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Social Cost-Benefit Analysis of Cultivation and Wild Harvesting of Seaweed in Norway - Accounting for Impacts on Ecosystem Services

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Acknowledgement

With this master thesis, we mark the end of the two-year master program in Energy-, climate-, and environmental economics here at Ås. We reflect on two enriching, content-filled and educational years. Together with our fellow students and social sorority, we have created many cherished memories.

The work on this thesis has been rewarding and occasionally challenging, yet we will always remember this period as a time filled with laughter more than frustration. We are proud of ourselves for standing together and overcoming obstacles throughout this process. We will miss this time.

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List of abbreviations and explanation of selected words and terms

Macroalgae = seaweed = kelp

Cultivation rig = seaweed farm

Hatchery = where the production of cuttings occurs.

A. nodosum = *Ascophyllum nodosum* (no: grisetang, en: North Atlantic rockweed)

S. latissima = *Saccharina latissima* (no: sukkertare, en: sugar kelp)

Biomass = the total mass and weight of the seaweed in a context.

Soil amendment = Any material added to improve the soil`s physical condition, indirectly affecting plant growth[1].

Plant amendment = Any material added to improve plant growth[2].

Liquid biostimulant = Liquid plant amendment made of seaweed extracts[3].

Kelp meal = A soil amendment in the form of powder made of dried and milled seaweed[4].

Biochar = Charcoal made of seaweed through pyrolysis for use as soil amendment[5].

CO_2 sequestration = "*The capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere*" (Herzog & Golomb, 2004, p. 1).

Benefit transfer = "*is the use of pre-existing empirical estimates from one or more settings where research has been conducted previously to predict measures of economic value or related information for other settings*" Johnston et al. (2021). Also called value transfer.

Ecosystem services (ES) = Millennium Ecosystem Assessment (2005a) defines ecosystem services as "*the benefits people obtain from ecosystems*" and divides them into four categories:

i. *Supporting ES:* Nutrient cycling, soil formation, primary production etc.

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[1] (David & Wilson, 2000, p. 1)
[2] (Pennsylvania Department of Agriculture, n.d)
[3] (EBIC, 2023, p. 1)
[4] (Chalker-Scott, 2019, p.1)
[5] (Brassard, 2019, p.109)

ii. *Provisioning ES*: food, fresh water, wood and fiber, fuel etc.
iii. *Regulating ES:* climate regulation, disease regulation, water purification etc.
iv. *Cultural ES*: aesthetic, spiritual, educational, recreational etc.

CBA = Cost-Benefit Analysis

CPI = Consumer Price Index

GHG= Greenhouse gas

NPV = Net present value

PPP = Purchase Power Parity

PV = Present Value

VAT = Value Added Taxes

WTP = Willingness to Pay

Abstract

The aim of this thesis has been to investigate the socio-economic profitability of cultivating *S. latissima* or wild harvesting *A. nodosum* in Norway for different types of plant- and soil amendments. We have examined the amendments liquid biostimulant, kelp meal and biochar. This is done using a Cost-Benefit Analysis (CBA) where the profitability has been assessed by calculating the net present value (NPV) of the total benefit- and cost effects associated with priced effects related to the different alternatives. Non-priced effects are also presented, and sensitivity analysis performed. The project period is assumed to be 20 years, starting from 2024; and the reference alternative is a natural kelp forest which is not commercially used. The analysis has been limited to investigate the potential on 10 hectares. What sets this thesis apart from previous CBAs on this topic is the inclusion of the ecosystem services (ES) and their impact on the profitability.

The six project alternatives and the resulting NPV are:

i. Cultivation of *S. latissima* to produce liquid biostimulant, with a NPV = 174 million NOK
ii. Cultivation of *S. latissima* to produce kelp meal, with a NPV = - 89 million NOK
iii. Cultivation of *S. latissima* to produce biochar, with a NPV = - 106 million NOK
iv. Wild harvesting of *A. nodosum* to produce liquid biostimulant, with a NPV = - 8 million NOK
v. Wild harvesting of *A. nodosum* to produce kelp meal, with a NPV = - 284 million NOK
vi. Wild harvesting of *A. nodosum* to produce biochar, with a NPV = - 302 million NOK

Our CBA identifies the cultivation of *S. latissima* to produce liquid biostimulant as the only socio-economically profitable project alternative. For all project alternatives, the provisioning ES in terms of biomass produced valued at the market price, has naturally a large positive impact on the NPV. Regulating ES in the form of CO_2 sequestration as a benefit have little impact on the NPV. For all the wild harvesting alternatives, the environmental damage costs, reflecting all ES made up of both use and non-use values of a natural kelp forest, impacts the NPV negatively. In order for cultivation to become financially profitable, external effects on ES have to be internalized through subsidies or other compensation schemes.

Sammendrag

Formålet med denne masteroppgaven har vært å undersøke om det er samfunnsøkonomisk lønnsomt å dyrke *S. latissima* eller villhøste *A. nodosum* i Norge til bruk som ulike typer plante- og jordforbedringsmidler. Midlene vi har sett på er flytende biostimulant, tang/tare mel og biokull. Dette er undersøkt gjennom en Nytte-Kost Analyse (NKA) hvor lønnsomheten er blitt vurdert ut fra netto nåverdien (NNV) av de samlede nytte- og kostnadseffektene for prissatte effekter tilknyttet ulike alternativer. Ikke-prissatte effekter er også presentert og en sensitivitetsanalyse er utført. Prosjektperioden er antatt å være 20 år, og starter fra 2024; hvor referansealternativet er en naturlig tareskog som ikke utnyttes kommersielt. Analysen har vært begrenset til å undersøke potensialet for et område på 10 hektar. Denne oppgaven skiller seg fra tidligere NKA på dette området fordi vi har inkludert økonomisk verdsetting av økosystemtjenester (ØT) og deres påvirkning på lønnsomheten.

De seks prosjektalternativene og deres NPV er:

i. Dyrking av *S. latissima* til å produsere flytende biostimulant fikk en NNV = 174 millioner NOK
ii. Dyrking av *S. latissima* til å produsere taremel fikk en NNV = - 89 millioner NOK
iii. Dyrking av *S. latissima* til å produsere biokull fikk en NNV = - 106 millioner NOK
iv. Villhøsting av *A. nodosum* til å produsere flytende biostimulant fikk en NNV = - 8 millioner NOK
v. Villhøsting av *A. nodosum* til å produsere tangmel fikk en NNV = - 284 millioner NOK
vi. Villhøsting av *A. nodosum* til å produsere biokull fikk en NNV = - 302 millioner NOK

Vår NKA identifiserer dyrking av *S. latissima* til å produsere flytende biostimulant som det eneste samfunnsøkonomisk lønnsomme prosjektalternativet. For alle prosjektalternativene, er den forsynende ØT i form av biomasse verdsatt med markedsprisen, og har naturligvis en stor positiv påvirkning på NNV. Den regulerende ØT CO_2 sekvestrering som en fordel har liten påvirkning på NNV. For alle alternativer knyttet til villhøsting påvirker miljøskadekostnadene, som reflekterer alle ØT bestående av bruks- og ikke-bruksverdier av en naturlig tareskog, NNV negativt. For at dyrking skal bli bedriftsøkonomisk lønnsomt, må eksterne effekter på ØT internaliseres gjennom subsidier eller andre kompensasjonsordninger.

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1. Introduction

1.1 Background

Norway has the world's second largest coastline after Canada (Gjertsen et al., 2020, p. 1) thanks to its extensive amounts of islands. The maritime area of Norway exceeds its land area by six times (Norwegian Environment Agency, 2023). This presents an opportunity for Norway in possessing significant amounts of ocean resources. The concept of blue economy, based on the principle of sustainable value and resource utilisation within maritime areas, is an important focal point in Norway (European Commission, 2021). Prime Minister Jonas Gahr Støre leads The International Ocean Panel where Norway plays a crucial role alongside its partners in promoting sustainable ocean management worldwide (Government, 2021). The 2023 report from the Ocean Panel underscores, among other findings, seaweed cultivation as a method to mitigate Greenhouse gas (GHG) emissions by its potential to sequester carbon (Ocean Panel, 2023, p. 9).

In 2021, the Norwegian Seaweed Association was established for cultivators, wild harvesters and producers of seaweed in Norway (Norwegian Seaweed Association, n.d). While wild seaweed harvesting has been done for centuries, cultivation companies are still in their early development stages (NBFN, 2023, p. 2). Some cultivation companies are closely tied to research centres, while others have faced bankruptcy. We failed to find financial analysis of wild harvesting, but there exist financial analyses of the economic viability of cultivated seaweed. However, there are few social Cost-Benefit Analysis (CBA) that account for impacts on ecosystem services (ES). Ecosystem services are the benefits that ecosystems and nature provide to humans (Management Forum for the Norwegian Sea Areas, 2018, p. 7). Since ES do not have a market price, they are often excluded from socio-economic analyses. For example, Menzies et al. (2021) conducted a CBA of seaweed cultivation without accounting for the impact on ES. A monetary value on ES would allow for comparison and better visualise the impact on the socio-economic profitability.

The European Union's Farm to Fork Strategy demonstrates an increasing focus on sustainable agriculture (European Commission, n.d). One key strategy to achieve this is by replacing mineral fertiliser with more environmentally friendly alternatives that benefit both plants and the soil. Plant and soil amendments are products, in organic matter, that is added to the soil to improve the soil and plant condition (Garbowski et al., 2023, p. 1; Bonilla et al., 2012, p. 479). According to Wei et al. (2020, p. 2), substitution of mineral fertiliser with organic soil and plant amendments, have several positive effects on crops, environmental emissions and carbon sequestration in soil. Therefore, it is interesting to explore seaweeds potential as a soil or plant amendment.

Seaweed, once processed, can be transformed into various soil and plant amendments such as biostimulants, kelp meal and biochar. In this thesis, liquid biostimulant is categorised as plant amendment, while kelp meal and biochar are categorised as soil amendments. The World Bank (2023) recognises the significant potential of seaweed as liquid biostimulant as a valuable plant amendment. Kelp meal has been made in Norway since the 1930`s and is still used as a soil amendment (Østgaard & Indergaard, 2017), and is included due to its basic characteristics. Biochar has promising capabilities to effectively sequester CO_2 for hundreds or even thousands of years (SINTEF, n.d).

1.2 Problem statement

The aim of this thesis is to address the following problem statement: *Is it socio-economically viable to cultivate or wild harvest seaweed in Norway for production of soil or plant amendments?*

To answer this problem statement, we will conduct a social CBA. In a CBA a reference alternative is established to describe the current situation and serves as a baseline to the other project alternatives (DFØ, 2023, p. 65). In this thesis, the reference alternative is a hypothetical coastal area in Norway with natural kelp forests, but with no commercial use of the biomass. The area is sometimes specified to Ålesund due to certain area specific calculations. However, we do not look specifically at the condition of the kelp forests around Ålesund, and this CBA serves as a generic example applicable to many coastal locations in Norway.

We will analyse three alternative products from cultivated seaweed, and the same three alternative products for wild harvested seaweed. The seaweed species *Saccharina latissima* is used for cultivation, whereas *Ascophyllum nodosum* is utilised for wild harvest. In total six project alternatives will be analysed:

I. **Cultivation**

i. Cultivating *S. latissima* to produce liquid biostimulant
ii. Cultivating *S. latissima* to produce kelp meal
iii. Cultivating *S. latissima* to produce biochar

II. **Wild harvesting**

iv. Wild harvest *A. nodosum* to produce liquid biostimulant
v. Wild harvest *A. nodosum* to produce kelp meal
vi. Wild harvest *A. nodosum* to produce biochar

1.3 Research questions

By exploring the six project alternatives, we will address the following five research questions:

i. Is it socio-economic profitable to cultivate or wild harvest seaweed?
ii. If any, which is the most profitable option of cultivation and wild harvesting?
iii. If any, which option is the most profitable among liquid biostimulant, kelp meal, and biochar?
iv. How does accounting for ecosystem services like carbon sequestration impact the profitability of the six project alternatives?
v. Which factors have the greatest impact on the socio-economic profitability?

These questions will be answered within a specific framework, which will be further described in chapter 4.1. Therefore, the results will be valid and accountable only within the established framework.

1.4 Reading guide

The thesis is structured as follows: Chapter 2 reviews the theoretical foundation and method behind CBA and methods for economic valuation of ecosystem services. Chapter 3 describes the seaweed industry in order to derive the project alternatives for cultivation and wild harvest. Chapter 4 describes the performed CBA and present the results for each of the six project alternatives. Chapter 5 discusses the results. Chapter 6 concludes on the five research questions and provides recommendations for future studies.

2. Theory and method

2.1 Socio-economic analysis

Socio-economic analysis involves evaluating how the utilisation of resources impacts the welfare of the society. Given the scarcity of public resources, determining their optimal allocation makes it necessary with a comprehensive consideration of all benefits and costs associated with a particular usage. What makes a socio-economic analysis interesting is the examination of the benefits and costs that impact the entire population, rather than solely from a governmental or business perspective (DFØ, 2023, p. 36). Benefits are equal to what society is willing to pay (WTP) to achieve them, whereas costs are determined by the value of the resource in its best alternative use. For a decision to be socio-economically profitable, the aggregated beneficial effects must exceed the overall costs. However, choosing one alternative usage means abandoning the others. Hence, a standardised unit of measurement is essential for comparing alternatives. Whenever possible, benefits and costs are quantified in monetary terms (DFØ, 2023, p. 37).

2.2 Welfare economics

Welfare economics aims to determine when one resource allocation is superior to another, raising ethical considerations and decision criteria. Utilitarianism, commonly used in economics, involves weighing the total utility levels of all individuals in society (Perman et al., 2011, p. 7). While welfare denotes a societal good, utility refers to individual pleasure (Perman et al., 2011, p. 62).

Economists often make decisions based on efficiency (Perman et al., 2011, p. 65). This method allows for ranking without relying on ethical principles (Perman et al., 2011, p. 7). Kaldor-Hicks efficiency serves as an example of an efficiency criterion, extensively utilised in economics (Stringham, 2001, p. 41). Posner (1980, as cited in Stringham, 2001, p. 42) defines Kaldor-Hicks criteria as "*Resources are allocated efficiently in a system of wealth maximization when there is no reallocation that would increase the wealth of society*". Or as Perman et al. (2011, p. 102) further elaborates: "*i) the winners could compensate the losers and still be better off and ii) the losers could not compensate the winners for the reallocation not occurring and still be as well off as they would have been if it did occur*".

Another related approach is Pareto-efficiency, which implies that an allocation of resources is efficient if it cannot make one person better off without making another worse off (Perman et al., 2011, p. 94). Applying this principle in socio-economic analysis entails that a decision, or allocation of resources, is Pareto-efficient if the net benefits exceed the costs sufficiently, allowing for compensation of the losers while still maintaining overall welfare improvement (Boardman et al., 2014, p. 31).

2.3 Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) is a socio-economic analysis with the aim of achieving a more efficient allocation of resources within society. When considering a policy or project meant to enhance the current situation, it is necessary to systematically assess all associated benefits and costs. The net benefit is determined in comparison to the status quo, i.e., development without the project, where net benefit represents the difference between identified benefits and the costs incurred by society (Boardman et al., 2014, p. 2).

Both costs and benefits are quantified in monetary terms. However, certain effects may not be valued, but is still crucial for evaluating a project`s socio-economic profitability, e.g., ecosystem services. These effects must be described comprehensively to assess their impact on profitability (DFØ, 2023, p. 144).

Socio-economic profitability is determined through discounting and calculating the net present value over the project`s lifetime, reflecting human preference for consuming now rather than in the future (Boardman et al., 2014, p. 12).

The following guidance provided by The Norwegian Agency for Public and Financial Management outlines the process for conducting a CBA (DFØ, 2023).

Step 1 and 2: Project definition and identifying relevant alternatives

The project definition should outline the observed problem and its underlying causes which makes it necessary to change from the current state. This includes defining the reference alternative, also known as “business as usual”, which portrays the present situation and expected development in the absence of any policy implementation. The reference alternative serves as a benchmark to assess effects in Step 3 (p. 54, 65-66).

Subsequently, a set of relevant project alternatives aimed at solving the problem, is defined. The project alternatives are intended to address perceived societal issues. Each project alternative should be described in detail and include its expected lifetime to facilitate the identification of effects in the subsequent step (p. 81-82, 96).

Step 3: Identify and describe the effects

The aim of this step is to identify and describe all the effects arising from the different project alternatives. It is useful to start by identifying the stakeholders as this helps determining which benefits and costs that accrue and to whom. A beneficial effect is one that enhances the welfare of one or more individuals or the entire society, e.g., environmental benefits arising from reduced pollution. Conversely, a cost effect denotes an impact that reduces welfare of one or more individuals or the society, e.g., environmental costs incurred due to nature degradation. Costs include any use of resources that could otherwise be allocated to other societal areas. Therefore, investment costs are included, representing every physical input factor. Operating and maintenance costs are included being essential for sustaining performance (p. 100-103).

Step 4: Quantify, value and assess effects

The identified costs and benefits should be quantified and valued in monetary terms whenever possible. Benefits are assessed based on the WTP principle, whereas costs are valued using the opportunity cost (p. 118-120). For effects with an existing market price, this price is utilised. For non-priced effects, one method to use is value transfer, which involves using estimates from previous valuation studies. In cases where the policy impacts GHG-emissions, valuation must incorporate a carbon price (p. 132-137).

For non-priced effects that cannot be valued using conventional methods, a value-matrix (no: "*verdimatrisemetoden"*) is recommended. This approach will help systemise and document the assessment of non-priced effects, providing guidance when evaluating their impact on socio-economic profitability (p. 145).

Table 1: Value-matrix to decide the socio-economic value of non-priced effects (Directly translated from DFØ, p. 146-147).

Quantity/ unit value	Small	Medium	Large
Large negative	Medium negative	Large negative	Very large negative
Medium negative	Small negative	Medium negative	Large negative
Small negative	Insignificant/none	Small negative	Medium negative
Neither positive nor negative	Insignificant/none	Insignificant/none	Insignificant/none
Small positive	Insignificant/none	Small positive	Medium positive
Medium positive	Small positive	Medium positive	Large positive
Large positive	Medium positive	Large positive	Very large positive

Step 5: Evaluate socio-economic profitability

A project is socio-economic profitable if the aggregated benefits exceed the costs, incorporating both priced and non-priced effects. Priced effects are evaluated using the net present value method, whereby the effects over the project`s lifetime is discounted to a specified year using a discount rate (p. 172-173). The formula is outlined as follows (Boardman et al., 2014, p. 142):

$$PV(B) = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t}$$

$$PV(C) = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

Where PV denotes the present value of the benefits and the costs. B_t is benefits in year t for t = 0, 1, ..., n. C_t is costs in year t for t = 0, 1, ..., n. $\frac{1}{(1+i)^t}$ is the discount factor, where i is the social discount rate.

The net present value becomes: $NPV = PV(B) - PV(C)$.

The social discount rate applied in socio-economic analysis is determined by the Ministry of Finance, with a prescribed rate of 4% p.a. (i=0.04) recommended for analysis periods spanning from 0 to 40 years. This rate reflects the socio-economic opportunity cost associated with tied up capital to a particular policy (DFØ, 2023, p. 181).

Once the priced effects have been summed up, the non-priced effects must also be accounted for using the value-matrix and incorporated into the assessment of the profitability (p. 188).

Step 6: Conducting a sensitivity analysis

The sensitivity analysis aims to assess the socio-economic profitability`s sensitivity to changes in underlying assumptions by testing factors individually. This analysis can reveal both potentially negative and positive outcomes. This provide decision-makers with insights into the robustness of the different alternatives to changes in the most uncertain factors (p. 197-198). These uncertain factors are categorised based on their impact on profitability and the probability of deviation, helping identify the most critical factors for testing in the sensitivity analysis. Subsequently, these factors are examined by adjusting the underlying assumptions both upward and downward (p. 201-204).

Step 7: Describe the distributional effects

This step aims to highlight how the effects of the alternatives are distributed between different groups of the society. The purpose is not to influence the recommendation of a specific alternative but to provide supplementary information to the decision-maker. The analysis relies on an unweighted WTP approach, as socio-economic analysts are not tasked with incorporating political and ethical considerations. Often, certain groups may be perceived as winners of a policy implementation. However, if individuals are significantly disadvantaged by the outcome, compensation should be considered (p. 224-226).

Step 8: Give an overall assessment and recommend a policy

As a general guideline, the most profitable project alternative, if any, should be recommended, i.e., the policy with the highest total benefits relative to costs. This assessment must encompass both priced and non-priced effects. Thus, both the NPV and the evaluation of the non-priced effects must be considered. To address the uncertainty, the results from the sensitivity analyse, may influence the ranking of policies. The overall evaluation should take this into account, with distributional effects considered as supplementary information (p. 237-239).

2.4 Valuing ecosystem services

2.4.1 Ecosystem services

The Millennium Ecosystem Assessment (MEA) defines ecosystem services as "*the benefits people obtain from ecosystems*", and divides them into four categories: i) supporting services, ii) provisioning services, iii) regulating services, and iv) cultural services (MEA, 2005a, p. V). Supporting services are soil formation, photosynthesis, and nutrient cycling. Provisioning services are food, water, timber, and fiber. Regulating services are the ones affecting climate, floods, disease, wastes, and water quality. Cultural services provide recreational, aesthetic, and spiritual benefits.

2.4.2 Total Economic Value

As humans benefit from ecosystem services, it`s important to assign them value for comparison with other activities aimed at enhancing welfare. Economic valuation serves as a convenient measurement, providing a common unit for assessing their overall contribution to social welfare (MEA, 2005b, p. 130). The Total Economic Value (TEV) framework is commonly employed for this purpose, categorising impacts into use and non-use values:

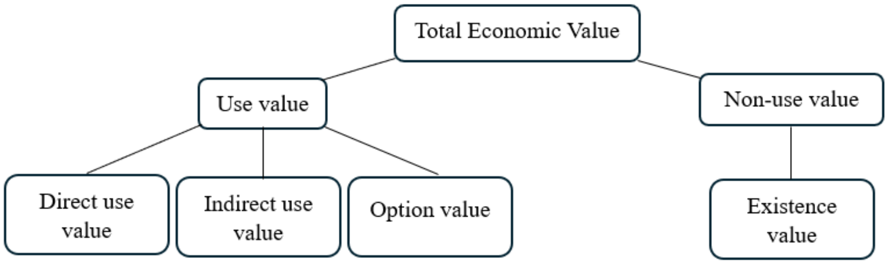

Figure 1:Total Economic Value Framework (MEA, 2005b, p. 132).

Ecosystem services used for human consumption and production are termed as use values, which are further categorised into three parts. Direct use values correspond to provisioning and cultural services, such as harvesting of food or enjoying wildlife. Indirect use values are those corresponding to regulating and supporting services, such as water being used as an intermediate input for producing final goods. Option value represents the value of retaining the ability to use an ecosystem service in the future. Non-use value, also known as existence value, refers to the value attributed to a resource simply by its existence, even if it is not currently utilised (MEA, 2005b, p. 133).

2.4.3 Valuation methods

Multiple methodologies exist for valuing the benefits provided by various ecosystem services. Table 2 outlines commonly used methods.

Table 2: Valuation methods for valuing ecosystem services. (Navrud, 2015, p. 15).

	Indirect	**Direct**
Revealed preferences	Travel Cost Method Hedonic Price Method Avoidance Cost	Market prices Replacement Costs
Stated preferences	Choice Experiments	Contingent Valuation

Revealed preferences are observed in the market, while stated preferences are based on hypothetical behaviour. Direct revealed preferences typically include privately owned ecosystem services traded in markets, resulting in market prices. Indirect revealed preferences also rely on observed behaviour but occur in surrogate markets. E.g., hedonic pricing where statistical techniques reveal implicit prices for each attribute of a paid service (MEA, 2005b, p. 134-135).

Direct stated preferences, like contingent valuation, involve placing people in hypothetical markets and ask about their WTP for a particular good or outcome (Field & Field, 2021, p. 139). Indirect stated preferences, such as choice experiments, determine WTP by observing changes in behaviour in response to alternations in the quantity, quality, and/or price of ecosystem service attributes (Navrud, 2015, p. 14).

Another approach is benefit transfer, which involves using estimates obtained from various methodologies in different contexts. However, the reliability of the original estimate is crucial for meaningful transfer, as benefit transfer has been subject of debate due to its frequent inappropriate use (MEA, 2005b, p. 135-136). Johnston et al. (2021) has provided guidelines to enhance the validity and credibility of such benefit transfers.

2.5 Method and data

For this thesis, thirteen Norwegian companies were contacted by e-mail with the aim of gaining a deeper understanding of the seaweed industry in Norway. Both wild harvesting companies and cultivation companies were contacted. However, only three cultivating companies expressed interest in further discussions. The objective of this engagement was to enhance our understanding of the current state of the seaweed industry and validate whether the values and estimates used in our thesis are representative for the industry.

Detailed information about the three companies is provided below, with approval obtained from each company to include this information. It is important to note that while we obtained information from these companies, no data used in this thesis is sourced from them.

Table 3: List of informants from the three cultivating companies interviewed.

Name	Company	Position	E-mail
Carl Erik Bergwitz-Larsen	Pursea	Founder/CEO	bikberg@gmail.com
Hermann Peter Schips	Kelpinor	CEO	hermann.schips@kelpinor.no
Kim Kristensen	Arctic Seaweed	Founder & CEO // Mechanical Engineer	kim@aseaweed.com

All the informants represented cultivation companies. Informal and unstructured interviews were conducted to allow open-ended questions, allowing the informants to narrate their experience and insights (Udir, 2021, p. 4). Therefore, we did not use an interview guide since we wanted the informants to talk freely.

Throughout the process of writing this thesis, we have reached out via e-mail to several researchers and individuals associated with the industry to address a range of questions. The goal was to gain a deeper understanding of related sectors and fields beyond our expertise. For example, we contacted a wild harvester and a hatchery abroad, as well as researchers specialising in soil and plant health. Additionally, we reached out to a pyrolyse facility in Norway (OBIO)[6], from which we obtained permission to use one estimate. The information gathered from these individuals have been crucial in enhancing our understanding and validating our findings. We have not cited them

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[6] https://www.obio.no/hjem

as sources, since we have used their information only to confirm that our findings aligns with industry perspective.

For literature searches Google Scholar, Web of Science and Oria have been frequently used to find reliable sources. In obtaining cost estimates for the CBA, market prices were utilised. This involves extensive internet searches to locate market prices for various items. Multiple sources were consulted in this pursuit, and many of the selected sources represent an average derived from the available sources.

To formulate ourselves clearly, artificial intelligence (AI), specifically ChatGPT[7], has been used. AI can be a valuable tool when used correctly (NMBU, n.d). In this thesis, AI has solely been used to optimize our own formulations. We have not used AI to generate text directly. Therefore, all our sources are valid.

2.5.1 Extensively used articles for assumptions

The "Technical Report on Seaweed Hatchery and Sea Grow-out Site Design" have been used to make assumptions on the cost items associated with hatchery (McElligott et al., 2023). The study is part of the Seaweed Development Program and are co-founded by the Irish Government and EU. The report looks at costs associated with the set-up of two sample kelp hatchery scenarios (1) using 120 Litres boxes, and (2) using 500 Litres tanks. The hatchery will have the capacity to produce both 50kms and 250km of seed strings. The research looked at red seaweed. Despite the thesis examining brown seaweed, the findings remain applicable because the hatchery set-up is relatively similar across all seaweed types (Greenwave, n.d). The cost estimates are from 2022 and are based on prices exclusive of Value Added Tax (VAT).

The study by Wu et al., (2023a), was used to make assumptions about the cultivation rig and lifespan of the equipment used. This study provided a supplemental report with cost estimates and assumptions used in the main article, which was utilised to develop cost estimates associated with the rig (Wu et al., 2023b). The report provided cost estimates for a hatchery, which were also incorporated. If cost estimates from McElligott et al. (2023) report was overlining, cost estimates from McElligott were employed. All rig-related costs were considered, but we exclude estimates

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[7] ChatGPT: https://chatgpt.com/?oai-dm=1

for maintenance, insurance, and lease application from their study. Furthermore, we have utilised market prices from Norwegian suppliers.

A value transfer was done from Hynes et al.`s (2021) article “Valuing the ecosystem service benefits from kelp forest restoration: A choice experiment from Norway”. They found a significant WTP for kelp forest restoration and its provision of ES. We have used their estimated WTP for kelp forest restoration as the cost of changing the ES when removing the kelp forests when relying on wild harvesting. The value as we use it reflects the environmental damage costs and is adjusted to apply to households in Ålesund. Our estimate may be high as there was a demographic deviation in their study where a higher share than what is representative for Norway and Ålesund, had higher education. We used this estimate following the guidelines provided by Johnston et al. (2021) in an overarching way.

As seaweed-based plant and soil amendments have the potential of replacing mineral fertiliser, we attempted to find studies that had calculated the substitution effect. There are few studies of this, but we have chosen to include Prasedya et al.`s (2023) field experiment done in Indonesia. They investigated the impact of fermented brown seaweed on rice crops. The study had three scenarios: i) mineral fertiliser only, ii) 50% dose of mineral fertiliser in addition to 1 ton seaweed-based fertiliser, and iii) 50% dose of mineral fertiliser in addition to 2 ton seaweed-based fertiliser. Both scenarios with seaweed-based fertiliser showed positive effects on both soil and plants, including increased content of macronutrients such as nitrogen, phosphor and potassium. Although rice cultivation isn`t prevalent in Norway and fermentation isn`t part of our products, we utilise their findings to estimate the substitution potential and degree, focusing on the scenario employing two tons of seaweed-based fertiliser as a basis for our calculations.

3. Description of the seaweed industry

3.1 Macroalgae

Macroalgae, better known as seaweed, grows along the whole Norwegian coast and include around 480 species (NBFN, 2023, p. 2). Globally, kelp forest ecosystems are in decline, and around 40-60% have already been lost, due to pollution, overfishing, ocean heatwaves, coastal development and other factors. In Norway, overfishing has resulted in a decline of sea urchin[8] predators, leading to an extensive increase of the sea urchins negatively affecting the kelp forests. However, there are signs of recovery in some regions, attributed to climate change and crab predation (Verbeek et al., 2021, p. 15).

Seaweed can be divided into three main groups: green algae (*Chlorophyta*), brown algae (*Phaeophyceae*) and red algae (*Rhodophyta)* (NIBIO, n.d). This thesis focuses on brown seaweed, distinguishing between two types: seaweed which grows in the intertidal zone (no: tang), and seaweed which thrives underwater (no: tare) (The Norwegian Directorate of health, 2021, p. 8). The focus will be *Ascophyllum nodosum* for the former and *Saccharina latissima* for the latter (Rautenberger, 2023a).

Since the beginning of civilisation, seaweed has been explored and utilised across various industries, including pharmaceuticals, cosmetics, food and animal feed, and more recently, biofuel production (Rodriguez et al., 2019, p. 2). Recent trends in organic farming have uncovered the potential to use seaweed as an organic fertiliser in agriculture, due to seaweeds potential to enhance plant growth and productivity (Raghunandan et al., 2019, p. 267). Seaweed is recognised for its capability of taking up nitrogen (N) and phosphorus (P) (Hasselström et al., 2018, p. 1). Seaweed shows promise as soil amendment, providing protection to plants against both biotic and abiotic stress. Additionally, they are recognised for their ability to defend plants against diseases and pest (Raghunandan et al., 2019, p. 267).

Seaweed can also contain unwanted substances, such as cadmium, inorganic arsenic and iodine. Brown algae contain the highest concentration of iodine, even though levels vary significantly among species, growth locations, age and seasons (The Norwegian Directorate of health, 2021, p. 8).

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[8] Sea urchin (no: kråkebolle).

3.1.1 Ascophyllum nodosum

Figure 2: Illustration of A. nodosum (Arca, n.d).

A. nodosum is widely distributed along the entire Norwegian coastline, demonstrating adaptability to various marine conditions (Institute of Marine Research, 2022). According to Silva et al. (2019), *A. nodosum* is rich in carbohydrates and other substances, such as natural hormones, minerals, alginates, amino acids and trace elements that act positively on metabolic processes in plants. Their study emphasizes that *A. nodosum,* when used as biofertiliser, has important functions in terms of enhancing biochemical and physiological processes in plants, such as growth, control and high resistance to various abiotic factors (Silva et al., 2019, p. 920).

3.1.2 Saccharina latissima

Figure 3: Illustration of S. latissima (Redmond et al., 2014, p. 18).

S. latissima can be found along the entire Norwegian coastline and is one of Norway's most common kelps species (Rautenberger, 2023b). According to Rautenberger (2023b) *S. latissima* contains large amounts of alginate, that can be used as an additive, thickener and stabiliser. In addition, *S. latissima* contains a lot of minerals, fiber and bioactive substances with health-promoting effects. Ruud (2014) suggests that *S. latissima*, along with other seaweed species, is particularly well-suited for cultivation in Norway, as it is relatively easy to grow and produce substantial amounts of biomass within a season. Additionally, according to Sæther et al (2024, p. 21), *S. latissima* is a favourable choice for fertiliser.

3.2 Wild harvesting of seaweed

There exist many different methods and techniques to collect and harvest wild seaweed, often involving the use of boats, rakes, by diving, or manual harvesting from the shore (Monagail et al., 2017, p. 374). Wild harvesting means harvesting from a natural kelp forest. Currently, in Norway, *Laminaria hyperborea* (no: stortare, en: civie) and *A. nodosum* is the only macroalgae that is being utilised on an industry scale. They provide raw material to alginate and kelp meal (The Norwegian Directorate of Fisheries, n.d (b)).

In Chile and Japan, harvesters typically use hand-held cutting tool, whereas in France and Norway, bottom trawls or dredges are commonly used. Countries like South Africa, Australia and New Zealand often rely on beach-cast harvesting method (Lotze et al., 2019, p. 397).

Hand-held cutting is employed during low tide by manual harvesters working from the shore. Using a sickle, harvesters cut the seaweed from its root, leaving approximately 20 cm of the root intact to facilitate regrowth (UISTASCO, n.d).

Figure 4: Illustration of an A. nodosum harvester using a sickle (UISTASCO, n.d).

Harvesting seaweed from a boat is also a common technique. The harvesters use customised rakes designed for efficient raking of seaweed (Monagail et al., 2017, p. 374). The harvesters equipped with the rakes can harvest the seaweed at low and high tide, and they can immediately deposit the seaweed directly into the boat and move on to the next plant (UISTASCO, n.d). After harvesting, the seaweed is transported to the shore for further processing.

Figure 5: Illustration of using a rake when harvesting A. nodosum from a boat (UISTASCO, n.d).

Both hand-cutting and mechanical harvesting will affect the extent and the structure of the seaweed. However, the extent of the consequences will depend on the harvest intensity, the gear type, the scale, and the cutting methods used. Mechanical methods such as clear cutting or trawling can remove a significant portion of the plant, requiring many years for recovery (Lotze et al., 2019,

p. 399). Mechanical harvesting has faced criticism due to the potential over-exploitation of the seaweed resources, i.e., exceeding the natural renewal rate (Monagail et al., 2017, p. 376). This thesis will focus on the technique hand-cutting using sickles and rakes. This decision is driven by concerns surrounding the uncertainty of the sustainability of mechanical harvesting.

3.2.1 Environmental effects from seaweed harvesting

Natural kelp forests provide essential ecosystem services, e.g., nutrients and coastal protection as a supporting ES and carbon sequestration as a regulating ES. Large-scale removal of these forests can disrupt the provision of these services (Clark et al., 2021, p. 13). Marine seaweed forests serve as a crucial habitat, providing shelter, food, refuge and shade to a numerous marine organism. When these forests are harvested, marine organisms lose their homes, and the structure and conditions of these marine ecosystem's changes. Wild harvest can also impact the broader ecosystems by affecting important food sources, for example affecting the food supply for seabirds (Clark et al., 2021, p. 13).

3.2.2 Regulations of wild seaweed harvesting

There are significant differences in what activities are permitted or prohibited based on national policies. For example, in Norway, mechanical harvesting of seaweed is legal, whereas in Ireland, this method is banned (Lotze et al., 2019, p. 397). Mechanical harvesting is banned, because hand harvesting is seen as more sustainable (Vance et al., 2023, p. 1).

In Norway, there exists a regulation called "Forskrift om høsting av tang og tare" (1995), which is a regulation on harvesting seaweed, established under the Marine Resource Act. The purpose of this regulation is to promote the sustainable utilisation of seaweed resources. The regulations count for examination and harvesting of seaweed in Norwegian coastal zones, but do not cover areas subject to private property rights (Forskrift om høsting av tang og tare, 1995, §1-§2). Harvesting of *A. nodosum* is managed through private law legislation, and the landowner's permission is the only requirement needed i.e., harvesting of *A. nodosum* is not regulated (Institute of Marine Research, 2022).

3.3 Cultivation of seaweed

Currently, wild harvesting of seaweed is a bigger industry than cultivation in Norway. This dynamic is expected to shift over time. Cultivation of macroalgae is one of the fastest growing industries within aquaculture, representing an industry still in its early stages of development. The objective is to establish a profitable production that can contribute to increased quantity of food and feed produced in the ocean (NBFN, 2023, p. 2-3). In Norway, the primary species cultivated is *S. latissima* and *Alaria esculenta* (no: butare, en: winged kelp). These species are chosen due to their ease of cultivation and suitability for Norway's coastal areas (Norderhaug et al., 2020, p. 7).

One growing season in Norway for seaweed can typically look like this, whereas our analysis will be subject to this timeframe:

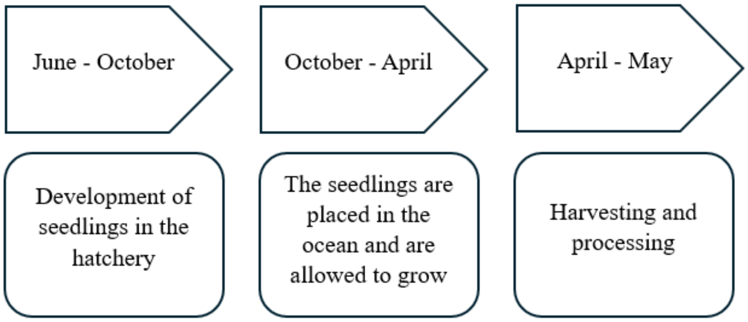

Figure 6: One growing season for cultivated seaweed. Translated and simplified based on NBFN (2023, p. 3).

3.3.1 Cultivation methods

Seaweed cultivation can take place on land within closed environments such as water tanks, ponds, or pipelines. However, the scalability of land-based cultivation is limited due to high maintenance costs. The most common method of seaweed cultivation involves inshore shallow water aquaculture, i.e., close to land. A recent approach involves situating cultivation sites near fish farm to utilise fish farm waste and for nutrients recycling (Zhang et al., 2022, p. 16-17). Such an integrated aquaculture system would be beneficial in terms of area planning. However, implementation of such systems faces obstacles due to the absents of necessary regulations and laws (The Norwegian Directive of Fisheries, 2018, p. 4). Therefore, the focus for further analysis will be on seaweed cultivation in inshore waters within Norway.

The initial steps take place in the hatchery, where the cultivation of cuttings occurs. This process is comprehensive, and the further description is therefore simplified. Sporelings that are obtained from a mother plant, are grown from microscopic phases. Once matured, the cuttings are sprayed onto thin seeding lines and wound onto spools. The cuttings can then either grow in boxes or in tanks. The main different is the infrastructure needed (McElligott et al., 2021, p. 16). Once matured, the cuttings are transferred to the sea, where they are left to grow and develop under natural conditions (McElligott et al., 2021, p. 11-14).

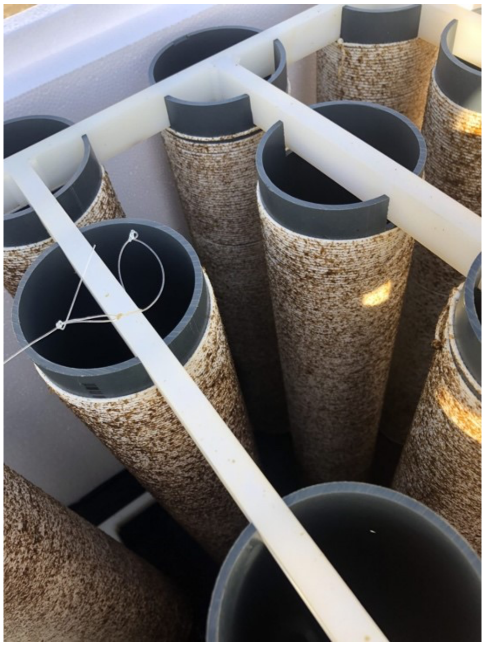

Figure 7: Illustration of seeding lines wrapped around spools (Steenhoek, 2021).

Commercial cultivation of seaweed at sea encompasses various techniques, including cultivation on seabeds, lines, ropes, and nets. Cultivation on lines or ropes involves fixing seeding lines onto long lines, which are then secured to buoys anchored to the seabed or floating on the surface (Titlyanov & Titlyanova, p. 229). This method is commonly used in Norway and Ireland (Ruud, 2014; McElligott et al., 2021, p. 29). At the end of the season, boats are being used to harvest the full-grown seaweed, which is then transported to further processing.

Figure 8: Illustration of cultivated seaweed. Credit: Sea Grove Kelp Co. (USDA, n.d).

3.3.2 Environmental effects of cultivation

Seaweed cultivation can have positive and negative impacts on the environment. According to the Norwegian Blue Forest Network (NBFN) large-scale seaweed cultivation has the potential to mitigate CO_2 concentrations in the atmosphere by storing carbon in the ocean floor, soil, or through substitution of products with higher GHG emissions, representing a regulating ES. Additionally, seaweed can enhance water quality by absorbing nutrients and oxygen, helping to lower pH concentrations in the water, which in turn contributes to mitigating ocean acidification which represents supporting ES. Furthermore, cultivation rigs can work as a habitat for many species, contributing to increased biological diversity (NBFN, 2023, p. 4).

Despite numerous positive impacts with seaweed cultivation, several negative effects may also arise. The instillation of seaweed rigs can disturb seabeds temporarily. Once established, these cultivation sites can reduce water currents, potentially increasing speeds around or beneath the structure affecting nutrients distribution. The seaweed cultivation site can cast shade, which can disrupt the growth of light dependent primary producers in the area. Seaweed cultivation can offer shelter and food sources, but when harvested it can expose the organisms to predators and the food supply is suddenly gone. The potential for wildlife entanglement within the seaweed sites presents a high environmental risk. Furthermore, nutrient levels can be affected as seaweed absorb nutrients from the water and convert them to biomass, potentially leading to changes in natural primary producer populations. Litter from the cultivation rig is a threat for wild animals, as animals may ingest the litter which can cause harm. One of the most significant environmental risks is the potential effects of genetic interaction between cultivated seaweed and wild populations. Lastly, seaweed cultivation poses high biosecurity risks such as spread of pests and diseases, that can spread to natural beds (Clark et al., 2021, p. 35-41).

3.3.3 Regulations of cultivation

Aquaculture production, like macroalgae, requires permits (Akvakulturloven, 2005, §4). Such permits are being given by the county authority. One permit gives the right to produce one species in a predefined area if several conditions are met, for example that the cultivation is environmentally responsible, and it aligns with area planning guidelines (§6).

3.4 Seaweed as soil and plant amendments

Today, to meet the requirements for a growing population, mineral fertiliser is commonly used to enhance agricultural production (Shukla et al., 2019, p. 19). Mineral fertiliser improves the supply of nitrogen (N), phosphorus (P) and potassium (K), which increase the yield of crops (IFA, n.d). However, the chemicals from mineral fertiliser pose serious threats to humans, plants and animal health. The Farm to Fork Strategy, part of EUs Green Deal, aims to accelerate the transition towards sustainable food production (European commission, n.d). Therefore, it is necessary to focus on more sustainable options such as soil and plant amendments derived from seaweed.

Soil amendment is any material added to improve a soil`s physical condition, including water retention, water infiltration, drainage and structure. Organic amendments come from sources that have been alive and increase the organic matter content in soil and will over time improve water- and nutrient-holding capacity. In other words, it indirectly affects plant growth. Further it will act as an important energy source for bacteria, fungi and earthworms that live in the soil (Davis & Wilson, 2000, p. 1). In this thesis, kelp meal and biochar are referred to as soil amendments.

Plan amendment is any material added to improve the plants growth, yield, quality, reproduction, flavour or other desirable characteristics (Pennsylvania Department of Agriculture, n.d). According to Bonilla et al. (2012, p. 479), organic amendments can reduce the occurrence of diseases caused by bacteria, fungus and parasites. In this thesis, liquid biostimulant is referred to as plant amendment.

3.4.1 Liquid biostimulant

Biostimulants was first used by horticulture specialists as a word to describe substances that promote plant growth without being soil improvers, nutrients, or pesticides. Later, it was distinguished from soil amendments because soil amendments are applied in larger quantities (Du Jardin, 2015, p. 4). EU set rules on fertilising products and amending regulations in 2019 and defines plant biostimulant as follows:

> "*plant biostimulant means a product stimulating plant nutrition processes independently of the product`s nutrient content with the sole aim of improving one or more of the following characteristics of the plant or the plant rhizosphere: a) nutrient use efficiency, b) tolerance to abiotic stress, c) quality traits, and d) availability of confined nutrients in soil or rhizosphere*" (EUR-Lex, 2019, Article 47(2)).

In this thesis, the biostimulant is liquid. As a natural preparation, liquid biostimulant will increase plant growth even under water and abiotic stress. Liquid biostimulants are more effective under horticulture crops, e.g., fruits and vegetables (Tarafdar, 2022, p. 1). Biostimulants can be extracted products from seaweed. Seaweed extracts are one of the most common components of plant biostimulants and are currently obtained from brown and green seaweeds. The extraction processes are many, including high or low pressure, temperature, crushing of frozen seaweeds, or alkaline, neutral, acidic or water extractions (EBIC, 2023, p. 1; Han et al., 2022, p. 2).

3.4.2 Kelp meal

When seaweed is harvested, dried and ground into fine powder, it turns into kelp meal (Chalker-Scott, 2019, p. 1). Although kelp meal is also referred to as algae fiber, it will in this thesis be constantly termed as kelp meal. According to Løes et al. (2022), the addition of kelp meal to the soil positively impacts plants due to its content of carbon (Ca), potassium (K), magnesium (Mg) and sodium (Na). The study demonstrated that kelp meal can be used as soil amendment. A remark her is that the study from Løes et al., (2022) looked at the residual product from the algae industry, and not the use of the whole product as it is done in this thesis.

3.4.3 Biochar

Biochar, created from biomass exposed to oxygen-limiting conditions (350–700°C), is utilised as a soil amendment due to its rich carbon content, high pH levels, stability, porosity and surface area (Brassard et al., 2019, p. 109). The temperature is found to have an impact on how much biomass remains after pyrolysis, where Pak et al. (2023, p. 3) found a reduction of yield from 66% to 34%. Studies show that biochar improves soils chemicals, physicals and biological properties that will lead to increased crop productivity. Unlike kelp meal and liquid biostimulant, the carbon in biochar, can be sequestered more than 1000 years once applied to the soil. Therefore, biochar can be a potential contributor in agriculture to reduce GHG emissions (Brassard et al., 2019, p. 109).

3.4.4 Limitations

Several limitations exist for seaweed as plant and soil amendments. For instance, seaweed contains potentially toxic elements (PTEs) like arsenic (As) and cadium (Cd), which can negatively impact soil health (Løes et al., 2022, p. 3). Still, it exists knowledge gaps, with one major concern being the potential long-term accumulation of PTEs in the plant's food chain (Eggen et al., 2022, p. 15). According to Roberts et al. (2015, p. 4), the main limitation of using seaweed biochar is the high concentration of sodium (Na), which can lead to increased soil salinity. Although earlier studies indicates that Na-components is leachable and have short-term positive effects on crop productivity, the research highlights the need to apply biochar to soils in advance of cropping to allow Na to decrease (Roberts et al., 2015, p. 4). These are just a few examples of the limitations associated with seaweed-based amendments (Roberts et al., 2015: Løes et al., 2022). Importantly, these limitations fall outside the scope of this thesis and are not considered within our framework.

3.5 Market potential and barriers

The primary drivers for using liquid biostimulant, kelp meal and biochar is the growing focus on sustainable agriculture and farming that support plant and soil health (World Bank, 2023, p.23).

Several studies, including the report from Ali et al. (2021), confirm the effectiveness of *A. nodosum* as a biostimulant. Limited studies have explored the biostimulant properties of *S. latissima*, and show varying effects and highlighted the need for further research. However, the study suggests for now that *S. latissima* could be a promising addition alongside well-established biostimulants derived from *A. nodosum* and other brown algae (Sæther et al., 2024, p. 22). Therefor there exists less research on *S. latissima* compared to *A. nodosum*, which may result in greater market barriers for *S. latissima*.

For biostimulant, it exists some challenges concerning poor reputation and the lack of convincing evidence of its efficiency (World Bank, 2023, p. 27). Also, better insight is required into the market demand since there are a lot of knowledge gaps. Biostimulant is also an expensive product, so it exists a risk of adopting it (World Bank, 2023, p. 28). A new factor influencing the demand for biostimulant is the rise of global fertiliser prices because of increased energy prices and the war in Ukraine. The result is that the market turns towards alternative products (World Bank, 2023, p. 27).

As mentioned earlier, seaweed cultivation is one of the fastest growing industry in the aquaculture sector with rapid development (NBFN, 2023, p.2). Recently, the application for seaweed has expanded significantly. Seaweed-based compounds are being explored for their use in various new emerging markets. These opportunities could further drive the cultivation of seaweed and its associated environmental and social benefits (World Bank, 2023, p. 6).

It is thus difficult to predict how the demand for seaweed-based products will develop, but as it is an increasing focus on sustainability and sustainable substitutes, it is likely we will see an increased demand for such products. Expected price for different products can be showed through the value pyramid for seaweed-based products:

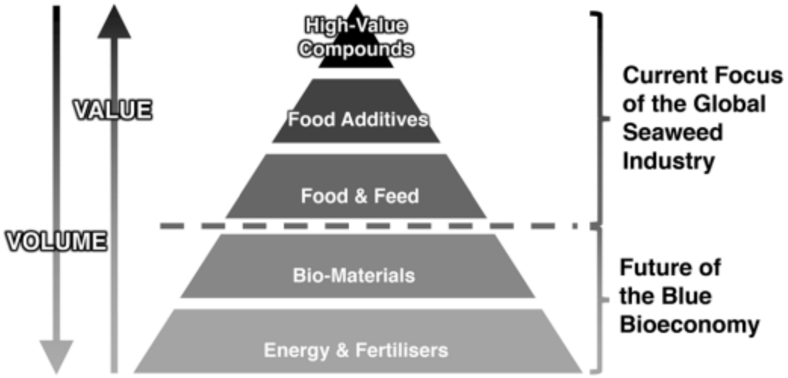

Figure 9: Value pyramid for seaweed biomass. Source: Hasselström et al., 2020, Fig. 3, p. 5.

High-value compounds such as pharmaceuticals give the highest market price, but the lowest volume. Conversely, fertilisers yield the highest volume, but lower market prices. As depicted in Figure 9, seaweed-based fertilisers are considered a forthcoming product, underscoring the current instability of the seaweed market for soil and plant amendment purposes. For instance, Menzies et al. (2021, p. 4) noted that market prices in the UK ranges from £1000 to £3000 per ton dried seaweed, equivalent to 11,826 NOK and 35,480 NOK in 2021, depending on which market it was being sold to. In contrast, the market price for mineral fertilisers as of December 2023 was approximately 6500 NOK per ton (Forbord, 2023). Given the ongoing development of seaweed for use as soil- and plant amendment, drawing conclusions about expected market outcomes and developments is challenging. The information provided reflects current circumstances and prospects.

4. Cost-benefit analysis

The aim of the cost-benefit analysis is twofold: firstly, to explore potential ways to utilise cultivated *S. latissima* and wild harvested *A. nodosum* as a seaweed soil or plant amendment. Secondly, it seeks to quantify the impact on different ecosystem services (ES). The design of the analysis is inspired by Boardman et al. (2014) and DFØ (2023) and will cover the steps explained in chapter 2.3.

4.1 Step 1- Project definition

The analysis deals with a hypothetical case project in a limited area, with the chosen location being Ålesund. Ålesund was selected due to the necessity for some specific area-based calculations and was found suitable as a medium-sized coastal city. The reference alternative is a natural kelp forest with no commercial use of biomass. The reference year (t=0) is 2024 and production is projected to last for 20 years.

There are two methods to acquire seaweed: cultivation or wild harvest seaweed. Cultivation offers the advantage of providing additional ES. It is well documented that seaweed can be used as a plant and soil amendment (McKinnon et al., 2004; Eyras et al., 2008; Ali et al., 2021).

Liquid biostimulant as a plant amendment is identified by the World Bank (2023) as a promising area for utilising seaweed. Kelp meal, even if lacking extensive research, is included for its basic characteristics. Lastly, biochar shows promise as a soil amendment and for its potential to sequester CO_2 for a long time when applied to the soil (Brassard et al., 2019, p. 109).

Our project alternatives can be illustrated and summarised as follows:

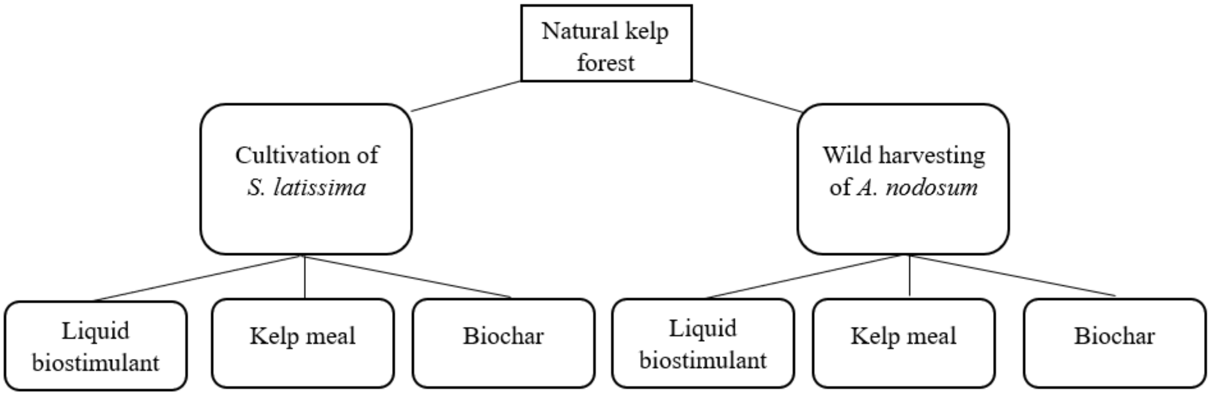

Figure 10:Illustration of the reference alternative and project alternatives.

I. **Cultivation**
   1. Cultivating *S. latissima* to produce liquid biostimulant
   2. Cultivating *S. latissima* to produce kelp meal
   3. Cultivating *S. latissima* to produce biochar

II. **Wild harvest**
   4. Wild harvest *A. nodosum* to produce liquid biostimulant
   5. Wild harvest *A. nodosum* to produce kelp meal
   6. Wild harvest *A. nodosum* to produce biochar

The analysis is limited to investigating the potential of cultivation and wild harvesting on an area of 10 hectares with a constant amount biomass every year. It is assumed that all biomass, i.e. the whole harvested plant, will be utilised. The size of 10 hectares is identified as suitable based on advice suggesting that a cultivation site must be of at least 10 hectares to be economically profitable (Marit Gjerstad, personal communication[9]). Additionally, The Norwegian Directorate of Fisheries (n.d) has a public register with permits to do aquaculture showing that permit sizes for those who cultivates *S. latissima* vary from 2 to 35 hectares, with a mean value of 9.3 hectares. Cultivation is assumed to be an efficient area use of 10 hectares. For wild harvesting, the 10 hectares area is seen as rotational, as new kelp forests needing time to grow. Wild harvesting undergoes annual rotations over a period of five years before reverting to the original area. Therefore, we assume wild harvesting every year on an area equivalent to 10 hectares in a larger area. We assume that the kelp forest is filled with *A. nodosum*.

Stakeholders associated with these alternatives include cultivators and wild harvesters as it promotes ways to utilise seaweed. Local communities will get new job opportunities and there will be local economic impacts. Furthermore, farmers and gardeners will get more sustainable options to use for crop management, reducing reliance on mineral fertilisers. Additionally, there will be climate benefits like CO_2 capture and storage in seaweed, which is a benefit for all households in Norway, and help to achieve ambitious climate goals.

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[9] Senior Advisor at Norges Vel. We have been given permission from Gjerstad to use this information.

To facilitate a thorough understanding of this comprehensive analysis, the following section describes the assumed supply chain and associated assumptions for both cultivation and wild harvesting.

Assumptions and supply chain for cultivation

A company who controls its whole supply chain is assumed to enhance clarity regarding cost streams involved. In reality, some firms have begun to specialise in specific areas such as technology or seedling development. See for instance the Norwegian Seaweed Association for an overview of various Norwegian seaweed firms[10].

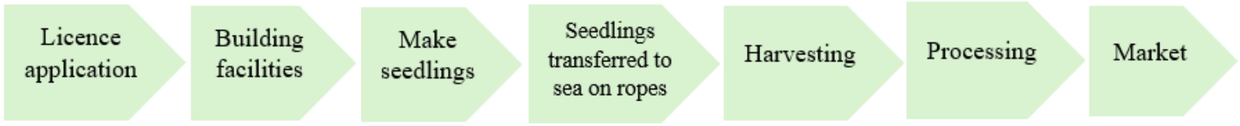

Figure 11:Supply chain of a cultivating company.

The initial step of establishing a cultivation site involves applying for licences to build the cultivation rig at sea, according to the Norwegian law regarding aquaculture permission (Andre arter-forskriften, 2004, §10a). Subsequently, facilities need to be built, including a production factory and a cultivation rig at sea. To maintain the freshness of the biomass, the production factory should be situated close to the cultivation rig. The factory will house various production equipment, as well as a hatchery for seedling production.

The cultivation rig, i.e., where the seaweed grows in the ocean, is based on a rig on 1 hectare from an article provided by Wu et al. (2023a). It is assumed that there will be 10 such rigs, as depicted in Figures 12 and 13. This method, known as the single layer longline method, is a commonly used method globally (Wu et al, 2023a, p. 2).

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[10] Norwegian Seaweed Association: https://www.norseaweed.no/medlemmer

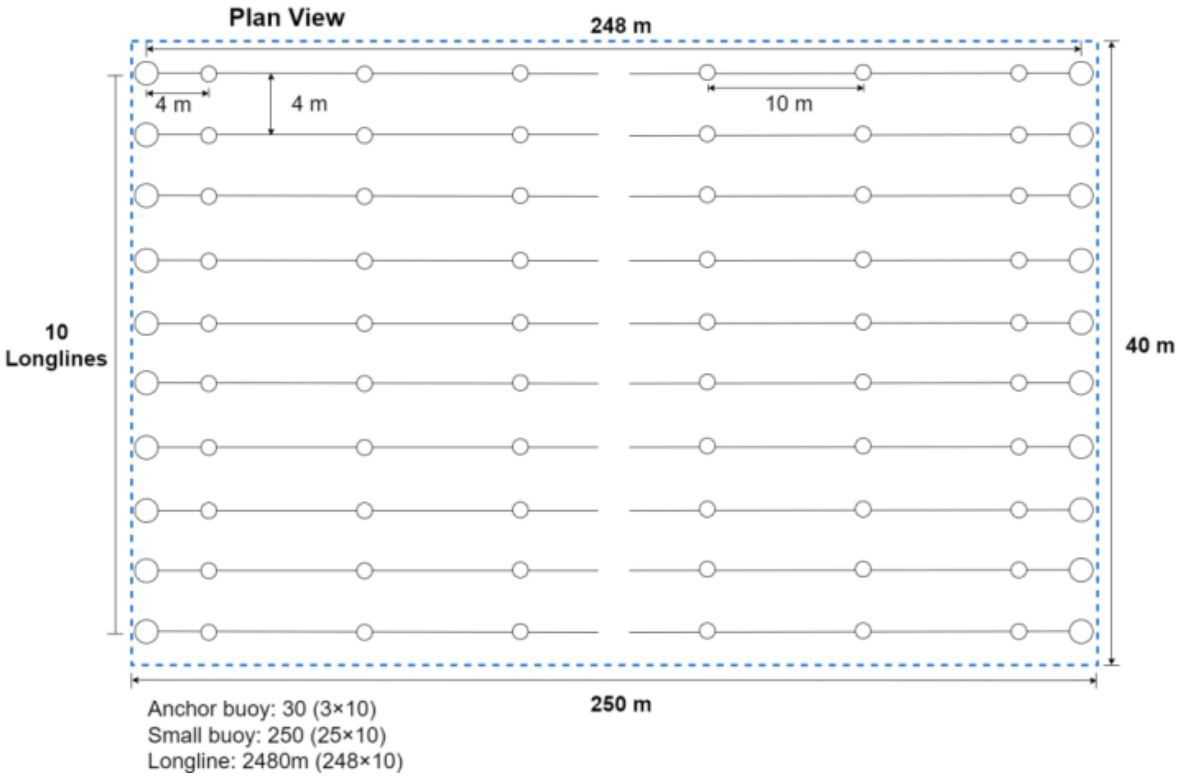

Figure 12: Illustration of the rig seen from above. Source: Wu et al. 2023a, fig 2a, p.3 "1 Hectare Seaweed Farm- Longline method Plan View".

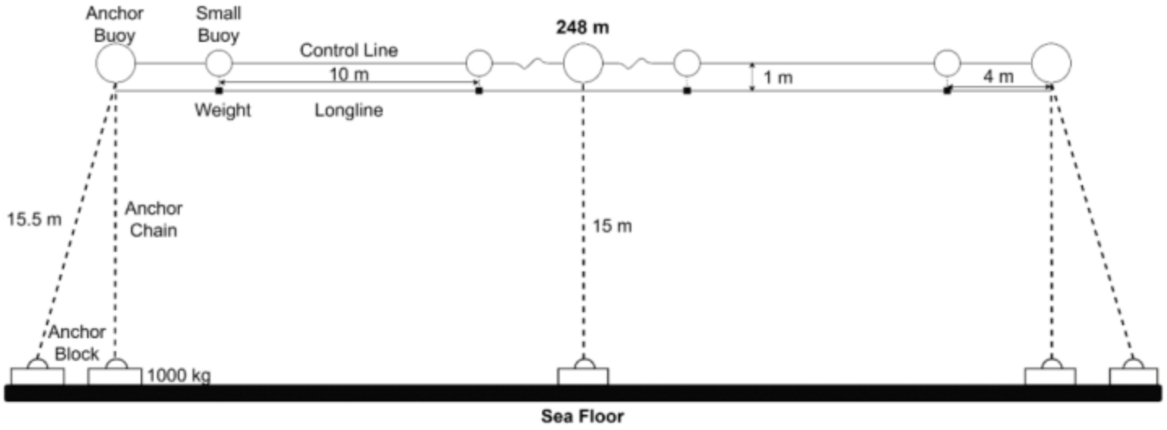

Figure 13: Illustration of the rig seen from the side. Source: Wu et al. 2023a, fig 2c, p.4 "1 Hectare Seaweed Farm Cross Section View- Single Layer".

The cultivation rig on 1 hectare has a capacity to produce 37.35 ton biomass fresh weight and 6.35 ton dry weight of *S. latissima* as stated in Wu et al. (2023b). This implies a ratio of 17% between fresh weight and dry weight, which will be adopted later in this thesis. Based on the illustration of the cultivation rig, we assume a flat seabed with consistent water depth across the entire site, whereas in reality, the seabed may have a gentle slope.

The production of seedlings, a process that can take up to four months (NBFN, 2023, p. 3), can begin once the facilities are established and follows the procedures as explained in chapter 3.3.1. Building the facilities and the production of seedlings are assumed to occur in the initial year 2024 (t=0), whereas production of seedlings happens every year during the project period until 2043 (t=19).

When the seedlings are large enough, the ropes are transferred to the cultivation rig at sea using a small boat. This happens around October the first year (t=0) and requires some seasonal workers. Then the seedlings are allowed to grow until May. When the time comes for harvesting, a large boat and seasonal workers are needed. Harvesting the cultivated seaweed takes only a few days and occurs the first time in t=1.

With 10 rigs covering 1 hectare each, the harvested seaweed amounts to approximately 374 tons. The facility is not expected to have the capacity to process this in one day. Therefore, the seaweed that does not go directly to production is being stored in the ocean to keep its freshness. Regardless of end-product, all the biomass is being dried and milled before further processing.

Liquid biostimulant and kelp meal is produced at the factory located near the rig. The process for liquid biostimulant production involves mixing the dried seaweed with distilled water, as outlined in Han et al. (2022, p. 2). Kelp meal, on the other hand, is the product obtained after drying and milling and requires no further processing.

Biochar production requires pyrolysis and is outsourced as the production of biochar also lead to production of other substances. This could more easily be utilised by a company specialised in pyrolysis, such as those involved in district heating (Obio, n.d.).

Once production is completed, the end-products are approximately 199 tons of liquid biostimulant, 64 tons of kelp meal, and 35 tons of biochar. These end-products are intended for business-to-business (B2B) sales and are being produced and sold for the first time in t=1. We assume every ton of product is being sold every year. From this point, the process of seedling development and end-product manufacturing will occur annually over the subsequent 19 years.

Assumptions and supply chain wild harvesting

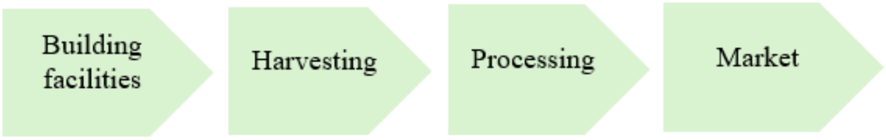

Figure 14: Supply chain of a wild harvesting company.

The first step in the harvesting of *A. nodosum* involves building a factory. The same capacity and equipment as required for cultivation is assumed, except for the hatchery. This happens in year 2024 (t=0).

Harvesting occurs over an area of 10 hectares and yields 400 tons of seaweed fresh weight, based on Baardseth (1970, sited in Institute of Marine Research, 2022) and Ugarte & Sharp (2012). The rate of dry weight is assumed to be consistent with *S. latissima*, i.e. 17%, resulting in 68 tons of dry weight. The harvesting happens manually using sickles and rakes. This method is chosen due to concerns about the uncertainty of the sustainability of mechanical harvesting (Vance et al, 2023, p.1). While harvesting can occur at any time of the year, the optimal period is from March to May (Sopp og nyttevekster, 2022, p. 2), meaning that harvesting and production starts in t=1.

Unlike cultivation, wild harvesters own their own harvesting boats and requires more seasonal workers. Additionally, a smaller factory is assumed due to a hatchery is not required. The subsequent steps in the process remains the same as with cultivation, although wild harvesting yields slightly more end-products: approximately 208 tons of liquid biostimulant, 68 tons of kelp meal and 37 tons of biochar.

Disclaimers

The main concern regarding using seaweed as plant and soil amendment, is the high level of PTEs. However, considering ongoing research initiatives such as SeaSoil (Nofima, 2024), an EU research project that is actively addressing this issue, we will omit this aspect from this thesis and assume that the problem will be solved. Furthermore, we assume that *S. latissima* can be employed as a soil amendment in line with *A. nodosum*.

Nutrient content of the amendments will most likely vary depending on production method and species used and may vary from one year to another (Kaur, 2020, p. 175). As we are investigating the potential of relying on cultivation or wild harvesting of seaweed, it is assumed that the different project alternatives have the same effect on the soil and plants.

4.2 Step 2- Quantification of impacts

Implementation of either of the alternatives will generate benefits or costs to the cultivating or harvesting company, consumers and the society at large. The table below provides a brief overview of these effects, which will be valued in Step 3 and in Step 4 we will consider non-priced effects. These effects apply to all project alternatives considered here, unless it is clearly stated in the table that the impact only relates to one or a few alternatives.

Table 4: Quantification of impacts.

Benefits		
Effect:	**Cultivation:**	**Wild harvesting:**
CO_2 sequestration (Regulating ES)	Cultivation provides a benefit through CO_2 sequestration as cultivation comes in addition to natural kelp forests (NBFN, 2023, p. 4). Cultivation of seaweed will sequestrate CO_2 in the biomass when growing in the ocean. However, long term effects depend on CO_2 footprint throughout the supply chain and emissions released when the different end-products are applied to the soil. Biochar stands out as the only project alternative capable of long-term CO_2 storage in the soil (Brassard et al., 2019, p. 109).	While kelp forests sequestrate CO_2, the reference alternative being the natural kelp forest means there is no additional effect on CO_2 sequestration for the project alternatives related to wild harvesting. According to Gundersen et al. (2011, p. 10), the utilisation of natural kelp forests is considered carbon neutral.
Positive impacts on ES	Seaweed cultivation can enhance water quality and reduce pH concentration in the water. Cultivation rigs can also work as a habitat for many species, contributing to increased biological diversity (NBFN, 2023, p. 4). Cultivation of	No effect as the ecosystem services provided is removed.

	seaweed can also extract nutrients like nitrogen, phosphor and carbon (Hasselström et al., 2018, p. 1). These benefits apply to all project alternatives related to cultivation.	
Soil and plant amendment seaweed substitute	Soil and plant amendment derived from seaweed offer the potential to partially replace other more CO_2 -intensive products such as mineral fertilisers. The primary focus in this thesis is on estimating the avoided CO_2 emissions resulting from this substitution (Wei et al., 2020, p. 2). This applies to all project alternatives.	
Gross income- sales of the product	Income generated from the sale of the product is included as a benefit. Annual output is held constant for all project alternatives. Market prices may vary based on whether the seaweed is cultivated or wild harvested, and seaweed species. In this analysis, prices will be held consistent regardless of method for acquiring the seaweed but will vary depending on the specific end-product. This reflects the value of seaweed as a provisioning service by providing raw material.	
Costs		
Effect:	**Cultivation:**	**Wild harvesting:**
Supporting ES	The seabed can be temporarily disturbed during rig installation. Changes in water currents can subsequently impact nutrient distribution which can have a negative impact on natural primary producers. The presence of seaweed rigs can cast shade, potentially affecting light dependent primary producers. Additionally, there is a potential for wildlife entanglement. Harvesting of the cultivated seaweed removes shelter and food sources for various organisms. Cultivated seaweed may absorb nutrients that natural organisms need to survive (Clark et al., 2021, p. 35-39). This applies to all project alternatives regarding cultivation.	Wild harvesting removes essential ES, e.g., providing of habitat, shelter, shade and as food. When harvested the structure and condition of these services changes (Clark et al., 2021, p. 13). This applies to all project alternatives regarding wild harvesting and will be referred to as environmental damage cost.
Provisioning ES	There is a risk of genetic pollution when it comes to	

	cultivation of seaweed. In Norway, as far as we know, the local mother plant is used, limiting this risk. However, a genetic diversity must maintain (Hasselström et al., 2018, p. 58). Risk of diseases to natural kelp forests is also a risk associated with cultivation (NBFN, 2023, p. 5). Since cultivation relies on synthetic ropes, lines or nettings, it poses a significant chocking or entanglement risk to wildlife (Clark et al., 2021, p. 40).	
Cultural ES	Cultivation sites can negatively impact recreation value and disturb the landscape picture as the cultivation rig requires many buoys. The closer the infrastructure are to land, the higher the potential visual impact on nearby residents and higher restrictions for recreational activities. This leads to reduced social acceptance (Cabral et al., 2016). Litter can negatively affect the recreational use value (Aanesen et al., 2018, p. 1).	
Investment	Cultivation of seaweed will require investments in factory, hatchery, cultivation rig at sea and different machinery and equipment, along with expenses for a cultivation license. The highest investment costs will occur in 2024. Over the next 19 years, the investment costs will fluctuate based on the estimated lifetimes of different costs components.	Wild harvesting of seaweed will require investments in factory, harvesting equipment and boats, and different machinery and production equipment. As with cultivation, the highest investment costs will occur in 2024. Over the next 19 years, the investment costs will fluctuate based on the estimated lifetimes of different costs components.

Labor, wages and social costs	All alternatives will require a work force consisting of both fulltime employees and seasonal workers. This generates cost in form of wages to the employees and social costs that the employer faces. It is assumed the same size of the work force every year from t=1. The first year (t=0) requires a smaller workforce.	
Operational costs	The operational costs include maintenance expenses (for factory, rigs, hatchery and different machinery and equipment), electricity costs and other expenses such as boat rental and municipal fees. Transportation and fuel costs are assumed to be included in maintenance costs. Operational costs are an annual expense.	The operational costs include maintenance expenses (for factory, boats and different machinery and equipment), electricity costs and municipal fees. Transportation and fuel costs are assumed to be included in maintenance costs. Operational costs are an annual expense.

4.3 Step 3- Economic valuation

All prices and costs of inputs utilised in this analysis are exclusive of Value Added Tax (VAT), and thus reflects the marginal production costs. Prices listed in foreign currencies are converted to Norwegian kroner (NOK) using purchase power parity (PPP) corrected exchange rates[11], and are then adjusted to 2024-NOK (January 2024) using the Norwegian Consumer Price Index (CPI)[12]. All Norwegian prices are also adjusted to 2024-NOK using the CPI. Thus, the implicit assumption is that the price of the cost and benefit effects increase over time at the same rate as CPI. This is a strict assumption, that is not always fulfilled, but is very often used in CBAs for simplicity when there is no specific price index for the cost or benefit effect in question. A supplemental table is listed in the Appendix C and D with the sources used for attaining the market prices.

4.3.1 Benefits of cultivation

CO_2 sequestration during the growth season for cultivation

Carbon sequestration is a regulating ES. The CO_2 sequestration estimate from cultivation is based on the short-term CO_2 effects in the ocean, i.e., what is being sequestrated during a growth season which is from October to May. Nordic Seafarm`s estimate is used, assuming 145 kg CO_2-

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[11] PPP corrected exchange rates: https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm

[12] CPI: https://www.ssb.no/priser-og-prisindekser/konsumpriser/statistikk/konsumprisindeksen

equivalents are sequestered per ton of biomass (Nordic Seafarm, n.d.). Nordic Seafarm is cultivating *S. latissima* and sea lettuce in Sweden and is used as it is close to our case, both with regards to geographic location and seaweed species. The carbon price is determined by the Ministry of Finance (2023) and we use their carbon price for "Category 5: Absorption and emission from forestry and land use". The Norwegian carbon prices reflect the marginal abatement costs (MAC) of achieving the national emission reduction goal rather than the theoretically correct marginal damage costs (MDC) of CO_2 emissions, i.e. the Social Cost of Carbon (SCC) which is the global damage costs of emitting 1 ton of CO_2. We assume that MAC=MDC=SCC and use the Norwegian carbon prices.

Table 5: Annual CO_2 sequestration valued in 2024-NOK for cultivation on 10 hectares from t=0.

Measurement unit	**Value**
Ton biomass for 10 ha	374
Kg CO_2 e sequestered per ton biomass	145
Kg sequestered CO_2 per year on 10 ha	54,158
Ton sequestered CO_2 per year on 10 ha	54
Carbon price	934
Valuation in NOK 2024	**50,583**

Soil and plant amendment cultivated seaweed substitute

Soil amendments derived from seaweed can substitute mineral fertilisers. While there is limited research on the extent of substitution, a field experiment conducted by Prasedya et al. (2023) in Indonesia found positive effects. The field experiment consisted of three scenarios and were related to rice crops and the use of fermented brown seaweed as soil amendment. The first scenario was using only mineral fertiliser. The second was replacing 150 kg mineral fertiliser with 1 ton seaweed-based soil amendment per hectare, and the third was replacing 150 kg mineral fertiliser with 2 ton seaweed-based soil amendment per hectare (p. 3). Both scenarios related to seaweed-based soil amendment had positive effects in comparison with only using mineral fertiliser. This included taller rice plants and faster maturing, and increased levels of nitrogen, phosphorus, and potassium. The authors highlight a significant increase in rice plant growth and productivity due to improvement in soil fertility. However, we caution against the transfer of these results to represent Norwegian soils and crops.

As calculating nutrient status is beyond the scope of this thesis, the underlying assumption for our calculations is uniform soil and plant amendment effects across all the project alternatives. We assume a scenario where 2 tons seaweed is needed to replace 150 kg mineral fertiliser to achieve the same soil nutritional status. According to Yara (2015, p. 3), production of 1 kg nitrogen-based fertiliser generates a carbon footprint of 3.6 kg CO_2-equivalents. The estimate is part of a life cycle assessment focused on ammonium nitrate, the primary nitrogen source in European agriculture. The calculation for tons replaced mineral fertiliser was based on the total product for each end-product. Subsequently, this was multiplied by 3.6 to account for the avoided CO_2 emissions and then further multiplied by the carbon price to assign a monetary value. See Appendix A for calculations.

Table 6: CO_2 benefits of replacing mineral fertiliser by different kinds of cultivated seaweed-based soil and plant amendments from t=1.

Product type	**NOK 2024**
Kelp meal	**16,013**
Liquid biostimulant	**50,058**
Biochar	**8,807**

Gross Income- sales of the product

The benefits from selling the end-products appear from t=1, and are valued at the market price farmers are willing to pay at retail level, exclusive of VAT. This is the value of seaweed production as a provisioning ES. For liquid biostimulant, the market price ranges from 5 to 16 Euros per litre according to the World Bank (2023, p. 27), so we use a mean price of 10 Euros per litre. As PPP rates are only available until 2022, the 10 Euros is adjusted to 2022, which is 9.41 Euros. In 2022, the PPP for Euro was 0.685[13] and 8.418 for NOK. By dividing these figures, we find that 1 Euro equals 12.29 NOK in 2022. Multiplying this with 9.41 Euro and adjusting for CPI gives 124.3 NOK in 2024.

Biochar market prices also vary depending on the raw material used to produce it. Seaweed is a relatively expensive material to use for biochar as little product remains after drying and pyrolysis compared with the fresh weight. Obio sells bags of 35 Litres which is equal to 10 kg at 499 NOK (Bondekompaniet, n.d.). Removing VAT, this becomes 40 NOK/kg. Biosa sells kelp meal at 49

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[13] Location used: Euro area (19 countries).

NOK/kg which without VAT becomes 39 NOK/kg (BiosaNorge, n.d.). See Appendix B for calculations.

Table 7: Annual gross income from product sales from t=1 in 2024-NOK for the different end products from cultivated seaweed.

Product type	Kg product	Price/kg	Yearly revenue
Liquid biostimulant	198,500	124	**24,673,550**
Kelp meal	63,500	39	**2,489,200**
Biochar	34,925	40	**1,397,000**

4.3.2 Costs of cultivation

Licence application

According to the Norwegian law regarding aquaculture permission (Andre arter-forskriften, 2004, §10a), the cultivator is required to remit a deposit of 3,000 NOK per 1,000 m² to ensure a safe clean up upon eventual closure of the facility. This deposit constitutes a one-time payment and will for the rig at 10 hectares (equal to 100,000 m²) amount to 300,000 NOK. This amount is assumed to cover the expenses to establish a firm and the process and acceptance of authorisation to cultivate.

Investment costs hatchery

Most cost estimates associated with the hatchery are taken from the McElligott et al. (2023, p. 40). The prices are from Ireland, and we assume the same prices for a hatchery in Norway. The report examines two scenarios: one involving cultivation up to 50 km of seeding line, and the other involving cultivation up to 250 km of seeding line (McElligott et al., 2023, p. 40). The 10 hectares cultivation rig is estimated to require 30 km of seeding line. Most of the cost items for the two scenarios in the report were similar. We assume similar hatchery costs for the 10 hectares cultivation rig on the premiss that the same production equipment is necessary, even if it operates at a lower capacity. For the other estimates that had different costs for the two scenarios, it has been chosen to adjust the costs for the 50 km scenario to suit the requirement of 30 km of seeding line. This was done by multiplying the costs for 50 km seeding line by 0.6 (since 30/50=0.6).

McElligott et al. (2023) separated the cost estimates into five rooms or areas. For the area “External”, the equipment needed is generator, seawater pump, pipework from pump and header tank. The room where electricity panels, water system and air systems are located, is referred to as

“Plant room”. “Prep room” is all equipment and consumables associated with the lab. “Culture rooms” is where the cuttings are maintained. Lastly, “Tank rooms” is where the box systems for the seeded strings are located, and cost estimates associated with this room is included. These rooms require approximately 300 m^2 (p. 18).

Most of the included costs associated with a hatchery are from McElligott et al. (2023). However, there are some costs that are not included. The additional costs included in our calculation are sourced from a report by Wu et al. (2023b) and have been categorised as "Others." These cost estimates cover spools, settling tubes, settling tube caps, PVC primer, and glue. Cost estimates for nutrients have been excluded, since McElligott et al (2023) provided an estimate for this. The costs from Wu et al. (2023b) are based upon a 1 hectare cultivation rig. Since these cost categories increase in line with the size of production, the cost categories are multiplied by 10 to represent costs associated with a cultivation rig of 10 hectares. The only adjusted price estimate is for the seeding line, as the initial source overlooked the length of the line needed. The seeding line estimate is sourced from Norway and reflects current market price excluding VAT.

The costs from McElligott et al. (2023) are provided in 2022-Euros for Ireland. To convert these to NOK 2024, PPP corrected exchange rates were used to convert 2022-Euros to 2022-NOK, and then the CPI in Norway was used to adjust 2022-NOK to January 2024-NOK. According to OECD (n.d), the purchasing power of 0.738 Irish Euros was equivalent to the purchasing power of one US dollar in 2022. For NOK the PPP-corrected exchange rate to US dollar was 8.418. PPP corrected exchange rate NOK to one Euro is therefore 11.4065 (8.418/0.738). When multiplying 11.4064 to Euro prices, the prices will be converted to 2022-NOK. Subsequently, CPI has been used to convert 2022-NOK to January 2024-NOK, with a price increase of 7.5% (SSB, 2024d).

The costs from Wu et al. (2023b), is provided in 2022 US dollar, and PPP and CPI has been used as in the previous paragraph to convert it into January 2024-NOK.

Table 8: Total investment costs in t=0 for a hatchery in 2024-NOK.

Investment Cost Hatchery	Value	Lifetime
External	539,487	20
Plant room	355,571	20
Prep room	536,005	20
Culture room	115,514	20
Tank rooms	132,272	20
Other	115,797	20
Seeding line	70,500	1
Sum	**1,865,146**	

Investment costs for the cultivation rig at sea

The cultivation rig at sea is based on a comparative analysis conducted by Wu et al. (2023a), which evaluates different rigs operating at a scale of 1 hectare. The chosen method in this analysis is the single layer longline method as it is a more common practice in Norway. Wu et al. (2023b) provides a more detailed paper with insights into the underlying assumptions and rationale for the figures employed. This serves as the foundation for constructing the rig, with adjustments made to Norwegian suppliers for the required equipment and materials. See Appendix C and D for sources used to attain the market prices.

Table 9: Investment costs for 10 cultivation rigs on 1 hectare per rig in 2024-NOK in t=0.

Investment 10 cultivation rigs	Unit value	Quantum	Sum	Lifetime
Small boat	300,000	1	300,000	20
Anchor block	1,018	300	305,400	20
Anchor chain	32,000	30	960,000	20
Anchor buoy	3,112	300	933,600	20
Longline	632	225	142,532	5
Control line	287	225	64,751	5
Small buoy	1,225	2500	3,062,500	20
Drop line	183	225	41,303	5
Line weight	200	2500	500,000	20
Work clothes	35,316	1	35,316	5
Sum			**6,345,402**	

Investment costs for the factory

In order to find the costs associated with a factory there is used property value and an estimate for building cost. The factory is meant to be adaptable for the three processing methods. Hence, it is important to bear in mind that these processes will not occur concurrently, i.e., the factory will contain only one production line. Components of the factory will include a hatchery, offices and the equipment for a single production line. It is assumed that 1,200 m² are appropriate.

The mean land value per m² within Ålesund municipality is used to derive an estimate of the property value. Land values in Norway varies and are depending on the size of the municipality and its population density. However, Ålesund was selected due to its suitability as a coastal city. As of 2022, the price was 2,715 NOK per m² (Benedictow et al., 2022, p. 27).

Utilising a building cost calculator sourced from Byggfakta (2024), it is estimated that an industrial building on 1,200 m² will incur an approximate cost of 13,599,600 NOK, exclusive VAT. Alternatively, one could consider purchasing existing buildings or opting for a rental arrangement. When looking at industry buildings on Finn.no with comparable sizes, prices typically range between 8,900,000 and 16,000,000 NOK. Considering the likelihood of maintenance requirements for these buildings, the estimate provided by Byggfakta appears to be reasonable.

Table 10: Investment costs for the factory in 2024-NOK in t=0.

Factory investments	**Value**
Property value	3,502,084
Building	13,599,600
Sum	**17,101,684**

Production equipment for cultivation

All the sources used to derive prices for production equipment are listed in Appendix C. All prices are in 2024-NOK and without VAT.

A tractor equipped with a claw is needed, as well as a trailor which is required on the pier for transporting the seaweed from the boat and to the factory. The tractor is to be utilised within the factory for transporting the product to various stations along the production line.

Drying of the biomass is conducted at 60°C for 48 hours, as outlined in Neveux et al, (2020, p. 540). To achieve this, shelves, an electric heater, and a dehumidifier with adequate capacity are assumed. Following the drying process, a hammermill is employed to grind the dried seaweed into very fine particles. All the project alternatives require drying and milling; the products differ only in the subsequent processes.

Table 11: Investment costs in t=0 for production equipment for all alternatives in 2024-NOK.

	Unit value	**Quantum**	**Sum**	**Lifetime**
Container	1,920	1	1,920	20
Log claw tractor	12,800	1	12,800	20
Tractor	299,900	1	299,900	20
Tractor trailor	24,000	1	24,000	20
Dryer shelves	41,480	7	290,360	20
Heater	218,999	1	218,999	10
Dehumidifier	24,738	1	24,738	10
Hammermill	72,639	1	72,639	10
Sum			**945,356**	

Biostimulants need to be extracted from dried seaweed. This is the most decisive step as the complexity is high to ensure maximum biological active molecules. Since cultivators and producers of seaweed-based products are keeping secrecy about methods, one specific extraction method is assumed to be used. This secrecy comes from their reliance on these methods to maintain a competitive advantage (Boukhari et al., 2020, p. 3). As biological knowledge lies beyond the scope of this thesis, a water extraction method using distilled water and autoclaving, as outlined in Han et al. (2022, p. 3), is assumed. Algea (n.d.) sells liquid biostimulants where the product formulation is 32% seaweed and the rest is other ingredients. Therefore, we assume that the dried seaweed of 63.5 ton constitutes 32% of the liquid biostimulant, resulting in the need for 136 ton distilled water. This is mixed in mixing tanks resulting in 199 ton finished product and the need for 199 IBC-containers on 1,000-litres. We assume no residual product.

Kelp meal is the product after drying and milling, resulting in 63.5 ton product, and only needs to be packed in paper bags. For production cost of biochar, an estimate of 6,100 NOK in operational costs per ton has been obtained from a Norwegian company called Obio[14] . This is the first company in Norway with this service and they expect economies of scale and reduced marginal production costs as the industry is growing. Dried seaweed is sent to pyrolysis whereas approximately 55% biomass remains after this process based on Pak et al. (2023, p. 5), resulting in 34.9 ton biochar.

Table 12: Production costs and equipment for the different end products in 2024-NOK from t=1.

	Unit value	**Quantum**	**Sum**	**Lifetime**
Biostimulant				
Distilled water	8,924	136	1,209,134	1
Mixing tank	10,568	5	52,839	5
IBC-container	4,750	199	945,334	1
Autoclave	50,754	1	50,754	20
Sum			**2,258,061**	
Kelp meal				
Paper bags	190	127	**24,181**	1
Biochar				
Production cost	6,100	35	213,043	1
Paper bags	190	70	13,328	1
Sum			**226,371**	

Labor, wages and social costs

It is assumed that five full time employees are needed for a facility of 10 hectares, and that they each have an annual gross salary of 600,000 2024-NOK. This is based on the annual median income in Norway being 608,000 NOK according to Statistics Norway (SSB, 2024a).

Most of the calculations and estimates are based on Ifs standards for employee costs (If, n.d). It has been assumed a mandatory employer`s national insurance contribution for each employee at Norway's highest rate of 14.1%. Ifs standards for employee costs also incorporated some additional costs into the national insurance contribution. Pension insurance (OPT) is estimated at a 4% rate,

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[14] https://www.obio.no/)

typically for the industry (Nielsen & Stakkestad, 2018). With an average sickness absence rate of 7% (SSB, 2024c), the company is estimated to cover 31,305 NOK for sick days, based on 16 calendar days of wage coverage before Norwegian Labour and Welfare Organisation (NAV) assistance (NAV, 2024). The cost calculation from If did not incorporate holiday pay, which is mandatory for all companies. The holiday pay has been estimated at a rate of 12% of their income (The Norwegian Labour Inspection Authority, 2024). By including all social costs, one person year costs the company 40% more than the gross salary paid to the employees.

Ifs calculator includes an estimate called “premises and equipment”, which covers expenses such as employee`s share of renting premises, work clothes, tools etc. These costs are not included in the overall wage and social cost calculation to prevent duplications, because they are accounted separately in other expense categories.

Seasonal workers are assumed to be hired locally from a company within the aquaculture sector. When hiring labor, social costs are paid by the company they are hired from (NHO, 2016). It has been estimated to employ 8 to 10 seasonal workers for approximately two months at the site, totaling about 1.5 person-years.

Wages and social costs accrue from t=1 and remain constant until year 19. However, in t=0, it is assumed 1 person-year of full-time employment is required due to the start of production in the hatchery and the deployment of seeding line.

Table 13: Annual costs of labor from t=1 including wages and all social costs for the factory, hatchery, rig and production. The table includes costs for full-time and seasonal workers. The table shows both costs per person-year and total costs for 5 full-time employees and 1.5 person-years in hired labor per year.

Wages and social costs of labour	**Cost per person-year**	**Total cost**
Full-time employees		
Annual gross wages	600,000	3,000,000
Other costs for full time employee		
Employer`s national insurance contributions	87,984	439,920
Professional injury Insurance	5,000	25,000
OPT (Pension insurance)	24,000	120,000
Administration cost and waiver of contribution	5,033	25,165
Absence due to illness	31,305	156,525
Training	10,000	50,000
Welfare and social measures	5,000	25,000
Holiday pay	72,000	360,000
Sum of wages and social costs for full-time employees	840,322	**4,201,610**
Seasonal workers	700,000	1,050,000
Total annual labor costs		**5,251,610**

Operational costs

Operational costs include electricity consumption for the hatchery, heating the factory, and production equipment. The mean electricity price for industry in 2023 is used and adjusted for CPI to 2024-NOK (SSB, n.d (a)). The price then becomes 0.7499 NOK/kWh without fees. This price is constant for every year in the project period. Annual electricity consumption is also assumed constant for every year. Additionally, expenses for renting a boat, fees to municipality, and maintenance are also accounted for, and assumed to be constant for every year in the project period. Sources for the assumed equipment is listed in Appendix C.

McElligott et al. (2023, p. 40), included an electricity price of €15,000 for a hatchery managing 50 km seeding line. This has been utilised for our hatchery that produces 30 km seeding line. Considering that in 2022, the average electricity price in Ireland was 0.37 EUR/kWh (Tait, 2024), one can approximate the annual electricity consumption and multiply this with the electricity price in Norway in 2024 by combining these figures. The electricity consumption for the hatchery then becomes 40,344 kWh as shown in Table 14.

An energy-use calculator from Enova (n.d.) was employed to estimate the energy consumption associated with heating the factory. It provided an estimate of 212 kWh per heated area for light industry. This was applied to the whole factory, i.e., 1,200 m^2.

The drying shelves have a capacity of 7,200 kg and there are assumed seven of these leading to a capacity of drying 50.4 ton in each drying round. With each drying round lasting 2 days, drying the entire cultivated biomass would require approximately 14 days, equivalent to 336 hours. The hammermill, operating at a capacity of 1,800 kg per hour, would require approximately 205.5 hours of production time.

The preceding paragraphs apply to all project alternatives related to cultivating *S. latissima*. The project alternative that differs is production of liquid biostimulant, which involves the use of a mixing tank and autoclave, leading to slightly higher energy consumption. The assumed autoclave has a capacity of 100 Litres, with an assumed production rate of 1,000 Litres per hour. Thus, for 199,000 Litres biostimulant, the autoclave operates for 199 hours. Additionally, five mixing tanks, each operating at 0.18 kW (totalling 0.9 kW), are assumed. The process of mixing the biostimulant is assumed to take 2 hours, resulting in 79.6 hours of production time.

Furthermore, an energy fee is required to be paid to the local grid operator to facilitate the delivery of electricity to the factory. This fee consists of both fixed and variable costs. The fixed cost depends on the hour of the day the energy consumption was highest. A mean value of the three days with the highest hourly consumption during a month decides which interval and thereby what to pay each month. We find our factory to be on the consumption interval 10 with a fixed cost on 3,866.67 NOK/month. The variable cost depends on whether the energy consumption happens during the day, night or weekends. We have used the variable cost for daytime energy consumption which is 0.2116 NOK/kWh (Elvia, 2023). These rates are excluded fees and therefore reflects the marginal production costs for the grid operator. The rates are applicable from 1. January 2024 and applies to companies and industries.

Table 14: Annual electricity consumption and costs in 2024-NOK from t=1 in different steps of the supply chain. Separate estimate for additional costs of equipment used to produce biostimulant. Electricity price on 0.7499 NOK/kWh is used.

	kW	hours	kWh	Annual cost
Hatchery			40,344	30,254
Factory (heating)			254,400	190,775
Heater	125.4	336	42,134	31,597
Dehumidifier	1.6	336	548	411
Hammermill	22.0	206	4,521	3,390
Energy fee (fixed+variable)				118,756
Total annual electricity costs				**375,182**
Mixing tank	0.9	80	72	54
Autoclave	4.5	199	896	672
Energy fee (variable)				205
Additional costs for biostimulant				**930**

In Norway, cultivators typically rent service boats. The rental price is based on the NabCat 1510 Katamaran (Brandstad, 2023), and was constructed in 2018 with a sales price of 26,000,000 NOK. It is estimated that 1% of the sales price is an appropriate annual rental from t=0, amounting to 260,000 NOK. This boat will be used during the harvesting and rig assembly phases.

Fee to municipality regarding water and wastewater is included here as it is a necessity for production and daily operations. As we choose Ålesund municipality as the reference area when estimating the property value, we continue to use them when looking at fee to municipality. The fee includes water and wastewater and include a subscription fee and a consumption fee (Framsikt, 2023). As municipalities can only recover their actual marginal costs of supply when determining their water and wastewater fee, we can use the fee directly in this CBA as it represents the marginal production costs.

Table 15: Other operational cost in 2024-NOK from t=0.

Water fee	45,411
Renting boat	260,000
Sum	**305,411**

Maintenance costs is an essential expense associated with the factory, rig, hatchery and other parts of the production. Annual maintenance is essential for the cultivation rig due to its exposure to varying weather conditions. The estimated maintenance costs for the small boat are 1,000 NOK per ft per year, as recommended by Strzelecki (2019). For buoy maintenance, it is estimated an annual maintenance cost of 1% of the initial cost (Wu et al., 2023a, p. 6). Additionally, for the rest of maintenance cost connected to the factory, rig, hatchery, and production equipment such as hammermill, heater, dehumidifier and tractor, a maintenance costs of 5% of the initial investment cost is estimated (Van den Burg et al., 2016, p. 243; Wu et al., 2023a, p. 6). For the tractor and small boat, it is assumed that the maintenance cost also covers costs associated with fuel for convenience as the distances are short.

Table 16: Annual maintenance cost connected to factory, hatchery, cultivation rig and production equipment in 2024 NOK from t=1.

Maintenance cost	**Value**
Factory	855,084
Hatchery	93,063
Rig	100,699
Small boat	23,000
Bouy	39,961
Hammermill	3,632
Heater	10,950
Dehumidifier	1,237
Tractor	14,995
Sum	**1,142,621**

In t=0, the operational cost differs from t=1 to t=19. The reason for this is that production in the factory starts at t=0, but the production of the end-products starts in t=1. Costs connected to heating the factory and hatchery, boat rental and fees to the municipality are included in t=0.

4.3.3 Benefits of wild harvesting

Soil and plant amendment wild harvesting seaweed substitute

For wild harvested *A. nodosum* there is assumed that 2 tons of seaweed is needed to replace 150 kg mineral fertiliser to achieve the same nutritional status, as assumed for cultivated *S. latissima*. Again, we multiplied the ton replaced mineral fertiliser with 3.6 to account for the avoided CO_2

emissions, and then further multiplied it with the carbon price to derive a monetary value. In the case of wild harvesting, it gave a slightly higher value due to the ability to replace a larger amount. See Appendix A for calculations.

Table 17: CO_2 benefits of replacing mineral fertiliser by different kinds of seaweed-based soil and plant amendments from t=1.

Product type	NOK 2024
Liquid biostimulant	**52,453**
Kelp meal	**17,150**
Biochar	**9,432**

Gross Income- sales of the product

The prices obtained from cultivation are also applied to wild harvested seaweed representing seaweed as a provisioning ES. See Appendix B for calculations.

Table 18: Annual gross income from t=1 in 2024-NOK for the different end products from wild harvested seaweed.

Product type	Kg product	Price/kg	Annual revenue
Liquid biostimulant	208,000	124	25,854,400
Kelp meal	68,000	39	2,665,600
Biochar	37,400	40	1,496,000

4.3.4 Costs of wild harvesting

Total investment cost

Wild harvesting requires less investments compared to cultivation. It is assumed a smaller factory as wild harvesters don`t need a hatchery, so this factory will be 300 m² smaller, i.e. 900 m². Using the same calculator provided by Byggfakta (2024), this amounts to 10,199,700 NOK in 2024.

To wild harvest on an area equivalent to 10 hectares, it is assumed two harvesting boats. The cost estimate for one boat is based on the boat used during cultivation. For detailed breakdowns of harvesting equipment and work clothes please see Appendix C and D. Production equipment is included in this table, and the costs associated with it are equivalent to those for cultivation.

Table 19: Total investment costs for wild harvesting in 2024-NOK in t=0. The table include costs associated with a factory, harvesting equipment, work clothes, boats and production equipment used for all three alternatives.

	Unit value	Quantum	Sum	Lifetime
Factory	10,199,700	1	10,199,700	20
Harvesting equipment	1,164	12	13,965	5
Work clothes	2,354	15	35,316	5
Boats	300,000	2	600,000	20
Production equipment				
Container	1,920	1	1,920	20
Tractor	299,900	1	299,900	20
The log claw tractor	12,800	1	12,800	20
Tractor trailor	24,000	1	24,000	20
Dryer shelves	41,480.00	8	331,840.00	20
Heater	218,999.00	1	218,999.00	10
Dehumidifier	24,738	1	24,738	10
Hammermill	72,639	1	72,639	10
Sum			**11,835,817**	

Production equipment by end-product

The same approach as with products derived from cultivated seaweed is assumed for wild harvested *A. nodosum* but adjusted for a slightly higher quantum. In the case of liquid biostimulant, the slightly higher quantum of more harvested biomass causes an increase in dry weight, resulting in more biostimulant. The higher amount of biostimulant require more distilled water and IBC containers. For both kelp meal and biochar, more paper bags are needed due to the higher biomass. The unit value remains constant and is therefore the same as with cultivation. Sources are listed in Appendix C.

Table 20: Total investment costs for production equipment by end-product in 2024-NOK from t=1.

	Unit value	Quantum	Sum	Lifetime
Biostimulant				
Distilled water	8,924	140	1,249,290	1
Mixing tank	10,568	5	52,839	5
IBC-container	4,750	208	988,087	1
Autoclave	50,754	1	50,754	20
Sum			**2,340,971**	
Kelp meal				
Paper bags	190	136	**25,894**	1
Biochar				
Production cost	6,100	37	228,140	1
Paper bags	190	75	14,242	1
Sum			**242,382**	

Labor, wages and social costs for wild harvesting

The labor, wages and social cost associated with wild harvesting are estimated similarly to cultivation. However, there are fewer estimated full-time employees and more seasonal workers involved. Specifically, it is assumed three full-time employees and 12 seasonal workers, which is equivalent to two person-years as each seasonal worker is expected to work an average for two months. The reduced need for full-time employees are attributed to the absence of hatchery work and rig operation supervision. More seasonal workers are predicted to be needed for harvesting tasks since manual labor is involved. The costs associated with labor will accrue in t=1 and remain constant until t=19. Unlike cultivation, there is no labor expenses in t=0, because it is assumed that harvesting will start in spring t=1.

Table 21: Annual costs of labor from t=1 including wages and all social costs for the factory, harvesting and production. The table includes costs for full-time employees and seasonal workers. The table shows both costs per person-year and total costs for three full-time employees and two person-years in seasonal workers. Stated in 2024 NOK.

Wages and social costs of labour	**Cost per person-year**	**Total cost**
Full time employees		
Annual gross wages	600,000	1,800,000
Other costs for full time employee		
Employer`s national insurance contributions	87,984	263,952
Professional injury Insurance	5,000	15,000
OPT (Pension insurance)	24,000	72,000
Administration cost and waiver of contribution	5,033	15,099
Absence due to illness	31,305	93,915
Training	10,000	30,000
Welfare and social measures	5,000	15,000
Holiday pay	72,000	216,000
Sum of wages and social costs for full-time employees	840,322	**2,520,966**
Seasonal workers	700,000	1,400,000
Total annual labor costs		**3,920,966**

Operational costs for wild harvesting

For electricity consumption related to wild harvested *A. nodosum*, we have followed the same approach as explained for cultivated *S. latissima*. An electricity price of 0.7499 NOK/kWh is used. The elements that change compared to cultivation is the hours required to produce the end-product and heating of the factory. The increase in biomass results in extended processing times with the hammermill to produce the end-product, resulting in higher kWh usage and annual costs. The additional costs for biostimulant will rise compared to cultivation, due to the increased biomass.

Table 22: Annual electricity consumption and costs in 2024-NOK in different steps of the supply chain from t=1. Separate estimate for additional costs of equipment used to produce biostimulant. Electricity price of 0.7499 NOK/kWh is used.

	kW	**hours**	**kWh**	**Annual cost**
Factory (heating)			190,800	143,081
Heater	125.4	336	42,134	31,597
Dehumidifier	1.6	336	548	411
Hammermill	22.0	222	4,884	3,663
Energy fee (fixed + variable)				96,838
Total annual electricity costs				**275,589**
Mixing tank	0.9	83	75	56
Autoclave	4.5	208	936	702
Energy fee (variable)				214
Additional costs for biostimulant				**972**

The maintenance costs for wild harvesting are calculated using the same conditions as for cultivation. Factory and production equipment including hammermill, heater, dehumidifier and tractor required a maintenance cost equivalent to 5% of the initial investment cost (Van den Burg et al., 2016, p. 243; Wu et al., 2023a, p. 6). Fuel needed for the tractor, is included in the maintenance costs. Additionally, the estimated maintenance costs for boats are 1,000 NOK per ft, as recommended by Strzelecki (2019).

Table 23: Annual maintenance costs associated with factory, boats, and production equipment from t=1. Stated in 2024-NOK.

Maintenance cost	**Value**
Factory	509,985
Boats	46,000
Hammermill	3,632
Heater	10,950
Dehumidifier	1,237
Tractor	14,995
Sum	**586,799**

In contrast to cultivation, fuel consumption has been estimated for the two small boats used during wild harvesting, as they are assumed to be utilised more frequently. The mean gasoline price in 2023 was 21.98 NOK inclusive of VAT (SSB, n.d (b)). The mean gasoline price has been converted to January 2024-NOK using CPI. According to Pedersen (2024), a 20% fee is included in the retail price, along with fixed fees totalling 7.34 NOK. Estimated gasoline price per litre is therefore 11.02 NOK without fees. The annual estimated gasoline usage is assumed to be 640 Litres since we have assumed that each boat will use one litre of gasoline per hour, and we will be harvesting for 8 hours per day over a period of 40 days. The annual fuel consumption starts in t=1.

The yearly fee to municipality regarding water and wastewater remains the same as for cultivation, i.e., 45,411 NOK, starting in t=0.

Table 24: Annual costs associated with water fee and fuel cost in 2024- NOK.

	Annual cost
Annual water fee	45,411
Annual cost fuel	7,052

Environmental damage cost

A Norwegian study conducted by Hynes et al. (2021) have through a discrete choice experiment estimated the WTP for kelp forest restoration activities. They value biodiversity, the role of kelp forests as nurseries for juvenile fish, and the overall area restored. Biodiversity refers to the species diversity and abundance in the area. It was defined by the number of species present per m^2 as the composition of the abundance. Nurseries for juvenile fish refers to the number of juvenile fish present per m^2. Area restored was presented in m^2 and is described as the total area of kelp forest restored (p. 4). However, the authors did not specify in detail what factors are included in the estimate regarding area restored. In their conclusion they write "*It is important to note that while the results show a positive and significant societal benefit associated with kelp restoration, the derived estimates of WTP do not reflect the total derived ecosystem service benefits of kelp forest restoration*" (p. 9).

The data was collected through an online survey in Norway in 2018 to represent the Norwegian public`s preferences. The authors highlight education level to deviate from what is in the population, which in this case was higher. They did not test the difference with educational levels. Based on the numbers from Hynes et al. (2021; table 5, p. 7), the WTP for a restored kelp forest area of 10,000 m^2 (equivalent to 1 hectare) is 5.78 Euros per household per year for 10 years. This is estimated from a random logit parameter and is significant at 5%.

We want to use this estimate as a value transfer and will follow the guidelines provided by Johnston et al. (2021) in an overarching way. Value transfers are often used in CBAs and are adoptions of an estimate derived from another study in another context. For this analysis, there is assumed that WTP for area restoration includes all ES provided by the kelp forest. This appears as a cost in this analysis as the kelp forest is being removed due to wild harvesting of biomass and will therefore be used as an environmental damage cost. The WTP estimate is stated in 2018-Euros and was converted to NOK using PPP corrected exchange rates and adjusted to 2024-NOK using the CPI. In 2024-NOK, the estimate becomes 94.61 NOK.

The original estimated WTP from Hynes et al.`s (2021) study reflects public preferences in Norway and applies to per household per year for ten years. For this analysis, we use it as an estimate to represent preferences of Ålesund`s households. As of the fourth quarter of 2023, Ålesund had a population of 67,866 people, with an average of 2.14 residents per household, resulting in approximately 31,713 households (SSB, n.d. (c)). The authors in Hynes et al. (2021, p. 5) noted that respondents appeared to be well-informed about marine protected areas and frequently engaged in water activities, a characteristic that we believe applies to Ålesund`s coastal population.

It would have been interesting to examine whether the WTP observed in this study aligns with the WTP in Ålesund. Unfortunately, obtaining a reliable average income figure for Ålesund was challenging, as some sources states that the income is lower than national average, while others state higher. Therefore, we lack a basis for adjusting for income elasticity in our analysis. According to SSB (n.d (c)), the educational level in Ålesund corresponds to the educational level in Norway. Therefore, the study has somewhat higher level of education than what is representative for Ålesund as well.

WTP per hectare is assumed constant and increases proportionally with the size of the kelp forest. The WTP for restoration of 10 hectares then becomes 946.1 2024-NOK. There would most likely be diminishing marginal utility of kelp forest restorations such that WTP for 10 hectares would have been smaller than WTP for 1 hectare times 10. We will include this estimate in the sensitivity analysis later.

While the study values the benefits the Norwegians get from kelp forest restoration, we have included it as a cost. It appears here as an environmental damage cost in the form of a lost ES made up of use- and non-use values of kelp forests. When stating WTP of restoring kelp forest, people could be motivated both by recreational use and non-use values such as existence value, i.e., the valuation of knowing something exists.

Table 25: Annual WTP for Ålesund municipality`s households s to restore 10 hectares kelp forests. The WTP applies annually for 10 years from t=1. Here reflected as environmental damage cost in 2024-NOK.

Measurement unit	**Annual cost**
Households in Ålesund	31,713
WTP/households for area restored 10 hectares	946
Annual environmental damage cost	**30,003,749**

4.4 Step 4- Non-priced effects

All non-priced effects are related to the different ecosystem services and is divided into what would accrue as a benefit or a cost. A summery is presented in Table 26 with all effects and their impacts.

4.4.1 Benefits from cultivation on ecosystem services

Supporting ecosystem services

Natural populations of *S. latissima* serves critical ecosystem roles in marine environments and significantly contribute to biodiversity in coastal ecosystems. According to Hasselström et al. (2018, p. 57), cultivated seaweed exhibit similar total species abundance as natural kelp forests provide habitat for numerous fish species. However, cultivated seaweed is likely to differ from wild seaweed in terms of habitat provision, and the biological impacts are not fully understood. Nonetheless, it is assumed that the cultivation will positively impact biodiversity through habitat formation, benefiting fish populations. It is important to note that this is a short-term effect since the seaweed is harvested every spring. The source also concluded that lobster and crab populations may benefit from the habitats provided by the anchors (Hasselström et al., 2018, p. 57).

Regulating ecosystem services

Seaweed can serve as a bioremediatory by removing pollutants through processes such as storage, burial, and recycling. It can extract nutrients like nitrogen, phosphorus and carbon from the water, converting them into proteins and pigments, which results in enhanced water quality (Clark et al., 2021, p. 20). The source stated that this capability is particularly applicable in localised areas of enrichment, such as close to fish farms and for remediating nutrients sources from land-based activities. However, it could also be benefits in locations with natural enriched coastal waters (Clark et al., 2021, p. 44). According to NBFN (2023, p. 4), cultivated seaweed can lower the pH concentration in the sea, which helps to reduce marine pollution. However, this effect is only significant if the cultivation is done on a large scale.

4.4.2 Benefits from long term CO_2 storage in biochar

The pyrolysis process used to produce biochar enhances the resistance of carbon compounds to biological degradation, thus enabling long-term CO_2 storage in the soil as a regulating ES. This method is viewed as a significant potential for CO_2 sequestration and considered a viable strategy for reducing GHG emissions in agriculture in Norway (NIBIO, 2020). However, research on seaweed-based biochar is relatively limited due to it being a new field of study. Ongoing projects led by DNV, SINTEF and other partners, aim to explore the use of cultivated seaweed for biochar production as a scalable CO_2 removal solution (DNV, n.d.; SINTEF, 2023). While it is established that biochar sequesters CO_2 over the long term, determining the net effect of CO_2 storage for seaweed biochar involves assessing whether the sequestration outweighs the emissions generated throughout the supply chain. As this evaluation presents challenges in terms of quantification, it is categorised as a non-priced effect, highlighting its positive potential while acknowledging the difficulty in assigning a monetary value at this stage.

4.4.3 Costs from cultivation on ecosystem services

Supporting services

According to Clark et al. (2021), cultivation rigs can cause an increase or decrease in ocean currents. Likely, this will have a minimal effect given the scale of the rig. The disturbance of seabeds during rig instillation is also expected to have minor impacts due to the rigs relatively small size (Clark et al., 2021, p. 44). Shading from the cultivation rigs has the potential to influence benthic communities and primary production in the water column (Hasselström et al., 2018, p. 57). In Ålesund, where sandy seabed dominates (NGU, 2021), it is likely there are few macrophytes, or aquatic plants, on the seafloor requiring sunlight. Consequently, shading is unlikely to result in significant negative effects. Entanglement of wildlife with ropes, lines and nets can result in injury or deaths (Clark et al., 2021, p. 45). This poses particular risks for protected or endangered species. During seaweed harvesting, organisms living in the seaweed lose their habitats and are suddenly exposed to predication risk, potentially endangering species that would otherwise settle on natural substrates. According to Clark et al. (2021, p. 45), the impact of this effect remains uncertain. Although nutrient uptake can have positive effects connected to seaweed cultivation, it may also present negative consequences. If there are limited nutrients in the sea, it could result in changes to natural populations of primary producers due to competition with the cultivated seaweeds for nutrients. According to Clark et al. (2021, p, 39), the impact of nutrients uptake will be minimal given the scale of the cultivation site.

However, seaweed farms could have undesirable effects if nutrient levels are reduced below what is required for natural populations of primary producers (e.g., phytoplankton). This could lead to changes in natural populations of primary producers through competition with the cultivated seaweeds for nutrients.

Provisioning services

Genetic transfer from cultivated seaweed to natural kelp forests pose a risk and negative impact on ecosystem services. In the scenario involving a 10 hectares cultivation rig, cuttings are sourced from a mother plant. *S. latissima* forests are found along the entire Norwegian coastline and are thus native species. According to Zhang et al. (2017, p. 1), cultivated seaweed has not resulted in adverse genetic consequences for natural kelp forests if local mother plant is used. Therefore, genetic transfer is not a risk associated with cultivation.

According to NBFN (2023, p. 5), the spread of diseases from cultivation rig constitutes one of the biggest risks for the natural kelp forest nearby. Disease outbreaks in cultivated seaweed pose a significant challenge for the seaweed industry in many countries. However, there is no documented evidence of diseases pathogens or parasites spreading from cultivated seaweed to natural kelp forests (NBFN, 2023, p. 5). According to Clark et al. (2021, p. 46), widespread disease outbreaks can have ecological consequences for cultivated and wild species and communities.

Cultivation, which relies on synthetic ropes, lines or nettings that often float and are resistant to degradation, poses a significant choking or entanglement hazard for wild fish if these materials are lost (Clark et al., 2021, p. 40). The study concludes that there is likely that some litter will happen due to cultivation activities.

Cultural services

The recreational value experienced by the locals are influenced by multiple factors, including the distance of infrastructure to the coastline, and the resulting visual impacts and limitations of recreational activities caused by associated buoys and lines. According to Cabral et al. (2016, p. 159), the closer the infrastructure are located to the coast, it tends to have a reduced economic production cost. However, the closer the infrastructure are to the coast, it imposes greater restrictions and recreational activities within the infrastructure. Consequently, closer infrastructure setups often face decreased social acceptance within the community. The 10 hectares cultivation rig is assumed to be located near the coastline, potentially within view of nearby residents and near recreational trails.

Litter can also have an impact on the cultural ES as it effects the recreational use value (Aanesen et al., 2018, p. 1).

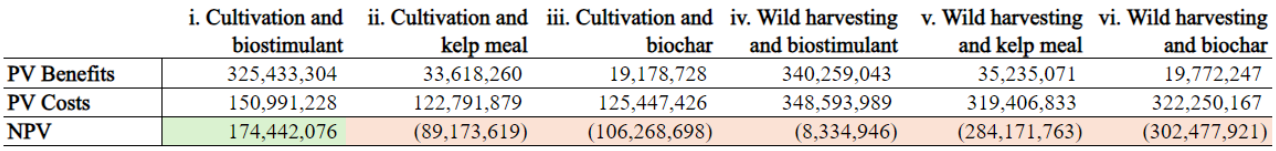
Table 26: A simplified version of the value matrix from Table 1 of the non-priced effects. Divided into positive, insignificant and negative effects. This applies to the project alternatives regarding cultivation.

Positive impacts on ecosystem services	
Supporting ES	
Biodiversity in coastal ecosystems	Positive
Regulating ES	
Bioremediation	Insignificant
Regulating ES	
Long-term storage of CO_2 in biochar	Positive (also applies to wild harvesting).
Negative impacts on ecosystem services	
Supporting ES	
Change in currents	Insignificant
Disturbance of seabed's	Insignificant
Shading	Insignificant
Nutrient uptake	Insignificant
Entanglement with wildlife	Negative
Exposure to predators	Uncertain
Provisioning ES	
Genetic transfer	Insignificant
Risk of diseases	Negative
Litter	Negative
Cultural ES	
Recreation value	Negative
Litter	Negative

4.5 Step 5- Net present value

As described in chapter 2.3, the net present value (NPV) involves discounting future effects using a discount rate, which in this case is 4% per year (DFØ, 2023, p. 181). NPV is determined by subtracting the present value (PV) of all costs from the PV of all benefits.

Table 27: Summary of total discounted benefits and costs over the project period of 20 years in 2024-NOK.



	i. Cultivation and biostimulant	ii. Cultivation and kelp meal	iii. Cultivation and biochar	iv. Wild harvesting and biostimulant	v. Wild harvesting and kelp meal	vi. Wild harvesting and biochar
PV Benefits	325,433,304	33,618,260	19,178,728	340,259,043	35,235,071	19,772,247
PV Costs	150,991,228	122,791,879	125,447,426	348,593,989	319,406,833	322,250,167
NPV	174,442,076	(89,173,619)	(106,268,698)	(8,334,946)	(284,171,763)	(302,477,921)

Based solely on the priced effects, the only project alternative that demonstrate socio-economic profitability is project alternative i. Cultivation of *S. latissima* to produce liquid biostimulant. This indicates that cultivating for use as liquid biostimulant is socio-economically profitable, based on the cost and benefit estimates derived in this thesis. Conversely, alternatives related to kelp meal and biochar, as well as wild harvesting to produce liquid biostimulant, yield negative NPVs and are not socio-economically profitable. For additional calculations of PV and NPV, see Appendix E.

4.6 Step 6- Sensitivity analysis

A sensitivity analysis has been performed to demonstrate the impact of uncertain factors on the net present value for the different project alternatives. This involves changing one factor at a time, considering both pessimistic and optimistic values relative to the expected value calculated in Step 3 and 5. The following uncertain factors have been examined within an interval of ±50%, except for the carbon price:

- Wages
- Investment cost
- Market price
- Social discount rate
- Environmental damage cost

Wages are included in the sensitivity analysis because they represent a significant portion of the total costs throughout the project period from t=1, particularly for the cultivation project alternatives. In the case of wild harvesting, wages become prominent from t=11 and onwards, due to environmental damage cost and its ecosystems services is no longer accounted for after t=10. Additionally high investment costs are a factor that typically impacts the net present value (DFØ, 2023, p. 203).

When analysing projects that impact GHG-emissions, the carbon price must be adjusted according to the Ministry of Finance`s (2023) expected paths. In addition to their projected carbon price paths, they have provided low and high price paths, amounting to 701 and 1,893 2024-NOK respectively, for use in sensitivity analysis within socio-economic analysis.

The market price, or gross income, is the benefit that is crucial for all project alternatives. While the market price for liquid biostimulant is considered relatively reliable, as described by the World Bank (2023), uncertainty surrounds the prices of kelp meal and biochar. Kelp meal is subject to varying prices, and biochar, particularly seaweed-based biochar, is recently being researched on, with limited available information. The market price also acts as a WTP for seaweed as a provisioning ES.

The social discount rate, set by the Ministry of Finance, reflects both the opportunity cost of capital and consumer preferences for immediate consumption over future consumption (DFØ, 2023, p. 177). For the analysis period of 0 to 40 years, the discount rate is established at 4% (DFØ, 2023, p. 181). Essentially, the discount rate indicates how we value future effects, diminishing their significance as they extend further into the future (DFØ, 2023, p. 174). Striking the right balance is crucial; too low a discount rate may inflate the net present value, while too high a rate may deflate it.

The cost associated with removing kelp forests and its ES, in this thesis referred to as environmental damage cost, is initially a pessimistic assumption. This assumption involves assuming a proportional increase in WTP from 1 hectare to 10 hectares, which constitutes the largest cost component for the wild harvesting project alternatives during the period from t=1 to t=10.

To illustrate how changes in these factors affect the NPV, the figures below present a summary of uncertain factors for each project alternative. The expected net present value is located at the intersection point (0), i.e., the base case. On the left-hand side (-) are optimistic values, representing an increase in the net present value, such as reducing wages. Conversely, on the right-hand side (+) are more pessimistic values, indicating an increase in costs, leading to a decrease in net present value.

The slope of the curve indicates how sensitive the NPV is to changes. A steep slope suggests that the NPV is highly sensitive to changes in the uncertainty factors, while a weak slope indicates that the NPV is not very sensitive to changes.

Additionally, if relevant, we will compare this against non-priced effects, calculate the break-even benefit or costs, and discuss expected market developments. When determining the break-even benefit or cost, which represent the amount of money required each year to achieve a net present value of zero, we use the concept of annuity. An annuity refers to a series of equal payments received or paid on a regular basis, like annual basis as in this analysis (SNL, 2022).

4.6.1 Sensitivity analysis for cultivation

Project alternative i.: Cultivation of *S. latissima* to produce liquid biostimulant

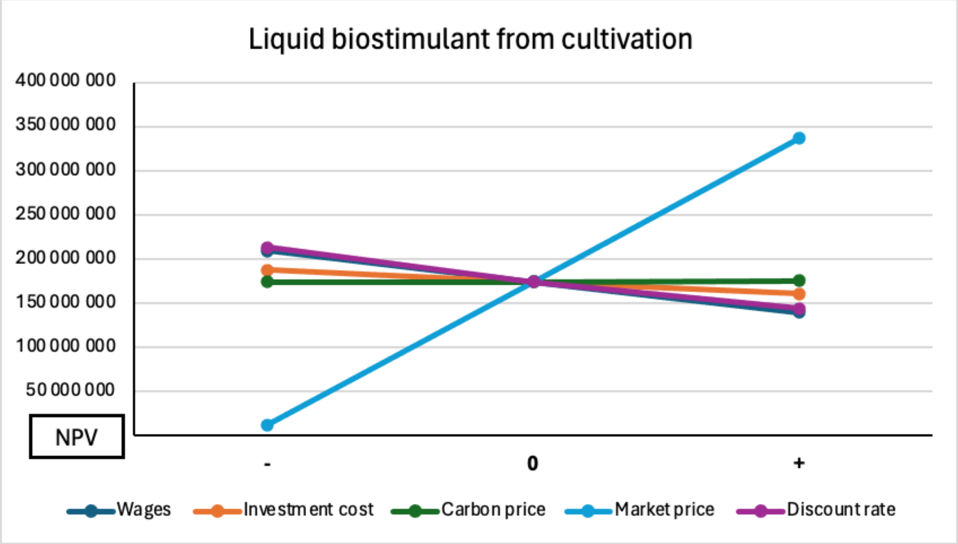


Figure 15: Sensitivity analysis of cultivation of S. latissima to produce liquid biostimulant. Sensitivity analyses are performed for labor cost (wages), market price of the product, investment costs, carbon price and the social discount rate. "0" refers to NPV calculated. At the original assumption and "+" and "-"refers to +50% and -50% of each factor, respectively.

The expected net present value for liquid biostimulant derived from cultivated *S. latissima* is 174,442,076 in 2024-NOK. For this project alternative, the market price of the product is clearly the most sensitive factor. The sensitivity factors investment costs, wages and carbon price exhibit a more gradual decline. All the uncertainty factors show a positive NPV when adjusted ± 50% or with a low/high carbon price, highlighting a quite robust net present value. Note that the carbon price is the least sensitive factor, and nearly doesn`t affect the NPV. The carbon price reflects seaweed cultivation as a regulating ES due to CO_2 sequestration, but it also includes the avoided emissions from mineral fertiliser production due to seaweed amendment substitute.

Even if the NPV is positive, there is some non-priced effects that must be included in the discussion whether a project is socio-economically profitable or not. For the break-even (i.e. NPV=0) the annuity is calculated showing that annual costs must be 12,835,753 NOK. Since a cultivation facility on 10 hectares represent a relatively small-scale production of seaweed, the negative effects associated with cultivation and its ES is found to have a small probability of exceeding a cost of 12,835,753 NOK annually.

According to the World Bank (2023, p. 29), the agricultural sector is increasingly open to adopt alternatives to mineral fertilisers, with biostimulants emerging as a leading solution. The global biostimulant market is projected to grow at a compound annual growth rate of around 10 percent, driven significant by the demand for alternatives to mineral fertiliser. Biostimulants, particularly seaweed-based products, present attractive market opportunities due to their relatively straightforward production processes, low regulatory requirements, and rapid route to market (World Bank, 2023, p. 29-30). From a socio-economic perspective, there is potential for a reduction in the market price while still maintaining profitability. Currently, the primary barrier to widespread adoption of this product is its high market price.

Project alternative ii.: Cultivation of *S. latissima* to produce kelp meal

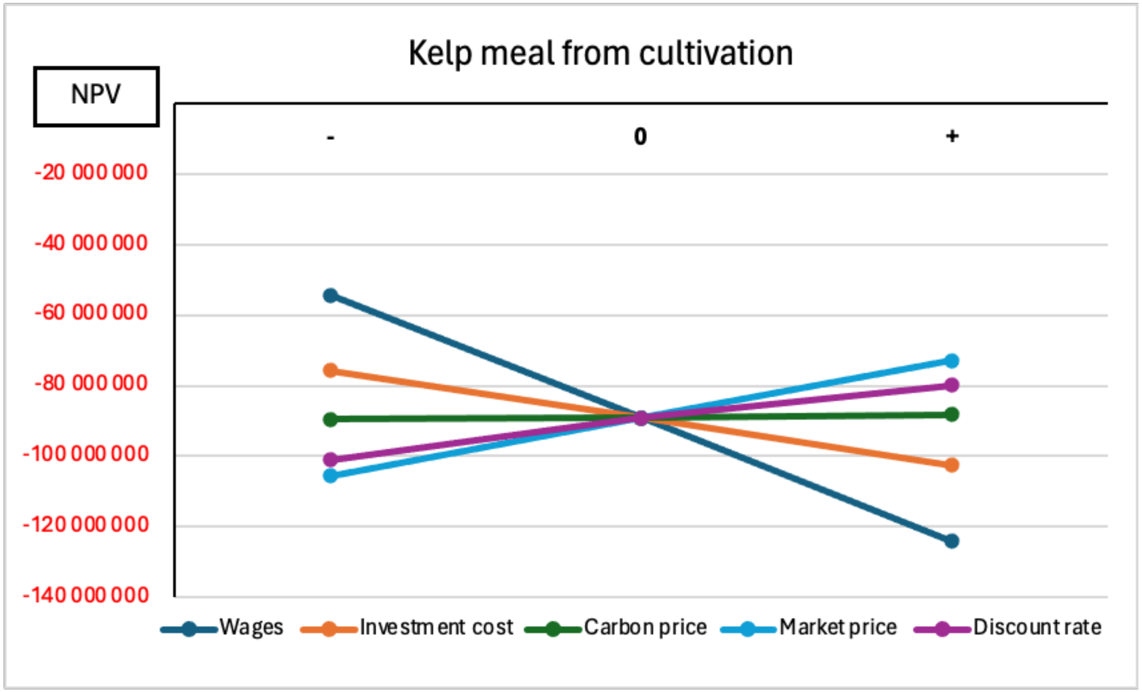


Figure 16: Sensitivity analysis for cultivation of S. latissima for production of kelp meal. Sensitivity analyses are performed for labor cost (wages), market price of the product, investment costs, carbon price and the social discount rate. "0" refers to NPV calculated. At the original assumption and "+" and "- "refers to +50% and -50% of each factor, respectively.

Cultivated *S. latissima* used for kelp meal has an expected net present value of –89,173,619 NOK, whereas the annuity is 6,561,551 NOK. The uncertainty factors that the NPV is most sensitive to are wages, market price of the product and investment costs. All calculated NPVs are negative, but break-even can be achieved by e.g. increasing the market price by 103 NOK/kg, resulting in a market price of 142 NOK/kg. We have no basis for saying this is possible neither in the short or long term. Such a price level seems too high for widespread adoption given the fact that kelp meal as a soil amendment would require application in larger quantities than liquid biostimulant as a plant amendment.

Project alternative iii.: Cultivation of *S. latissima* to produce biochar

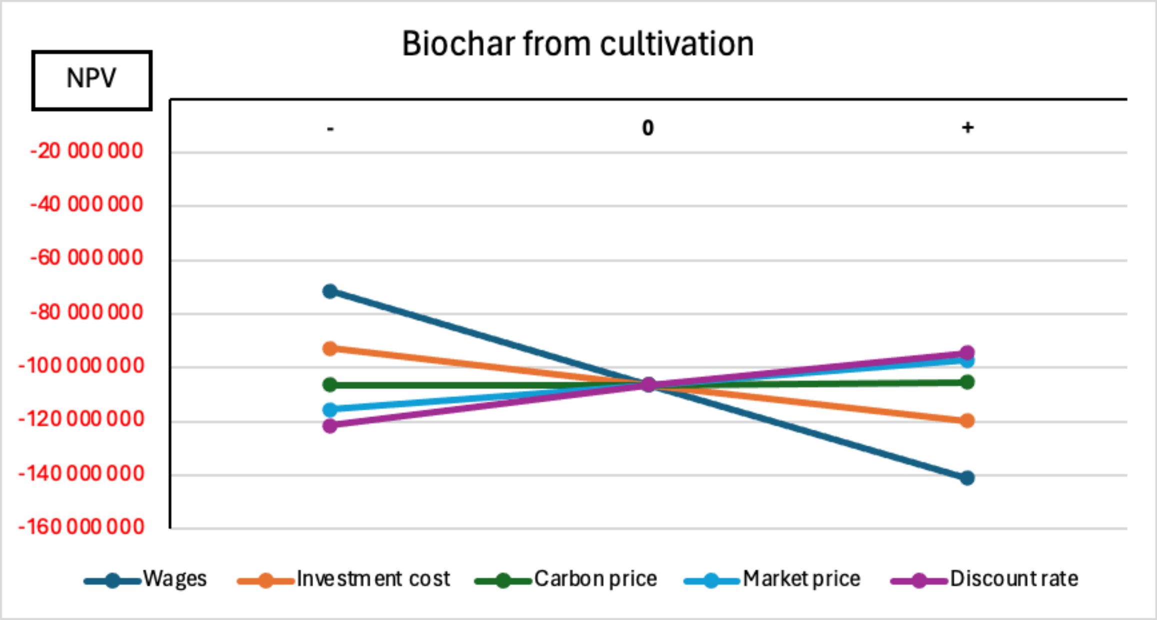


Figure 17: Sensitivity analysis for cultivation of S. latissima for production of biochar. Sensitivity analyses are performed for labor cost (wages), market price of the product, investment costs, carbon price and the social discount rate. "0" refers to NPV calculated. At the original assumption and "+" and "-"refers to +50% and -50% of each factor, respectively.

Cultivation of *S. latissima* for biochar production yields a NPV of –106,268,698 NOK at the original assumptions. Figure 17 shows the NPV to be most sensitive to labor costs (wages) and the investment costs, as these have the steepest curves. However, even when each of these two costs are reduced by 50%, NPV remain well below zero. For the other factors such as market price of the product, carbon price, and social discount rate, the sensitivity is small. The break-even analysis shows a negative annuity of biochar of 3,953,574 NOK. This corresponds to a needed increase in the market price of biochar of approximately 113 NOK, totalling to 153 NOK/kg for NPV to go from negative to zero. This seems very unlikely.

Additionally, one valuable aspect of biochar, which is challenging to quantify but holds significant potential, is its ability to store CO_2 long-term in the product. This effect is particularly important today as we strive to reduce CO_2 emissions. However, considering the scenario of the 10 hectares facility and the low product yield per ton biomass, it seems unlikely that the value of CO_2 storage will exceed 3,953,574 NOK annually over the next 20 years. Also, who is to pay for the CO_2 benefit, is it the consumers through the market price or the government as a compensation for producing this common benefit?

As investment cost is a sensitive factor, a reduction in cost over time is possible due to the learning curve. For example, solar power market has experienced rapid growth in recent years driven by increased demand. This growth has result in the establishment of several companies (Nilsen, 2016), facilitated by decreased production-and installing costs due to technological development, growing environmental awareness, the implementation of support mechanisms and increasing electricity prices. Consequently, the average price of solar power has significantly decreased (Tveiten, 2020, p. 11). This effect is called the learning curve (Abernathy & Wayne, 1974). A Norwegian biochar producer, Obio, suggest that achieving economies of scale and reducing unit costs will likely result in lower market price over time[15]. However, the anticipated advantages from economies of scale and reduced unit costs are not expected to correspond to an advantage of nearly 4 million NOK annually over the next 20-years.

4.6.2 Sensitivity analysis for wild harvesting

Project alternative iv.: Wild harvesting of *A. nodosum* to produce liquid biostimulant

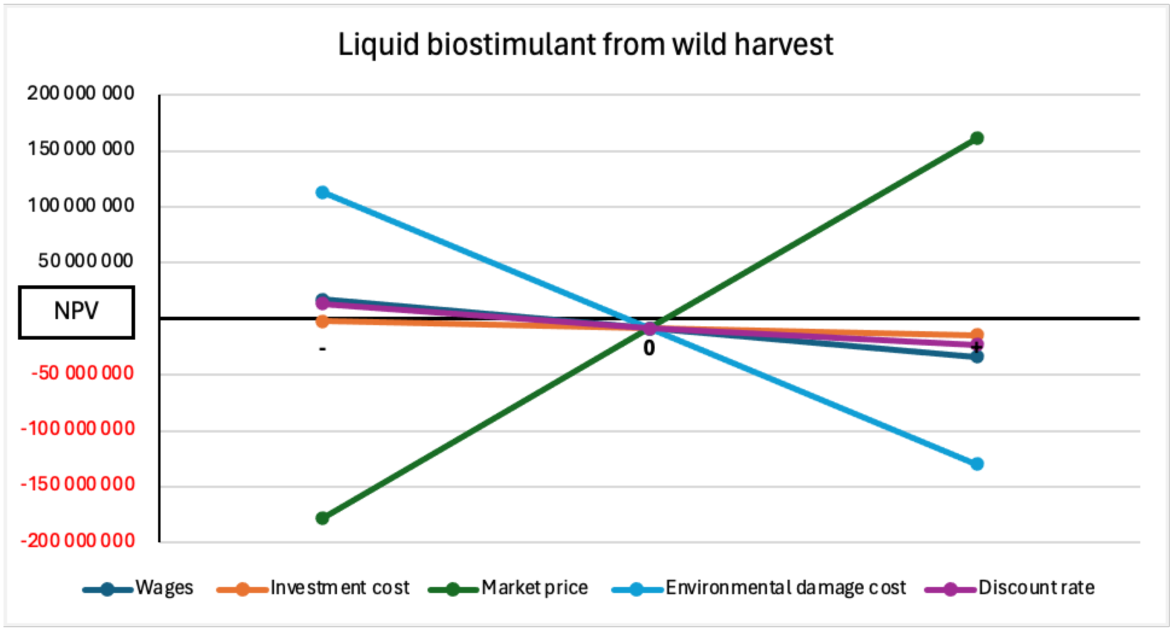


Figure 18: Sensitivity analysis of wild harvesting of A. nodosum to produce liquid biostimulant. Sensitivity analyses are performed for labor cost (wages), investment cost, market price of the product, carbon price, environmental damage cost and the social discount rate. "0" refers to NPV calculated. At the original assumption and "+" and "-"refers to +50% and -50% of each factor, respectively.

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[15] Personal communication. https://www.obio.no/

Figure 18 shows that the profitability of wild harvesting of *A. nodosum* for liquid biostimulant production is very sensitive to changes in the market price and changes in the environmental damage cost. Wages, investment costs, and the social discount rate on the other hand, show much flatter NPV-curves, and NPV is more robust to changes in these factors. When compared to the cultivation of *S. latissima* for use as liquid biostimulant, increases in the costs associated with kelp forest removal have a significant, negative impact on NPV. Decreases in market prices easily makes NPV even more negative. As NPV is negative in the base case, a break-even annuity calculation shows that the annual cost would need to be reduced by 613,300 NOK for the NPV to reach zero.

Recovering this cost would require an increase in the market price by 3 NOK/kg which seems small but still unrealistic since a lower, rather than higher, market price is needed in order for this product to substitute mineral fertilisers. As previously mentioned, the market for biostimulants is promising according to the World Bank (2023). This increases the likelihood of increased competition and a potential competition for specialisation among manufacturers. This drives innovation, leading to long-term cost reductions. Similar trends have been observed in the renewable energy market, particularly in solar power and wind power. With decreasing costs, and increased competition, market prices are expected to decrease as well.

Considering the environmental damage cost, our value transfer estimate seems relatively high. Therefore, we think the probability of an increase in these costs is low. Calculating the annuity for the ten years the environmental damage cost is included and dividing this by all households in the community of Ålesund (31,713 households), gives a value of 32 NOK per household/years. This means that the environmental damage costs (in terms of WTP for kelp forest restoration) must be reduced by 32 NOK per household, i.e., from 946 to 914 NOK, for the NPV to go from negative to break-even (NPV=0). As this implies a reduction in annual WTP/household per year of only 3.5%, we think it is not unlikely that this could happen.

Project alternative v.: Wild harvesting of *A. nodosum* to produce kelp meal

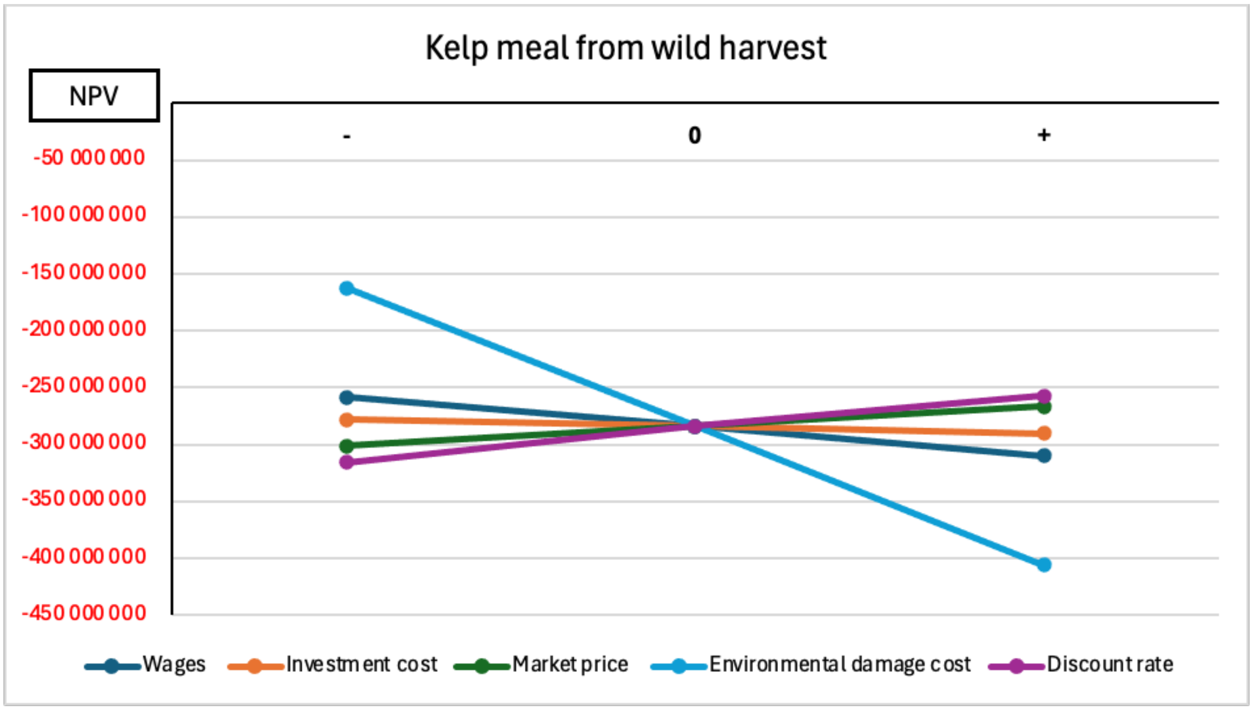

Figure 19: Sensitivity analysis of wild harvesting of A. nodosum to produce kelp meal. Sensitivity analyses are performed for labor cost (wages), investment cost, market price of the product, carbon price, environmental damage cost and the social discount rate. "0" refers to NPV calculated. At the original assumption and "+" and "- "refers to +50% and -50% of each factor, respectively.

For wild harvesting of *A. nodosum* for kelp meal production, figure 19 shows that the NPV is most sensitive to changes in environmental damage cost. The sensitivity analysis also shows that even when adjusting these factors by ± 50%, the NPV remains negative. To achieve an NPV of zero, substantial benefits need to be realised from this project alternative, considering the annuity of 20,909,856 NOK. The market price for instance would have to increase by 307 NOK, resulting in 346 NOK/kg. This is three times more of what would be needed for kelp meal from cultivated *S. latissima*.

Wages, market price, investment and discount rate have a relative gentle curve, and the NPV are not that sensitive for changes in these factors.

Project alternative vi.: Wild harvesting of *A. nodosum* to produce biochar

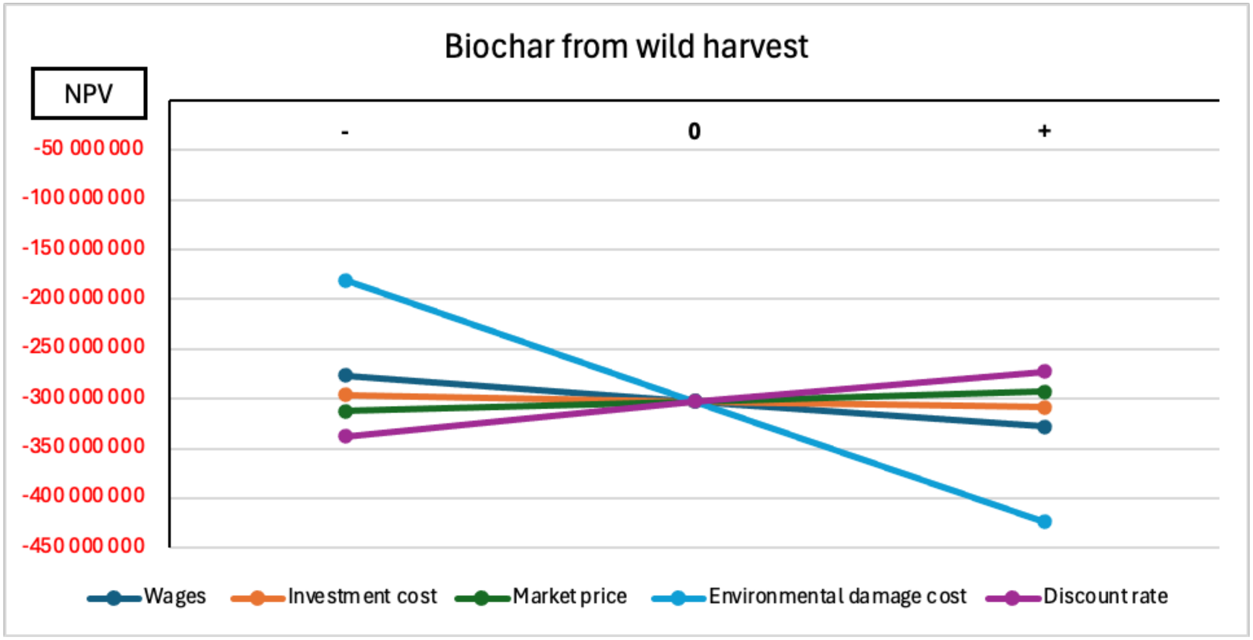

Figure 20: Sensitivity analysis of wild harvesting of A. nodosum to produce biochar. Sensitivity analyses are performed for labor cost (wages), investment cost, market price of the product, carbon price, environmental damage cost and the social discount rate. "0" refers to NPV calculated. At the original assumption and "+" and "-"refers to +50% and -50% of each factor, respectively.

Similar to the previous project alternative for wild harvesting, this project alternative demonstrates that the NPV is highly sensitive to the environmental damage cost. Conversely, uncertainty factors such as wages, market price, and investment costs exhibit robustness. The calculated annuity is of 22,256,855 NOK suggesting that non-priced benefits must be highly valued to offset the high costs associated with this alternative. However, given the current circumstances, it is unlikely that this will occur, despite biochar`s long-term CO_2 effects compared to liquid biostimulant and kelp meal. Perhaps in the future, if the climate problems worsen and affect more people than today, the benefits of CO_2 storage may be valued higher.

4.7 Step 7- Distributional effects

The purpose of this step is to explain how the priced and non-priced effects of the project alternatives are distributed among different groups in society. Based on used data and our own assessment, we have concluded that it is mainly three interest groups that will experience an impact from either wild harvesting or cultivation of seaweed; the cultivating or harvesting company, the population in Ålesund, and the society as a whole.

All the costs connected to the three project alternatives concerning cultivation, will come to the attention of the company engaged in cultivation. In contrast, for the wild harvesting alternatives, the biggest share of cost accrues to households in Ålesund as the kelp forests is being removed. This is reflected as environmental damage cost consisting of a loss in ES made up of both use and non-use values, e.g. the existence value.

We believe that no specific group is notably negatively affected by any of the six project alternatives. Although there is included a high environmental damage cost, this does not necessarily reduce the welfare of the local population in Ålesund where wild harvesting occurs. However, for the alternatives regarding cultivation, the visual impact of the cultivation rigs could be perceived negatively, but not significantly. If there are any "losers", it would be the local population in Ålesund, the reference area, who must view all the boys and are restricted in their leisure activities in the area.

The benefits from all the project alternatives will mainly be realised by cultivators and wild harvesters who receive payments for their products. Cultivation also contributes to additional CO_2 sequestration, benefiting society as a whole. Additionally, these products, derived from both cultivated and wild harvested seaweed, can help reduce the use of mineral fertilisers, supporting gardeners and farmers in making more sustainable choices, which aligns with the government requirements, like the Farm to Fork Strategy (European comission, n.d). Furthermore, it will benefit society by avoiding CO_2 emissions form the production of mineral fertiliser.

The "winners" are the wild harvesters or cultivators of *A. nodosum* or *S. latissima* that receives the highest benefit in form of gross income. For the cultivating alternatives, the government and the population in Norway, will get positive climate effects from the regulating ES as CO_2 sequestration is.

Cultivation of *S. latissima* not only provides habitats and living spaces for animals, but it also has the potential to enhance water quality. This benefits the marine organisms, which in turn can be advantageous for humans depending on them. Conversely, wild harvesting of *A. nodosum* will remove the habitat from the marine organisms, that in turn can have a negative effect on humans. However, given that we are examining a 10 hectares rig instillation or wild harvest 10 hectares natural kelp forest, the impact is relatively minor and unlikely to have significant positive or negative effects.

4.8 Step 8- Overall assessment and recommendation of project alternative

As an overall rule, the project alternative with the highest benefits relative to costs should be chosen, whit the NPV serving as the primary decision-making metric. While we acknowledge non-priced effects, these are considered not to be sufficient to have an impact on the NPV. Our sensitivity analysis has revealed that market price and environmental damage cost are the most sensitive factors.

The liquid biostimulant derived from cultivated *S. latissima* is the only project alternative with a positive NPV and is the recommended project alternative. Liquid biostimulant from *A. nodosum* shows a NPV that is negative but close to zero in the expected outcome. The sensitivity analysis reveals highly sensitive factors and the NPV could therefore be pushed both ways. Conversely, for cultivated seaweed to produce liquid biostimulant, the NPV remains robust and are consistently positive.

5. Discussion

5.1 CBA results

There are some studies that have examined the economic viability of seaweed cultivation, but even fewer have considered the impacts on ecosystem services (ES). We fail to find comparable analyses for wild-harvested seaweed, despite this practice having been carried out for a long time. We do not see it appropriate to compare our results with any of these studies, as they all have such different system boundaries for the task. Some have not included a specific end-product or have only focused on certain ES. What we do find, however, is that several studies identify market price as important for economic profitability. See for instance Menzies et al. (2021) and Collins et al. (2022).

The market prices used for the NPV calculation in this thesis are uncertain, as they vary considerably in reality, and predicting future prices is challenging. Prices applied to kelp meal and biochar should have been higher in the short term and may decrease in the long term as it is few suppliers. As liquid biostimulant is highlighted as a promising market, one could expect more suppliers which in turn speaks for a lower market price long-term. This would also benefit the end-user that faces more requirements connected to sustainable agriculture. It is crucial that substitutes for mineral fertilisers becomes affordable.

It is interesting that cultivated *S. latissima* for production of liquid biostimulant shows a remarkably high positive NPV. Searches on Proff.no, reveals that there are few to no profitable cultivation firms[16]. Since this is a socio-economic analysis, we find it surprising, since valuation of the ecosystem services didn`t significantly contribute to the NPV. Instead, the market price appears to be the most sensitive factor identified through sensitivity analysis. However, substantial cost reductions would be required to make the NPV negative, highlighting the potential to lower the market price sufficiently.

We have assumed that all the products will be sold, which may be unrealistic in the short term. Given the increasing emphasis on sustainable agriculture in Norway, it might rapidly become realistic. The potential to lower the market price for cultivated seaweed to produce liquid biostimulant highlights the possibility of this rapid shift. Additionally, the World Bank (2023) has

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[16] https://www.proff.no/

highlighted the promising market for liquid biostimulants. Therefore, these outcomes may not be surprising after all, at least not for liquid biostimulants.

Even if liquid biostimulant from cultivated seaweed was the only project alternative with positive NPV, biostimulant from wild harvested seaweed also has potential to reach zero based on the results from the sensitivity analysis. Compared to the project alternatives of producing kelp meal and biochar from wild harvesting or cultivation, the NPV for liquid biostimulant is notably higher. This is because liquid biostimulant is the only end-product that increases its weight after drying due to distilled water being added. Kelp meal remains the same, while biochar reduces its weight due to pyrolysis. More product gives more gross income which is the biggest benefit in all project alternatives.

However, if research confirms the viability of seaweed-based biochar and the positive net effect on CO_2, this perspective may change. The ability of biochar to store CO_2 long-term could be essential for achieving climate goals and as a result potentially increasing the valuation of CO_2 storage. It is therefore challenging to draw definite conclusions, given the evolving seaweed cultivation industry, where changes happen quickly. It is important to note that this consideration specifically apply to project alternative iii. Cultivation of *S. latissima* for production of biochar and vi. Wild harvesting of *A. nodosum* for production of biochar.

Before conducting the sensitivity analysis, we anticipated that wages would be a highly sensitive factor, given it being a high share of the costs. However, after completing the sensitivity analysis, it became clear that wages only had an impact on project alternatives ii. and iii. This observation can be attributed to the fact that the benefit from the product was much higher for liquid biostimulant compared to kelp meal and biochar.

More surprisingly, the project alternatives involving wild harvesting of *A. nodosum* to produce kelp meal and biochar are not profitable. One reason for this could be the small percentage of yields from the processed biomass for kelp meal and biochar. Additionally, it may be due to the relation between amount harvested and the cost estimates. In our project alternatives for wild harvest, we assumed a two-month period to harvest on a 10 hectares area, yielding 400 ton of biomass. The low NPV, can be a suggestion that our cost estimates may be to high relative to the amount harvested each year. As mentioned earlier, wild harvesting can occur throughout the entire year, potentially resulting in a much larger total biomass harvested. Therefore, the low NPV could indicate high investment cost relative to the biomass harvested.

Non-priced effects mainly apply to the alternatives regarding cultivation. As the cultivation rigs assumed in this thesis is considered a small-scale farm, the non-priced effects are found not sufficient for any of the project alternatives. However, we found a high WTP for kelp forest restoration from Hynes et al. (2021) reflecting that Norwegian preferences value ES high. If, in the future, large-scale farms are the case, the public preferences may value the impact on the natural kelp forests from cultivation rigs such that it has bigger impact on the NPV.

5.2 Limitations

This thesis primarily focuses on cultivation of *S. latissima* and wild harvesting of *A. nodosum* for production of soil and plant amendments. However, it was challenging to gather information on current practises for wild harvesting and cultivation. Despite our attempts to reach out to wild harvesters and cultivators, only three cultivators were willing to engage further, while none of the wild harvesters responded. This impacts our understanding more significantly for cultivation compared to wild harvesting. This presents a weakness as we did not achieve a representative sample for either group.

Detailed biological and chemical knowledge is mostly outside the scope of this thesis. Our understanding of how *S. latissima* as amendment affect soil and plant dynamics and how carbon is released over time is limited due to the lack of research in this field. Therefore, we assume that *S. latissima* has a similar effect as *A. nodosum*, even though this is uncertain. There is also a knowledge gap regarding potentially toxic elements (PTEs) in cultivated and wild harvested seaweed, and the potential limitations or prospects of using seaweed as soil and plant amendments. In this thesis, we assumed that this problem is solved, and that toxic elements are not present or have been removed at zero cost. This is obviously a simplification. The extraction of liquid biostimulant, and the production of kelp meal and biochar affect nutrient and pH levels differently. These differences have been excluded from this analysis as researchers have confirmed that kelp meal and liquid biostimulant are suitable for soil and plant amendments, whereas biochar is still in its early stages of development. Since biochar is in its early stages of development, there is uncertainty regarding the salinity levels it causes. This uncertainty is excluded and therefore represent a weakness in our analysis.

In the contexts of the CBA, certain assumption has been made that limits this thesis. It was assumed that both cultivators and wild harvesters would not have any residual end-products after the selling season. This assumption is significant for wild harvesters and cultivators to avoid excess inventory, which in turn affect the quantity of harvested kelp. We also assumed that cultivated *S. latissima* can be sold in the same way as *A. nodosum*. This could potentially affect the market prices for the different products.

Due to these limitations, the results from our CBA should be interpreted with caution. However, the CBA provides an overview of the main benefit and cost drivers, and order-of-magnitudes estimates of the socio-economic profitability of the three products produced from wild harvesting or cultivation.

6. Conclusion and recommendation

6.1 Conclusion

The aim of this thesis was to address the problem statement: Is it socio-economically viable to cultivate or wild harvest seaweed in Norway for production of soil or plant amendments?

To answer this, we conducted a Cost-Benefit Analysis of using a hypothetical 10 hectares coastal area for cultivation or wild harvesting of seaweed for three products; resulting in six project alternatives:

I. **Cultivation**
  i. Cultivating *S. latissima* to produce liquid biostimulant
  ii. Cultivating *S. latissima* to produce kelp meal
  iii. Cultivating *S. latissima* to produce biochar

II. **Wild harvest**
  iv. Wild harvest *A. nodosum* to produce liquid biostimulant
  v. Wild harvest *A. nodosum* to produce kelp meal
  vi. Wild harvest *A. nodosum* to produce biochar

These project alternatives were compared to the reference alternative, which was **not** conducting any wild harvesting or cultivation of the illustrative 10 hectares case area.

The CBA was used to answer five research questions:

i. **Is it socio-economic profitable to cultivate or wild harvest seaweed?**

Only cultivation had one project alternative with positive NPV which was production of liquid biostimulant. However, what is socio-economic profitable deviates from what is financially profitable. Given today's circumstances, wild harvesting is financially profitable whereas cultivation is not. The reason is the valuation of natural kelp forests and its ecosystem services (ES) which is included in this socio-economic analysis. In order to offset this difference, the cultivators can be compensated for its production of positive external effects like CO_2 sequestration.

ii. If any, which is the most profitable option of cultivation and wild harvesting?

Cultivation was the most profitable option; but only for production of liquid biostimulant. For kelp meal and biochar, both wild harvest and cultivation were not profitable but the NPV for cultivation for these two products was less negative than wild harvesting for the same products.

iii. If any, which option is the most profitable among liquid biostimulant, kelp meal, and biochar?

Liquid biostimulant is most profitable. The NPV for cultivation to produce liquid biostimulant was positive, while it for wild harvesting was negative but with positive outcomes in the sensitivity analysis.

iv. How does accounting for ecosystem services like carbon sequestration impact the profitability of the six project alternatives?

The effect on a small-scale farm was not big. We have considered the short-term CO_2 sequestration and substitution of mineral fertiliser to avoid CO_2 emissions as a regulating ES benefit. The NPV showed robustness against the carbon price in the sensitivity analysis, and it did not impact the NPV. Seaweed as a provisioning ES is reflected through the market price of the product, which had the largest impact on the NPV. The environmental damage cost associated with removing natural kelp forests and its provision of ES had a large negative impact on the project alternatives related to wild harvesting. There were also non-priced ES effects, but we found them to be negligible, with no significant effect on the NPV.

v. Which factors have the greatest impact on the socio-economic profitability?

For cultivation to produce liquid biostimulant, the market price of the product has the largest effect on the NPV when looking at the percentage change relative to the base case. For cultivation to produce kelp meal and biochar, the labor cost (wages) had the largest effect on the NPV when looking at the percentage change relative to the base case.

For all the wild harvesting project alternatives, the environmental damage cost had the largest effect on the NPV when looking at the percentage change relative to the base case.

6.2 Recommendations further research

One aspect we found lacking in the literature on seaweed is its CO_2 impact. More in-depth research on its sequestration potential, as well as the emissions released throughout the value chain is important when extending the CBA framework to also include life cycle CO_2 emissions over the entire value chain. Understanding the net CO_2 effect is crucial before scaling up this industry. Our analysis shows that it is important to estimate the wider ES impacts, e.g. in terms of including environmental damage costs of wild harvesting and potentially also cultivation, but more research into these environmental damages is clearly needed. Furthermore, one should also examine whether there is other seaweed-based product than analysed here that could yield higher socio-economic profitability.

Additionally, a critical factor is whether it is possible to create a stable and predictable market for seaweed. This is essential for an economically sustainable seaweed industry. Also, the products must be affordable for end-users in order for them to adopt such products. As cultivation is the big focus for seaweed, how can cultivations become financially profitable? In the case where cultivation is profitable socio-economically, but not financially due to e.g. ecosystem services like CO_2 sequestration and avoided environmental damage from wild harvest which the cultivators are not compensated for; there is a need for government regulations to internalize these external effects. This could be through subsidies to cultivators, environmental taxes on wild harvesting, or a combination of these two. However, further research into the quantification and economic valuation of these external effects are needed to find optimal subsidy/compensation schemes for cultivation and/or tax levels for wild harvesting. Further, it might not become profitable until larger biomass of seaweed is produced. Then the question becomes whether this is possible without acquiring larger areas for seaweed cultivation. If larger areas for cultivation are needed: can extensive seaweed cultivation be combined with sustainable use of our coastal areas and their ecosystem services?

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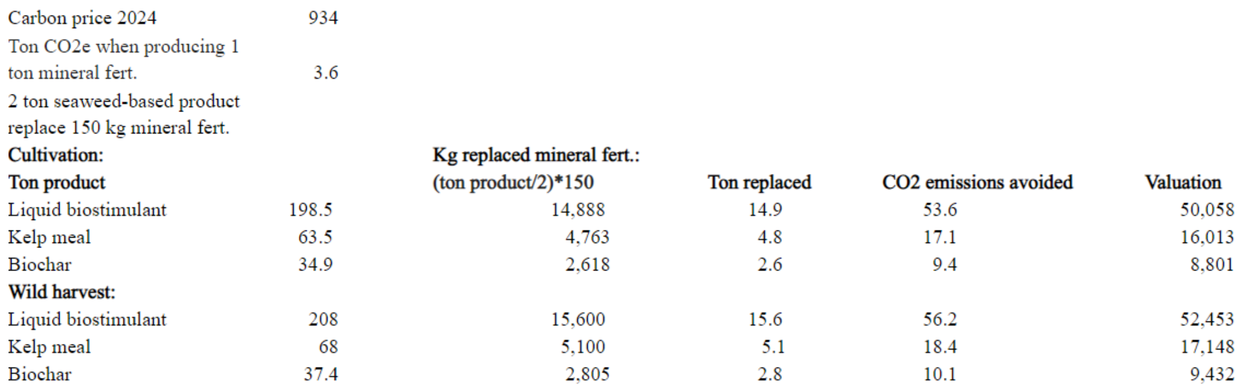
Appendices

Appendix A: Replacement of mineral fertiliser



Carbon price 2024	934				
Ton CO2e when producing 1 ton mineral fert.	3.6				
2 ton seaweed-based product replace 150 kg mineral fert.					
Cultivation:		**Kg replaced mineral fert.:**			
Ton product		**(ton product/2)*150**	**Ton replaced**	**CO2 emissions avoided**	**Valuation**
Liquid biostimulant	198.5	14,888	14.9	53.6	50,058
Kelp meal	63.5	4,763	4.8	17.1	16,013
Biochar	34.9	2,618	2.6	9.4	8,801
Wild harvest:					
Liquid biostimulant	208	15,600	15.6	56.2	52,453
Kelp meal	68	5,100	5.1	18.4	17,148
Biochar	37.4	2,805	2.8	10.1	9,432

Appendix B: Annual gross income from product sales

	Cultivation	**Wild harvesting**
Liquid biostimulant:		
Ton dried biomass	64	68
Share of biostimulant in product formulation	0.32	0.32
Ton other ingredients	135	140
Ton total product	199	208
Kg total product	198,500	208,000
Price per kg (exc. VAT)	124	124
Annual income	24,673,550	25,854,400
Kelp meal:		
Ton dried biomass	64	68
Kg dried biomass	63,500	68,000
Price per kg (exc. VAT)	39	39
Annual revenue	2,489,200	2,652,000
Biochar:		
Ton dried biomass	64	68
Share after pyrolysis	0.55	0.55
Kg after pyrolysis	34,925	37,400

Price per kg (exc. VAT)	40	40
Annual revenue	1,397,000	1,496,000

Appendix C: Sources utilised in Chapter 4.3.2 and 4.3.4 for market prices.

Item:	**Source:**	**Effect:**
Small boat	Båt Berge AS. (2024). *Øien 710 F m/Yamaha F80 hk*. Finn. https://www.finn.no/boat/forsale/ad.html?finnkode=342881924	Cultivation rig
Anchor block	Ølen Betong. (2023). *Produktkatalog*. https://www.olenbetong.no/static/files/nedlastinger/VAkatalog2023_med_priser_Mars23.pdf	Cultivation rig
Anchor chain	Marineshop. (n.d.). *Bryggekjetting Galvanisert*. Retrieved 4. April 2024 from https://www.marineshop.no/kjetting/144399/bryggekjettinggalvanisert-150m-langlenket-din-763	Cultivation rig
Anchor buoy	Båtvarehuset AS. (n.d.). *Fortøyningsbøye MB100*. Retrieved 4. April 2024 from https://www.baatvarehuset.no/products/fortoyningsboyle-hardplast-orange	Cultivation rig
Longline, control line and drop line	Høcom. (n.d.). *DANLINE FORTØYNINGSTAU 110 M GRØNN*. Retrieved 4. April 2024 from https://www.hocom.no/p/20103/1852-danline-fortoeyningstau-110-m-groenn	Cultivation rig

Small buoy	Hovdan Poly AS. (n.d.). *Bøye Kort Stang Cce-2 50" Rød Polyform (Mr)*. Retrieved 4. April 2024 from https://www.hovdan-poly.no/produkt/boye-kort-stang-cce-2-50-rod-polyform-mr/	Cultivation rig
Line weight	Skorsteinsutstyr. (n.d.). *Lodd 1,5kg*. Retrieved 4. April 2024 from https://skorsteinsutstyr.no/produkt/lodd-15-kg/	Cultivation rig
Seeding line	Witre. (n.d.). *Tauverk hvit nylon*. Retrieved 22. April from https://www.witre.no/no/wno/tauverk-hvit-nylon-79165?infinity=ict2~net~gaw~cmp~17685972716~ag~~ar~~kw~~mt~~acr~6049238426&gad_source=1&gclid=Cj0KCQjw2PSvBhDjARIsAKc2cgNCO2SS0fkHi-9fSh6AIgVHDGnFsCnupItOhXzCovPvwXbvhBydQ1saAmJGEALw_wcB	Hatchery
Tractor	Tym-Norge. (n.d.). TYM F50Chn. Retrieved 9. April 2024 from https://www.tym-norge.no/produkt/tym-f50chn/?gad_source=1&gclid=Cj0KCQjwztOw	Production equipment
Tractor trailor	Wee. (n.d.). *Tipphenger Vestland 1200 kg nyttelast*. Retrieved 9. April 2024 from: https://www.wee.no/produkter/landbruksutstyr-gardsutstyr/tilhengere-kraner/tilhengere/tipphenger-vestland-1200-kg-nyttelast/22134?gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkBKSU3u4TOQ6j-YBm0KM5WL0acR2u6kkuZ3L7Q4GWqgYnfj9HnXgPUaAqKHEALw_wcB	Production equipment
Log claw	Wee. (n.d.). *Tømmerklo til traktor LG200*. Retrieved 9. April 2024 from https://www.wee.no/produkter/skogsutstyr/trekuttere-treklyper/tommerklo-til-traktor-lg200	Production equipment
Container	Agder container. (n.d.). *Container hjul*. Retrieved 9. April 2024 from https://www.agdercontainer.no/shop/product/container-hjul-1400-kg	Production equipment

Shelves	Sono. (n.d.). *Grenreol K1000 2-sidig 6250 mm 6 søyler*. Retrieved 9. April 2024 from https://www.sono.no/lager-industri/lager/grenreoler/grenreol-k1000-2-sidig-6250-mm-6-soyler-112870.html	Production equipment
Electric heater	Trotec. (n.d.). *Elektrisk varmeapparat TEH 400*. Retrieved 10. April 2024 from https://no.trotec.com/shop/elektrisk-varmeapparat-teh-400.html?em_src=cp&em_cmp=feed/no/16492/kelkoono/1410000160&fdcampaign=feed/no/16492/kelkoono/1410000160&utm_source=kelkoo&utm_medium=portale&utm_campaign=kelkoo-no1410000160	Production equipment
Dehumidifier	Inneklimagruppen. (n.d.). *Avfukter CR290B F-DRY ROTOR*. Retrieved 10. April 2024 from https://www.inneklimagruppen.no/productdetails.php?product=11&gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkBC4LCVsCrMFu98dmR0WGBpl9z1vE9ULkOYGaO_Z14Qlg_wb5tAA6MaAiLWEALw_wcB	Production equipment
Hammermill	Expondo. (n.d.). *Hammer Mill -22 kW -800 - 1800 kg/t*. Retrieved 10. April from https://www.expondo.no/wiesenfield-hammer-mill-22-kw-800-1800-kg-t-10280328?utm_medium=affiliate&utm_source=tradetracker&medium=affiliate	Production equipment
Distilled water	The distilled water company. (n.d.). *Distilled water 1000 litres*. Retrieved 10. April 2024 from https://www.thedistilledwatercompany.com/distilled-water-1000-litres	Production equipment
Mixing tank	Polsinelli. (n.d.). *Mixing tank 1000 L*. Retrieved 10. April 2024 from https://www.polsinelli.it/en/mixing-tank-1000-l-P1692.htm	Production equipment
IBC-container	Auer packaging. (n.d.). *IBC CONTAINER MED PLASTPALL*. Retrieved 10. April 2024 from https://www.auer-packaging.com/no/no/IBC-Container-Med-plastpall/IBC-1000-K-225.80.html?customer_type=private&gad_source=1&gclid=CjwKCAjw7-SvBhB6EiwAwYdCAfM_ro_qYe1t4i3WZNtdb3u1-Rf1qjTVSf6d-YtIqShxf_yT4IttEhoCsRQQAvD_BwE	Production equipment
Autoclave	Neuvar. (n.d.). *Microwave Steam Sterilizer | Autoclave Vertical NEUPS11 100L*. Retrieved 11. April 2024 from https://www.neuvar.com/product/microwave-steam-sterilizer-autoclave-vertical-mslps11-100l/?gad_source=1&gclid=Cj0KCQjwlN6wBhCcARIs	Production equipment

	AKZvD5gErbsuxnEX29cq20443BoXIEtUKK7eypD1mmxA96CtOauq2gxg2soaAgmOEALw_wcB	
Paper bags	Log. (n.d.). *POTETPOSE 5KG U/T*. Retrieved 10. April 2024 from https://www.log.no/produkt/potetpose-5kg-u-t-100/	Production equipment
Rake type cutter	Vevor. (n.d.). *VEVOR landskapsrive, 915 mm hode aluminium*. Retrieved 4. April 2024 from https://eur.vevor.com/asphalt-rake-c_12233/vevor-landscape-rake-36-head-aluminum-landscape-rake-102-36-adjustable-handle-p_010504691225?lang=no&currency=nok&adp=gmc&country=NO&utm_source=google&utm_medium=cpc&utm_id=20577684134&utm_term=&utm_language=no&gad_source=1&gclid=Cj0KCQjwq86wBhDiARIsAJhuphmnC2Bpvd7U8aWJZcyYqKFQmfBrbJNyXqW5ffN2AK2ebLpbLdgLBWsaAj8HEALw_wcB	Wild harvest equipment
Sickle	Felleskjøpet. (n.d.). *Sigd 85 Jærmodel Hamre*. Retrieved 4. April 2024 from https://www.felleskjopet.no/hjem-og-fritid/hage/hageredskaper/river-og-raker/sigd-diamant-jaermod-hamre-50235081/	Wild harvest equipment

Appendix D: Working clothes

Item	**NOK-2024/item**	**Source**
Rain pants	719	Skittfiske. (n.d.). *Ålesund Regnbukse Orange*. Retrieved 4. April 2024 from https://www.skittfiske.no/aalesund-oljeklede/146130/aalesund-%C3%A5lesund-regnbukse-orange-s-fluoriserende-orange-selebukse?channable=056dcc6964003134363133330ab&gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkDf2bkhooMAPg3OVCKAo0mwXDBTXQhPj_Y-6T5i4inobein0Rg-9HsaAg0iEALw_wcB
Rubber boots	183	Billige arbeidsklær. (n.d.). *Dunlop Pricemastor gummistøvler*. Retrieved 4. April 2024 from https://billige-arbeidsklaer.no/dunlop-pricemastor-gummistovler-gronn/501_42.html?gad_source=1&gclid=Cj0KCQjwztOwBh

		D7ARIsAPDKnkBhdrnU7cYSl97UkIkrXPNlcchhxHnFwkCpFqapy-WThhQ3BDd_oasaAlUEEALw_wcB
Rain jacket	799	Skittfiske. (n.d.). *Ålesund Regnjakke Orange*. Retrieved 4. April 2024 from https://www.skittfiske.no/aalesund-oljeklede/146138/aalesund-%C3%A5lesund-regnjakke-orange-l-fluoriserende-orange-regnjakke?channable=056dcc6964003134363133338b3&gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkDGuG7mVKz7MrMVyi0bcK3KAbCGmGYr2gpYi-YVz5uVDpG452Qw9ZwaAl_dEALw_wcB
Fleece	279	Billige arbeidsklær. (n.d.). *Ocean 2-i-1 fleecejakke*. Retrieved 4. April 2024 from https://billige-arbeidsklaer.no/ocean-2-i-1-fleecejakke-hi-vis-orange/135958_M.html?gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkD0eKeegBvVSO0oiCXXtWO-jgfFjpX9UbmyFxEwhfrFW22UkuxvF6AaAht2EALw_wcB
Glowes	95	Allpro. (n.d.). *Fiskerihansker 670-Arm uten fôr*. Retrieved 4. April 2024 from https://allpro.no/products/fiskerihansker-670-arm-uten-for?variant=47233766195479&currency=NOK&utm_medium=product_sync&utm_source=google&utm_content=sag_organic&utm_campaign=sag_organic&gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkCIRkE3vqG8PW8tB2RrjtiCMRD_z7X6KMrPv7_9ZPA6WlLQhg2Gl8IaAq33EALw_wcB
Caps	79	Billige arbeidklær. (n.d.). *Clique Classic Cap*. Retrieved 4. April 2024 from https://billige-arbeidsklaer.no/clique-classic-cap-dark-navy/131969_ONESIZE.html
Life jacket	199	XXL. (n.d.). *Sport II, flytevest, unisex*. Retrieved 4. April 2024 from https://www.xxl.no/helly-hansen-sport-ii-flytevest-unisex-mork-bla/p/1169881_1_Style?gad_source=1&gclid=Cj0KCQjwztOwBhD7ARIsAPDKnkD0_x33vcARji-CGZcD7a1aH3n7C4qgaRETwWP33WXfBdf2kQ9SIFwaAoEjEALw_wcB&gclsrc=aw.ds

Appendix E: Net present value

Costs of cultivating on 10 hectares over the lifetime of 20 years

t=	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043
Licence	300,000																			
Factory	17,101,684																			
Hatchery	1,865,146	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500	70,500
Cultivation rig	6,345,402					283,902					283,902					283,902				
Equip.prod	945,356										316,376									
Wages	840,322	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610	5,251,610
Op.cost	431,052	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409	1,823,409
Sum	27,828,962	7,145,519	7,145,519	7,145,519	7,145,519	7,429,421	7,145,519	7,145,519	7,145,519	7,145,519	7,745,797	7,145,519	7,145,519	7,145,519	7,145,519	7,429,421	7,145,519	7,145,519	7,145,519	7,145,519
Additional costs:																				
Biostimulant		2,258,991	2,155,398	2,155,398	2,155,398	2,208,237	2,155,398	2,155,398	2,155,398	2,155,398	2,208,237	2,155,398	2,155,398	2,155,398	2,155,398	2,208,237	2,155,398	2,155,398	2,155,398	2,155,398
PV biostimulant	27,828,962	9,042,798	8,599,220	8,268,481	7,950,463	7,921,452	7,350,650	7,067,932	6,796,089	6,534,701	6,724,589	6,041,698	5,809,325	5,585,890	5,371,048	5,351,449	4,965,835	4,774,842	4,591,194	4,414,610
Kelp meal		24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181	24,181
PV kelp meal	27,828,962	6,893,942	6,628,790	6,373,837	6,128,689	6,126,318	5,666,318	5,448,383	5,238,829	5,037,336	5,249,119	4,657,300	4,478,173	4,305,936	4,140,323	4,138,721	3,827,961	3,680,732	3,539,165	3,403,044
Biochar		226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371	226,371
t=	6235368.701	3733747.7	3733747.4	3733747.1	3733746.8	3338716.435	3733746.2	3733745.9	3733745.6	3733745.3	256376.4332	3733744.7	3733744.4	3733744.1	3733743.8	3338712.796	3733743.2	3733742.9	3733742.6	3733742.3

Benefits of cultivating on 10 hectares over the lifetime of 20 year

Biostimulant:																				
t=	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CO2 sequestration	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583
Substitution		50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058	50,058
Gross income		24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550	24,673,550
PV	50,583	23,821,337	22,905,132	22,024,165	21,177,082	20,362,579	19,579,403	18,826,349	18,102,259	17,406,018	16,736,556	16,092,842	15,473,887	14,878,737	14,306,478	13,756,229	13,227,143	12,718,407	12,229,237	11,758,882
Kelp meal:																				
CO2 sequestration	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583
Substitution		16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013	16,013
Gross income		2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200	2,489,200
PV	50,583	2,457,497	2,362,978	2,272,094	2,184,706	2,100,678	2,019,883	1,942,195	1,867,495	1,795,669	1,726,605	1,660,197	1,596,343	1,534,945	1,475,909	1,419,143	1,364,561	1,312,078	1,261,613	1,213,089
Biochar:																				
CO2 sequestration	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583	50,583
Substitution		8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807	8,807
Gross income		1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000	1,397,000
PV	50,583	1,400,375	1,346,515	1,294,726	1,244,929	1,197,047	1,151,007	1,106,737	1,064,170	1,023,241	983,885	946,043	909,657	874,670	841,029	808,682	777,579	747,672	718,915	691,265

Costs of wild harvesting on 10 hectares over the lifetime of 20 years

t=	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
year	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043
Total invest cost	11,835,817					49,281					365,657					49,281				
Wages		3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966	3,920,966
Op. cost	45,411	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852	914,852
Environmental damage cost		30,003,749	30,003,749	30,003,749	30,003,749	30,003,749	30,003,749	30,003,749	30,003,749	30,003,749	30,003,749									
Sum	11,881,228	34,839,566	34,839,566	34,839,566	34,839,566	34,888,848	34,839,566	34,839,566	34,839,566	34,839,566	35,205,223	4,835,818	4,835,818	4,835,818	4,835,818	4,885,099	4,835,818	4,835,818	4,835,818	4,835,818
Additional costs:																				
Biostimulant		2,259,075	2,238,391	2,238,391	2,238,391	2,291,231	2,238,391	2,238,391	2,238,391	2,238,391	2,291,231	2,238,391	2,238,391	2,238,391	2,238,391	2,291,231	2,238,391	2,238,391	2,238,391	2,238,391
PV biostimulant	11,881,228	35,671,771	34,280,656	32,962,170	31,694,394	30,559,314	29,303,249	28,176,201	27,092,501	26,050,481	25,331,261	4,595,271	4,418,530	4,248,587	4,085,179	3,984,761	3,776,978	3,631,710	3,492,028	3,357,720
Kelp meal		25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894	25,894
PV kelp meal	11,881,228	33,524,482	32,235,078	30,995,268	29,803,142	28,697,373	27,554,680	26,494,885	25,475,851	24,496,010	23,800,881	3,158,075	3,036,611	2,919,818	2,807,518	2,726,900	2,595,708	2,495,873	2,399,878	2,307,575
Biochar		242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382	242,382
PV biochar	11,881,228	33,732,643	32,435,233	31,187,724	29,988,197	28,875,310	27,725,773	26,659,398	25,634,036	24,648,112	23,947,132	3,298,702	3,171,828	3,049,835	2,932,534	2,847,108	2,711,292	2,607,012	2,506,742	2,410,329

Benefits of wild harvesting on 10 hectares over the lifetime of 20 year

t=	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Biostimulant:																				
Substitution		52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453	52,453
Gross income		25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400	25,854,400
PV		24,910,436	23,952,342	23,031,098	22,145,287	21,293,545	20,474,563	19,687,079	18,929,884	18,201,812	17,501,742	16,828,598	16,181,344	15,558,985	14,960,562	14,385,156	13,831,881	13,299,885	12,788,351	12,296,492
Kelp meal:																				
Substitution		17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150	17,150
Gross income		2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600	2,665,600
PV		2,579,567	2,480,353	2,384,955	2,293,226	2,205,025	2,120,216	2,038,669	1,960,259	1,884,864	1,812,369	1,742,663	1,675,637	1,611,190	1,549,221	1,489,636	1,432,342	1,377,252	1,324,281	1,273,347
Biochar:																				
Substitution		9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432	9,432
Gross income		1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000	1,496,000
PV		1,447,530	1,391,856	1,338,323	1,286,849	1,237,355	1,189,764	1,144,004	1,100,004	1,057,696	1,017,016	977,900	940,288	904,123	869,349	835,913	803,762	772,848	743,123	714,542

Appendix F: Sensitivity analysis

Cultivation

NPV	-50%	0	50%
Biostimulant			
Wages	209,349,401	174,442,076	139,534,752
Investment cost	187,852,555	174,442,076	161,031,598
Carbon price	174,098,152	174,442,076	175,846,990
Market price	12,411,621	174,442,076	336,472,532
Discount rate	213,626,215	174,442,076	144,019,646
Kelp meal			
Wages	(54,266,294)	(89,173,619)	(124,080,944)
Investment cost	(75,763,141)	(89,173,619)	(102,584,097)
Carbon price	(89,405,998)	(89,173,619)	(88,227,809)
Market price	(105,520,120)	(89,173,619)	(72,827,118)
Discount rate	(101,077,805)	(89,173,619)	(79,926,652)
Biochar			
Wages	(71,361,374)	(106,268,698)	(141,176,023)
Investment cost	(92,858,220)	(106,268,698)	(119,679,177)
Carbon price	(106,477,468)	(106,268,698)	(105,420,065)
Market price	(115,442,755)	(106,268,698)	(97,094,642)
Discount rate	(121,484,825)	(106,268,698)	(94,450,009)

Wild harvesting

NPV	**-50%**	**0**	**50%**
Biostimulant			
Wages	17,413,919	(8,334,946)	(34,083,810)
Investment	(2,259,590)	(8,334,946)	(14,410,301)
Market price	(178,120,007)	(8,334,946)	161,450,116
Environmental damage cost	113,343,695	(8,334,946)	(130,013,586)
Discount rate	13,342,487	(8,334,946)	(22,946,711)
Kelp meal			
Wages	(258,422,898)	(284,171,763)	(309,920,628)
Investment	(278,096,407)	(284,171,763)	(290,247,118)
Market price	(301,676,677)	(284,171,763)	(266,666,848)
Environmental damage cost	(162,493,123)	(284,171,763)	(405,850,403)
Discount rate	(315,936,450)	(284,171,763)	(257,286,118)
Biochar			
Wages	(276,729,056)	(302,477,921)	(328,226,786)
Investment	(296,402,565)	(302,477,921)	(308,553,276)
Market price	(312,302,107)	(302,477,921)	(292,653,734)
Environmental damage cost	(180,799,281)	(302,477,921)	(424,156,561)
Discount rate	(337,789,178)	(302,477,921)	(272,838,363)

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