protein ($)/(kg)	0,61	0,97	58,88
Processing costs soy protein ($)/(kg)	0,12	0,11	-5,20
Processing costs seaweed protein ($)/(kg)	0,00	0,04	N/A
Total processing costs protein ($)/(kg)	0,12	0,15	24,47

Shipping costs soy protein ($)/(kg)	0,31	0,29	-5,20
Shipping costs seaweed protein ($)/(kg)	0,00	0,03	N/A
Total shipping costs protein ($)/(kg)	0,31	0,33	5,34
Total costs protein ($)/(kg)	1,04	1,45	38,95

The side by side comparison of costs in Appendix 4 shows that, from an LCC perspective, soybean outperforms seaweed in every aspect of the product’s lifecycle. This is the case for both total kg produced and kg of protein production. An increase in replacement percentage will therefore always disproportionately increase total life cycle costs.

Qualitative Indicators

Qualitative indicators were assessed using a scoring system whereby the integrated system scenario was compared to the baseline scenario using a positive (+), neutral (+-), and negative score (-). Assessment of these indicators can be found in Table 3. The integrated system scenario had a positive effect on land use, biodiversity, labor conditions, license to produce and pesticide use. A neutral score was assigned to consumer drivers and barriers, subsidies and employment opportunities. The integrated system scenario had a negative effect on diseases and pests.

Table 3. Assessment of qualitative indicators of the integrated system (1.6% seaweed replacement) compared to the baseline (soybean only).

Indicator	**Score**
Land use	+-
Biodiversity	+
Susceptibility to diseases/pests	+
Pesticide use	+
Subsidies	+-
License to produce	+
Employment opportunities	+
Consumer drivers and barriers	+-

3.3C. Compare integrated production system to original target production system

In this section, a comparison of the new integrated production system is made with the original production system based on the three sustainability pillars. The findings of the integrated system are discussed, allowing for a clear comprehension of the feasibility of the new integrated system.

Environmental Indicators

When looking at the environmental indicators, replacement of soy can have a positive impact, for example on water use, nutrient flows of nitrogen and phosphorus, water consumption and several heavy metals. However, for some indicators it will negatively change. CED will heavily increase, as will the use of diesel. The increase in energy demand can be attributed to the large amounts of energy required for drying seaweed, which is the hotspot in energy use during the life cycle of *S.lattissima* (van Oirschot et al., 2017). These results seem to contradict our own finding that GHG emissions will decrease by 1.6% under the alternative scenario. This could partly be explained by GHG not solely being caused by energy use, for example the hotspot for GHG emissions of soy production occurred in the cultivation stage, due to degradation of plant material (Dalgaard et al., 2008; Lehuger et al., 2009). However, it is likely that these differences occurred due to the use of several studies within our comparison, which all had slightly different methodologies. The integration of *S.lattissima* resulted in a large increase of arsenic per kg of protein. Given that arsenic soil pollution is already an issue with animal wastes, arsenic increase due to seaweed inclusion will likely exacerbate this issue (Liu et al., 2015). An increase in cadmium and lead was also observed as a result of integration. Concentrations must be carefully monitored as they bioaccumulate through the food chain and can lead to health implications in high concentrations (Aycicek, Kaplan Ince, & Yaman, 2018).

Integration of *S.lattissima* also resulted in positive benefits on biodiversity and pesticide use. A positive benefit on biodiversity was given based on the ability of seaweed to promote biodiversity through their added physical structure which provides habitat for a wide range of species in the North Sea (Carr, 1994; Graham, 2004). Furthermore, reducing use of and thus demand of soybean may ease deforestation rates which are responsible for a large loss of biodiversity in Brazil (Fearnside, 2005). Integration of seaweed also had a positive effect on pesticide use through a decrease in pesticide use as seaweed cultivation does not require pesticides (Duarte, Wu, Xiao, Bruhn, & Krause-Jensen, 2017). With pesticide use also a cause of biodiversity loss, the reduction in pesticide use would have a positive impact on biodiversity (Beketov, Kefford, Schäfer, & Liess, 2013). A positive impact on susceptibility to diseases and pests was given as the integrated system would reduce biodiversity loss. This would have a positive impact on susceptibility to diseases as biodiversity loss has been shown to increase disease transmissions (Gilbert, 2010). A neutral impact was given on land-use as although integration will decrease soybean land use, it is not clear when accounting for seaweed land-use whether this would be a net positive impact. This is because there are currently no methodologies for assessing land-use at sea (water-surface use). Although this was not considered in the scenario as the indicator was only applicable to seaweed, the capacity of seaweed to remediate nutrients should be considered. This is because seaweed uptakes nutrients i.e. nitrogen in the water which has a positive impact on the environment through reducing the impact of eutrophication (Neveux, Bolton, Bruhn, Roberts, & Ras, 2018).

In the seaweed-scenario, the decrease in environmental pressure compared to the 100% soy-scenario is near to 1.6% for various indicators, namely GHG emissions, nutrient leaching and input, and water consumption. The decrease in nutrient input can be explained by S. lattissima requiring no fertilizer during cultivation as they are able to absorb and remove nutrients from surrounding waters instead (Duarte, Losada, Hendriks, Mazarrasa, & Marba, 2013). As 1.6% of soy is being replaced with seaweed in this scenario, this shows that replacement of soy with seaweed has the potential to significantly reduce the environmental impact of protein production for animal feed within the Brazilian soy protein production for the Netherlands. The primary limitation for a further decrease in these environmental impacts seems to be the maximum amount of *S. lattissima* that can be produced in the Dutch North Sea.

Economic Indicators

From an economic perspective, replacement of soy meal for seaweed meal in animal feed is not feasible. Production costs are disproportionately high for seaweed protein cultured in the North Sea compared to soy protein in Mato Grosso to the extent that a replacement of 1.6% results in an increase of total lifecycle costs of 39%. Technical innovations, increasing yield and reducing costs, or market innovations, increasing price, are required for seaweed protein to be an economically feasible alternative to soy protein.

Social Indicators

Last but not least are the social indicators. From a social perspective, replacement of soymeal with seaweed feed for animals may have a fairly positive impact. The positive impact is largely directed at the cultivation of seaweed. Seaweed in the North Sea is a relatively young and pilot scale process chain currently used to demonstrate its production feasibility in Europe. This signifies that the production side is still under development. Therefore, attesting for the social indicators is quite a difficult task. The variances in the social aspects conducted in this case study could be due to the mature and large-scale technology of the linear soybean production system. Taking this into account, the innovativeness of the seaweed cultivation could have a positive influence on the social benefits. Employment and labor conditions could contribute to nourishing coastal communities and economies by attracting new proficiencies, providing new jobs opportunities, and building synergetic working conditions. With the escalation of public awareness of the sustainable and environmental benefits of seaweed, the acceptance of consumers (i.e. farmers) to cultivate and utilize seaweed could also increase. This could lead to additional pressure on the Dutch government and policy makers to enhance subsidies and create licenses to produce for seaweed cultivation. Although soybean production might perform better socially than the integrated seaweed production system at the present time, it is anticipated that the European seaweed value chain will grow and upscale production in the future.

4. Discussion on Framework

The use of the framework in the case study was a nice testing opportunity, allowing for the identification of strengths and weaknesses of the framework. The framework focuses on three domains, the environmental, economic, and social, by the use of environmental LCA, LCC, and social LCA. This makes the approach of the framework very integral. However, limitations occurred for all three tools. The first major limitation was data availability. Where environmental data for soybean was sufficient, this was not the case for seaweed. The cultivation of seaweed is a relatively young practice and therefore research concerning seaweed is limited. Both for cultivation and other stages of the life cycle. Another issue arising for seaweed is the lack of methodology for conducting a marine LCA. Indicators used in a terrestrial LCA, such as water use or land use, are not applicable to marine LCAs using the same methodologies. Even though marine systems do use water and space.

Lack of available data was also an issue in the other two domains. For the LCC, there was not only a lack of available data, but also a lack of good quality data. Furthermore, there was a problem with the inclusion of indicators. In an LCC, the environmental costs and externalities are barely included causing the monetary value to not align with the actual costs. For the use of the LCA, the inclusion of impact categories was a factor of uncertainty as well. The LCAs studied for the case study did not only use different impact categories, the scope and boundaries differed as well, making it difficult to get a complete set of data for both soy and seaweed. If there were common impact categories, the unit was not always the same, still not allowing for direct integration. For the social LCA, the difficult part was the quantification of indicators. For many of the chosen indicators, this was not possible causing a problem with comparing indicators for soy and seaweed. This made integration also a lot more difficult. Moreover, some social indicators, like license to produce, have room for interpretation i.e. are subjective. Therefore, drawing conclusions from these, even in a qualitative manner, is not very reliable.

The three life cycle tools (LCA, LCC and SLCA) are the main tools used in this framework because the whole life cycle of a product is considered, taking every life stage into account. The LCA methodology is described in international standards (ISO), making it a strong tool. However, for the LCC and SLCA, methodologies are still in development making these more challenging to conduct. The use of these three tools also makes the framework very time-consuming. During the case study it was observed that data collection from already performed LCAs was also time-consuming and considering the issues, the preference lies in conducting the three assessments instead of extracting data solely from literature.

The use of the life cycle tools was supplemented by a biodiversity tool as not all indicators could be assessed. The biodiversity tool used was the CWM index. As with the social LCA, not all data could be quantified. Furthermore, the use of data extracted from literature caused difficulty in integrating. Even though the framework is not designed for general comparisons between land-based and marine-based production, opportunities for integration can be identified. These opportunities are likely to address real and wanted solutions by the industry by involving stakeholders in determining indicators and/or strengths and weaknesses.

5. Conclusion and Recommendations

The CASSIS framework aims to characterize and integrate food production systems, in a circular and sustainable manner. For this, the framework takes three important factors into account: Environmental, economic and social, the pillars of sustainability. To be able to quantify these factors, several indicators were identified. Environmental indicators that were identified are: nutrient flow of phosphorus and nitrogen, greenhouse gas emission, water use, land use, energy use, use of pesticides, heavy metal content, biodiversity, and susceptibility to diseases and pests. Economic indicators are production costs, processing costs and shipping costs. Social indicators that were defined are: consumer drivers and barriers, employment opportunities, labor conditions, subsidies, spatial planning, license to produce, willingness to change, alternative applications, and health impacts. Within the framework, relationships between these indicators exist. For example, land use change and energy use contribute to greenhouse gas emissions, and subsidies may contribute to willingness to change. Relationships between indicators of different pillars also exist. For example, environmental impacts such as pollution caused by nutrient flow can affect the social license to produce.

A target food system and an alternative food system, which are identified in the framework, are both assessed based on the mentioned indicators. For this, life cycle assessment, life cycle costing, social life cycle assessment, and the CMW index are used. Outputs provided by these tools are used to integrate systems with each other and allow for comparison of the new integrated system to the baseline system i.e. the current food production system. Qualitative indicators are compared using a scoring system.

The use of the framework in a practical sense was tested by a case study. Soybean in animal feed was partially substituted (1.6%) by seaweed (Saccharina latissima), resulting in an increase in energy demand and fossil fuel use, and heavy metal content of the feed. For the other environmental indicators included like water consumption and greenhouse gas emissions, a slight decrease is shown. The economic analysis of the integrated system shows an increase in production and processing costs, resulting in 39% higher total costs. The assessment of the qualitative indicators shows the integrated system will have a positive effect on land use, biodiversity, labor conditions, license to produce, and pesticide use. There is no present effect on consumer drivers and barriers, subsidies, and employment opportunities. Lastly, the integrated system has a negative effect on disease and pest susceptibility.

The use of the framework for the case study resulted in the following recommendations for future users:

- To avoid issues regarding data availability or LCA boundaries and impact category inclusion, it is recommended that the LCA, LCC and SLCA are conducted by the framework user. Because of time limitations, this was not possible for the case study.
- To overcome differences in monetary value and actual costs, an environmental cost-benefit analysis is recommended.
- For the CWM index of biodiversity, conducting experimental field studies is recommended over a literature study to overcome issues in data availability and quantification.
- For the integration of the qualitative social indicators, it is recommended to assign weighting factors to these indicators. By doing this, the integration is less difficult, and indicators are ranked to the wishes of the user.

References

Alleway, H. K., C. L. Gillies, M. J. Bishop, R. R. Gentry, S. J. Theuerkauf, and R. Jones. 2019. The Ecosystem Services of Marine Aquaculture: Valuing Benefits to People and Nature. BioScience. 69:59–68. doi:10.1093/biosci/biy137.

Almeida, V. E. S. D., Friedrich, K., Tygel, A. F., Melgarejo, L., & Carneiro, F. F. 2017. Use of genetically modified crops and pesticides in Brazil: growing hazards. *Ciencia & saude coletiva*, *22*, 3333-3339.

Almela, C., Jesús Clemente, M., Vélez, D., & Montoro, R. 2006. Total arsenic, inorganic arsenic, lead and cadmium contents in edible seaweed sold in Spain. *Food and Chemical Toxicology*, *44*(11), 1901–1908. https://doi.org/10.1016/j.fct.2006.06.011

Andrea, M. C. D. S., Romanelli, T. L., & Molin, J. P. (016. Energy flows in lowland soybean production system in Brazil. Ciência Rural, 46(8), 1395-1400.

ATSDR - Agency for Toxic Substances and Disease Registry. 2011. Detailed Data Table for the 2011 Priority List of Hazardous Substances that Will be the Subject of Toxicological Profiles Available from: www.atsdr.cdc.gov/SPL.

Aycicek, M., O. Kaplan İnce, and M. Yaman. 2008. Effect of Cadmium on Germination, Seedling Growth and Metal Contents of Sunflower (Helianthus annus L.). Asian J. Chem. 20.

Azapagic, A., Stamford, L., Youds, L., & Barteczko-Hibbert, C. 2016. Towards sustainable production and consumption: a novel decision-support framework integrating economic, environmental and social sustainability (DESIRES). Computers & Chemical Engineering, 91, 93-103.

Balmford, A., & Bond, W. 2005. Trends in the state of nature and their implications for human well-being. *Ecology Letters*, *8*(11), 1218-1234.

Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J. S., Nakashizuka, T., Raffaelli, D., & Schmid, B. 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecology letters, 9(10), 1146-1156.

Banach, J. L., Hoek-van den Hil, E. F., & van der Fels-Klerx, H. J. 2020. Food safety hazards in the European seaweed chain. Comprehensive Reviews in Food Science and Food Safety, 19(2), 332-364.

Barker, A.V., Pilbeam, D.J. 2007. Hand Book of Nutrition, 2nd ed. CRC Press, Boca Raton, pp. 662.

Beketov, M. A., Kefford, B. J., Schäfer, R. B., & Liess, M. 2013. Pesticides reduce regional biodiversity of stream invertebrates. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1305618110

Bekhet, H. A., & Abdullah, A. 2010. Energy use in agriculture sector: input-output analysis. *International Business Research*, *3*(3), 111.

Berger-Neto, A., Jaccoud-Filho, D. de S., Wutzki, C. R., Tullio, H. E., Pierre, M. L. C., Manfron, F., & Justino, A. 2017. Effect of spray droplet size, spray volume and fungicide on the control of white mold in soybeans. *Crop Protection*, *92*, 190–197. https://doi.org/10.1016/j.cropro.2016.10.016

Berkum, S. V. 2008. Towards sustainable soy an assessment of opportunities and risks for soybean production based on a case study in Brazil. Hague, LEI Wageningen UR.

Bernard, M. 2018. Seaweed diseases and pests. Retrieved from https://edepot.wur.nl/475726

Bernieri, T., Rodrigues, D., Barbosa, I. R., Ardenghi, P. G., & da Silva, L. B. 2019. Occupational exposure to pesticides and thyroid function in Brazilian soybean farmers. *Chemosphere*, *218*, 425-429.

Bickel, U., and J. M. Dros. 2003. The Impacts of Soybean Cultivation on Brazilian Ecosystems. Available from: https://tropicalsoybean.com/sites/default/files/The%20Impacts%20of%20soybean%20production%20on%20Brazilian%20Ecosystem_Bickel,%202003.pdf

Brancalion, P. H. S., L. C. Garcia, R. Loyola, R. R. Rodrigues, V. D. Pillar, and T. M. Lewinsohn. 2016. A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and ongoing initiatives. Nat. Conserv. 14:1–15. doi:10.1016/j.ncon.2016.03.003.

Burney, J., S. Davis, and D. Lobell. 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Natl. Acad. Sci. U. S. A. 107:12052–7. doi:10.1073/pnas.0914216107.

Butchart, S. H., Walpole, M., Collen, B., Van Strien, A., Scharlemann, J. P., Almond, R. E., ... & Carpenter, K. E. 2010. Global biodiversity: indicators of recent declines. Science, 328(5982), 1164-1168.

Campbell, I., Kambey, C. S. B., Mateo, J. P., Rusekwa, S. B., Hurtado, A. Q., Msuya, F. E., … Cottier-Cook, E. J. 2019b. Biosecurity policy and legislation for the global seaweed aquaculture industry. Journal of Applied Phycology. https://doi.org/10.1007/s10811-019-02010-5

Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., … Stanley, M. 2019a. The Environmental Risks Associated With the Development of Seaweed Farming in Europe—Prioritizing Key Knowledge Gaps. Frontiers in Marine Science, 6, 107. https://doi.org/10.3389/fmars.2019.00107

Carr, M.H. 1994. Effects of macroalgal dynamics on recruitment of a temperate reef fish. Ecology, 75, 1320–1333.

Castanheira, É. G., & Freire, F. 2013. Greenhouse gas assessment of soybean production: Implications of land use change and different cultivation systems. *Journal of Cleaner Production*, *54*, 49–60. https://doi.org/10.1016/j.jclepro.2013.05.026

Castanheira, É. G., R. Grisoli, S. Coelho, G. Anderi da Silva, and F. Freire. 2015. Life-cycle assessment of soybean-based biodiesel in Europe: comparing grain, oil and biodiesel import from Brazil. J. Clean. Prod. 102:188–201. doi:10.1016/j.jclepro.2015.04.036.

Cattelan, A. J., and A. Dall'Agnol. 2018. The rapid soybean growth in Brazil. OCL. 25:D102. doi:10.1051/ocl/2017058.

CBS. (2014). Achtergrondinformatie en handelsstromen (soja). Retrieved from: https://www.cbs.nl/nl-nl/achtergrond/2014/33/achtergrondinformatie-en-handelsstromen--soja-- [Accessed on April 30th, 2020]

Chavarro‐Mesa, E., Ceresini, P., Pereira, D., Vicentini, S., Silva, T., Ramos‐Molina, L., … Júnior, J. R. V. 2020. A broad diversity survey of Rhizoctonia species from the Brazilian Amazon reveals the prevalence of R. solani AG‐1 IA on signal grass and the new record of AG‐1 IF on cowpea and soybeans. *Plant Pathology*, *69*(3), 455–466. https://doi.org/10.1111/ppa.13142

Childs, S. P., Buck, J. W., & Li, Z. 2018. Breeding soybeans with resistance to soybean rust (Phakopsora pachyrhizi). *Plant Breeding*, *137*(3), 250–261. https://doi.org/10.1111/pbr.12595

Conforti, P., & Giampietro, M. 1997. Fossil energy use in agriculture: an international comparison. *Agriculture, ecosystems & environment*, *65*(3), 231-243.

Corguinha, A. P. B., Gonçalves, V. C., Souza, G. A. de, Lima, W. E. A. de, Penido, E. S., Pinto, C. A. B. P., … Guilherme, L. R. G. (2012). Cadmium in potato and soybeans: Do phosphate fertilization and soil management systems play a role? *Journal of Food Composition and Analysis*, *27*(1), 32–37. https://doi.org/10.1016/j.jfca.2012.05.001

Corguinha, A. P. B., Souza, G. A. de, Gonçalves, V. C., Carvalho, C. de A., Lima, W. E. A. de, Martins, F. A. D., … Guilherme, L. R. G. (2015). Assessing arsenic, cadmium, and lead contents in major crops in Brazil for food safety purposes. *Journal of Food Composition and Analysis*, *37*, 143–150. https://doi.org/10.1016/j.jfca.2014.08.004

Costello, C., Cao, L., Gelcich, S., Cisneros, M. A., Free, C. M., Froehlich, H. E., Golden, C. D., Ishimura, G., Macadam-Somer, I., Maier, J., Mangin, T., Melnychuk, M. C., Miyahara, M., de Moor, C., Naylor, R., Osio, G. C., Parma, A. M., Amargos, F. P., Plantinga, J., … Thilsted, S. H. (n.d.). The Future of Food from the Sea. 60.

Cottrell, R. S., Fleming, A., Fulton, E. A., Nash, K. L., Watson, R. A., & Blanchard, J. L. (2018). Considering land–sea interactions and trade-offs for food and biodiversity. Global Change Biology, 24(2), 580–596. https://doi.org/10.1111/gcb.13873

Curran, M. A. (2014). Strengths and Limitations of Life Cycle Assessment. In W. Klöpffer (Ed.), Background and Future Prospects in Life Cycle Assessment (pp. 189–206). https://doi.org/10.1007/978-94-017-8697-3_6

Da Silva, V. D. P. R., De Oliveira, S. D., Hoekstra, A. Y., Dantas Neto, J., Campos, J. H. B. C., Braga, C. C., De Araújo, L. E., Aleixo, D. D. O., De Brito, J. I. B., De Souza, M. D., & De Holanda, R. M. (2016). Water Footprint and Virtual Water Trade of Brazil. *Water*, *8*(11), 517. https://doi.org/10.3390/w8110517

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., Pengue, W. A. (2008). LCA of Soybean Meal. International Journal of LCA, 13(3), 240–254.

Del Ponte, E. M., Godoy, C. V., Li, X., & Yang, X. B. (2006). Predicting Severity of Asian Soybean Rust Epidemics with Empirical Rainfall Models. *Phytopathology*, *96*(7), 797–803. https://doi.org/10.1094/PHYTO-96-0797

Díaz, O., Tapia, Y., Muñoz, O., Montoro, R., Velez, D., & Almela, C. (2012). Total and inorganic arsenic concentrations in different species of economically important algae harvested from coastal zones of Chile. *Food and Chemical Toxicology*, *50*(3–4), 744–749. https://doi.org/10.1016/j.fct.2011.11.024

Díaz, S., & Cabido, M. (1997). Plant functional types and ecosystem function in relation to global change. *Journal of vegetation science*, *8*(4), 463-474.

Dolezal, F., Spitzbart, C., & Mötzl, H. (2014). Survey of allocation methods in life cycle assessments of wood based products. Performance and maintenance of bio-based building materials influencing the life cycle and LCA, 5.

Doppenberg, J. 2017. Soybean Meal Quality by Origin: Economic Value of Hipro Soybean Meal in Least Cost Formulations.

Druon, J. N., Schrimpf, W., Dobricic, S., & Stips, A. (2004). Comparative assessment of large-scale marine eutrophication: North Sea area and Adriatic Sea as case studies. Marine Ecology Progress Series, 272, 1-23.

Duarte C. M., Losada I. J., Hendriks I. E., Mazarrasa I., & Marbà N. (2013) The role of coastal plant communities for climate change mitigation and adaptation. Nat Clim Chane 3(11):961–968

Duarte, C. M., M. Holmer, Y. Olsen, D. Soto, N. Marbà, J. Guiu, K. Black, and I. Karakassis. 2009. Will the Oceans Help Feed Humanity? BioScience. 59:967–976. doi:10.1525/bio.2009.59.11.8.

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? Frontiers in Marine Science, 4. https://doi.org/10.3389/fmars.2017.00100

Dunstan, P. K., & Bax, N. J. (2008). Management of an invasive marine species: defining and testing the effectiveness of ballast-water management options using management strategy evaluation. ICES Journal of Marine Science, 65(6), 841-850.

EC. (2002). Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on undesirable substances in animal feed - Council statement. *Official Journal of the European Communities* L 140/10, pp. 10-22.

Echeveste da Rosa, C. R. (2015). Asian Soybean Rust Resistance: An Overview. *Journal of Plant Pathology & Microbiology*, *06*(09). https://doi.org/10.4172/2157-7471.1000307

Ecobichon, D. J. (2000). Our changing perspectives on benefits and risks of pesticides: a historical overview. *Neurotoxicology*, *21*(1-2), 211-218.

Ecobichon, D. J. (2001). Pesticide use in developing countries. *Toxicology*, *160*(1-3), 27-33.

EFSA (European Food Safety Authority). (2004). Opinion of the scientific panel on contaminants in the food chain related to lead as undesirable substance in animal feed. The EFSA Journal, 2(6), 20. https://doi.org/10.2903/j.efsa.2004.71

EFSA (European Food Safety Authority). (2009). Scientific opinion on arsenic in food. The
EFSA (European Food Safety Authority). (2014). Dietary exposure to inorganic arsenic in the European population. *EFSA Journal, 12*(3), 68. https://doi.org/10.2903/j.efsa. 2014.3597 3597.

EFSA CONTAM Panel (EFSA Panel on Contaminants in the Food Chain). (2010). Scientific opinion on lead in food. *EFSA Journal, 8*(4), 151. https://doi.org/10.2903/j.efsa. 2010.1570 1570.

EFSA CONTAM Panel (EFSA Panel on Contaminants in the Food Chain). (2011). Scientific Opinion on tolerable weekly intake for cadmium. *EFSA Journal, 9*(2), 19. https://doi. org/10.2903/j.efsa.2011.1975 1975.

EFSA Journal, 7(10), 199. https://doi.org/10.2903/j.efsa.2009.1351

EFSA Scientific Committee. (2015). Statement on the benefits of fish/seafood consumption compared to the risks of methylmercury in fish/seafood. *EFSA Journal, 13*(1), 36. https://doi.org/10.2903/j.efsa.2015.3982 3982.

Embrapa, S. (2008). Tecnologias de produção de soja-Região Central do Brasil 2009 e 2010. *Londrina: Embrapa Soja: Embrapa Cerrados: Embrapa Agropecuária Oeste.*

FAO. (2014). Environmental performance of animal feeds supply chains: 32 Guidelines for quantification. Livestock Environmental Assessment and Performance Partnership. 33 FAO, Rome, Italy.

FAO. 2017. The future of food and agriculture: Trends and challenges (Food and Agriculture Organization of the United Nations).

Fearnside, P. M. (2001). Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation*, *28*(1), 23-38.

Fearnside, P.M. 2005. Deforestation in Brazilian Amazonia: History, rates and consequences. Conservation Biology 19(3): 680-688.

Fehlenberg, V., Baumann, M., Gasparri, N. I., Piquer-Rodriguez, M., Gavier-Pizarro, G., & Kuemmerle, T. (2017). The role of soybean production as an underlying driver of deforestation in the South American Chaco. *Global environmental change*, *45*, 24-34.

Finnveden, G. (2000). On the limitations of life cycle assessment and environmental systems analysis tools in general. The International Journal of Life Cycle Assessment, 5(4), 229–238. https://doi.org/10.1007/BF02979365

Finnveden, G., & Moberg, Å. (2005). Environmental systems analysis tools – an overview. Journal of Cleaner Production, 13(12), 1165–1173. https://doi.org/10.1016/j.jclepro.2004.06.004

Finnveden, G., M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, and S. Suh. 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91:1–21. doi:10.1016/j.jenvman.2009.06.018.

Flach, R., Skalský, R., Folberth, C., Balkovič, J., Jantke, K., & Schneider, U. A. (2020). Water productivity and footprint of major Brazilian rainfed crops – A spatially explicit analysis of crop management scenarios. *Agricultural Water Management*, *233*, 105996. https://doi.org/10.1016/j.agwat.2019.105996

FNP, C. e comércio. 2011. Agrianual 2011: Anuário de Agricultura Brasileira.

Franzese, P. P., Cavalett, O., Häyhä, T., & D'Angelo, S. (2013). Integrated Environmental Assessment of Agricultural and Farming Production Systems in the Toledo River Basin (Brazil) (p. 75). United Nations Educational, Scientific and Cultural Organization (UNESCO).

Galhardi, J. A., Leles, B. P., de Mello, J. W. V., & Wilkinson, K. J. (2020). Bioavailability of trace metals and rare earth elements (REE) from the tropical soils of a coal mining area. *Science of The Total Environment*, *717*, 134484.

Gamboa, G., Kovacic, Z., Di Masso, M., Mingorría, S., Gomiero, T., Rivera-Ferré, M., & Giampietro, M. (2016). The Complexity of Food Systems: Defining Relevant Attributes and Indicators for the Evaluation of Food Supply Chains in Spain. *Sustainability*, *8*(6), 515. https://doi.org/10.3390/su8060515

Garcia, Luiz C., Machado Júnior, C. R., Bochnia, G. P., Weirich Neto, P. H., & Raetano, C. G. (2016). ADJUVANTS IN FUNGICIDE SPRAYING IN WHEAT AND SOYBEAN CROPS. *Engenharia Agrícola*, *36*(6), 1110–1117. https://doi.org/10.1590/1809-4430-eng.agric.v36n6p1110-1117/2016

Garcia, Luiz Cláudio, Martins, M. A., Frare, I. C., Melo, M. H., Neto, E. M., Filho, R. Z., … Maidl de Souza, N. (2020). Efficiency of soybean crop fungicide spray applications at timed intervals based on a calendar schedule versus agrometeorological data. *Crop Protection*, *132*, 105128. https://doi.org/10.1016/j.cropro.2020.105128

Gentry, R. R., Alleway, H. K., Bishop, M. J., Gillies, C. L., Waters, T., Jones, R. (2019). Exploring the potential for marine aquaculture to contribute to ecosystem services. Reviews in Aquaculture.

Gibbs, H. K., Rausch, L., Munger, J., Schelly, I., Morton, D. C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N. F. (2015). Brazil's soy moratorium. Science, 347(6220), 377-378.

Gilbert, N. More species means less disease. Nature (2010). https://doi.org/10.1038/news.2010.644

Godfray, C., J. Beddington, I. Crute, L. Haddad, D. Lawrence, J. Muir, J. Pretty, S. Robinson, S. Thomas, and C. Toulmin. 2010. Food Security: The Challenge of Feeding 9 Billion People. Science. 327:812–8. doi:10.1126/science.1185383.

Goldsmith, P. D. (2008). Soybean production and processing in Brazil. In Soybeans (pp. 773-798). AOCS Press.

Graham, M.H. 2004. Effects of local deforestation on the diversity and structure of southern California giant kelp forest food webs. Ecosystems, 7, 341–357.

Greco, F. M., Bindraban, P. S., & Stattman, S. L. (2009). Analysis of the Soybean debate: a case study on the debate about labor conditions in Brazil (No. 292). Plant Research International.

Greendeals (2018). Soja in Nederland. *Samenvatting Green deal 207.* Accessed 27-4-2020
Grießhammer, R., Benoît, C., Dreyer, L. C., Flysjö, A., Manhart, A., Mazijn, B., ... & Weidema, B. (2006). Feasibility study: integration of social aspects into LCA.

Grieshop, C. M., and G. C. Fahey. 2001. Comparison of Quality Characteristics of Soybeans from Brazil, China, and the United States. J. Agric. Food Chem. 49:2669–2673. doi:10.1021/jf0014009.

Güven, K. C., Akyüz, K., & Yurdun, T. (1995). Selectivity of heavy metal binding by algal polysaccharides. *Toxicological & Environmental Chemistry*, *47*(1–2), 65–70.

Höök, M., & Tang, X. (2013). Depletion of fossil fuels and anthropogenic climate change—A review. *Energy policy*, *52*, 797-809.

Hörtenhuber, S., Piringer, G., Zollitsch, W., Lindenthal, T., & Winiwarter, W. (2014). Land use and land use change in agricultural life cycle assessments and carbon footprints—The case for regionally specific land use change versus other methods. *Journal of Cleaner Production*, *73*, 31–39. https://doi.org/10.1016/j.jclepro.2013.12.027

Howarth, R., D. Anderson, J. Cloern, C. Elfring, C. Hopkinson, B. Lapointe, T. Malone, N. Marcus, K. McGlathery, A. Sharpley, and D. Walker. 2000. Nutrient pollution of coastal rivers, bays and seas. Issues Ecol. 7.

ILO. (2018). Concepts and Definitions of Employment Indicators Relevant to Young People. 40.

Ingle, K. N., Polikovsky, M., Chemodanov, A., & Golberg, A. (2018). Marine integrated pest management (MIPM) approach for sustainable seagriculture. Algal research, 29, 223-232.

ISO. (2006). ISO14040, Environmental management - Life cycle assessment - Principles and framework. Geneva: ISO.

Jak, R. G., Bos, O. G., & Lindeboom, H. J. (2009a). Instandhoudingsdoelen Natura 2000-gebieden Noordzee (No. C065/09). IMARES.

Jallow, M. F., Awadh, D. G., Albaho, M. S., Devi, V. Y., & Thomas, B. M. (2017). Pesticide risk behaviors and factors influencing pesticide use among farmers in Kuwait. Science of the total environment, 574, 490-498.

Jansen, H. M., S. Van Den Burg, B. Bolman, R. G. Jak, P. Kamermans, M. Poelman, and M. Stuiver. 2016. The feasibility of offshore aquaculture and its potential for multi-use in the North Sea. Aquac. Int. 24:735–756. doi:10.1007/s10499-016-9987-y.

Jansen, H. M., Tonk, L., van der Werf, A., van der Meer, I., van Tuinen, S., van der Burg, S., ... & Brouwers, E. (2019). Development of Offshore Seaweed Cultivation: food safety, cultivation, ecology and economy: synthesis report 2018 (No. C012/19). Wageningen Marine Research.

Jeswani, H. K., Azapagic, A., Schepelmann, P., & Ritthoff, M. (2010). Options for broadening and deepening the LCA approaches. Journal of Cleaner Production, 18(2), 120–127. https://doi.org/10.1016/j.jclepro.2009.09.023

Junk, W. J., Da Cunha, C. N., Wantzen, K. M., Petermann, P., Strüssmann, C., Marques, M. I., & Adis, J. (2006). Biodiversity and its conservation in the Pantanal of Mato Grosso, Brazil. Aquatic Sciences, 68(3), 278-309.

Jurgilevich, A., Birge, T., Kentala-Lehtonen, J., Korhonen-Kurki, K., Pietikäinen, J., Saikku, L., & Schösler, H. (2016). Transition towards Circular Economy in the Food System. Sustainability, 8(1), 69. https://doi.org/10.3390/su8010069

Karkacier, O., & Goktolga, Z. G. (2005). Input–output analysis of energy use in agriculture. Energy Conversion and Management, 46(9-10), 1513-1521.

Kastens, J. H., Brown, J. C., Coutinho, A. C., Bishop, C. R., Esquerdo, J. C. D. (2017). Soy moratorium impacts on soybean and deforestation dynamics in Mato Grosso, Brazil. PloS one, 12(4), e0176168.

Kessler, J. J., Rood, T., Tekelenburg, T., & Bakkenes, M. (2007). Biodiversity and socioeconomic impacts of selected agro-commodity production systems. The Journal of Environment & Development, 16(2), 131-160.

Khan, A. H., Levac, E., Van Guelphen, L., Pohle, G., & Chmura, G. L. (2018). The effect of global climate change on the future distribution of economically important macroalgae (seaweeds) in the northwest Atlantic. Facets, 3(1), 275-286.

Kim, J. K., Kraemer, G., & Yarish, C. (2019). Evaluation of the metal content of farm grown Gracilaria tikvahiae and Saccharina latissima from Long Island Sound and New York Estuaries. *Algal Research*, *40*, 101484. https://doi.org/10.1016/j.algal.2019.101484

Langlois, J., Sassi, J.-F., Jard, G., Steyer, J.-P., Delgenes, J.-P., & Hélias, A. (2012). Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels, Bioproducts and Biorefining, 6(4), 387–404. https://doi.org/10.1002/bbb.1330

Lathuillière, M. J., Johnson, M. S., Galford, G. L., & Couto, E. G. (2014). Environmental footprints show China and Europe's evolving resource appropriation for soybean production in Mato Grosso, Brazil. *Environmental Research Letters*, *9*(7), 074001. https://doi.org/10.1088/1748-9326/9/7/074001

Lathuillière, M. J., Miranda, E. J., Bulle, C., Couto, E. G., & Johnson, M. S. (2017). Land occupation and transformation impacts of soybean production in Southern Amazonia, Brazil. *Journal of cleaner production*, *149*, 680-689.

Lavelle, P., R. Dugdale, Scholes, A. Berhe, E. Carpenter, L. Codispoti, A. Izac. 2005. Chapter 12 - Nutrient cycling. Millennium Ecosystem Assessment. 1. Ecosystems and Human Well-Being: 331-353.

Lehuger, S., Gabrielle, B., & Gagnaire, N. (2009). Environmental impact of the substitution of imported soybean meal with locally-produced rapeseed meal in dairy cow feed. Journal of Cleaner Production, 17(6), 616-624.

Li, T., Zhang, H., Liu, Z., Ke, Q., Alting, L. (2014). A system boundary identification method for life cycle assessment. The International Journal of Life Cycle Assessment, 19(3), 646-660.

Lindgren, E., F. Harris, A. D. Dangour, A. Gasparatos, M. Hiramatsu, F. Javadi, B. Loken, T. Murakami, P. Scheelbeek, and A. Haines. 2018. Sustainable food systems—a health perspective. Sustain. Sci. 13:1505–1517. doi:10.1007/s11625-018-0586-x.

Lisa Chase, & Grubinger, V. (2014). Chapter 1: Introduction to Food Systems. In *Food, Farms and Community: Exploring Food Systems* (p. 24). University Press of New England.

Liu, X., W. Zhang, Y. Hu, E. Hu, X. Xie, L. Wang, and H. Cheng. 2015. Arsenic pollution of agricultural soils by concentrated animal feeding operations (CAFOs). Chemosphere. 119:273–281. doi:10.1016/j.chemosphere.2014.06.067.

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., ... & Tilman, D. (2001). Biodiversity and ecosystem functioning: current knowledge and future challenges. *science*, *294*(5543), 804-808.

Loureiro, R., Gachon, C. M. M., & Rebours, C. (2015). Seaweed cultivation: Potential and challenges of crop domestication at an unprecedented pace. New Phytologist, 206(2), 489–492. https://doi.org/10.1111/nph.13278

Ludwig, M. P., Dutra, L. M. C., Lucca Filho, O. A., Zabot, L., Uhry, D., & Lisboa, J. I. (2010). Produtividade de grãos da soja em função do manejo de herbicida e fungicidas. *Ciência Rural, 40*(7), 1516-1522.

Magdoff, F., L. Lanyon, and B. Liebhardt. 1997. Nutrient Cycling, Transformations, and Flows: Implications for A More Sustainable Agriculture. In: Advances in Agronomy. Vol. 60. Elsevier. p. 1–73. Available from:

Makkar, H. P. S., G. Tran, V. Heuzé, S. Giger-Reverdin, M. Lessire, F. Lebas, and P. Ankers. 2016. Seaweeds for livestock diets: A review. Anim. Feed Sci. Technol. 212:1–17. doi:10.1016/j.anifeedsci.2015.09.018.

Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., & Nobre, C. A. (2008). Climate change, deforestation, and the fate of the Amazon. science, 319(5860), 169-172.

Markowitz, T. M., Harlin, A. D., Würsig, B., & McFadden, C. J. (2004). Dusky dolphin foraging habitat: overlap with aquaculture in New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *14*(2), 133-149.

Maulvault, A. L., Anacleto, P., Barbosa, V., Sloth, J. J., Rasmussen, R. R., Tediosi, A., … Marques, A. (2015). Toxic elements and speciation in seafood samples from different contaminated sites in Europe. *Environmental Research*, *143*, 72–81. https://doi.org/10.1016/j.envres.2015.09.016

McGlade, J. M. 2002. 12 The North Sea Large Marine Ecosystem. In: Large Marine Ecosystems. Vol. 10. Elsevier. p. 339–412. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1570046102800647

MEA. (2001). Millennium ecosystem assessment. Millennium Ecosystem Assessment.

Meade, B., Puricelli, E., McBride, W. D., Valdes, C., Hoffman, L., Foreman, L., & Dohlman, E. (2016). Corn and soybean production costs and export competitiveness in Argentina, Brazil, and the United States. USDA Economic Information Bulletin, 154.

Mitkas, and J. M. Gómez, editors. Information Technologies in Environmental Engineering. Springer Berlin Heidelberg, Berlin, Heidelberg. p. 189–202. Available from: http://link.springer.com/10.1007/978-3-540-88351-7_14

Mittermeier, R. A., ed. 2004. Hotspots revisited: earth's biologically richest and most endangered terrestrial ecoregions. 1. engl. ed. CEMEX, Mexico City.

Miwa. 1990. Global nutrient flow and degradation of soils and environment. Trans. 14th Int. Congr. Soil Sci.

Neveux, N., J. J. Bolton, A. Bruhn, D. A. Roberts, and M. Ras. 2018. The Bioremediation Potential of Seaweeds: Recycling Nitrogen, Phosphorus, and Other Waste Products. In: Blue Biotechnology. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany. p. 217–239. Available from: http://doi.wiley.com/10.1002/9783527801718.ch7

Niero, M., & Rivera, X. C. S. (2018). The Role of Life Cycle Sustainability Assessment in the Implementation of Circular Economy Principles in Organizations. Procedia CIRP, 69, 793–798. https://doi.org/10.1016/j.procir.2017.11.022

Nordborg, M., Davis, J., Cederberg, C., & Woodhouse, A. (2017). Freshwater ecotoxicity impacts from pesticide use in animal and vegetable foods produced in Sweden. *Science of the Total Environment*, *581*, 448-459.

Olmedo, P., Pla, A., Hernández, A. F., Barbier, F., Ayouni, L., & Gil, F. (2013). Determination of toxic elements (mercury, cadmium, lead, tin and arsenic) in fish and shellfish samples. Risk assessment for the consumers. *Environment International*, *59*, 63–72. https://doi.org/10.1016/j.envint.2013.05.005

Ometto, F., Steinhovden, K. B., Kuci, H., Lunnbäck, J., Berg, A., Karlsson, A., … Ejlertsson, J. (2018). Seasonal variation of elements composition and biomethane in brown macroalgae. *Biomass and Bioenergy*, *109*, 31–38. https://doi.org/10.1016/j.biombioe.2017.11.006

Onakpa, M. M., Njan, A. A., & Kalu, O. C. (2018). A Review of Heavy Metal Contamination of Food Crops in Nigeria. *Annals of Global Health*, *84*(3), 488–494. https://doi.org/10.29024/aogh.2314

Pelletier, N. L., Ayer, N. W., Tyedmers, P. H., Kruse, S. A., Flysjo, A., Robillard, G., Ziegler, F., Scholz, A. J., Sonesson, U. (2007). Impact Categories for Life Cycle Assessment Research of Seafood Production Systems: Review and Prospectus. The International Journal of Life Cycle Assessment, 12(6), 414–421.

Pereira, E. J. D. A. L., Ferreira, P. J. S., de Santana Ribeiro, L. C., Carvalho, T. S., & de Barros Pereira, H. B. (2019). Policy in Brazil (2016–2019) threaten conservation of the Amazon rainforest. Environmental Science & Policy, 100, 8-12.

Peteiro, C., & Freire, Ó. (2013). Epiphytism on Blades of the Edible Kelps Undaria pinnatifida and Saccharina latissima Farmed under Different Abiotic Conditions. Journal of the World Aquaculture Society, 44(5), 706–715. https://doi.org/10.1111/jwas.12065

Petrillo, A., De Felice, F., Jannelli, E., Autorino, C., Minutillo, M., & Lavadera, A. L. (2016). Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system. Renewable Energy, 95, 337–355. https://doi.org/10.1016/j.renene.2016.04.027

Philips (2015). Life cycle assessment: finding the best approach for your company. [Accessed on April 30. 2020].

Potin, P., Bouarab, K., Salaün, J.-P., Pohnert, G., & Kloareg, B. (2002). Biotic interactions of marine algae. Current Opinion in Plant Biology, 5(4), 308–317. https://doi.org/10.1016/S1369-5266(02)00273-X

Potting, J., Hanemaaijer, A., Delahaye, R., Hoekstra, R., Ganzevles, J., & Lijzen, J. (2018). Circular economy: What we want to know and can measure (Policy Report No. 3217; p. 92). PBL Netherlands Environmental Assessment Agency.

Prudêncio da Silva, V., van der Werf, H. M. G., Spies, A., & Soares, S. R. (2010). Variability in environmental impacts of Brazilian soybean according to crop production and transport scenarios. *Journal of Environmental Management*, *91*(9), 1831–1839.

Rajauria, G. 2015. Seaweeds: a sustainable feed source for livestock and aquaculture. In: Seaweed Sustainability. Elsevier. p. 389–420. Available from: https://linkinghub.elsevier.com/retrieve/pii/B9780124186972000155

Repórter Brasil. 2008. Os impactos das Lavouras sobre a Terra, o Meio e a Sociedade, Soja e Mamona. Available from: https://reporterbrasil.org.br/documentos/o_brasil_dos_agrocombustiveis_v1.pdf

Rhoden, A. C., Costa, N. L., de Santana, A. C., Gabbi, M. T. T., & Janeque, R. A. (2017). Analysis of the Generation of Formal Employment by the Soybeans Production Chain in the Rio Grande Do Sul State/Brazil: 2002-2015. *International Journal of Development Research*, *07*(12), 18065–18070.

Richards, P., Pellegrina, H., VanWey, L., & Spera, S. (2015). Soybean Development: The Impact of a Decade of Agricultural Change on Urban and Economic Growth in Mato Grosso, Brazil. *PLoS ONE*, *10*(4). https://doi.org/10.1371/journal.pone.0122510

Ricotta, C., & Moretti, M. (2011). CWM and Rao's quadratic diversity: a unified framework for functional ecology. *Oecologia*, *167*(1), 181-188.

Ridoutt, B., Motoshita, M., & Pfister, S. (2019). An LCA impact assessment model linking land occupation and malnutrition-related DALYs. *The International Journal of Life Cycle Assessment*, *24*(9), 1620–1630. https://doi.org/10.1007/s11367-019-01590-1

Roessing, A. C., and J. J. Lazzarotto. 2004. Criação de empregos pelo complexo agroindustrial da soja / Antonio Carlos Roessing, Joelsio José Lazzarotto & Londrina: Embrapa.

Roleda, M. Y., Marfaing, H., Desnica, N., Jónsdóttir, R., Skjermo, J., Rebours, C., & Nitschke, U. (2019). Variations in polyphenol and heavy metal contents of wild-harvested and cultivated seaweed bulk biomass: Health risk assessment and implication for food applications. *Food Control*, *95*, 121–134. https://doi.org/10.1016/j.foodcont.2018.07.031

Rolfe, J., Bennett, J., & Louviere, J. (2000). Choice modelling and its potential application to tropical rainforest preservation. *Ecological Economics*, *35*(2), 289-302.

Romanelli, T. L., Nardi, H. D. S., & Saad, F. A. (2012). Material embodiment and energy flows as efficiency indicators of soybean (Glycine max) production in Brazil. Engenharia Agrícola, 32(2), 261-270.

Rönnlund, I., Reuter, M., Horn, S., Aho, J., Aho, M., Päällysaho, M., Ylimäki, L., & Pursula, T. (2016). Eco-efficiency indicator framework implemented in the metallurgical industry: Part 1—a comprehensive view and benchmark. The International Journal of Life Cycle Assessment, 21(10), 1473–1500. https://doi.org/10.1007/s11367-016-1122-9

Ruiz, G. M., Carlton, J. T., Grosholz, E. D., & Hines, A. H. (1997). Global invasions of marine and estuarine habitats by non-indigenous species: mechanisms, extent, and consequences. American zoologist, 37(6), 621-632.

Ruiz, G. M., Rawlings, T. K., Dobbs, F. C., Drake, L. A., Mullady, T., Huq, A., & Colwell, R. R. (2000). Global spread of microorganisms by ships. Nature, 408(6808), 49-50.

Santos, J. A., Juliatti, F. C., Santos, V. A., Polizel, A. C., Juliatti, F. C., & Hamawaki, O. T. (2007). Caracteres epidemiológicos e uso da análise de agrupamento para resistência parcial à ferrugem da soja. *Pesquisa Agropecuária Brasileira, 42*(3), 443-447.

Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2015). The seasonal variation in the chemical composition of the kelp species Laminaria digitata, Laminaria hyperborea, Saccharina latissima and Alaria esculenta. *Journal of Applied Phycology*, *27*(1), 363–373. https://doi.org/10.1007/s10811-014-0327-1

Schmidt, J. H. (2008). Development of LCIA characterisation factors for land use impacts on biodiversity. *Journal of Cleaner Production*, *16*(18), 1929-1942

Schrank, W. E., & Wijkström, U. (2003). Introducing fisheries subsidies. FAO, Rome, Italy.

Schubel, J. R., and K. Thompson. 2019. Farming the Sea: The Only Way to Meet Humanity's Future Food Needs. GeoHealth. 3:238–244. doi:10.1029/2019GH000204.

Seghetta, M., Hou, X., Bastianoni, S., Bjerre, A. B., Thomsen, M. (2016). Life cycle assessment of macroalgal biorefinery for the production of ethanol, proteins and fertilizers–a step towards a regenerative bioeconomy. Journal of cleaner production, 137, 1158-1169. https://doi.org/10.1016/j.jclepro.2016.07.195

Seghetta, M., Romeo, D., D'Este, M., Alvarado-Morales, M., Angelidaki, I., Bastianoni, S., & Thomsen, M. (2017). Seaweed as innovative feedstock for energy and feed – Evaluating the impacts through a

Life Cycle Assessment. *Journal of Cleaner Production*, *150*, 1–15. https://doi.org/10.1016/j.jclepro.2017.02.022

Selvam, G. G., and K. Sivakumar. 2014. Influence of seaweed extract as an organic fertilizer on the growth and yield of Arachis hypogea L. and their elemental composition using SEM–Energy Dispersive Spectroscopic analysis. Asian Pac. J. Reprod. 3:18–22. doi:10.1016/S2305-0500(13)60179-7.

Siemen van Berkum and Just Dengerink, 2019. Transition to sustainable food systems: the Dutch circular approach providing solutions to global challenges. Wageningen, *Wageningen Economic Research*, Report 2019-082. 40 pp.; 2 fig.; 6 tab.; 72 ref.

Sivasankari, S., V. Venkatesalu, M. Anantharaj, and M. Chandrasekaran. 2006. Effect of seaweed extracts on the growth and biochemical constituents of Vigna sinensis. Bioresour. Technol. 97:1745–1751. doi:10.1016/j.biortech.2005.06.016.

Sosa-Gómez, D. R., Corrêa-Ferreira, B. S., Kraemer, B., Pasini, A., Husch, P. E., Vieira, C. E. D., … Lopes, I. O. N. (2020). Prevalence, damage, management and insecticide resistance of stink bug populations (Hemiptera: Pentatomidae) in commodity crops. *Agricultural and Forest Entomology*, *22*(2), 99–118. https://doi.org/10.1111/afe.12366

Spera, S. A., Cohn, A. S., VanWey, L. K., Mustard, J. F., Rudorff, B. F., Risso, J., & Adami, M. (2014). Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. *Environmental Research Letters*, *9*(6), 064010. https://doi.org/10.1088/1748-9326/9/6/064010

Sterling, B. & Charlebois, S. (2017). Building Social License to Operate within the Food System (Learning from the Lessons of Others).

Stichting Noordzeeboerderij. (2018). Kansen en belemmeringen voor 'Zeewierstarters'. Report commissioned by the Ministry of Agriculture, Nature and Food Quality.

Stranddorf, H. K., Hoffmann, L., & Schmidt, A. (2005). LCA technical report: impact categories, normalization and weighting in LCA. Update on selected EDIP97-data. FORCE Technology–Dk–TEKNIK. Dinamarca: Serietitel, 2003a. Retrieved from: https://lca-center.dk/wp-content/uploads/2015/08/LCA-technical-report-impact-categories-normalisation-and-weighting-in-LCA.pdf [Accessed on April 15th, 2020]

Taelman, S. E., Champenois, J., Edwards, M. D., De Meester, S., & Dewulf, J. (2015a). Comparative environmental life cycle assessment of two seaweed cultivation systems in North West Europe with a focus on quantifying sea surface occupation. *Algal Research*, *11*, 173–183. https://doi.org/10.1016/j.algal.2015.06.018

Taelman, S. E., De Meester, S., Schaubroeck, T., Sakshaug, E., Alvarenga, R. A. F., & Dewulf, J. (2014). Accounting for the occupation of the marine environment as a natural resource in life cycle assessment: An exergy based approach. *Resources, Conservation and Recycling*, *91*, 1–10. https://doi.org/10.1016/j.resconrec.2014.07.009

Taelman, S. E., Sfez, S., Meester, S. D., Dewulf, J., Dijk, W. van, Silva, V. P. da, Hende, S. V. D., Champenois, J., & Edwards, M. D. (2015b). *Environmental Life Cycle Assess- ment (LCA) of algae production in North West Europe (NWE)* (p. 35). EnAlgae Project. http://www.enalgae.eu/public-deliverables.htm.

Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J., 2012. Heavy metal toxicity and the environment. In A. Luch (Vol. Ed.), Molecular, clinical and environmental toxicology. Experientia supplementum: Vol. 101, (pp. 131–164). Basel: Springer.

Theuerkauf, S. J., Morris, J. A., Jr., Waters, T. J., Wickliffe, L. C., Alleway, H. K., Jones, R. C. (2019) A global spatial analysis reveals where marine aquaculture can benefit nature and people. PLoS ONE 14(10): e0222282. https://doi.org/10.1371/journal.pone.0222282

Tilman, D., and M. Clark. 2014. Global diets link environmental sustainability and human health. Nature. 515:518–522. doi:10.1038/nature13959.

Valero, M., Guillemin, M.-L., Destombe, C., Jacquemin, B., Gachon, C. M. M., Badis, Y., … Faugeron, S. (2017). Perspectives on domestication research for sustainable seaweed aquaculture. Perspectives in Phycology, 4(1), 33–46. https://doi.org/10.1127/pip/2017/0066

van den Boogaart, Lisanne van den; Wal, Jan Tjalling van der; Tonk, Linda; Bos, Oscar; Coolen, Joop; Poelman, Marnix; Vergouwen, Sophie; Duren, Luca van; Janssen, Henrice;
Timmermans, Klaas (2020). Geschiktheid zeewindparken voor maricultuur en passieve visserij : een kwantitatieve beoordeling van de kansrijkheid van de gebieden voor de potentiële productiviteit van een selectie aan commercieel interessante soorten.

van den Burg, S. W. K., Dagevos, H., & Helmes, R. J. K. (2019). Towards sustainable European seaweed value chains: A triple P perspective. *ICES Journal of Marine Science*, fsz183. https://doi.org/10.1093/icesjms/fsz183

Van den Burg, S. W. K., Dagevos, H., & Helmes, R. J. K. (2019). Towards sustainable European seaweed value chains: a triple P perspective. ICES Journal of Marine Science.

van der Werf, H. M. G., & Petit, J. (2002). Evaluation of the environmental impact of agriculture at the farm level: A comparison and analysis of 12 indicator-based methods. Agriculture, Ecosystems & Environment, 93(1), 131–145. https://doi.org/10.1016/S0167-8809(01)00354-1

van Oirschot, R., Thomas, J.-B. E., Gröndahl, F., Fortuin, K. P. J., Brandenburg, W., & Potting, J. (2017). Explorative environmental life cycle assessment for system design of seaweed cultivation and drying. *Algal Research*, *27*, 43–54. https://doi.org/10.1016/j.algal.2017.07.025

Vellinga, T. V., Gerber, P., & Opio, C. (2010). Greenhouse Gas Emissions from the Global Livestock Sector-Methodology for a life Cycle Assessment. Wageningen University and Research.

Vidal-Legaz, B., Antón, A., Maia De Souza, D., Sala, S., Nocita, M., Putman, B., Teixeira, R. F. M., European Commission, & Joint Research Centre. (2016). *Land-use related environmental indicators for life cycle assessment: Analysis of key aspects in land use modelling.* Publications Office.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of Earth's ecosystems. *Science*, *277*(5325), 494-499.

Walls, A., Edwards, M., Firth, L., & Johnson, M. (2017). Successional changes of epibiont fouling communities of the cultivated kelp Alaria esculenta: Predictability and influences.
Aquaculture Environment Interactions, 9, 57–71. https://doi.org/10.3354/aei00215

Weirich Neto, P. H., Fornari, A. J., Bauer, F. C., Justino, A., & Garcia, L. C. (2013). Fungicide application using a trailing boom in soybean fields. *Engenharia Agrícola*, *33*(4), 876–882. https://doi.org/10.1590/S0100-69162013000400026

Withers, P. J. A., Doody, D. G., & Sylvester-Bradley, R. (2018). Achieving Sustainable Phosphorus Use in Food Systems through Circularisation. Sustainability, 10(6), 1804. https://doi.org/10.3390/su10061804

Wood, D., Capuzzo, E., Kirby, D., Mooney-McAuley, K., & Kerrison, P. (2017). UK macroalgae aquaculture: What are the key environmental and licensing considerations?. Marine policy, 83, 29-39.

Yorinori, J. T., Paiva, W. M., Frederick, R. D., Costamilan, L. M., Bertagnolli, P. F., Hartman, G. E., … Nunes, J. (2005). Epidemics of Soybean Rust (*Phakopsora pachyrhizi*) in Brazil and Paraguay from 2001 to 2003. *Plant Disease*, *89*(6), 675–677. https://doi.org/10.1094/PD-89-0675

Ziep, T., V. Wohlgemuth, M. F. Emmenegger, J. Reinhard, and R. Zah. 2009. SQCB - Sustainability Quick Check Tool for Biofuels. In: I. N. Athanasiadis, A. E. Rizzoli, P. A.

Appendices

Appendix 1. Search Engines and Keywords

Search engines:

Google scholar, Scopus, Web of Science, WorldCat, and Elsevier.

Key words:

Circular food production, circular production, sustainable food production framework, land and sea based food systems, framework development, offshore production, seaweed biodiversity, economic feasibility, seaweed North Sea, seaweed farming environmental impact, seaweed and mussel North Sea, environmental impact tools, environmental valuation, cost-benefit analysis, economic valuation, Mytilus edulis, offshore seaweed framework, plantaardige eiwitten, eiwitgewassen consumptie, nutrient inputs in agriculture, seaweed in agriculture, nutrient leaching, nutrient use of seaweed, seaweed nutrient uptake, nutrient output seaweed, seaweed extract in plants, netherlands agriculture nutrients, soybean protein, metal accumulation seaweed, metal impact, health effect seaweed, health effect soybean, soybean composition netherlands, soybean pesticide use, seaweed cow performance, environmental risk, seaweed cultivation, seaweed aquaculture, seaweed product, seaweed cultivation, netherlands carbon conventional agriculture, consumer acceptance seaweed, protein composition of seaweed, ISO LCA, LCA methodology, impact categories LCA, LCA limitations.

Appendix 2. Data Collection for Case Study - Soybean

Table 1. Data collection of environmental indicators for soybean production.

Indicator	**Value**	**Indicator unit**	**Functional unit of LCA**	**Location**	**Additional comments**	**Article Ref**
GHG	0.721 2.475	Kg CO2 eq kg CO2 eq	Kg SBM Kg protein	Argentina	Palm oil as marginal oil	Dalgaard et al. (2008)
GHG	3.91 × 10+2	Kg CO2 eq	1000 Kg feed	Brazil	Feed with 13.8% soy meal	Lehuger et al. (2009)
GHG	694 1.735	Kg CO2 eq kg CO2 eq	1000 kg soybean Kg protein	Center-West Brazil	Takes transportation to Rotterdam into account CW includes matto grasso	da Silva et al. (2010)
GHG	337 0.843	Kg CO2 eq Kg CO2 eq	1000 kg soybean Kg protein	South Brazil	Takes transportation to Rotterdam intro account	da Silva et al. (2010)
Land use **Land Transformation** **(Deforestation)**	0.34 0.00085 (2001-2005): 455 1.1375 (2006-2010): 97 0.2425	ha yr^{-1} ton^{-1} ha/yr m^2 yr^{-1} ton^{-1} m^2 yr^{-1} m^2 yr^{-1} ton^{-1} m^2 yr^{-1}	1 ton soybean kg protein 1 ton soybean Kg protein 1 ton soybean Kg protein	Mato Grosso, Brazil	Total production	Lathuillière et al. (2014)
Land Occupation	1890 4.725 2070 5.175	m^2 yr^{-1}	1000 kg soybean Kg protein 1000 kg soybean Kg protein	Center-West, Brazil Southern Brazil	Production to delivery (Rotterdam, NL) Splits Matto Grasso in two sections	da Silva et al. (2010)
Water Footprint **Green water** **Blue water**	1880 4700 1860 4650 0 0	Litre	Kg soy Kg protein Kg soy Kg protein Kg soy Kg protein	Toledo River Basin, Brazil	Measured separately	Franzese et al. (2013)

Grey water	19.4 48.5		Kg soy Kg protein			
Water use	1908 4.77	$m^3 yr^{-1}$	ton soybean Kg protein	Mato Grosso, Brazil	Total production	Lathuillière et al. (2014)
Pesticides	Insecticides: 8.6E-03 0.0215 Fungicides: 1.5E-03 0.00375 Herbicides: 8.4E-0.4 0.0021	CTUe (Comparative Toxic Units Ecotoxicity) per kg harvested crop	Kg soybean Kg protein Kg soybean Kg protein Kg soybean Kg protein	Brazil	Looked at soybean meal in feed for several animals	Nordborg et al. (2017)
Energy use	7800 2786 6.965	MJ MJ MJ	Hectare of soy Tonne of soy Kg protein	Mato Grosso, Brazil		Andrea et al. (2016)
Fossil fuel use	41.7 15.3 0.03825	L L L	Hectare of soy Tonne of soy Kg protein	Mato Grosso, Brazil		Romanelli et al. (2012)
Fertilizer (N input) **N fertilizer**	8 8 0.0071	kg kg kg	Ha soy Ha Kg protein	Mato Grosso, Brazil		Raucci et al. (2015) Castanheira et al. (2015)
Fertilizer (P input)/P2O5	84 0.075 80 0.071	Kg Kg Kg Kg	Ha soy Kg protein Ha soy Kg protein	Mato Grosso, Brazil		Raucci et al. (2015) Castanheira et al. (2015)
Fertilizer (K input/	90 0.08	Kg Kg	Ha soy Kg protein	Mato Grosso,		Raucci et

K2O)	80 0.071	Kg	Ha Kg protein	Brazil		al. (2015) Castanheira et al. (2015)
Nitrate water emissions	86.08 0.077	Kg NO3	Ha	Mato Grosso, Brazil		Castanheira et al. (2015)
Phosphate water emissions	0.86 0.00077	Kg P2O5	Ha Kg protein	Mato Grosso, Brazil		Castanheira et al. (2015)
Phosphorus water emissions	0.49 0.00044	Kg P	Ha Kg protein	Mato Grosso, Brazil		Castanheira et al. (2015)

Table 2. Data collection on heavy metals in soybean (*Glycine max (L.) Merr.*) grains.
All values in mg/kg dry weight.

Study	**EC, 2002 ***	**Corguinha et al., 2015**			**Corguinha et al., 2012**		**Galhardi, Leles, de Mello, & Wilkinson, 2020**			
Year		**2010-2011**			**Not specified**		**Not specified**			
Location		**Mato Grosso and Minas Gerais States, Brazil**			**Mato Grosso and Minas Gerais States, Brazil**		**Figueira city, Paraná State, Brazil (cultivated lands close to a coal mining area)**			
	Value	**Mean**	**Min**	**Max**	**Mean**	**SD**	**Mean**	**SD**	**Min**	**Max**
Arsenic (As)	40	0.065	0.053	0.078			0.02	0.01	0.01	0.07
Inorganic Arsenic (iAs)	2									
Cadmium (Cd)	1				0.018	0.003	0.04	0.03	0.01	0.10
Mercury (Hg)	0.1									
Lead (Pb)	10	0.103	0.090	0.114			4.70E-03	6.50E-03	6.60E-04	2.50E-02
Zinc (Zn)							44	15	26	73
Chromium (Cr)							1.2	0.1	1.1	1.5
Copper (Cu)							9.2	2.7	6.1	13.6
Iron (Fe)							80	27	53	157
Nickel (Ni)							2.2	2.2	0.2	7.1
Cobalt (Co)							0.06	0.04	0.02	0.20
Manganese (Mn)							54	67	16	336
Vanadium (V)							0.02	0.02	0.01	0.09
Thorium (Th)							2.00E-02	4.90E-02	1.30E-03	2.20E-01
Uranium (U)							7.30E-04	1.10E-03	1.10E-04	4.50E-03

* Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on undesirable substances in animal feed - Council statement

Appendix 3. Data Collection for Case Study - Saccharina latissima

Table 1. Data collection of the environmental indicators for Saccharina latissima.

Indicator	Value	Indicator unit	Functional unit of LCA	Location	Article Ref
GHG	21.7 0.0217	Kg CO2-eq	Tonne dried protein Kg dried protein	Europe	van Oirschot et al. (2017)
Land Use (water surface)	208 0.266	km^2	Hectare of S. latissima Kg dried protein	Denmark	Seghetta et al. (2015, 2016, 2017)
Water Use	61870 2.97 0.004	mg	208km2 Hectare of S. latissima Kg dried protein	Denmark	Seghetta et al. (2015, 2016, 2017)
Energy use	62000 5636 79.4	MJ MJ	Hectare of S. latissima Tonne DM of S. latissima Kg dried protein	Denmark	Seghetta et al. (2015) van Oirschot et al. (2017)
Fossil fuel use	472 42.9 0.6	Litre Litre	Hectare of S. latissima Tonne DM of S. latissima Kg dried protein	Denmark	Seghetta et al. (2015) van Oirschot et al. (2017)
Nitrogen uptake	165 0.0011	kg	Hectare Kg dried protein		Schiener et al. (2015)
Phosphorus uptake	32 0.0002	kg	Hectare Kg dried protein	Denmark	Seghetta et al. (2016)

Table 2. Data collection on heavy metals in Saccharina latissima.

All values in mg/kg dry weight.

Article Ref.	**EC, 2002 ***	**Roleda et al., 2019**			**Ometto et al., 2018**			**Schiener, Black, Stanley, & Green, 2015**			**Maulvault et al., 2015**	
Year		**2015-2016**			**2014-2015**			**2010-2011**			**Sep-Dec 2013**	
Location		**Trondheim and Bodø, Norway & Pleubian, France**			**Trondheim, Norway**			**The isle of Seil, Scotland**			**Solund, Norway (contaminated site)**	
	Value	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**SD**
Arsenic (As)	40	69.767	52.326	99.419	79	28	120	67.25	3.00	88.00	43	0
Inorganic Arsenic (iAs)	2	1.20	0.90	1.71	1.359	0.482	2.064	1.157	0.052	1.514	0.39	0.00
Cadmium (Cd)	1	0.60	0.21	0.99	2.718	0.760	4.600				0.13	0.00
Mercury (Hg)	0.1	0.033	0.001	0.105	<0.05	<0.05	<0.05				0.03	0.00
Lead (Pb)	10	0.20	0.05	0.70	<0.49	<0.48	<0.5	1.163	0.200	2.200	0.18	0.03
Zinc (Zn)					47.5	32.0	66.0	22.63	8.00	31.00	20	1
Chromium (Cr)					1.438	0.750	<2.5	2.888	1.100	5.000	<LOD	-
Copper (Cu)					3.7	2.4	6.5	2.375	2.000	5.000	<LOQ	-
Iron (Fe)					175	<150	230	586	16	1280	37	4
Nickel (Ni)								1.488	0.600	3.400	<LOD	-
Molybdenum (Mo)								0.488	0.200	0.900		
Silver (Ag)					<0.97	<0.95	<0.99					
Cobalt (Co)											0.05	0.01

LOD stands for below limit of detection. LOQ stands for below limit of quantification. Values exceeding the EU limits have been marked red.

* Directive 2002/32/EC of the European Parliament and of the Council of 7 May 2002 on undesirable substances in animal feed - Council statement

Appendix 4. LCC Comparison Graphs for the Case Study

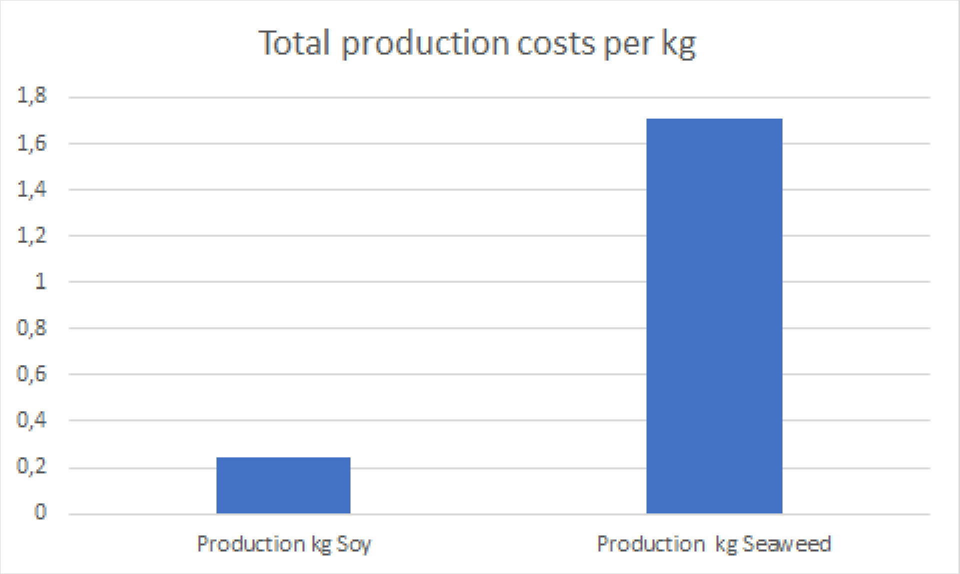


Figure 1. Comparison production costs in dollars

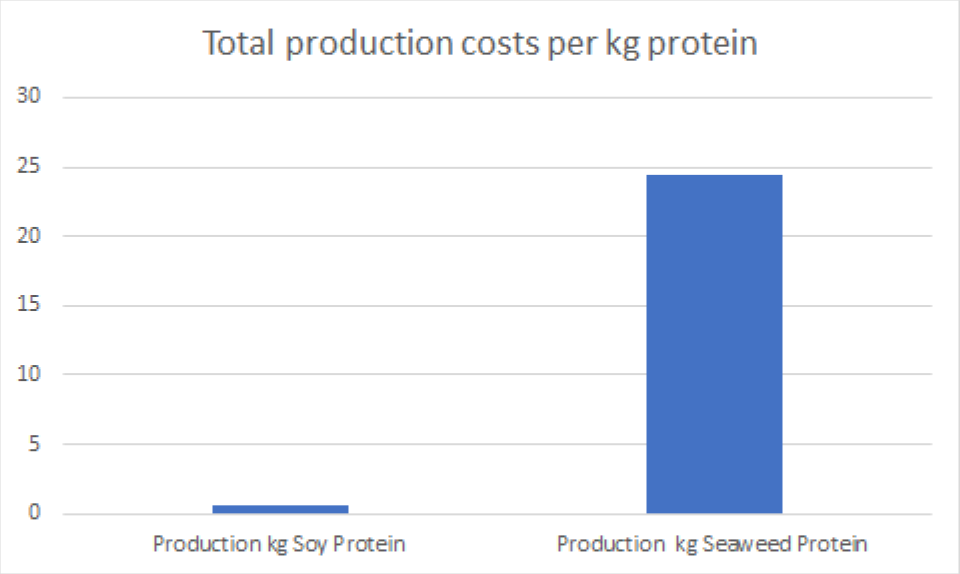


Figure 2. Comparison protein production in dollars

Figure 3. Comparison shipping costs in dollars

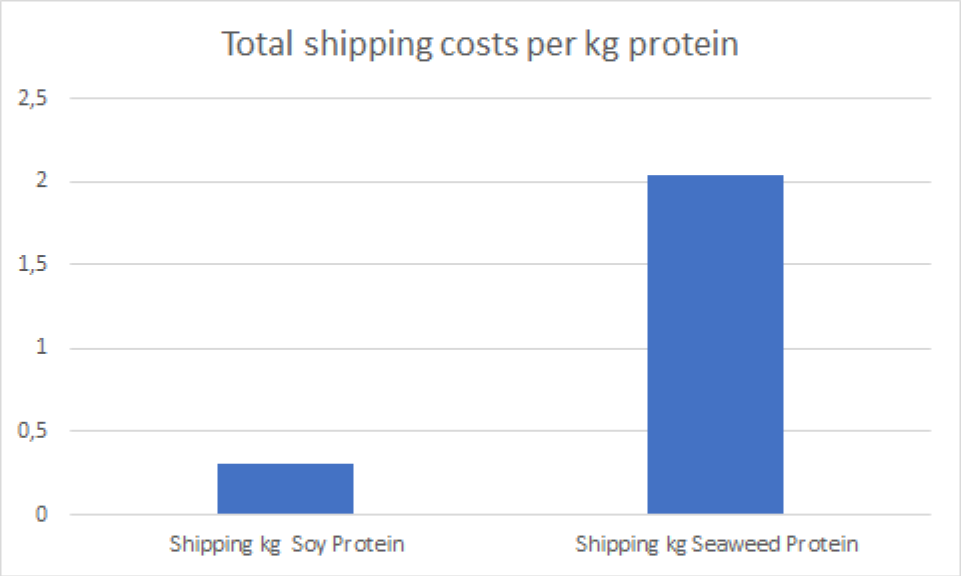


Figure 4. Comparison protein shipping costs in dollars

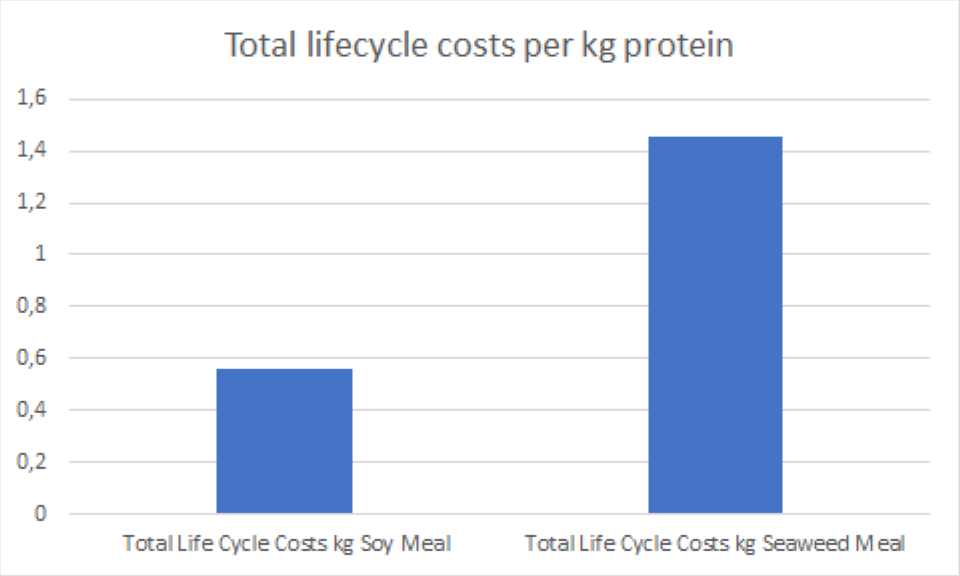


Figure 5. Comparison total life cycle costs in dollars

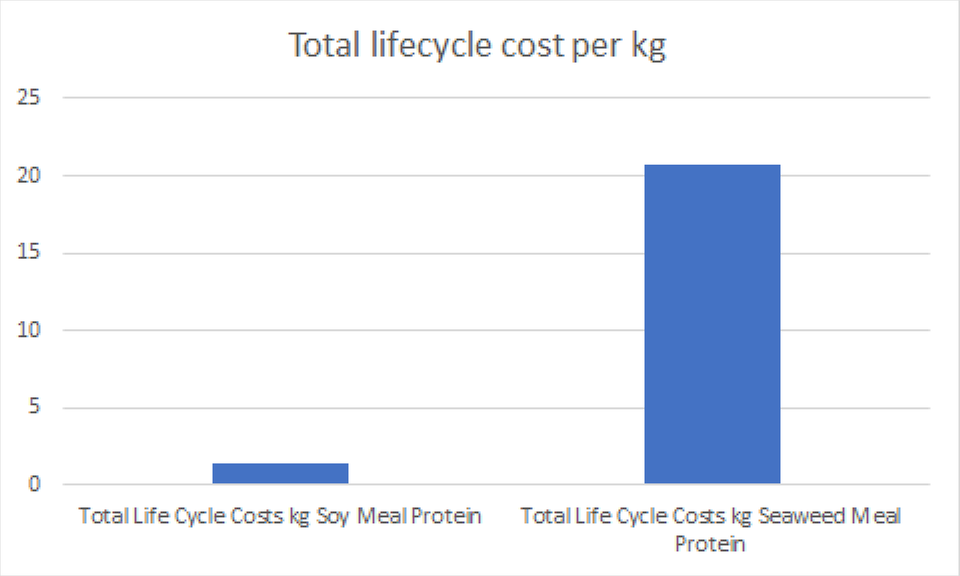


Figure 6. Comparison protein total life cycle costs in dollars