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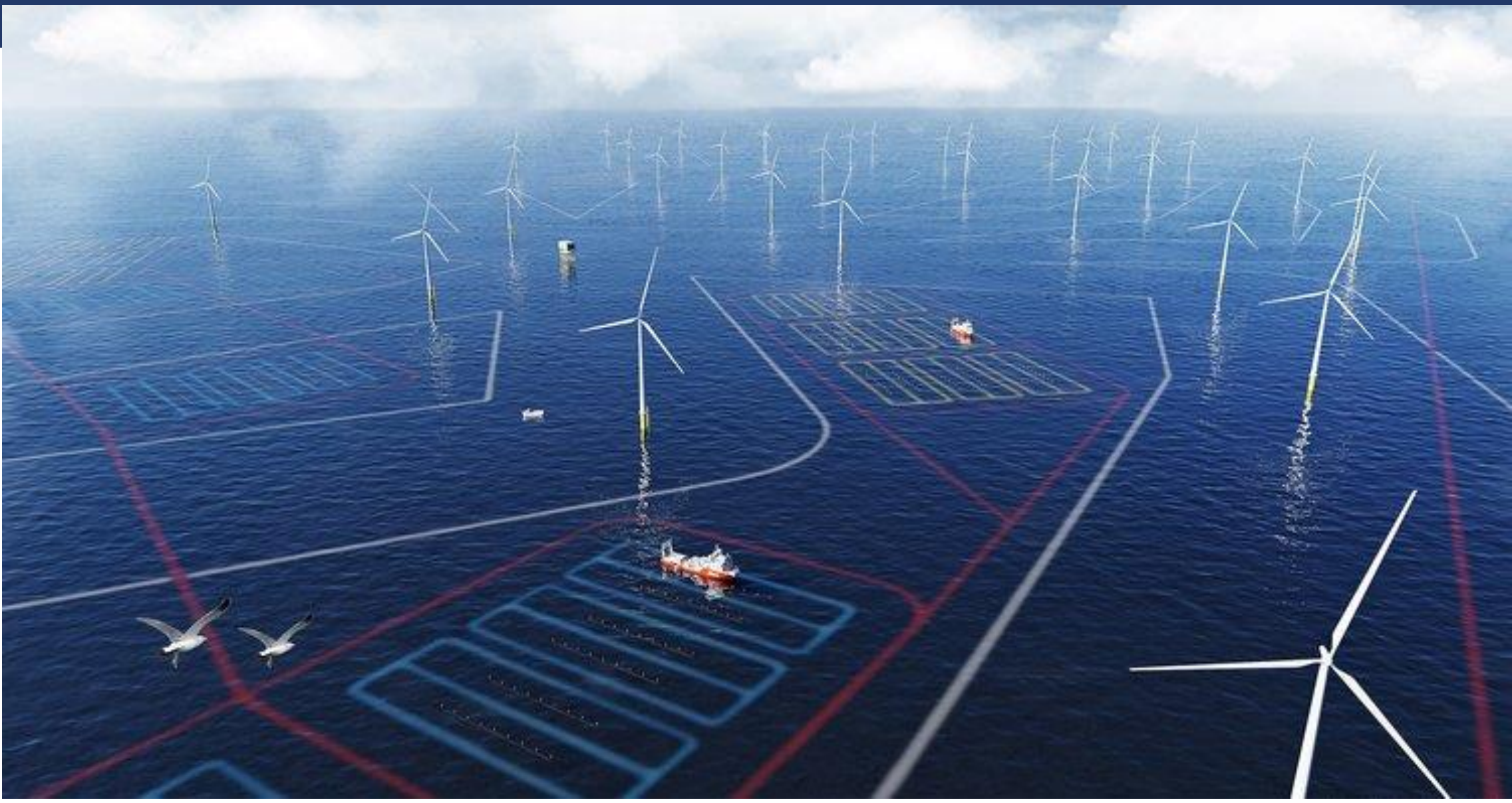

The nutrient bioextraction potential of offshore macroalgae cultivation

A study on the establishment of ecosystem services through large-scale offshore macroalgae cultivation in the North Sea

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"No water, no life.

No blue, no green."

~ Sylvia Earle, Oceanographer

Cover picture by (North Sea Farmers, n.d.)

The nutrient bioextraction potential of offshore macroalgae cultivation

A study on the establishment of ecosystem services through large-scale offshore macroalgae cultivation in the North Sea

By

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Abstract

Due to the increasing impact of terrestrial agriculture on climate change, the attention of a myriad of industries is shifting towards the use of alternative, low-emission resources. Seaweed cultivation has presented itself as a contribution to the mitigation of the increased pressure on current resources. However, coastal and offshore marine areas are often unfit for seaweed cultivation due to increasing maritime activity. As wind farm areas are increasing, offshore seaweed aquaculture in multi-use platforms at sea (MUPS) has been proposed as one of the possibilities for smart use of ocean space. Apart from providing a multitude of benefits through the many applications of seaweed, it is also widely suggested that seaweed could offer ecosystem services during its growth by means of nutrient bioextraction of eutrophied waters. In this thesis, the critical nutrient flows of cultivation of *S. latissima* in MUPS at the North Sea are quantified using a dynamic mathematical nutrient model, and the impact on the marine vicinity is assessed. The assessment is performed for two scenarios: (1) a seaweed farm producing for a high-value chemicals factory, and (2) a seaweed farm producing for a fuel biorefinery. Both these scenarios are modelled over the course of one cultivation season on four offshore wind farm locations in the North Sea. Moreover, an analysis is performed on the potential role of monitoring technologies in offshore seaweed aquaculture in MUPS. The results of this study are combined to assess whether it is possible to establish ecosystem services through large-scale offshore seaweed cultivation in MUPS at the North Sea using monitoring technologies and nutrient analyses. The analysis in this study showed that offshore seaweed cultivation has a promising potential for nutrient bioextraction in the North Sea. However, nitrate depletion could occur during the last months of cultivation, when primary productivity is naturally lower. It is recommended that further research on the ecological effects of this nitrate depletion is conducted, and measures are taken to minimise the risk of detrimental effects. It is concluded that a combination of nutrient analyses and monitoring technologies could provide a more comprehensive understanding of the impact of large-scale offshore seaweed cultivation. Subsequently, this can create a solid foundation for the development of ecosystem services and the further development of the offshore seaweed sector in the near future.

Land and water are two basic resources for humanity that are in high demand; they are essential for producing myriad essential resources. However, these resources are under pressure due to population growth, economic development, and environmental changes. Due to this increased pressure on terrestrial resources, the attention of a myriad of industries is shifting towards the use of alternative, low-emission resources. Seaweed cultivation has presented itself as a contribution to the mitigation of the increased pressure on current resources. Seaweed, also referred to as macroalgae, is a highly useful type of algae and can be used for numerous products such as cosmetics, health products, horticulture, food industries, textiles, and biofuel production. In addition to offering a wide range of advantages through its applications, it is also frequently suggested that seaweed could provide ecosystem services during its growth by bioextracting nutrients from eutrophic waters. Although large-scale seaweed farming has been practised for decades in Asia, it has only recently become a commercial industry in Europe. However, European seas are congested; coastal sites are becoming scarce and offshore aquaculture development often collides with other maritime activities, resulting in competing claims to marine space. Currently, there are seven operational offshore wind farms in the North Sea. By 2030, it is expected that ten additional offshore wind farms will be constructed in the Dutch part of the North Sea. Subsequently, offshore seaweed aquaculture in multi-use platforms at sea (MUPS) has been proposed as one of the possibilities for smart use of ocean space. However, as this is a relatively young technology, there are still many unknowns. As nutrient load and primary productivity gradually decrease when moving further offshore, analysing the nutrient dynamics of seaweed in an offshore context is worth looking at in more detail.

Analysing the nutrient dynamics of a large-scale seaweed farm is complex but can be done in several ways. In-person monitoring of the seaweed growth is impractical due to the distance from shore, the risk for personnel, labour expenses, and the required output volume. Therefore, remote sensing could be a viable monitoring option, resulting in a better understanding of the nutrient flows. Another option, which has been widely recommended by scholars, is to create dynamic mathematical models of the carbon and nutrient flows of seaweed cultivation. These measures could improve the understanding of the nutrient dynamics of large-scale seaweed cultivation. A better understanding of these nutrient flows could aid the current position of seaweed cultivation in terms of the establishment of ecosystem services through policies and potential monetary benefits.

In this study, critical nutrient flows of large-scale seaweed cultivation in MUPS at the North Sea are quantified, and the impact on local nutrient stocks is assessed. This assessment is performed by developing a dynamic nutrient model. In this model, two seaweed farming scales were modelled: (1) a farm producing for a high-end chemicals factory and (2) a farm producing for a biorefinery for fuels. These two farms were modelled on four current and future wind farm locations during one cultivation season, using location-dependent environmental variables as influx data. For this analysis, the seaweed species *S. latissima* was selected, as this is the most commonly cultivated species in Europe. From the results of this model, an assessment was made of the nutrient uptake dynamics of carbon, nitrogen, and phosphorus, and the impact on the local nutrient stocks.

Moreover, this study examines how monitoring technologies can best be used in seaweed cultivation in MUPS. This assessment was performed by a combination of expert interviews and literature research. Furthermore, this study aims to translate the ecological impact of seaweed cultivation into ecosystem services. This assessment was conducted through literature research and expert interviews. Furthermore, the results of the nutrient analysis are used to assess the potential of ecosystem services. In addition, potential challenges and opportunities in establishing these ecosystem services are discussed. Finally, the results of this study are combined to assess whether it is possible to establish ecosystem services through large-scale offshore seaweed cultivation in the North Sea using monitoring technologies and nutrient analyses.

From the nutrient analysis, it becomes clear that offshore seaweed cultivation in MUPS has a significant potential for nutrient bioextraction. Through the results of the mathematical model, it was demonstrated that up to $2.84*10^8$ [kg] of carbon, $1.25*10^7$ [kg] of nitrogen, and $2.10 *10^6$ [kg] of phosphorus could be bioextracted at a large-scale offshore seaweed farm during one cultivation season. Another finding in this assessment is that the yield and the carbon content from the farms located further from shore are higher. This is likely caused by the relatively lower and more stable temperature further from shore – which is beneficial for the growth and carbon uptake – compared to farms relatively closer to shore.

In addition to the nutrient bioextraction potential, the impact on the local marine nutrient stocks was assessed. This assessment concluded that phosphate and carbon do not appear to limit seaweed growth in an offshore context in the North Sea. However, the nitrate uptake of large-scale offshore cultivation seemed to have the potential of depleting the local nitrate stocks, which could induce unforeseen effects on the marine ecosystem. Therefore, further research using hydrodynamic biogeochemical nutrient models is recommended.

In the assessment of the role of monitoring technologies, the advantages, disadvantages, opportunities and associated costs of various monitoring technologies were discussed. This assessment concluded that some common monitoring technologies, such as small unoccupied aircraft systems, satellites, and autonomous/unoccupied surface vehicles, do not appear to provide the features that an offshore farm requires due to high operational expenditures, inadequate monitoring capabilities, or low manoeuvrability. Other monitoring technologies, such as smart buoys, remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs), appear to be a better fit for large-scale offshore seaweed cultivation. Smart buoys could be used to conduct measurements on environmental variables. ROVs and AUVs could be used for detailed local inspection of the crops and infrastructure. These measurements are especially attractive in the current early stage of the industry, where cultivation methods are being developed, and local effects are still being understood. When the industry gradually moves from research to exploitation, measurements of environmental variables can be minimised, and inspections with the goal of maximising output can be implemented.

The assessment of the translation of ecological effect into ecosystem services was conducted through an analysis of the current European and Dutch policy climate regarding seaweed cultivation. In addition, an assessment of current barriers in cultivation technologies was performed. These analyses concluded several findings. First, although some initiatives and subsidies are available for seaweed cultivators in the nursery phase, the need for more grants and more favourable policies is essential for the European seaweed sector to take off. However, the main barrier to a more favourable policy and subsidy climate regarding seaweed aquaculture is the uncertainty of detrimental ecological effects. This barrier could be overcome by providing the seaweed industry with a solid foundation on the nutrient bioextraction potential and impact of offshore seaweed cultivation. A part of this solution could be developing advanced nutrient models. The exploratory nutrient assessment in this study illustrates that offshore seaweed cultivation in MUPS has a significant potential for nutrient bioextraction; however, advanced biogeochemical nutrient models are needed to fully grasp these dynamics and their effects on the local marine environment. Furthermore, it was concluded that in order to translate the avoided social costs through nutrient extraction into legislation and compensation, the nutrient content of seaweed would best be measured through laboratory measurement of the nutrient content of the seaweed, combined with registration of the amount of seaweed produced. These statistics, in combination with mathematical models and real-time data from monitoring technologies, could lead to a better understanding of the ecological effects of large-scale offshore seaweed cultivation and, subsequently, to a solid foundation for the further development of the offshore seaweed industry.

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For the past two years, I have attended the MSc Industrial Ecology at Delft University of Technology and Leiden University with enormous satisfaction and joy. The past seven months mark the final stretch of my road to becoming an industrial ecologist. I am grateful to contribute to research on a topic that sparked my interest during my studies: seaweed.

This project started with an open-ended question about the ecological effects of large-scale offshore seaweed cultivation. As I deep-dived into this topic, I knew I was getting myself into a challenging project. Modelling biological processes is not only complex but also outside of my comfort zone. I hoped that pursuing a research scope outside my comfort zone would enable me to gain experience that would be beneficial for my career as an industrial ecologist and valuable in general. Looking back at my progress, I am astonished by the sense of accomplishment I felt after becoming more proficient in conducting nutrient analyses, developing code, and the mathematics behind these processes. While I am still far from an expert, I have learned valuable insights about the possibilities of seaweed's cultivation and application. I hope seaweed and I cross paths again in my career, as I look forward to diving deeper into this fascinating sector.

I sincerely hope you will enjoy the read, and this report will provide you with new insights.

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List of abbreviations and definitions

ASV	Autonomous Surface Vehicle
AUV	Autonomous Underwater Vehicle
Benthos	The lowest ecological zone in a water body. It usually involves the sediments on the seafloor
C	The symbol for the chemical element carbon
CapEx	Capital expenditures
DIC	Dissolved inorganic carbon: sum of carbon dioxide, bicarbonate and carbonate
DIN	Dissolved inorganic nitrogen: sum of nitrate, ammonia, and nitrite
DIP	Dissolved inorganic phosphorus: sum of phosphoric acid, phosphate and hydrogen phosphate
DOC	Dissolved organic carbon: is mostly created by marine organisms and consumed in the surface ocean. It mainly consists of carbohydrates, proteins, and other substances that marine bacteria may readily utilise.
DOM	Dissolved organic matter: a heterogeneous mixture that mainly consists of bacteria, algae, and the byproducts of plant degradation.
DON	Dissolved organic nitrogen: the nitrogen-containing component of DOM in aquatic ecosystems
DOP	Dissolved organic phosphorus: the phosphorus-containing component of DOM in aquatic ecosystems
dw	Dry weight: the weight of seaweed after drying
Ecological carrying capacity	The maximum amount of seaweed that can be harvested without having a substantial detrimental impact on the ecological functioning of an area.
Ecosystem service	The benefits that humans depend on, consciously or unconsciously, directly or indirectly. They are provided by functioning natural or engineered ecosystems.
GHG	Greenhouse Gas
Half-saturation constant	the concentration supporting an uptake rate one-half the maximum rate
IMTA	Integrated Multi-Trophic Aquaculture
IoT	Internet of Things
LCA	Life Cycle Assessment
Macroalgae	Seaweed
Microalgae	Microscopic algae invisible to the naked human eye
MFA	Material Flow Analysis
MUPS	Multi Use Platform at Sea
N	The symbol for the chemical element nitrogen
OpEx	Operational Expenditures
O&M	Operation & Maintenance
P	The symbol for the chemical element phosphorus
Pelagic zone	The water column of the open, free ocean waters, away from shore.
POM	Particulate organic matter
ROV	Remotely Operated Vehicle
Saccharina latissima	Also known as *S. latissima* or sugar kelp. A brown alga of the family Laminariaceae
Social costs	an estimate of the economic costs, or damages, of emitting greenhouse gases into the atmosphere
Spring bloom	A significant increase in phytoplankton stock, lasting until late spring or early summer.
sUAS	Small Unoccupied Aircraft Systems
TEA	Techno-Economic Assessment
USV	Unoccupied Surface Vehicle

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1. Introduction

1.1 Background

Two fundamental resources for humankind for which there is an increasing demand are land and water; both are crucial resources for the production of crucial resources. Population growth, economic development, and environmental changes put these resources under pressure (Schneider et al., 2010). Agricultural activities are considered key drivers of ecosystem and biodiversity loss (Diaz et al., 2019). As terrestrial agriculture has an increasing impact on climate change, attention is shifting towards the use of alternative, low-carbon resources (Verschuuren, 2016). Aquaculture is expected to play a crucial role in supplying myriad resources to the ever-increasing human population (Troell et al., 2014; FAO, 2018).

The European Union is reinforcing its transition to a low-carbon and low-energy economy through various interconnected policies and mechanisms (Eckert et al., 2021). The Blue Growth concept, a long-term strategy to support sustainable growth in the marine sector (Soma et al., 2018), has sparked interest in offshore technologies. In addition, the EU's ambition to become a low-energy economy and use secure, safe, competitive, locally produced, and sustainable energy has been bolstered by mounting evidence of climate change and growing reliance on energy. With fossil fuel reserves dwindling and the amount of greenhouse gases in the environment rising, there is increasing demand for the development of more sustainable energy sources. The offshore production of seaweed to produce advanced biofuels could play a vital role in the transition toward a more sustainable energy economy (Tagliapietra, 2019).

A contribution to the mitigation of the aforementioned increased pressure on resources could present itself in the form of seaweed cultivation. Seaweed, also referred to as macroalgae, is a highly useful type of algae and can be used for cosmetics, health products, horticulture, food industries, textiles, and biofuel production (Olanrewaju et al. 2015a, 2015b). Furthermore, its cultivation has the potential to provide high volumes of nutrient-rich food for human consumption. Seaweed farms also act as a CO_2 sink, as they release carbon that can be buried in sediments or exported to the deep sea (Duarte et al., 2017). Therefore, seaweed cultivation has also been acknowledged as an opportunity to capture greenhouse gas (GHG) emissions. Moreover, aquatic farms appear to be more sustainable than land-based agriculture, as their products do not require chemical fertiliser, fresh water, or land, which are all important drawbacks of land-based agriculture (Tiwari et al., 2015). Optimising and innovating the seaweed industry could therefore be a highly sustainable and socially beneficial venture.

Coastal sites in The North Sea are congested (McGlade, 2002). Therefore, moving the operation offshore would be an obvious choice. However, offshore development often collides with other maritime activities, resulting in competing claims to marine space. Multi-Use Platforms at Sea (MUPS) could be an approach to optimising seaweed cultivation. The multi-use procedure is depicted in Figure 1. The North Sea is a location with potential for offshore aquaculture development, as it is considered a highly productive sea (McGlade, 2002). The North Sea has a high nutrient load and high primary productivity in coastal areas, which gradually decreases when moving further offshore. Currently, there are seven operational offshore wind farms in the North Sea. By 2030, it is expected that ten additional offshore wind farms will be constructed in the Dutch part of the North Sea (Ministry of Housing, Spatial Planning, and the Environment, 2020). Subsequently, interest in the multi-use of these offshore wind farms is increasing.

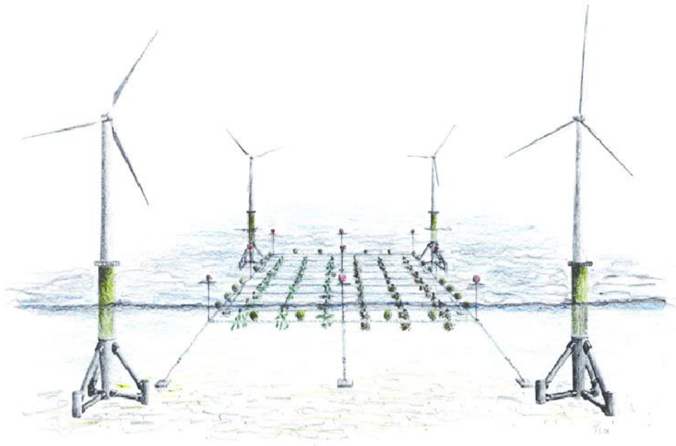


Figure 1: Sketch drawing of potential multi-use management of a wind farm (Michler et al., 2007))

As in-person monitoring is impractical due to the distance from shore, risk for personnel, labour expenses, and the required output volume, remote sensing could be a viable monitoring option. Fortunately, sensor technology and data availability advances have aided the application of remote sensing to assess macroalgae biomass dynamics, tissue composition, and nutrient concentrations. As a result, deploying Autonomous Underwater Vehicles (AUVs) and other remote monitoring vehicles could greatly assist the infrastructure of offshore aquatic farms.

Offshore aquatic farming in MUPS is a relatively young technology, and there is still much to learn. Nederlandse Organisatie voor Toegepaste Natuurwetenschappelijk Onderzoek (TNO) has been researching processing of seaweed to produce fuels, chemicals and high-value (co-)products. Recently, TNO has launched a team researching the possibilities of seaweed cultivation systems in offshore wind farms. Research is also being conducted on monitoring technologies and the contribution this technology could bring to seaweed farming. The current plan is to conduct research on monitored seaweed cultivation in these Dutch offshore wind farms in the North Sea. The research presented in this thesis is carried out on behalf of TNO, Delft University of Technology, and Leiden University. The exact research objectives can be found in the section Research aim.

1.2 Problem statement

Large-scale seaweed farming has been practised for decades in Asia (Cheng, 1969), but it has only recently become a commercial industry in Europe (Bostock et al., 2016). In the Netherlands, seaweed cultivation only takes place on a small scale, and offshore aquatic farming is globally not present. This form of aquaculture has rapidly expanded in Asia, and later Europe due to the increasing demand for seaweed. The development of large-scale seaweed aquaculture in Europe has the potential to play a significant role in addressing future resource requirements. Still, it must be executed in a way that does not jeopardise current ecosystems and the usage and value of existing marine resources.

Offshore aquatic farming has been proposed as one of the possibilities for smart use of ocean space, leading to opportunities for innovative entrepreneurship (Röckmamn et al., 2017). The advantages of offshore aquatic farming are numerous. However, as it is a relatively new technology, many unknowns remain.

The effect that seaweed cultivation in MUPS at the North Sea has on the ecosystem around wind farms is also an area that is still subject to research. One of the main questions for offshore seaweed cultivation is the ecological carrying capacity, i.e. the maximum amount of seaweed that can be harvested without having a substantial detrimental impact on the ecological functioning of the North Sea. For example, scaling up seaweed farms could disrupt nutrient balances, cause a nuisance for marine life, or cause other unforeseen problems. To successfully create a baseline for safe operating conditions and assess the ecological effects of placing this technology in offshore wind farms, TNO first needs to establish what exactly needs to be monitored by the monitoring system. So far, ex-ante LCA studies have shown a positive environmental impact in the eutrophication category during the cultivation phase due to the uptake of nutrients by seaweed cultivation (Droog, 2021). However, when farms are scaled up, and the proportion of nutrients removed by seaweed cultivation exceeds the natural and anthropogenic addition of nutrients, an imbalance of nutrients may occur. This will result in nutrient concentrations that are lower than those required for natural primary productivity (Campbell et al., 2019). This imbalance in nutrient concentration may also result in disharmonised water quality and biodiversity. Hence, to sustainably intensify offshore aquaculture without causing ecosystem damage, more research is required to determine the exact ecological effects.

1.3 Existing literature and research gap

As a result of the growing interest and demand for seaweed, an increasing amount of research is performed on the feasibility and the ecological effects of (offshore) seaweed aquaculture in the Netherlands. However, as it is a fairly new concept, there is still a lot to be discovered. The existing literature is analysed in this section, and research gaps are stated.

1.3.1 Seaweed cultivation in Europe

A basic understanding of seaweed species, lifecycles and common cultivation practices in Europe is important to understanding aquaculture's ecological effects. A brief elaboration on this is given in this section.

Seaweeds are divided into three principal phyla, based on their pigmentation: Chlorophyta (green algae), Rhodophyta (red algae) and Ochrophyta-Phaeophyceae (brown algae). These phyla are further divided into thousands of groups based on their metabolic processes, their structural polysaccharides, and the important pigments they include (Burg et al., 2012). Brown algae, also referred to as kelp, are dominant in Europe due to their high growth rate at lower temperatures (Raven et al., 2002). In particular, the *Saccharina latissima* is the most cultivated species in Europe (Araújo et al., 2021).

The natural lifecycle of seaweed is complex and varies widely between species. As illustrated in Figure 2, seaweed begins as a microscopic spore in the sporangia (structure in which spores are formed) on the seaweed blades. These spores develop into male or female gametophytes. The minuscule gametophytes produce eggs and spermatozoids, which fertilise and grow to form sporophytes. These sporophytes hatch onto their surroundings, grow, and develop larger leaves over the course of several months (depending on species). As the kelp grows, its sporangia release more spores, after which the process starts again.

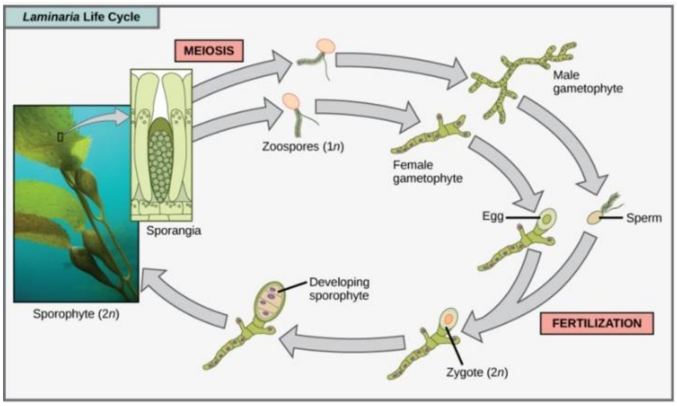


Figure 2: The natural lifecycle of the brown algae Laminaria (Open Stax College, 2013)

The lifecycle of produced brown algae is fairly similar to the natural lifecycle. The production of large brown kelp species (e.g. *Undaria pinnatifida* and *Saccharina latissima*) typically begins in autumn or the beginning of winter, when the sporangia are induced to release spores by temperature and/or osmotic shock. The produced zoospores develop into gametophytes, after which they fertilise and form sporophytes. Subsequently, the sporophytes are cultured on small ropes or twines. After hatching onto these ropes or twines, the sporophytes are transferred to the sea (Rolin et al., 2017).

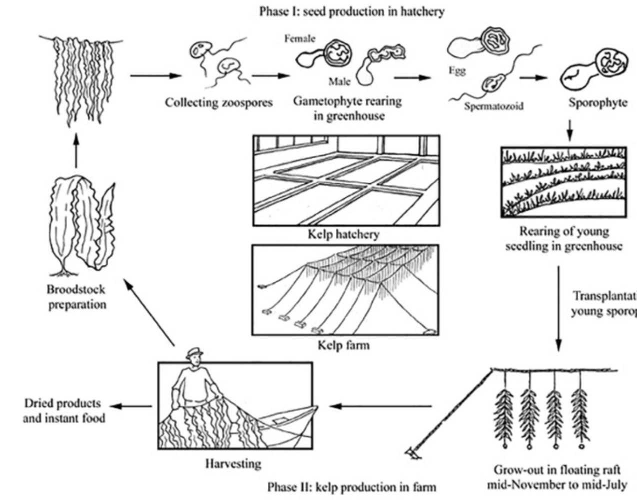


Figure 3: The production lifecycle of brown algae

A variety of long-line systems with vertical droppers are used in Asian brown seaweed production; comparable growth techniques have been successfully tested in European countries (Peteiro et al., 2016). The aforementioned seeded material is deployed and suspended from a mooring structure. Typical culture systems are illustrated in Figure 4. Brown algae typically have an optimal growth rate at 1 to 5 metres below the surface. Culture systems can be anchored with anchors (A) or fixed poles (B). Typical culture rope systems include either (C1) the hanging, (C2) horizontal, or (C3) hanging ropes.

Marine conditions are typically rougher when moving further off the coast, so the aforementioned culture systems are less suitable. Additionally, anchored culture systems are less suitable as the sea gets deeper due to high friction from currents on the longer structural ropes. Therefore, several other culture systems that are more appropriate for offshore conditions have been designed. As offshore aquaculture is still a relatively new technology, designs are still in development. There are a number of designs, and some prove to be more successful than others. One example of a successful design is a type of ring structure along with wind farms. This design has been successfully tested in deep waters (> 100 m) in the early 2000s in the North Sea (Buck and Buchholz, 2004). The ring structure culture system is illustrated in Figure 5. An example of a less successful design was the SPAR buoy and H-frame design, which was tested in the North Sea in 2012 (see Figure 6). The buoyancy-changing passive system was designed to protect the structure and biomass from adverse weather (Buck et al., 2017). However, during deployment, part of the structure came loose, causing the system to sink. (Bak et al., 2020). In conclusion, it is crucial to consider the extreme offshore weather conditions when deploying aquaculture in MUPS.

As anchorage and protection are a challenge in the harsh offshore conditions, wind farm structures may offer a solution (Reith et al., 2005). An example of a wind farm integrated with seaweed aquaculture is seen in Figure 7. Solutions like these would offer a multitude of benefits, such as lower CapEx and OpEx, and reduce potential conflicts with fisheries (Buck and Buchholz, 2004). Furthermore, attaching seaweed aquaculture to wind farm structures offers the possibility of installing the

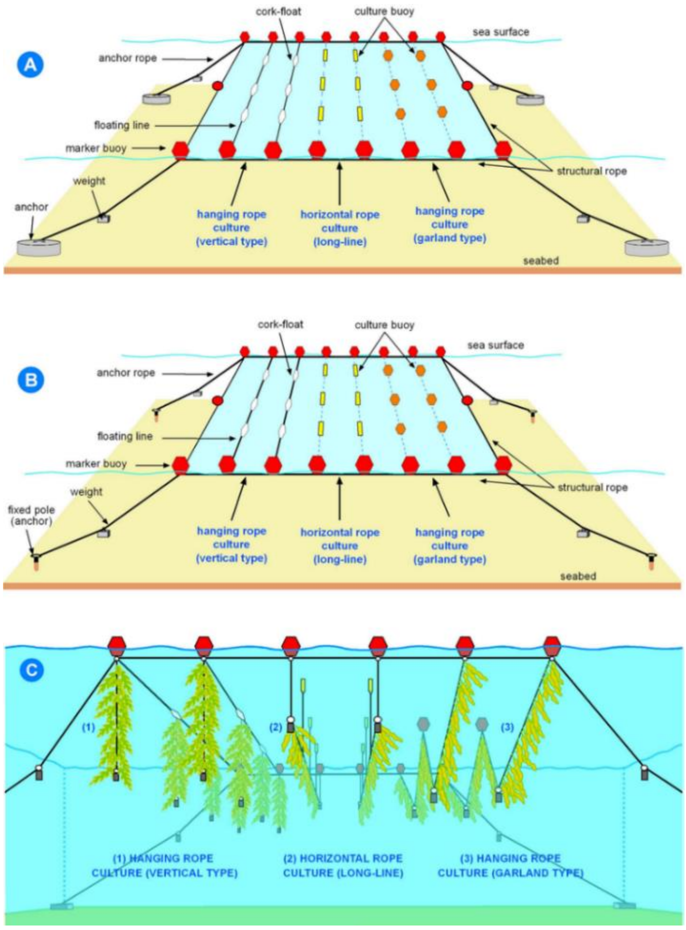


Figure 4: Floating raft culture (Peteiro et al., 2016)

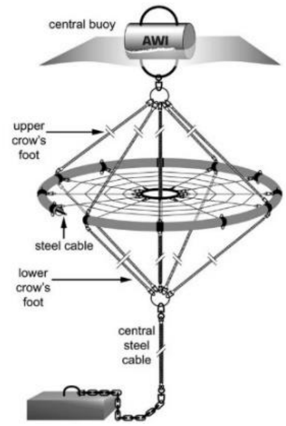


Figure 5: Design for ring culture system at offshore locations (Buck and Buchholz, 2004)

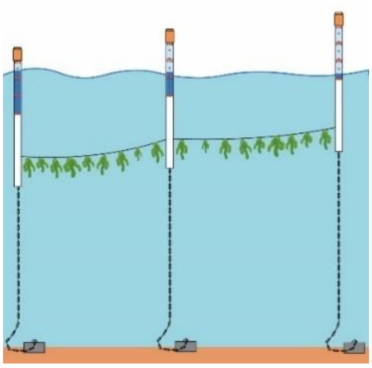


Figure 6: H-frame SPAR buoy seaweed cultivation system

cultivation system at different depths. However, as this is a novel technology, the optimal design is still a subject of research.

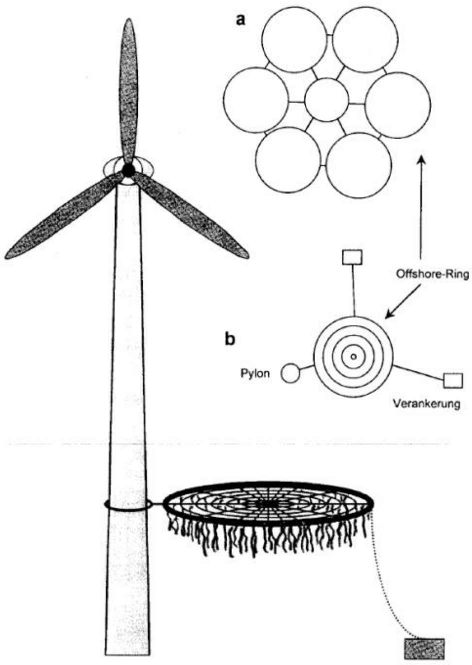


Figure 7: Wind farm integration with seaweed cultivation ring (Reith et al., 2005)

One of the latest successfully tested designs for offshore cultivation is the Macroalgae Cultivation Rig (MACR), developed by Ocean Rainforest. The system was designed to withstand the hydrodynamic forces of the North Atlantic Ocean, using durable, lightweight, and relatively low-cost materials. The design is displayed in Figure 8 and consists of a polysteel fix line (C), two main surface floats (D), 1 to 1.5t steel anchors (E), and a number of culture lines (B)). The design was successfully tested with various types of macroalgae. Although the MACR is currently considered one of the most successful offshore cultivation systems (Bak et al., 2018), several challenges must be tackled. First, yield should be increased, and OpEx should be lowered to improve financial viability. Longer culture lines, optimised seeding methods, selective breeding, and mechanised harvesting methods could contribute to the further optimisation of the MACR.

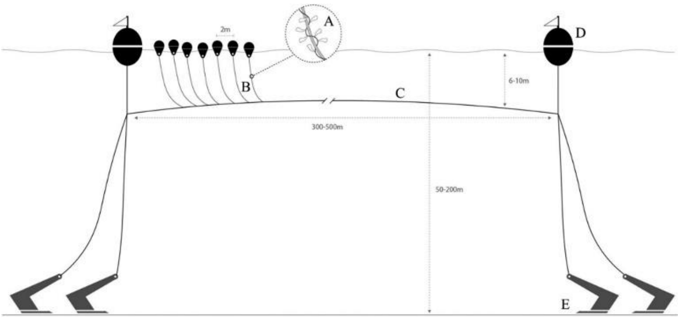


Figure 8: Schematic drawing of the Macroalgae Cultivation Rig (MACR), developed by Ocean Rainforest (Bak et al., 2018)

1.3.2 Current applications of seaweed

Seaweed has myriad applications and services for human use, which have changed over the centuries. In this section, the most common applications of seaweed are discussed.

Food

The most well-known application of seaweed is the food industry. Roughly 47% of the produced seaweed is used as human food (Ullman et al., 2021). The earliest evidence of seaweed use can be found in Emperor Shen Nung's compendium of "Chinese herb" from 2700 BC (Kasimala et al., 2015). In Asia, seaweeds have been used for centuries in soups, salads, low caloric dietetic foods and other types of meals. As seaweed as food has increased in popularity, the demand has now also spread to Europe, North America and South America (Kılınç et al., 2013).

According to a growing body of studies, consumption of algal food products may have health and nutritional benefits. Although seaweeds have a highly variable composition, they generally have a high nutritional value. They are low in lipid, contain essential amino acids and have high fibre and carbohydrate content (Rajapakse and Kim, 2011). Carotenes, vitamin C, and vitamin B12, typically exclusively found in animal-based goods, are all abundant in seaweeds. However, several fundamental problems, such as the effects of seasonal and regional variation on the composition and nutritional content of algal biomass, remain unsolved (Wells et a., 2016).

Additionally, seaweeds tend to accumulate heavy metals (arsenic), iodine and other minerals (Makkar et al., 2016). Consumption of seaweed in large amounts could pose a threat to human health. Toxic and other unwanted conditions may be avoided if seaweed minerals are regularly monitored.

Consumer acceptance is one of the most significant issues when incorporating seaweed into food products. When choosing their cuisine, customers are influenced by sensory characteristics such as flavour, sight, and texture (Birch et al., 2019). Some people dislike the taste of seaweed, while others dislike the greenish colour generated by its pigments. This dislike could be because seaweed is not often consumed in Western countries (Palmieri and Forleo, 2020).

Hydrocolloids

Another significant application of seaweed is the production of hydrocolloids. Over 50% of produced seaweeds are used to produce hydrocolloids (Ullman et al., 2021). Hydrocolloids are non-crystalline substances and consist of large molecules that can be dissolved in water to create a thicker (viscous) substance, solution or gel. The three main hydrocolloids extracted from seaweed are agar, alginates and carrageenan.

Feedstock for biofuels

The current consumption of fossil fuels is not only limited in sustainability due to its finite resources but also by detrimental environmental consequences. Because fossil fuel sources are rapidly depleting, renewable fuels– including biofuels – will become increasingly vital in meeting energy demands. Some common seaweed species, like *Saccharina latissima*, could become a promising feedstock for biofuels. Seaweed contains between 85 and 90% water, making it ideal for biofuel production processes such as anaerobic digestion for biogas and fermentation for ethanol. Additionally, several seaweed species, such as the *Saccharina latissima*, have a high carbohydrate and low lignin content. These characteristics make these species ideal for bioethanol production.

Furthermore, when comparing seaweed-based ethanol or methanol with other prevailing fuels, a myriad of studies show a significant decrease in, e.g. GHG emissions, ozone depletion and fossil depletion (Singh, 2011; Alvarado-Morales, 2012; Langlois, 2012; Peng, 2020). However, a significant constraint in the prospect of industrial seaweed biofuel production is that commercial-scale quantities of macroalgal fuel are currently not economically feasible, as macroalgal cultivation solely for biofuels is not profitable yet (Yong et al., 2022). Expanding the current production line and producing high-value products could make macroalgal cultivation more profitable (Davis et al., 2017).

Fertilisers

Coastal populations along the Atlantic coast of Europe have been exploiting seaweed for soil improvements for centuries; wreck seaweed was scavenged and spread on dunes to be dried for year-round preservation (Arzel, 1987). The mineral composition of fibre acts as a valuable fertiliser and source of trace elements, while the fibre content acts as a soil conditioner and aids moisture retention. These activities dwindled with the upcoming of synthetic chemical fertilisers. However, as organic farming has been gaining popularity in recent years, seaweed-based fertilisers could return for a small-scale revival (Løes et al., 2021).

Cosmetics

Seaweed has a myriad of applications in cosmetics. Marine cosmetics, also known as phycocosmetics, are widely spread and an economic reality. Lotions and creams containing a seaweed hydrocolloid are the most common cosmetic products linked with seaweeds. The hydrocolloids alginate and carrageenan improve the moisture retention of the skin.

Fodder

Seaweeds have a long history of utilisation as livestock feed. It was mentioned to be included in livestock diets in Ancient Greece and Iceland sagas thousands of years ago. Furthermore, seaweed in the diets of livestock and wildlife has been common in e.g. Ireland, France, the Scottish Islands, Scandinavia, the United States and Germany (Evans and Critchley, 2014; Chapman and Chapman, 1980; Hansen et al., 2003). However, with the upcoming of nutritional sciences in the first half of the 20th century, it became the general consensus that seaweeds contained too few nutrients to be recommended for livestock (Evans and Critchley, 2014).

Since the 1960s, when Norway began making seaweed meals from kelp, seaweeds have regained popularity as feed additives (McHugh, 2002). Seaweeds are currently considered a valuable alternative feed for livestock due to their content of nutrients, micro-minerals, complex carbohydrates, pigments and polyunsaturated fatty acids (Evans and Critchley, 2014). Brown, red and green seaweeds have been successfully tested in the diets of, amongst others, ruminants, pigs, poultry and rabbits. A fascinating result from these investigations is that seaweeds seem to have the ability to significantly reduce ruminal methane production (Hristov et al., 2015; Maia et al., 2016; Kinley et al., 2020). However, as mentioned previously, seaweed has a highly variable composition. Therefore, it is suggested that more research is conducted to assess the effects of specific compositions on ruminants and their products.

Nutritional supplements and medicines

The use of seaweed for medicinal purposes dates back centuries. For example, findings from ~14,600 years ago suggest that the inhabitants of Chile had a firm reliance on coastal resources for food and medicine (Dillehay, 2008). Since then, various claims have been made about seaweed's nutritional and health advantages. While the use of seaweed in therapeutic and health-promoting applications is prevalent in Asian countries, it is still a relatively new concept in Westernised countries. Seaweed is often used in nutritional supplements in Europe due to its high content of carbohydrates, protein, lipid, proline, nutrients, chlorophyll, and potassium (Syad et al., 2013). These supplements are most commonly available as pills, oils, and powders.

Seaweeds have been claimed to have healing properties for a variety of disorders, including cardiovascular disease, metabolic syndrome, diabetes, cancer, and many others. However, many of the alleged medical properties of marine algae have yet to be verified (Brown et al., 2014), have high production costs, and complex approval procedures (Jan Wilco Dijkstra, pers. comm., August 10, 2022). Therefore, the use of seaweed as a nutritional supplement is currently more common than as a medicine.

Bioplastics

As plastic pollution is a significant concern in today's world, the development of biodegradable plastics could mitigate this problem. These plastics take less time to decay, are non-toxic, save energy during manufacture, reduce waste generated or space necessary to manage waste, release less GHGs, and consume fewer fossil fuels (Porta, 2019). Bioplastic crafted from seaweeds – given a green manufacturing method is used – could enhance the bioplastic marketplace and contribute to the bioeconomy (Lim et al., 2021).

Integrated multi-trophic aquaculture

Integrated multi-trophic aquaculture (IMTA), similar to polyculture, is a system where two or more aquatic organisms are farmed together (see Figure 9). Species at lower trophic levels (typically invertebrates or plants) use waste products from higher trophic species (typically fish) as nutrients. Potential benefits of these types of artificially balanced ecosystems could include:

- Mutually beneficial relationships between cultured organisms;

- Enhanced profitability per cultivation unit;
- Mitigation of eutrophication;
- Economic diversification.

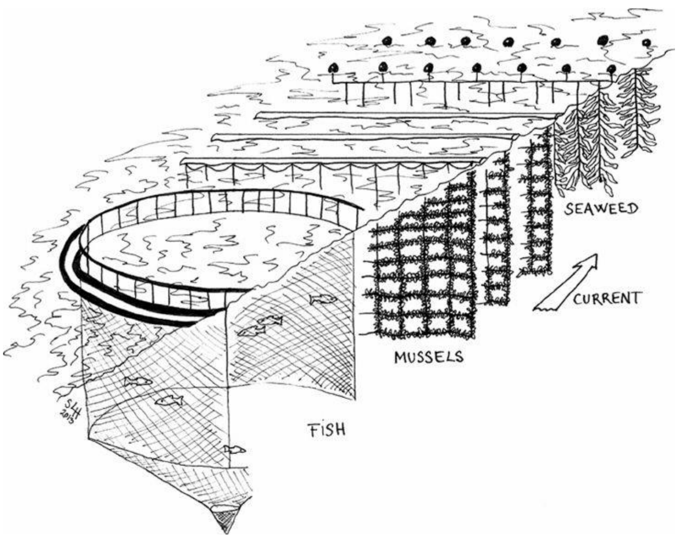


Figure 9: Example of an IMTA (Holdt and Edwards, 2014)

Ecosystem services

As discussed above, seaweed can provide a myriad of products and benefits after harvesting. However, during growth, it can also provide services to humans. The benefits of the natural environment and healthy ecosystems to the human world are referred to as ecosystem services.

The production of seaweed is a sector that has the ability to support both economic growth and ecosystem services (Hasselström et al., 2018). Various studies show that macroalgae cultivation has the potential to sequester significant amounts of carbon, nitrogen and phosphorus (Broch and Slagstad, 2012; Holdt and Edwards, 2014; Pechsiri et al., 2016). This could be especially beneficial for eutrophicated European coasts.

Looking at it from this perspective, seaweed cultivation has two interesting foci: an 'industrial' product and an 'environmental' measure (Hasselström et al., 2020). Although there may be a double benefit to seaweed farming, unless regulators successfully connect the two through financial recompense to farms, such as compensation for ecosystem services, it must compete on its own as an industrial product. The ecosystem services of seaweed are discussed in more detail in the chapter Ecosystem services.

Future applications

Researchers are just starting to discover the stunning possibilities of seaweed applications; besides the expansion of the previously discussed applications, there are still many new technologies under development.

One technology currently receiving a lot of attention is the use of chlorophyll based-dyes obtained from seaweeds in dye-sensitised solar cells (DSSC). A DSSC is a type of low-cost solar cell belonging to the group of thin-film solar cells (Al-Alwani et al., 2016). Using natural pigments instead of chemicals results in a non-toxic, environmentally friendly, less labour intensive and low-cost process (Orona-Navar, 2021). These characteristics make the chlorophyll based-dyes an attractive alternative to conventional chemical synthesis processes.

Another future application of seaweed could be to function as a biosorbent in wastewater. Due to the increasing number of industries and populations, the presence of heavy metals in water bodies has risen. This phenomenon could lead to hazardous consequences for human health and the environment. Current methods for the sequestration of these materials are generally expensive, and seaweed or algae have proven to be a sustainable solution for environmentally friendly adsorbent production (Zhad, 2022).

Finally, a third future application of seaweed could be to extract cellulose from it. Cellulose is the main component of, e.g. paper, cardboard and textiles. The cellulose for these products is currently mainly extracted from terrestrial plants like wood, cotton, flax, hemp, and Jute. However, the cellulose in biomass is partially degraded due to the severe chemical treatment, resulting in environmental concerns (Ververis, 2004). Fast-growing biomass with a high amount of cellulose, such as seaweed, is therefore gaining attention as a supplementary source of cellulose (Baghel et al., 2021).

1.3.2 Ecological effects of seaweed cultivation

The cultivation of seaweed results in a multitude of ecosystem interactions, which may be advantageous (ecosystem services) or detrimental (ecological impact) to the local ecosystem. In this section, the currently known ecological effects of offshore seaweed aquaculture on the marine ecosystem are elaborated upon.

Release of artificial material

To provide a stable substrate for growing seaweed, large-scale seaweed cultivation necessitates the inclusion of artificial materials. As mentioned previously, common systems are constructed of intricate combinations of moorings, lines, and floats. The synthetic aquacultural systems are designed in a way to resist the rough conditions of the ocean. However, if seaweed farms are improperly managed, synthetic parts of the farm may come loose and pollute the marine vicinity. Parts removed from the farm may contribute to environmental pollution problems, like rising plastic contamination in the marine environment and mortality of megafauna. Marine equipment such as netting and buoys are known to release microplastics directly into the ocean (Napper et al., 2022). Therefore, large-scale seaweed cultivation could also result in an increased release of microplastics. The overall amounts and effects of the addition of artificial material are currently unknown. Hence, cultivation operations must be managed responsibly to ensure that the deployed infrastructure is in good condition and suitable to prevent accidental loss of parts (Campbell et al., 2019).

Release of particulate and dissolved organic matter

Oceanic particulate organic matter (POM) and dissolved organic matter (DOM) are significant additions to the world's organic matter reservoirs. Their production and consumption are crucial to the global carbon and nutrient cycles (Barrón and Duarte, 2015; Zhang et al., 2017).

POM can be released by seaweed due to death, physical damage from waves, tissue erosion, and damage from grazers. The organic matter is frequently suspended in the pelagic zone before landing on the benthos. POM may accumulate on the ocean floor, driving the metabolism of benthic microbes and changing the composition of macrobenthic communities. More scientific research is needed to put into perspective what scales and environmental conditions released POM could have harmful effects (Campbell et al., 2019).

DOM is released continuously during growth (Chen et al., 2020). The exact composition of DOM is still subject to research, but it is thought to consist of a complex mixture containing primarily carbohydrates that can contribute to the ocean's dissolved organic carbon (DOC), nitrogen (DON) and phosphorus (DOP) pool (Wada et al., 2013). Ecological implications are believed to be insignificant at low concentrations. However, when released in high quantities, DOC can change the composition and balance of the local microbial communities. The scale of these implications is currently unknown and is highly dependent on the farming scale, local hydrodynamics and seasonality (Campbell et al., 2019.

Release of reproductive material

Selecting and modifying organisms that can live in human eco-environments and exhibit desirable features for human use, also known as domestication, is a lengthy and challenging process (Larson et al., 2014). It often involves a multi-generational relationship between the cultivators and the target organism.

Large-scale seaweed farming methods will inevitably lead to further domestication of wild seaweed cultivars (Valero et al., 2017). Domesticated *Saccharina japonica* (Dongfang no.7) is already widely used on aquatic farms (Li et al., 2016). The exact ecological effects of domesticated seaweed are still prone to research. Still, “crop-to-wild” gene flow has a potential environmental impact, as well as competition with wild populations and hybridisation with natural stands (Halling et al., 2013; Loureiro et al., 2015). It has been suggested to implement more research activities, focused monitoring, and sterile cultivars through national seed banks to reduce the risk of adverse ecological impact (Loureiro et al., 2015; Cottier-Cook et al., 2016; Valero et al., 2017).

Addition of noise

Small to medium-scale macroalgae farms are unlikely to cause any significant ecological effects due to the increase of traffic in the vicinity of the farm (e.g., boats for O&M, harvesting activities). However, if farms are scaled up, local vessel traffic will increase. The increased noise resulting from traffic could cause behavioural reactions from marine life that contribute to local or regional population loss, and adverse environmental effects (such as habitat displacement and barrier effects) may be seen. Although this adverse could be minimsed by the implementation of innovations such as E-boats, this effect should be considered when choosing the site for a macroalgae farm.

Artificial habitat creation

Several studies have investigated the interaction of macroalgae cultivation sites with organisms in their vicinity. For example, these sites are known to interact with various plankton, benthic species, and other epifauna and megafauna species. As prevailing macroalgae cultivation systems are synthetic, man-made objects, they could replace or disturb existing habitats. For example, seaweed is known to compete with phytoplankton for nutrients in both low and high nutrient levels (Fong et al., 1993). Furthermore, large-scale seaweed cultivation could alter the benthic community structure by releasing high amounts of POM (Cromey et al., 2002). A study on the ecological effects of aquaculture of *Saccharina latissima* concluded that the amount of benthic infauna increased in the vicinity of the farm (Visch et al., 2020), meaning that the farm positively impacted its surroundings. Lastly, natural kelp beds are known to provide habitat to a wide variety of epifauna and megafauna species (Norderhaug et al., 2005). However, the likelihood that epifauna and megafauna will avoid or be drawn to cultivation activities is unknown. Any reaction is likely to be location- and species-specific (Campbell et al., 2019).

Habitat for diseases, parasites and non-native species

Cultivated seaweeds are susceptible to diseases, parasites and pests that can cause dramatic drops in biomass production. Despite the growing interest in seaweed aquaculture in Europe, diseases, parasites and pests have rarely been researched.

According to Bernard (2018), seaweed diseases are divided into non-infectious and infectious. The former can be caused by various natural and unnatural circumstances. For instance, it can be caused by (sudden) changes in temperature, irradiance, salinity or nutrient availability. Infectious diseases are generally caused by pathogens such as bacteria, oomycetes, filamentous algae or other organisms.

Different disease management strategies have been put forth and tested with varying degrees of success. In case of diseases or other pests, a common method in Asia is to wash the seaweed with acids, iodine or high-nitrogen substances (Kim et al., 2014). However, these procedures are not advised for widespread application in the North Sea because they may not only negatively impact the seaweed biomass but could also result in significant environmental contamination (Bernard, 2018).

As the aforementioned methods against diseases are often considered rudimentary and expensive, prevention should be the main priority for seaweed cultivation in the North Sea (Bernard, 2018). Techniques such as reducing the stocking density could aid in the containment of disease outbreaks. Another suggested method is to lower the culture ropes in times of high irradiance to avoid additional stress caused by light.

Lastly, regular in-person or automated monitoring could aid in the early detection of diseases (Kambey et al., 2020).

When species are introduced to a different ecosystem due to direct or indirect human activity, they could cause significant changes. These species are called non-native species. Once introduced to this new habitat, it is considered extremely difficult, and in most cases almost impossible, to eliminate them. An example is the introduction of the brown kelp *U. pinnatifida* in France in 1983 (Kraan, 2017). Although it was thought incapable of reproducing, it quickly established itself in the area and has since expanded widely. To prevent scenarios like this, the European Commission has implemented a strict set of rules regarding the introduction of invasive alien species (European Commission, 2020). The risk of introducing harmful non-native species should be minimised by following these rules and responsible farm management.

Absorption of light

Whereas natural macroalgae populations are constrained by the amount of available habitat with sufficient light conditions for growth (Burrows, 2012), cultivated kelp must be grown in surface waters at depths where irradiance levels are optimal. Large-scale kelp cultivation could indirectly alter the light influx reaching the benthos. Furthermore, it could shade underlying habitats (e.g., phytoplankton, benthic macroalgae) and cause damage to the ecosystem. Seaweed and culture systems were shown to reduce the amount of light reaching the seafloor at a depth of 9 meters by 1.4% (MacroFuels, 2020). Shading is more likely to impact benthic communities susceptible to change, like seagrass meadows or maerl beds (Eriander et al., 2017). The possibility of adverse benthic shading effects should be considered when choosing a cultivation system and stocking density and when siting the project. To determine potentially harmful interactions at larger scales, a targeted monitoring effort examining phytoplankton changes and their repercussions would be required (Campbell et al., 2019).

Absorption of kinetic energy

Seaweed farms need a water flow to grow. Tidal and wave energy will be absorbed and deflected by the seaweed farms, which could change the flow conditions in the local marine habitat (Campbell et al., 2019). In an observational study by Jackson et al. (1983), it was found that currents in a natural kelp forest are slower than those outside; observed current velocities were about a third of the environment. Changes in water flow may reduce the amount of water exchange required to maintain growth-critical nutrient levels, which may impact a water body's carrying capacity for cultivation (Shi et a., 2011). This phenomenon may increase when macroalgae farms are scaled up. Strategic siting, predictive modelling, and smart cultivation designs should be implemented to make informed decisions and minimise the risk of this ecological effect.

Absorption of microplastics

Microplastic pollution is pervasive throughout the (marine) environment (Alimba and Faggio, 2019). Various studies have demonstrated that microplastics adhere to the surface of suspended seaweeds (Raju et al., 2022) and are absorbed by seaweeds (Li et al., 2020). Microplastic accumulation may diminish the photosynthetic capacity and increase oxidative stress (Karalija et al., 2022). A number of studies showed that these effects could result in reduced growth (Casado et al., 2013; Bergami et al., 2017). In addition, Interestingly, some studies show contained or even enhanced growth when macroalgae are exposed to microplastics (Sjollema et al., 2016). More investigation is required to completely comprehend the consequences because it is yet unclear how various microplastics alter seaweeds' metabolism. It has especially been recommended to assess edible macroalgae's sorption and absorption rates (Alimba and Faggio, 2019).

Absorption of carbon

Seawater absorbs carbon dioxide, which is naturally present in the atmosphere. Water and carbon dioxide combine to form carbonic acid (H_2CO_3). This weak acid dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). As a result of human-driven increases in atmospheric carbon dioxide concentrations, more carbon dioxide is evaporating into the oceans. Aquaculture of fish and other anthropogenic emissions contribute carbon to the marine carbon cycle (Pelletier et al., 2009). As more CO_2 is absorbed, the pH drops, and the sea turns more acidic. Seagrass beds, tidal salt marshes, mangroves, and seaweed aquaculture, on the other hand, are examples of vegetated ecosystems that significantly contribute to global carbon storage in biomass (Duarte et al., 2013). It is unlikely that carbon removal from large-scale seaweed cultivation will cause significant detrimental effects due to the marine waters' chemistry and inherent buffering capacity (Campbell et al., 2019). However, large amounts of photosynthetic materials could take up enough carbon to raise the local pH and mitigate the effects of ocean acidification (Duarte et al., 2017).

Absorption of nutrients

Macroalgae absorb inorganic nutrients from the marine environment during their growth (Kerrison et al., 2015). Beneficial restorative effects may occur when the volume and proportion of nutrients removed are equivalent to those provided by anthropogenic activities. However, if farming reduces nutrient concentrations below those needed for primary production in the natural world, negative effects may result. In this case, large-scale seaweed cultivation could remove a significant quantity of nutrients from the marine environment (Lüning and Pang, 2003)..

Common macroalgae aquaculture systems tend to affect the hydrodynamic movement in the vicinity. On a larger scale, the impact on the water flow could affect the carrying capacity of the marine environment by lowering the amount of water exchange required to maintain the proper amounts of nutrients for growth (Shi et al., 2011). Due to this effect, the macroalgae farm could become nutrient-limited during growth.

Various models and calculations have been developed to predict the nutrient uptake of macroalgae farms. For example, an analysis of the inorganic nitrogen needs for a hypothetical large farm (20 km^2) in the Scottish Clyde Estuary found that 480 tons of nitrogen were extracted annually for a location producing 20 t/ha of dry weight (Aldridge et al., 2012). In another study by Van der Molen et al. (2017), the potential production of four coastal macroalgae farms in the UK and Dutch coastal waters were modelled. These farms were located in Strangford Lough, Sound of Kerrera, Lynn of Lorne and Rhine plume. The model did not detect any large-scale changes in environmental conditions in the environment of the simulated farms. Although this seems like an encouraging finding, further research has been suggested. As this research was conducted in a coastal context, where nutrient concentrations are generally higher (Lubsch and Timmermans, 2019), an assessment of seaweed cultivation in nutrient-poor could provide interesting insights. Therefore, analysing the nutrient dynamics in an offshore context is worth looking at in more detail.

1.3.3 The nutrient dynamics of seaweed

Dissolved nutrients are crucial for the growth of seaweed. Essential nutrients needed for the photosynthesis and growth of seaweed are dissolved inorganic carbon, nitrogen and phosphorus (Roleda et al., 2019). The rate at which these nutrients are assimilated strongly depends on environmental factors such as, e.g. light, temperature, water movement, desiccation, and salinity (see Figure 10). The nutrients are assimilated through the diffusion boundary layer and the cell wall. The products of photosynthesis, exudation and respiration (O_2, OH^-, H^+) are also emitted through these layers. The nutrients enter the cell through active transport, facilitated diffusion, and passive diffusion. An example of nitrate entering a seaweed cell is given in Figure 11. As mentioned previously, seaweed is also known to discharge POM and DOM (which contain DOC, DON, and DOP) due to erosion.

When seaweed is cultivated in an open system, nutrient limitations may occur. A nutrient is considered “limiting” when seaweed requires more than is naturally available (Harrison and Hurd, 2001). Nutrient limitation often results in growth restriction. Hence, it is essential to consider naturally available nutrient stocks, the nutrient uptake rate, and environmental factors to optimise the growth of seaweed.

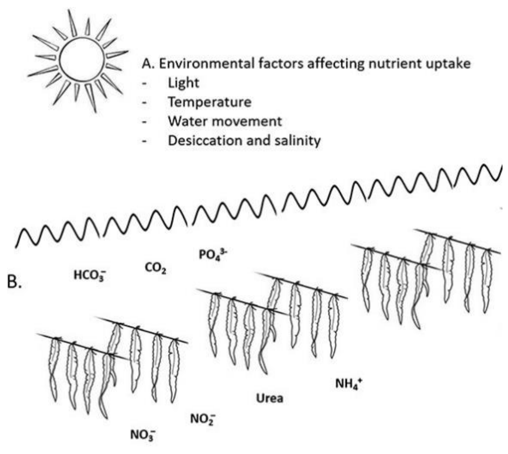


Figure 10: Schematic overview of (A) the environmental factors that regulate the nutrient uptake of seaweed and (B) inorganic carbon, nitrogen and phosphorus (Roleda et al., 2019)

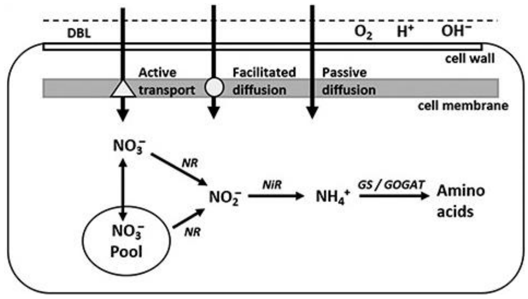


Figure 11: Nitrogen uptake dynamics of seaweed (Roleda et al., 2019)

1.3.4 Prospects of the seaweed market in Europe

Seaweed farming is becoming more popular in the European seas (Bak, 2018). The European Blue Growth plan and national and regional development programs, such as the Dutch Proseaweed program, are, amongst others, driving the increase in interest (van den Broek and van Swam, 2018). However, the production and use of seaweed is still considered a minor sector (van den Burg, 2021).

Dutch seaweed farmers wonder how they can compete in the global seaweed value chain as they seek to grow their seaweed business. Therefore, removing barriers in the European supply chains is now the top priority for farmers and entrepreneurs. The main barriers in the supply chain are:

- High costs of production;
- Rising consumer demand for seaweed-based goods;
- Competition, particularly from Asian countries;
- Worries about the environment and food safety (van den Burg, 2021).

According to Barbier et al. (2019), there is a potential to improve the current position in the European supply chain. This can be done by understanding the present production yields in Europe through homogenised measurements of biomass production. Furthermore, the (national) licensing processes should also be streamlined for improved efficiency and transparency. Implementing these strategies, with more education, training, programs for the entire industry, and a promotion campaign for the social acceptance of seaweed concessions could severely benefit the European seaweed market (Barbier et al., 2019).

1.3.5 Research gap

Various studies on seaweed, its cultivation and its ecological effects have been investigated. As indicated in the previous sections, many subjects in seaweed cultivation (in MUPS) and its ecological effects are still prone to research. In this section, gaps in currently available knowledge are identified.

As mentioned in a vast amount of studies, the exact impact of seaweed cultivation on marine nutrient balances remains unclear. It has been widely recommended that carbon and nutrient cycles are (further) modelled to assess whether the absorption of carbon and nutrients contributes to an overall positive or negative environmental effect (van den Burg et al., 2013; van der Molen et al., 2018; Campbell et al., 2019; van den Burg et al., 2021). For this model, it is of great importance to consider the farm's scale, intensity and location (Eggertsen and Halling, 2021). Gaining a better understanding of the impact on marine nutrient cycles is useful for various reasons. Firstly, this will aid in developing more complete results in LCAs for seaweed cultivation in MUPS. Secondly, the environmental benefits of seaweed products compared with other products are not easily quantified due to a lack of data (Van den Burg et al., 2021). By modelling the nutrient flows, more data can be generated. Finally, a better understanding of the impact on nutrient cycles could be a building block in securing the sustainability of seaweed aquaculture. These findings could stimulate more favourable policies regarding seaweed aquaculture in MUPS.

Quantitative information on the cultivation's environmental effects is not only useful for the aforementioned reasons but is also required to evaluate costs and benefits in monetary terms. High concentrations of nutrients can cause eutrophication, detrimental algal blooms and promote the rapid expansion of bothersome or opportunistic macroalgae, all of which have unfavourable effects on coastal ecosystems and the economy (Kim et al., 2015). A better understanding of these nutrient flows could aid the current position of seaweed cultivation in terms of policies and potential monetary benefits.

Various studies have recommended implementing monitoring systems for the observation of e.g. phytoplankton changes, nutrient concentrations, toxics and other unwanted conditions, early detection of diseases, and “crop-to-wild” gene flows (Valero et al., 2017; Campbell et al., 2019; Kambey et al., 2020). However, it remains unclear how exactly these monitoring systems can best be used in an MUPS context.

1.4 Research aim

This study seeks to quantify critical nutrient flows of seaweed cultivation in MUPS, and assess the impact on the marine vicinity in the North Sea. Moreover, this study seeks to examine how monitoring systems can best be used in seaweed cultivation in MUPS at the North Sea. Furthermore, this study aims to translate the ecological impact of seaweed cultivation into ecosystem services. Finally, the results of this study are combined to assess whether it is possible to establish ecosystem services through large-scale offshore seaweed cultivation in the North Sea using monitoring technologies and nutrient analyses.

1.5 Research questions

The findings in the sections Problem statement, Existing literature and research gap, and Research aim led to the following main research question:

“Can ecosystem services be established through large-scale offshore macroalgae cultivation in MUPS at the North Sea, using nutrient analyses and monitoring technologies?”

The following sub-questions are addressed to answer the main research question:

(1) *“What is the impact of macroalgae cultivation in MUPS at the North Sea on the marine nutrient cycles in the vicinity?”*

(2) *“What role can a monitoring system play in seaweed cultivation in MUPS at the North Sea?”*

(3) *“In what ways can the ecological effects of seaweed cultivation in MUPS at the North Sea be translated into ecosystem services?”*

1.6 Scientific and societal relevance

The results of this study fill a knowledge gap and are highly relevant from both a scientific as well as a societal perspective. In this section, the relevance and added value to scientific groups and society are elaborated upon.

As mentioned previously, seaweed cultivation in MUPS is a fairly new subject on the scientific scene. Therefore, many topics could still be the subject of research. This research project can contribute on a scientific level, as it will explore uninvestigated research topics recommended by previous studies mentioned in the section Existing literature and research gap. The outcomes of this study will provide knowledge that can be used to improve the cultivation of seaweed in MUPS, and explore the role of monitoring systems. Furthermore, it strengthens the understanding of seaweed cultivation in MUPS, which could benefit the development of more favourable policies in this sector.

Conducting this research is relevant from a societal perspective for various reasons. As mentioned previously, current sources of food, chemicals, textile and fuels are under pressure and significantly impact climate change. Optimised seaweed cultivation could benefit society as it could provide an alternative source of protein, chemicals, textile or biofuel (Dhargalkar et al., 2005). Although seaweed is a resource with vast potential, it remains a relatively untapped good in Europe. It is important to recognise various biotechnological issues and societal restraints in its cultivation (Chopin et al., 2014). Gaining a better understanding and optimising its environmental, economic and technical aspects could depressurise the impact of current finite resources.

1.7 Thesis structure

This thesis report consists of logically consecutive chapters that lead to the answer to the sub-questions and concludes with the answer to the main research question. The research methodology is covered in chapter 2. In this chapter, the general research approach is explained. Furthermore, the collection of data is elaborated upon. Moreover, the model that is used to calculate the impact of macroalgae cultivation on marine nutrient flows is explained. Thereafter, the results are presented and analysed in the chapter Results & Analysis. In addition, the model results are validated in this chapter, and a sensitivity analysis is conducted in chapter 4. Discussion, the results are discussed, and the uncertainties and limitations of this research are elaborated upon. The findings of this research are presented in the chapter Conclusion. This thesis report concludes with a recommendation for policy, industry and future research.

2. Methodology

In this chapter, the applied methods for answering the sub-questions are covered. Furthermore, the collection of data is elaborated upon.

2.1 Applied methods

The methods used to generate answers for each sub-question are elaborated upon in the following sections.

2.1.1 Method for modelling the impact of macroalgae cultivation on marine nutrient cycles

The sub-question *"what is the impact of macroalgae cultivation in MUPS at the North Sea on the marine nutrient cycles in the vicinity?"* is answered by using the model of Broch and Slagstad (2012). This model is designed to calculate the growth, composition, and nutrient dynamics of the *Saccharina latissima*, the most cultivated seaweed species in Europe.

The method for modelling the impact of macroalgae cultivation on marine nutrient cycles is elaborated upon in the following section. First, the model of Broch and Slagstad (2012) and the main modelling equations are explained. Furthermore, the modelled scenarios and locations are elaborated upon. Finally, the data collection method is elucidated.

2.1.1.1 Model

A dynamic model is established, closely following the calculations set up by Broch and Slagstad (2012). The model estimates dry weights and carbon, nitrogen and phosphorus reserves with a variable C/N and C/P ratio. Furthermore, seasonal changes in algal growth, composition and nutrient scavenging potential can be simulated. Moreover, the calculations are based on location-dependent variables and can be scaled to different farm sizes. These calculations fit the purpose of this research (See Research aim). Thus, basing the calculations of this thesis on the model of Broch and Slagstad (2012) is a fitting choice The model was constructed in Python v3.9.7 and can be found in Appendix L. A manual for running the script is included in the code.

A schematic overview of the model is presented in Figure 12. The dynamic model incorporates carbon, nitrogen and phosphorus reserves, which makes it possible to simulate changes in composition and realistically assess seasonal growth. For a more detailed description of nutrient dynamics in macroalgae, please see 1.3.3. A complete list of the main variables can be found in Table 1, while the main parameters are listed in Table 2. The main equations of the model are presented in the section Main modelling equations.

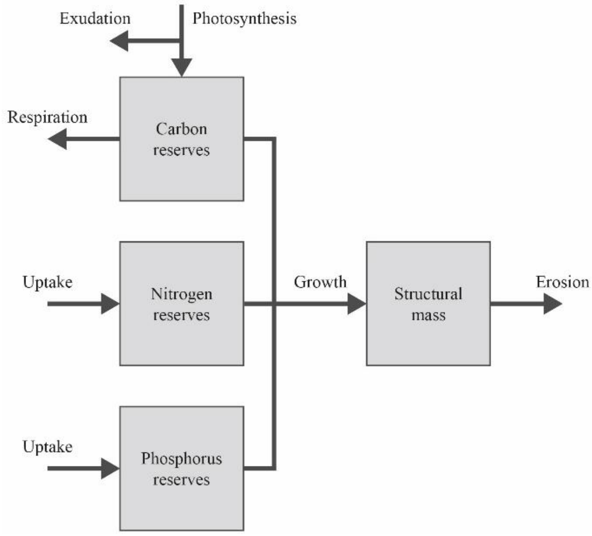


Figure 12: Schematic overview of the mathematical model used in this research

As described in Table 1, the four state variables in the model are: frond area (A), nitrogen reserves (N), phosphorus reserves (P) and carbon reserves (C). The unit of frond area (A) is dm^2. Nitrogen reserves (N), phosphorus reserves (P) and carbon reserves (C) are measured in g N (g sw)$^{-1}$, g P (g sw)$^{-1}$, and g C (g sw)$^{-1}$, respectively. These state variables are given *per gram structural mass* (sw). By structural mass, the kelp frond minus the nitrogen (N), phosphorus (P) and carbon (C) reserves is meant. The various aspects of biomass are given in three derived variables: W_S (structural weight), W_d (dry weight) and W_w (wet weight). The dry weight is referred to as the weight of the macroalgae after processing and drying, whereas the wet weight is the fresh weight (including absorbed water) directly after the harvest. The structural weight is the dry weight minus the mass of the surplus storage (carbon, nitrogen, phosphorus) reserves.

Symbol	Unit	Description
A	dm^2	Frond area, state variable
C	g C (g sw)$^{-1}$	Carbon reserves, relative to W_S, state variable
N	g N (g sw)$^{-1}$	Nitrogen reserves, relative to W_S, state variable
P	g P (g sw)$^{-1}$	Phosphorus reserves, relative to W_S, state variable
μ	day^{-1}	Specific growth rate
W_w	g	Total wet weight of sporophyte
W_d	g	Total dry weight
W_s	g	Dry weight of structural mass
β	g O_2 dm^{-2} h^{-1}(µmol photons m^{-2} s^{-1})$^{-1}$	Photoinhibition parameter
P_S	g O_2 dm^{-2} h^{-1}	Photosynthesis parameter
I	µmol photons m^{-2} s^{-1}	Irradiance (PAR)
T	◦C	Water temperature
U	ms^{-1}	Water current speed
X_N	µmol L^{-1}	Substrate nitrate concentration
X_P	µmol L^{-1}	Substrate phosphate concentration

Table 1: Model variables

For the modelling, some key assumptions were made. Firstly, it is assumed that each reserve and the structural mass have fixed chemical compositions. This assumption results from the dynamic energy budget (DEB) theory and is called the assumption of *strong homeostasis* (Kooijman, 2000). This assumption does not indicate that the overall chemical composition of the macroalgae stays fixed during growth. Instead, the kelp's composition is determined by the relative amount of each of the three reserves and the ratio of these reserves to the structural mass. The second assumption is that frond area (A) is proportional to the volume and to the structural mass. The parameter k_A indicates the structural mass per area. In the current calculations, increasing or decreasing reserves has no effect on volume or area, but it may cause the lamina density to vary. Finally, salinity, water turbidity and wave exposure are assumed not to influence growth and nutrient uptake rates.

Broch and Slagstad (2012) did not include phosphorus as a nutrient in the original model. However, phosphorus appears to be a critical nutrient for the growth of seaweed (Lubsch and Timmermans, 2019; Roleda, 2019) and is very relevant in assessing the ecological effects. Phosphorus has therefore been included in the model. According to Lubsch and Timmermans (2019), the N:P ratio in the *S. latissima* is 6:1. It is therefore assumed that phosphorus follows the same nutrient uptake dynamics as nitrogen according to this ratio.

The model of Broch and Slagstad (2012) includes four environmental variables: irradiance (I), water temperature (T), water current speed (U) and substrate nutrient concentrations (X). These four variables are used in this study as well.

Symbol	Value	Unit	Description
A_0	6	dm^2	Growth rate adjustment parameter
α	$3.75 * 10^{-5}$	$g\,C\,dm^{-2}\,h^{-1}(\mu mol\ photons\ m^{-2}\,s^{-1})^{-1}$	Photosynthetic efficiency
C_{min}	0.01	$g\,C\,(g\,sw)^{-1}$	Minimal carbon reserve
C_{struct}	0.20	$g\,C\,(g\,sw)^{-1}$	Amount of carbon per unit dry weight of structural mas
γ	0.5	$g\,C\,g^{-1}$	Exudation parameter
ε	0.22	A^{-1}	Frond erosion parameter
I_{sat}	200	$\mu mol\ photons\ m^{-2}\,s^{-1}$	Irradiance for maximal photosynthesis
J_{max}	$1.4 * 10^{-4}$	$g\,N\,dm^{-2}\,h^{-1}$	Maximal nitrate uptake rate
Z_{max}	$2.3 * 10^{-5}$	$g\,P\,dm^{-2}\,h^{-1}$	Maximal phosphate uptake rate
k_A	0,6	$g\,dm^{-2}$	Structural dry weight per unit area
k_{dw}	0.0785	-	Dry weight to wet weight ratio of structural mass
k_C	2.1213	$g\,(g\,C)^{-1}$	Mass of carbon reserves per gram carbon
k_N	2.72	$g\,(g\,N)^{-1}$	Mass of nitrogen reserves per gram nitrogen
k_P	2.72	$g\,(g\,P)^{-1}$	Mass of phosphorus reserves per gram nitrogen
m_1	0.1085	-	Growth rate adjustment parameter
m_2	0.03	-	Growth rate adjustment parameter
μ_{max}	0.18	day^{-1}	Maximal area specific growth ratio
N_{min}	0.01	$g\,N\,(g\,sw)^{-1}$	Minimal nitrogen reserve
N_{max}	0.022	$g\,N\,(g\,sw)^{-1}$	Maximal nitrogen reserve
N_{struct}	0.01	$g\,N\,(g\,sw)^{-1}$	Amount of nitrogen per unit dry weight of structural mas
P_{min}	0.0017	$g\,P\,(g\,sw)^{-1}$	Minimal phosphorus reserve
P_{max}	0.0037	$g\,P\,(g\,sw)^{-1}$	Maximal phosphorus reserve
P_{struct}	0.0017	$g\,P\,(g\,sw)^{-1}$	Amount of phosphorus per unit dry weight of structural mas
P_1	$1.22 * 10^{-3}$	$g\,C\,dm^{-2}\,h^{-1}$	Maximal photosynthetic rate at $T = T_{P1}$ ◦K
P_2	$1.44 * 10^{-3}$	$g\,C\,dm^{-2}\,h^{-1}$	Maximal photosynthetic rate at $T = T_{P2}$ ◦K
a_1	0.85	-	Photoperiod parameter
a_2	0.3	-	Photoperiod parameter
R_1	$1.41 * 10^{-5}$	$g\,C\,dm^{-2}\,h^{-1}$	Respiration rate at $T = T_{R1}$
R_2	$5.429 * 10^{-4}$	$g\,C\,dm^{-2}\,h^{-1}$	Respiration rate at $T = T_{R2}$
T_{R1}	280	◦K	Reference temperature for respiration
T_{R2}	290	◦K	Reference temperature for respiration
T_{AP}	1,737.7	◦K	Arrhenius temperature for photosynthesis
T_{APH}	25,924	◦K	Arrhenius temperature for photosynthesis at high end of range
T_{APL}	27,774	◦K	Arrhenius temperature for photosynthesis at low end of range
T_{AR}	29,644.1	◦K	Arrhenius temperature for respiration
$U_{0.65}$	0.03	ms^{-1}	Current speed at which $J = 0.65J_{max}$
HS_N	4	$\mu mol\ L^{-1}$	Nitrate uptake half saturation constant
HS_P	0.67	$\mu mol\ L^{-1}$	Phosphate uptake half saturation constant

Table 2: Model parameters

2.1.1.2 Main modelling equations

Detailed descriptions of the main equations of the model are provided in this section. Differential Equation 1(rate of change of frond area), 7 (rate of change in nitrogen reserves), 9 (rate of change in carbon reserves) and 16 (rate of change in phosphorus reserves) form the basis of the model.

Rate of change of frond area

$$\frac{dA}{dt} = [\,\mu - \nu\,]A$$

Equation 1: Rate of change of frond area

Differential equation 1 describes the rate of change with respect to time (t). In this equation, variable μ is the specific growth rate. The variable ν is described as frond erosion (dependent on the frond area).

Specific growth rate

$$\mu = f_{area} f_{photo} f_{temp} \min\{1 - \frac{N_{min}}{N}, 1 - \frac{C_{min}}{C}\}$$

Equation 2: Specific growth rate

Equation 2 is used to calculate the specific growth rate of the macroalgae. The equation is dependent on the effect of size, temperature, and seasonal influence on growth rate. Furthermore, the function is dependent on the minimal reserve carbon or nitrogen pool. It is assumed the reserve phosphorus pool does not influence the growth rate.

Effect of size on growth rate

$$f_{area}(A) = m1 \exp\left(-\left(\frac{A}{A_0}\right)^2\right) + m2$$

Equation 3: Effect of size on growth rate

In the model of Broch and Slagstad (2012), it is assumed that smaller algae grow relatively faster than larger ones. The effect of size on the specific growth rate (Equation 2) is described in Equation 3.

Effect of temperature on growth rate

$$f_{temp}(T) = \begin{cases} 0.08\mathrm{T} + 0.2 \text{ for } -1.8 \le \mathrm{T} < 10 \\ 1 \text{ for } 10 \le \mathrm{T} \le 15 \\ 19/4 - \mathrm{T}/4 \text{ for } 15 < \mathrm{T} \le 19 \\ 0 \text{ for } \mathrm{T} > 19 \end{cases}$$

Equation 4: Effect of temperature on growth rate

Equation 4 describes the effect of temperature on the specific growth rate of the algae. The equation illustrates that the growth rate is highest if the water temperature is between 10 and 15 degrees Celsius. The growth rate is zero when the water temperature is above 19 degrees Celsius.

Photoperiodic effect

$$f_{photo}(n) = a1\,[1 + sgn(\lambda(n))|\lambda(n)|^{\frac{1}{2}}] + a2$$

Equation 5: Photoperiodic effect

Studies by Sjøtun (1995) and Kain (1989) show that *S. latissima* is a “season anticipator”, which means that, rather than e.g. reduced nutrient availability, external triggers induce changes in the growth pattern. Day length is most likely the seasonal trigger in this process (Lüning, 1993). The main effect of this function is to let the specific growth rate increase when day length increases (during spring and early summer), and let the specific growth rate decrease when day length decreases (during fall and winter).

Frond erosion

$$\nu(A) = \frac{10^{-6}\exp(\varepsilon\, A)}{1 + 10^{-6}\exp((\varepsilon\, A) - 1)}$$

Equation 6:Frond loss

Various studies show that due to frond erosion, *S. latissima* continuously loses tissue during its growth. The main causes of biomass erosion are water motion, age of tissue and wave exposure (Sjøtun 1993; Kawamata 2001; Buck and Buchholz 2005). In this model, it is assumed that biomass erosion takes place continuously and that it is proportional to the frond area (A).

Rate of change in nitrogen reserves

$$\frac{dN}{dt} = k_A{}^{-1} J - \mu(N + N_{struct})$$

Equation 7: Rate of change in nitrogen reserves

The rate of change in nitrogen reserves is calculated with differential Equation 7. The total amount of nitrogen in the macroalgae is calculated by the sum of reserve and structural nitrogen. In the equation above, k_A is inverted. This inversion transforms this parameter into area per structural mass. After k_A is multiplied by the nitrate uptake rate, and the portion that is used for structural mass is subtracted.

Nitrate uptake rate

$$J = NA_N * J_{max}[1 - \exp\left(-\frac{U}{U_{0.65}}\right)]\left(\frac{N_{max} - N}{N_{max} - N_{min}}\right)\frac{X_N}{HS_N + X_N}$$

Equation 8: Nitrate uptake rate

The equation above consists of four separate factors. The first is J_{max}, which describes the maximal nitrate uptake rate. The second factor takes into consideration the effect of water current speed on the uptake rate. The third factor describes the nitrogen reserve concentrations of the macroalgae. The last factor incorporates the substrate nitrogen concentration and the half-saturation constant for nitrate uptake.

Rate of change in carbon reserves

$$\frac{dC}{dt} = k_A{}^{-1}\big[P(I,T)\big(1 - E(C)\big) - R(T)\big] - \mu(C + C_{struct})$$

Equation 9: Rate of change in carbon reserves

The functions P, E, and R describe photosynthesis, exudation and respiration, respectively. The fixed fraction used for structural mass is subtracted, as seen in the factor to the most right of Equation 9.

Gross photosynthesis

$$P(I,T) = P_S(T)\ [1 - \exp(-\frac{\alpha\ I}{P_S(T)})]\ \exp\ (-\frac{\beta\ I}{P_S(T)})$$

Equation 10: Gross photosynthesis

As seen in Equation 10, the gross photosynthesis of the macroalgae is dependent on the irradiance (I) and the water temperature (T). The unit of P is expressed as g C dm^{-2} d^{-1}. For P_S, P_{max}, and $P_{max}(T)$, see Equation 23, Equation 24, and Equation 25, respectively, in Appendix G: Maximal photosynthetic rate.

Respiration

$$R(T) = r_1\ \exp\ (\frac{T_{AR}}{T_{R1}} - \frac{T_{AR}}{T})$$

Equation 11: Respiration

Respiration is the process of gas exchange between plants and its environment, often in the form of oxygen and carbon dioxide. The release of carbon through respiration is calculated using Equation 11. The respiration is dependent on the water temperature. The first parameter in this equation, r_1, states the respiration rate at T_{R1}. As illustrated in Figure 13, the respiration rate is assumed to behave linearly with respect to T. T_{AR} is the Arrhenius temperature (deducted from the Arrhenius equation) estimated from the respiration rates at T_{R1} and T_{R2}.

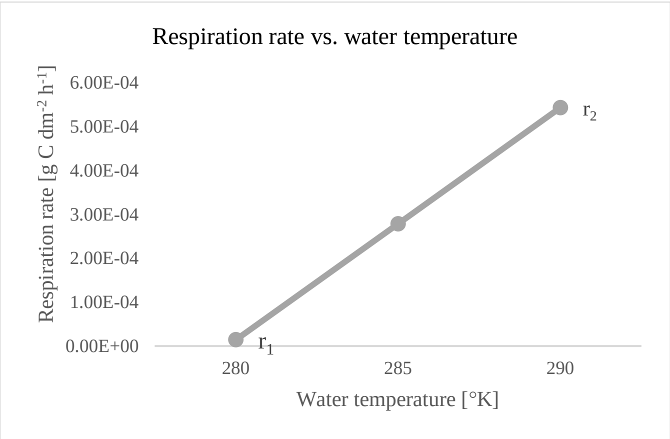


Figure 13: Respiration rate vs. water temperature

Exudation

$$E(C) = 1 - \exp\ [\gamma(Cmin - C)]$$

Equation 12: Exudation rate

In addition to respiration, exudation is another important metabolic loss process of macroalgae. As seen in Figure 12, the exudate is directly subtracted from the photosynthate. The exudation rate is dependent on the amount of carbon in the reserves and is extracted directly from the photosynthate (see Figure 12).

Rate of change in phosphorus reserves

$$\frac{dP}{dt} = {k_A}^{-1}\ Z - \ \mu(P + P_{struct})$$

Equation 13: Rate of change in phosphorus reserves

The rate of change in the phosphorus reserves is calculated using Equation 13. The equation is similar to Equation 7. However, in Equation 13, the nitrogen-specific variables are replaced by phosphorus-specific variables.

Phosphate uptake rate

The uptake rate of phosphate of the macroalgae is computed using

$$Z = NA_P *\ Z_{max}[1 - \exp\left(-\frac{U}{U_{0.65}}\right)]\left(\frac{P_{max} - P}{P_{max} - P_{min}}\right)\frac{X_P}{HS_P + X_P}$$

Equation 14: Phosphate uptake rate

Similar to Equation 8, the first factor (Z_{max}) describes the maximal phosphate uptake rate. The second factor integrates the effect of the current speed on the phosphate uptake rate. The third factor describes the phosphorus reserve concentrations. Finally, the last element incorporates the substrate phosphate concentrations and the half-saturation constant of phosphate uptake.

Structural weight

$$W_S = k_A * A$$

Equation 15: Structural weight

The structural weight is assumed to be equal to the dry weight, minus the weight of the surplus nutrient reserves. The structural weight is proportional to the frond area.

Dry weight

$$W_d\ = k_A\ [1 + k_N(N - N_{min}) + N_{min} + k_C(C - C_{min}) + C_{min}\ + k_P(P - P_{min}) + P_{min}\ ]\ A$$

Equation 16: Dry weight

The C-, N-, and P-reserves may also contain carbohydrates, nitrates (NO_3^-) and phosphates (PO_4^{3-}), respectively. Therefore, the actual weights of the reserves are higher than the weights of simply the carbon, nitrogen and phosphorus in them. Thus, parameters k_C, k_N and k_P are introduced. These parameters describe the mass of the surplus carbon, nitrogen and phosphorus reserves.

Total carbon, nitrogen and phosphorus

$$C_{total} = (C + C_{struct}) * W_S$$

Equation 17: Total carbon

$$N_{total} = (N + N_{struct}) * W_S$$

Equation 18: Total nitrogen

$$P_{total} = (P + P_{struct}) * W_S$$

Equation 19: Total phosphorus

The total amounts of carbon, nitrogen and phosphorus are calculated according to Equation 17, Equation 18, and Equation 19.

Carbon, nitrogen and phosphorus contents

$$C_{content} = \frac{C_{total}}{W_d}$$

Equation 20: Carbon content

$$N_{content} = \frac{N_{total}}{W_d}$$

Equation 21: Nitrogen content

$$P_{content} = \frac{P_{total}}{W_d}$$

Equation 22: Phosphorus content

The carbon, nitrogen and phosphorus contents are calculated as a fraction of dry weight, using Equation 20, Equation 21, and Equation 22.

2.1.1.3 Modelled scenarios

Nutrient uptake dynamics have high variability between different seaweed species (Lubsch, 2020). As mentioned previously, the *Saccharina latissima* is the most cultivated species in Europe (Araújo et al., 2021). Therefore, this thesis will focus on the cultivation of this specific seaweed species and model the scenarios according to the nutrient uptake dynamics of the *Saccharina latissima*.

To model the nutrient uptake of the farm as realistic as possible, it is essential to consider the farm's scale, intensity and location (Eggertsen and Halling, 2021). TNO is interested in the following two scales: (1) a farm that will produce sufficient seaweed to keep a high-value chemicals factory running, (2) a farm that will produce sufficient seaweed to keep a biorefinery for fuels running. The two scenarios, their scales, and sources, are depicted in Table 3.

Scenario	Purpose	Gross area	Productive area	Source
1	High-value chemicals	75,000,000 [m^2]	4,125,000 [m^2]	(Macro Cascade, 2015)
2	Biorefinery for fuels	6,603,000,000 [m^2]	369,000,000 [m^2]	(Macrofuels, 2019)

Table 3: Modelling scenarios, including gross area, productive area and source

Brown algae such as the *Saccharina latissima* are winter kelp, and growing seasons are typically from October or November to May or June. At temperatures higher than 18 °C, the growth rate of *S. latissima* drastically stagnates, and the algae may even die. Therefore, the seaweed is harvested in May or June, before the water reaches temperatures of 18 °C (Klijnstra et al., 2020). In the model, the cultivation of the *Saccharina latissima* from October to June is calculated.

The expected yield per square metre of each scenario has been selected based on a literature study. The expected yield for offshore seaweed cultivation is depicted in Table 4.

Species	Expected yield [kg/m^2 dw]	Source
Saccharina latissima	2	(Klaas Timmermans, pers. comm. March 21, 2022)
Laminaria digitata / Saccharina latissima	1.5	(Van den Burg et al., 2012)
Laminaria digitata	3.0	(Florentinus et al., 2008)
Laminaria digitata	2.0	(Reith et al., 2005)
Laminaria digitata	2.0	(Buck and Buchholz, 2004)

Table 4: Expected yield for offshore seaweed cultivation

A reliable estimation of the yield per square metre would be 2 kg dw based on the findings in Table 4. All parameters for the farms are listed in Table 5.

2.1.1.4 Modelled locations

As mentioned in the section Background, ten additional offshore wind farms are expected to be constructed by 2030. The locations of the current and future wind farms are depicted in Figure 14. To model the nutrient dynamics of the hypothetical seaweed farms, location-specific data was extracted from the WaterInfo database. The following four measurement locations were chosen:

- Noordwijk, 20 [km];
- Noordwijk, 70 [km];
- Terschelling, 50 [km];
- Walcheren, 20 [km].

These locations were selected as they were the closest to the North Sea's current and future wind farms displayed in Figure 14. The locations from which the data was extracted are depicted in Figure 15.

The modelled scenarios cover a large area (see Table 3); farms of these scales are unlikely to fit within the current sizes of wind parks. In reality, farms of these scales would extend beyond the borders of the wind farms. However, for this research, it was assumed that all modelled scenarios fit on each of the four wind park locations depicted in Figure 15.

Figure 14: Current and future wind farms in the North Sea (Rijksoverheid, 2022)

Figure 15: Locations of collected data from WaterInfo and Eastern Scheldt

2.1.1.5 Data collection

The model of Broch and Slagstad (2012) includes the following four environmental variables:

- Irradiance (I);
- Water temperature (T);
- Water current speed (U);
- Substrate nitrate (X_N);
- Substrate phosphate (X_P).

Data was collected from the WaterInfo database from Rijkswaterstaat, Ministerie van Infrastructuur en Waterstaat (2022). This database shows current, expected and historical water measurement data from Rijkswaterstaat at various locations in the Netherlands. As this database did not have data on irradiance available, it is assumed that the irradiance levels at the modelled locations have a similar value as the irradiance levels in the Eastern Scheldt (Figure 15). This data was publicly available in a study performed by Jiang et al. (2022), in which the carrying capacity of *Saccharina latissima* cultivation in the Eastern Scheldt was modelled. Data on the local water temperature, water current speed, substrate nitrate, and substrate phosphate were all extracted from the WaterInfo database. The values were converted to the correct unit and averaged per month over the following five years of cultivation seasons:

- October 2015 – June 2016;
- October 2016 – June 2017;
- October 2017 – June 2018;
- October 2018 – June 2019;
- October 2019 – June 2020;
- October 2020 – June 2021.

The complete data lists are listed in Appendix K.

2.1.2 Method for assessment of the role of monitoring systems

The sub-question *"What role can a monitoring system play in seaweed cultivation in MUPS at the North Sea?"* is answered by a combination of expert interviews and literature research.

2.1.3 Method for assessment of ecosystem services

The sub-question *"In what ways can the ecological effects of seaweed cultivation in MUPS atn the North Sea be translated into ecosystem services?"* is answered by literature and desk research, and expert interviews. Furthermore, the results of sub-question 1 are used to assess potential ecosystem services. In addition, potential challenges and opportunities in establishing these ecosystem services are discussed.

2.2 Conceptual framework

A conceptual model is generated based on the main research question, sub-questions and methods given above. The model is displayed in Figure 16.

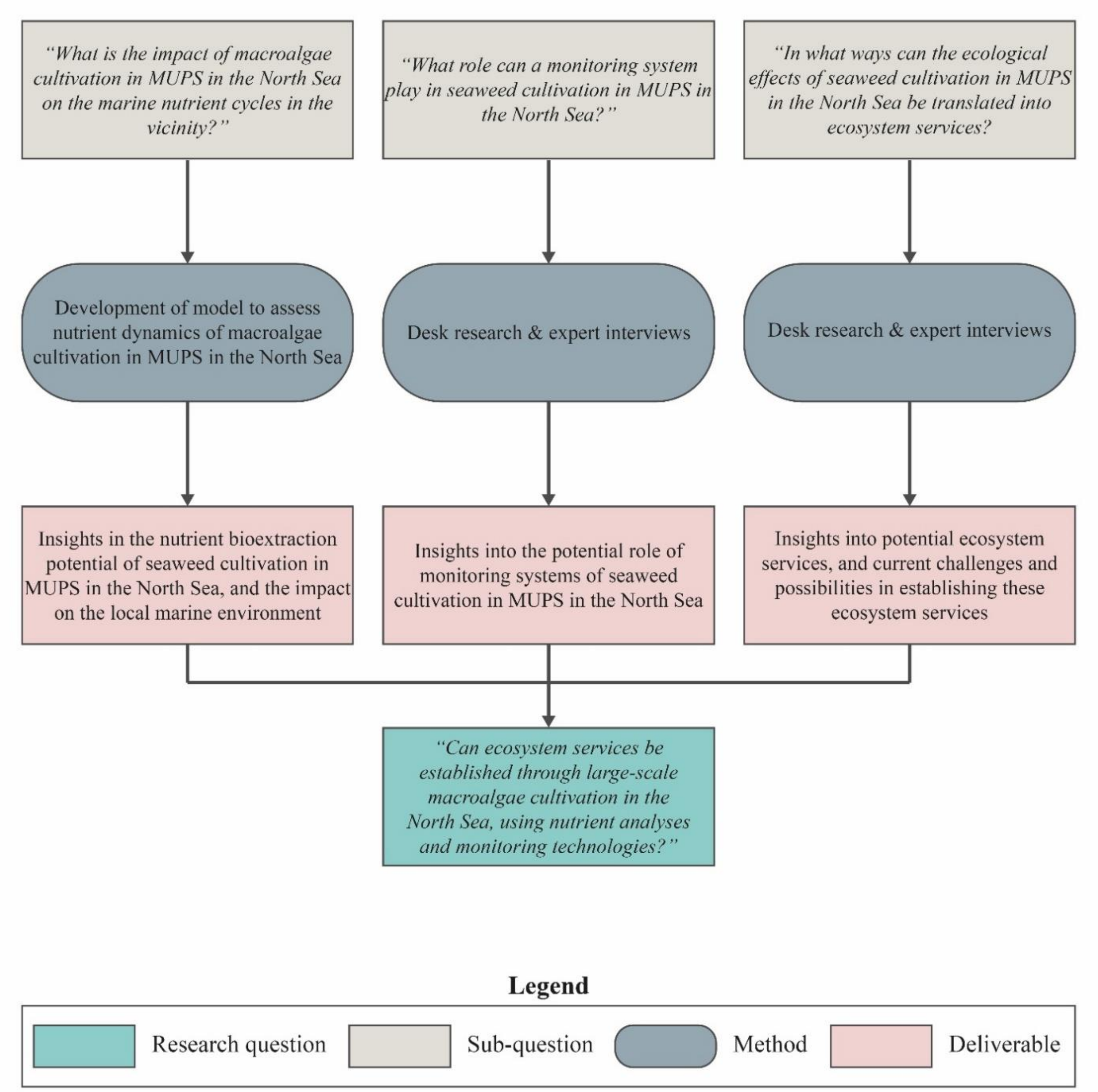


Figure 16: Conceptual model

3. Results & Analysis

The following chapter presents the results of the *S. latissima* nutrient dynamic and growth model for every location and scenario. In sections 3.1.1 and 3.1.2, the nutrient dynamics through the cultivation season (October to June) and the nutrient levels at the moment of harvest are given. Subsequently, in sections 3.2.1 and 3.2.2, the results are analysed. The model results are compared to existing literature and validated in section 3.4. Finally, in 3.5, a sensitivity analysis is performed to assess how “sensitive” the model is to fluctuations in the parameters and data on which it is built.

3.1 Results

The model was run over one cultivation season, using location-specific data. The results and trends are given and described in the following section.

3.1.1 Nutrient dynamics

The nutrient dynamics and growth of macroalgae can fluctuate quite heavily during its growth (Lubsch and Timmermans, 2019). Therefore, it is essential to consider the nutrient dynamics and growth during the entire development of the macroalgae. This section gives the nutrient dynamics of scenarios 1, 2 and 3 for every farm location. The farm parameters per location are stated in Table 5. A culture density (number of seaweed individuals per metre of line) similar to Jiang et al. (2022) has been selected. Deployment day and harvest day have been set to October 1st and June 30th, respectively. In the Netherlands, the harvesting of seaweed is most common in May (Jan Wilco Dijkstra, pers. comm. August 10, 2022). The harvest time in the model was set to June 30th to evaluate optimal harvest time. Several location-dependent parameters, such as the temperature, nitrate and phosphate content, irradiance and current speed can be found Figure 17-A to E. In addition, growth and nutrient dynamics, such as frond area, dry weight, carbon, nitrogen, and phosphorus content, and nitrate/phosphate uptake rates are given in Figure 17-F to L. In-depth information, such as the structural weight, gross photosynthesis, C/N and C/P ratios, and total carbon, nitrogen and phosphorus amount, can be found in Figure 18. Please note that all graphs are given per individual of the *S. latissima*. Detailed files with each dynamic per hour of the cultivation period are given in Appendix J.

3.1.1.1 Nutrient dynamics and growth, Noordwijk 20 km

The model results for Noordwijk 20 km offshore seaweed farming location are depicted in Figure 17. In-depth graphs are given in Figure 18. The results are given per seaweed unit of the *S. latissima* during the cultivation season from October to June. The individual nutrient dynamics and growth results for the Noordwijk 20 km farm can be seen in Appendix A.1: Noordwijk 20 km.

The step-profile of the influx data (Figure 17-A to E) is because the data is averaged per month. The water temperature shows a declining trend towards and during the winter months (October to March), and an increasing trend during the spring and summer months (March to June). Nitrate and phosphate concentrations in the seawater fluctuate during the year and peak from January to March. This phenomenon is related to the decrease in irradiance, which results in lower growth rates of algae and phytoplankton, and thus lower absorption of nitrate and phosphate (Noordzeeloket, 1990). Irradiance declines heavily towards and during the winter months and peaks during spring and summer. The current speed at Noordwijk 20 km shows an inclining trend from October to June.

The frond area and dry weight remain rather stable from deployment until January. From February onwards, however, both growth dynamics increase rapidly to 37.1 [dm^2] and 25.46 [g] per individual, respectively, at the moment of harvest. Nitrate and phosphate uptake peak during the first days of exposure at the farming site but decline rapidly towards mid-October. Both nitrate and phosphate uptake show an increasing trend from mid-October to June. These uptake rates are dependent on the substrate nutrient concentration and the current speed (the latter provides the supply of new nutrients). The seaweed's nitrogen and phosphorus content (given per fraction of dry weight) increase rapidly after the culture rope is installed at the Noordwijk 20 km site. Nitrogen and phosphorus content increase to about 3% and 0.5%, respectively, after which they gradually decrease towards the moment of harvest. The total amount of accumulated nitrogen and phosphorus in the tissue (see Figure 18-E and F) increase from February to April, after which they show a slight decline. The seaweed tissue's carbon content and total carbon (see Figure 17-L and Figure 18-D) remain quite stable until March. However, both dynamics show a generally increasing trend towards June. As the carbon content is dependent on the irradiance and temperature of the water, the increase could be explained by the growing irradiance and temperature from March onwards. The model results are further analysed in 3.2.1.1.

	Noordwijk 20 km	Noordwijk 70 km	Terschelling 50 km	Walcheren 20 km
Lattitude	52.37	52.59	53.78	51.66
Longitude	4.03	3.63	4.89	3.25
Culture density per metre of line	70	70	70	70
Initial biomass per metre of line [$g\ C\ m^{-1}$]	0	0	0	0
Deployment day of year	274	274	274	274
Harvest day of year	181	181	181	181

Table 5: Farm parameters per location as used in the model

3.1.1.2 Nutrient dynamics and growth, Noordwijk 70 km

The model results for Noordwijk 70 km are given in Figure 17. In-depth graphs are given in Figure 18. The individual nutrient dynamics and growth results for the Noordwijk 70 km farm can be seen in Appendix B.2: Noordwijk 70 km. Similar to the Noordwijk 20 km site, the water temperature at the Noordwijk 70 km site decreases before and during the winter, and increases during spring and summer. The rise in the temperature, however, takes place at a slower pace than at the Noordwijk 20 km site. Furthermore, nitrate and phosphate concentrations fluctuate throughout the years and peak from January to March. Irradiance is lowest in December and increases towards July. The current speed at Noordwijk 20 km shows a gradually increasing trend from October to June. The frond area and dry weight remain stable from the moment of deployment in October to January. In February, both grow rapidly. The frond area stabilises from May onwards. The dry weight, however, shows an increasing trend until the moment of harvest at the end of June.

Similar to the nutrient dynamics of the Noordwijk 20 site, the nitrate and phosphate uptake rates at the Noordwijk 70 km peak shortly after the deployment of the culture rope at the beginning of October. Both the nitrogen and phosphorus uptake rates stabilise in mid-October/November and gradually increase towards June. The nitrogen and phosphorus content of the seaweed rises to ± 3% and ±0.5% quickly after deployment. From January onwards, nitrogen and phosphorus content show a slightly sharper decline than the results from Noordwijk 20 km. As seen in Figure 18-E and F, the total amount of accumulated nitrogen and phosphorus rapidly increases from February to April, after which it stagnates. Similar to the seaweed at the Noordwijk 20 km site, the Noordwijk 70 km farm shows a rapid increase in carbon from May to June. The model results of this farm are discussed in 3.2.1.2.

3.1.1.3 Nutrient dynamics and growth, Terschelling 50 km

The model results for the Terschelling 50 km farming site are depicted in Figure 17. In-depth graphs are seen in Figure 18. The individual nutrient dynamics and growth results for the Terschelling 50 km farm can be seen in Appendix B.3: Terschelling 50 km. The seawater's temperature, nitrate and phosphate concentrations, irradiance and current speed at the Terschelling 50 km site show similar trends to the other farms. The phosphate concentration in March is quite low. As can be seen in Appendix K, the standard deviation of this concentration is rather high. Therefore, it is likely caused by measurement errors in the WaterInfo database. The frond area is stable from the moment of deployment to January, after which it increases rapidly from February to April. In the last two months of cultivation, the frond area slightly decreases. Similar to the other sites, the dry weight remains close to zero from October to January, after which it shows a significant increase until harvest. The nitrate/phosphate uptake and nitrogen/phosphorus/carbon content depict similar trends to the other sites. The model results of the Terschelling 50 km farm are discussed in 3.2.1.3.

3.1.1.4 Nutrient dynamics and growth, Walcheren 20 km

The model results for the Walcheren 20 km seaweed farming site are illustrated in Figure 17. In-depth graphs are given in Figure 18. The individual nutrient dynamics and growth results for the Walcheren 20 km farm are given in Appendix B.4: Walcheren 20 km. The temperature, nitrate and phosphate concentration, irradiance and current speed of the Walcheren 20 km site show similar trends to the other farming sites. The frond area rapidly grows to ±35 [dm^2] from February to April, after which it stabilises and only fluctuates lightly. The growth rate of dry weight shows a remarkable trend. Similar to the other farming sites, the dry weight of the seaweed grows gradually from February to May. However, during the last month of cultivation, the dry weight reduces drastically. Possible explanations for this behaviour are discussed in section 3.2.1.4.

The nitrogen and phosphorus dynamics of the seaweed at the Walcheren 20 km farm show similar dynamics to the other farms. Nitrate and phosphate uptake peak after deployment and show an overall increasing trend from mid-October to June. The average uptake rate is somewhat higher than the farms located further offshore, however. The nitrogen and phosphorus contents of the seaweed grow to ±3% and ±0.5% rapidly and show a gradually decreasing trend from November to June. In June, both the nitrogen and phosphorus content show a sharp increase. The carbon content shows similar behaviour to the other farms. However, in June, the carbon content drops heavily from ±26.8% to ±20.6% in one month. These results and possible explanations for them are discussed in 3.2.1.4.

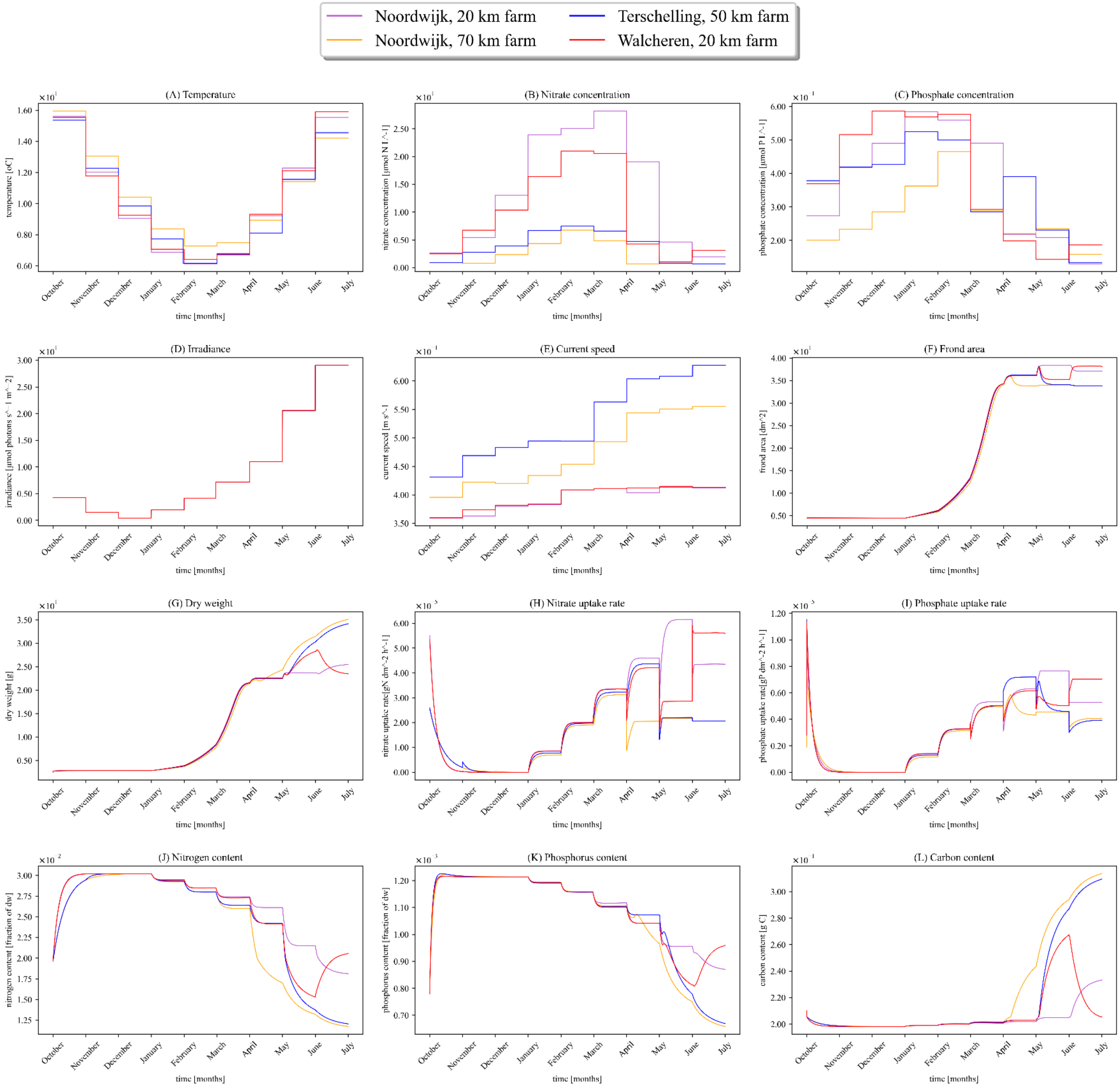


Figure 17: Model results for all offshore seaweed farming locations. ***Results are given per individual of the S. latissima.*** *(A) Temperature; (B) nitrate concentration; (C) phosphate concentration; (D) irradiance; (E) current speed; (F) frond area; (G) dry weight; (H) nitrate uptake rate; (I) phosphate uptake rate; (J) nitrogen content; (K) phosphorus content; (L) carbon content.*

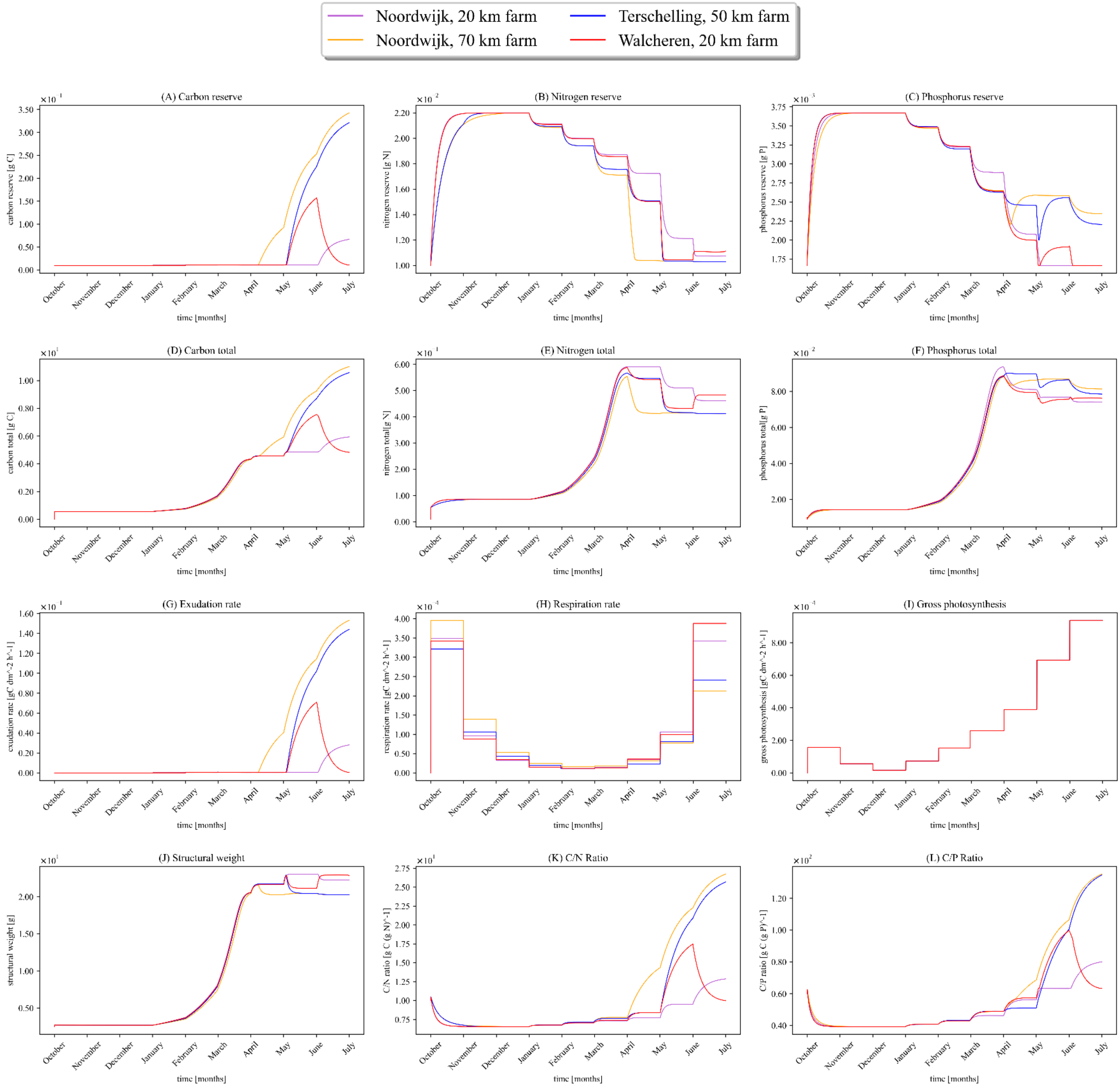


*Figure 18: Model results for all offshore seaweed farming locations. **Results are given per individual of the S. latissima**.(A) Carbon reserve; (B) nitrogen reserve; (C) phosphorus reserve; (D) carbon total; (E) nitrogen total; (F) phosphorus total; (G) exudation rate; (H) respiration rate; (I) gross photosynthesis; (J) structural weight; (K) C/N ratio; (L) C/P ratio.*

3.1.2 Harvest results

In addition to the nutrient and growth dynamics, it is essential to consider the seaweed's composition at the moment of harvest. The composition of the seaweed at the moment of harvest represents the total amount of extracted nutrients.

In the following section, the modelled results at the moment of harvest are given per farming site. The farm parameters per location that are used in the model are stated in Table 5. Additionally, the total amount of bioextracted nutrients for one cultivation season for each scenario is presented. The bioextracted nutrients per scenario are given in Table 6 to Table 9. In-depth information is given in Appendix C: In-depth model results - Harvest**.**

3.1.2.1 Harvest results, Noordwijk 20 km

The harvest results for the Noordwijk 20 km farming site are presented in Table 6. At this site, 1.78 [kg] dw of seaweed can be harvested per square metre at the end of June. The seaweed has a carbon content of 23.3%, which amounts to a total of 0.42 [kg] of bioextracted carbon per square metre of the farm. Furthermore, the harvested seaweed has a nitrogen content of 1.8%; this totals up to 0.032 [kg] of bioextracted nitrogen per square metre of the farm. Lastly, the seaweed has a phosphorus content of 0.29% at the moment of harvest. This percentage amounts to 0.0052 [kg] bioextracted phosphorus per square metre. In-depth information about this farm can be found in Appendix C.1: Noordwijk 20 km and Appendix G.1.

3.1.2.2 Harvest results, Noordwijk 70 km

The harvest results for the Noordwijk 70 km farming site are presented in Table 7. The yield per square metre of farm is 2.46 [kg] dw, which is slightly higher than the yield at the Noordwijk 20 km farming site. The carbon content of the harvested seaweed is 31.4%, which is the highest carbon content of all farms. This comes down to 0.78 [kg] of bioextracted carbon per square metre of the farm. The nitrogen content of 1.17 % of the seaweed at this farm is slightly lower than the Noordwijk 20 km farm. This amounts to 0.029 [kg] of bioextracted nitrogen per square metre of the farm. Lastly, the results show that the phosphorus content of the seaweed is 0.23%, which means that per square metre of the farm, 0.0057 [kg] of phosphorus is bioextracted. More in-depth information about the harvest results of this farm can be found in Appendix C.2: Noordwijk 70 km and Appendix G.2.

3.1.2.3 Harvest results, Terschelling 50 km

The harvest results for the Terschelling 50 km farming site are presented in Table 8. A total of 2.39 [kg] dw of seaweed can be harvested from this farming site. The carbon content of the seaweed is 30% (0.74 [kg] N per square metre) at this site. The nitrogen content is 1.21% (0.028 [kg] N per square metre). Lastly, the phosphorus content of the harvested seaweed at this site is 0.23%. Therefore, 0.0.0055 [kg] of phosphorus is bioextracted per square metre of the Terschelling 50 km farm. In-depth information about this farm can be found in Appendix C.3: Terschelling 50 km and Appendix G.3.

3.1.2.4 Harvest results, Walcheren 20 km

The harvest results for the Waclheren 20 km farming site are given in Table 9. According to the model results, 1.64 [kg] dw per square metre of the farm can be harvested at this site. The carbon content of the harvested seaweed at this farm is 20.6%, which is the lowest of all the farms. However, the model results show a nitrogen content of 2.06%, which is the highest of all farms. 0.03 [kg] of nitrogen is bioextracted when one square metre of the farm is harvested. Lastly, this farm's phosphorus content – which is 0.32% – also appears to be the highest. However, as the total yield per square metre is lower than the other farming sites, the bioextracted phosphorus per is similar to other farms. More in-depth information is found in Appendix C.4: Walcheren 20 km and Appendix G.4.

Noordwijk 20 km site

	Productive area [m^2]	Dry weight [kg]	Extracted carbon [kg]	Extracted nitrogen [kg]	Extracted phosphorus [kg]
per plant	0.014	$25.5 * 10^{-3}$	$5.94 * 10^{-3}$	$4.62 * 10^{-4}$	$7.42 * 10^{-5}$
per m^2	1.0	1.78	$4.16 * 10^{-1}$	$3.23 * 10^{-2}$	$5.19 * 10^{-3}$
Scenario 1	4,125,000	$7.35 * 10^{6}$	$1.72 * 10^{6}$	$1.33 * 10^{5}$	$2.14 * 10^{4}$
Scenario 2	369,000,000	$6.58 * 10^{8}$	$1.53 * 10^{8}$	$1.19 * 10^{7}$	$1.92 * 10^{6}$

Table 6: Harvest results for the Noordwijk 20 km site

Noordwijk 70 km site

	Productive area [m^2]	Dry weight [kg]	Extracted carbon [kg]	Extracted nitrogen [kg]	Extracted phosphorus [kg]
per plant	0.014	$35.0 * 10^{-3}$	$11.0 * 10^{-3}$	$4.12 * 10^{-4}$	$8.14 * 10^{-5}$
per m^2	1.0	2.46	$7.70 * 10^{-1}$	$2.88 * 10^{-2}$	$5.70 * 10^{-3}$
Scenario 1	4,125,000	$1.01 * 10^{7}$	$3.18 * 10^{6}$	$1.19 * 10^{5}$	$2.35 * 10^{4}$
Scenario 2	369,000,000	$9.05 * 10^{8}$	$2.84 * 10^{8}$	$1.06 * 10^{7}$	$2.10 * 10^{6}$

Table 7: Harvest results for the Noordwijk 70 km site

Terschelling 50 km site

	Productive area [m^2]	Dry weight [kg]	Extracted carbon [kg]	Extracted nitrogen [kg]	Extracted phosphorus [kg]
per plant	0.014	$34.1 * 10^{-3}$	$10.6 * 10^{-3}$	$4.12 * 10^{-4}$	$7.85 * 10^{-5}$
per m^2	1.0	2.39	$7.40 * 10^{-1}$	$2.88 * 10^{-2}$	$5.50 * 10^{-3}$
Scenario 1	4,125,000	$9.85 * 10^{6}$	$3.05 * 10^{6}$	$1.19 * 10^{5}$	$2.27 * 10^{4}$
Scenario 2	369,000,000	$7.91 * 10^{8}$	$2.73 * 10^{8}$	$1.06 * 10^{7}$	$2.03 * 10^{6}$

Table 8: Harvest results for the Terschelling 50 km site

Walcheren 20 km site

	Productive area [m^2]	Dry weight [kg]	Extracted carbon [kg]	Extracted nitrogen [kg]	Extracted phosphorus [kg]
per plant	0.014	$23.5 * 10^{-3}$	$4.83 * 10^{-3}$	$4.83 * 10^{-4}$	$7.63 * 10^{-5}$
per m^2	1.0	1.64	$3.38 * 10^{-1}$	$3.38 * 10^{-2}$	$5.34 * 10^{-3}$
Scenario 1	4,125,000	$6.78 * 10^{6}$	$1.39 * 10^{6}$	$1.40 * 10^{5}$	$2.20 * 10^{4}$
Scenario 2	369,000,000	$6.06 * 10^{8}$	$1.25 * 10^{8}$	$1.25 * 10^{7}$	$1.97 * 10^{6}$

Table 9: Harvest results for the Walcheren 20 km site

3.2 Analysis of results

3.2.1 Analysis of nutrient dynamics and growth

In the following section, the model results for the nutrient dynamics and growth of the seaweed are analysed. Trends are explained, and possible explanations for fluctuations in the nutrient dynamics and growth are given. The model results for the nutrient dynamics and growth are given in Figure 17 and Figure 18. In-depth information, such as the structural weight, gross photosynthesis, C/N and C/P ratios, and total carbon, nitrogen and phosphorus amount, can be found in Figure 18**.** Detailed files with each dynamic per hour of the cultivation period are given in Appendix G.

3.2.1.1 Analysis of nutrient dynamics and growth, Noordwijk 20 km

The model results for the Noordwijk 20 km farming site are depicted in Figure 17. In-depth graphs are given in Figure 18. Individual results for the Noordwijk 20 km farm are given in Appendix A.1: Noordwijk 20 km and Appendix C.2: Noordwijk 70 km.

As mentioned in 3.1.1.1, the frond area and the dry weight both remain stable from October to January. When analysing the behaviour of the seaweed from hour 0 to 2000 (approximately October to January) in Figure 18-H and I, it becomes clear that the gross photosynthesis is low and the respiration rate is relatively high during this period. The gross photosynthesis is dependent on the irradiance and temperature of the water (as demonstrated in Equation 10), and the respiration rate is dependent on the temperature (Equation 11). During the winter period, the irradiance is relatively low, which causes low photosynthetic rates. The temperature is relatively high while displaying a decreasing trend. Therefore, the respiration rate – which is found to be high at high temperatures – is too high for the seaweed to accumulate enough carbon to generate biomass. From February to June, both the irradiance and the temperature start to increase significantly. Considering these factors, the sudden increase in frond area and dry weight could mean that environmental variables become favourable for the gross photosynthesis to increase and rise above the respiration rate. This phenomenon can also be seen in Figure 21.

The nitrate and phosphate uptake peak and rapidly decrease during the first days of deployment at the Noordwijk 20 km farm. As seen in Equation 8 and Equation 14**,** the uptake rates are dependent on the substrate nutrient concentration, the nutrient reserves and the current speed. As seen in Figure 56, the substrate nutrient concentrations and current speed are relatively low during the first days of deployment. However, both the nitrogen and phosphorus reserve show a significant increase during the first days. Analysing the equations for the nutrient uptake rates, it can be concluded that a higher nutrient reserve results in a lower nutrient uptake rate, and vice versa. This corresponds with the trends in the graphs for nutrient uptake rates and nutrient reserves. Therefore, a possible explanation for the peak in nutrient uptake rates during the first days of deployment could be the low starting value in the nutrient values. The seaweed is exposed to nutrient-rich water, causing the nutrient reserves to increase. A result of this is that the uptake rate decreases.

From December to the harvest in June, both the nitrate and phosphate uptake rates show a gradually increasing trend. The uptake rates are partially influenced by the substrate nutrient concentrations. However, these concentrations drop from April to June (see Figure 17-B and C), while the uptake rates continue to grow. Another environmental variable influencing the nutrient uptake rate is the current speed; a higher current speed increases the nutrient uptake rates. Therefore, the increasing current speed can explain the growing nutrient uptake rates. As mentioned above, the nutrient (nitrogen and phosphorus) reserve is another factor influencing nutrient uptake rates. Both the nitrogen and the phosphorus reserve show a gradually decreasing trend from October to June (see Figure 18-B and C). As seen in Equation 7 and Equation 13, The rate of change in the nutrient reserves decreases when: (1) The nutrient uptake rates (J and Z) decrease; (2) The specific growth rate (μ) increases; or (3) The nutrient reserves (N and P) decrease. Statements 2 and 3 apply to this situation. Hence, the nutrient reserves decrease. This decrease in nutrient reserve causes the nutrient uptake rates to gradually increase from December to June.

The nitrogen and phosphorus contents show a sharp increase during the first month of cultivation, after which it gradually decreases until the harvest in June (see Figure 17J and K). As seen in Equation 21 and Equation 22, the nutrient content is dependent on the total amount of nutrients and the dry weight. The total amount of nutrients consists of the nutrients in the reserves and the biomass. As depicted in Figure 18-E and F, the total amount of nutrients increases with the growing dry weight from January to June. However, the nutrient reserves slightly reduce during this period for the reasons mentioned above. This decrease in nutrient reserves could be the reason for the seaweed's diminishing nitrogen and phosphorus contents.

Lastly, the carbon content remains relatively stable until February. A gradual increase along with the dry weight (Figure 14) is displayed from February to May. In June, the carbon content grows to 23.3%. This increase can be explained by the growing irradiance and temperature discussed above.

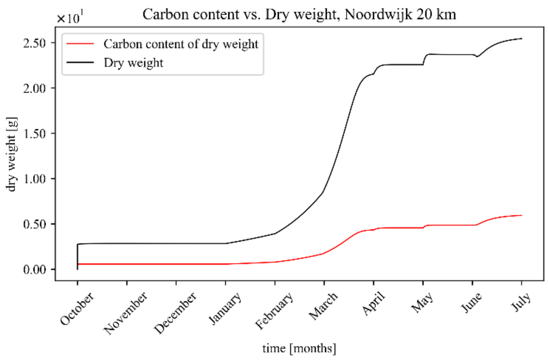


Figure 19: Carbon content of the dry weight, Noordwijk 20 km site

3.2.1.2 Analysis of nutrient dynamics and growth, Noordwijk 70 km

The model results for the Noordwijk 70 km farm are depicted in Figure 17 and Figure 18. Individual farm results are given in Appendix A.2: Noordwijk 70 km and Appendix B.2: Noordwijk 70 km.

The trends in the growth of dry weight and frond area are similar to the seaweed at the Noordwijk 20 km site. Possible explanations for this behaviour can be found in 3.2.1.1.

The nitrate and phosphate uptake trends are similar to the Noordwijk 20 km farm. However, although these nutrient uptake rates follow the same trends, the values are somewhat different. Both the uptake rates and the concentrations of the nitrate and phosphate are lower at the 70 km farm, as can be seen in Figure 17. Lubsch (2020) mentioned that nitrate and phosphate concentrations significantly decrease when moving away from the coast. In addition, N:P has a ratio from 54:1 in the nearshore region to 4:1 in the offshore region. As seen in Figure 15, the Noordwijk 70 km farm is located further from shore than the Noordwijk 20 km farm. As the uptake rates are partially dependent on the substrate concentration, the lower values in the nutrient uptake rates can be explained by the lower substrate concentrations.

Comparable to the Noordwijk 20 km farm, the nitrogen and phosphorus contents of the seaweed at the Noordwijk 70 km farm peak during the first days of deployment. From November to June, the contents gradually reduce. As discussed in 3.2.1.1, an explanation for this could be the diminishing nutrient reserves. Furthermore, although the nitrogen and phosphorus contents of the seaweed at the Noordwijk 70 km farm follow the same trend as the Noordwijk 20 km farm, the content values are somewhat lower. An explanation for this could be the lower nutrient concentrations when moving further off the shore.

The carbon content of the seaweed at the Noordwijk 70 km farm remains relatively stable (±20%) from October to March. The carbon content increases explosively to ±31% from April to June due to the increased irradiance and water temperature. This results in a higher growth rate (explained in more detail in 3.2.1.1). Comparing Noordwijk 20 km and Noordwijk 70 km in Figure 17-L, it can be seen that the average value of the carbon content of Noordwijk 70 km seaweed is higher than the Noordwijk 20 km seaweed. As seen in Equation 9, the rate of change in the carbon reserves is dependent on the gross photosynthesis, the exudation and the respiration rate, the specific growth rate, and the amount of carbon in the reserves. Analysing the environmental variables of the two locations, it becomes clear that the water temperature at the Noordwijk 20 km site (1) has a higher average and (2) increases more rapidly in spring and summer than at the Noordwijk 70 site. These temperatures correspond with measurements from KNMI (2020) (see Figure 20). As the respiration rate increases, as it does with higher temperatures, the outflow of carbon rises. This phenomenon is displayed in Figure 21 and Figure 22, where the development of the respiration rate and the gross photosynthesis can be seen. The respiration rate of the seaweed at the Noordwijk 70 km site increases at a slower rate than at the Noordwijk 20 km site in spring and summer. Hence, the seaweed of the Noordwijk 70 site contains a higher carbon content.

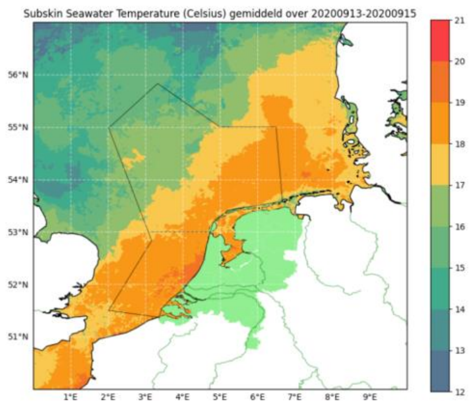


Figure 20: Map of three-day average seawater temperature in the North Sea (KNMI, 2020)

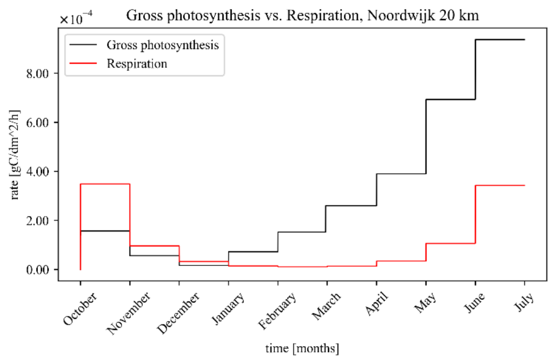


Figure 21: Gross photosynthesis and respiration, Noordwijk 20 km farm

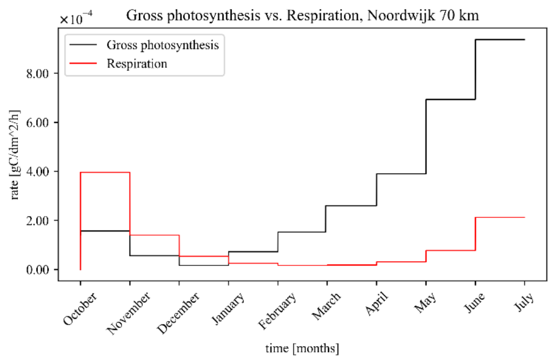


Figure 22: Gross photosynthesis and respiration, Noordwijk 70 km farm

3.2.1.3 Analysis of nutrient dynamics and growth, Terschelling 50 km

The model results for the Noordwijk 70 km farm are depicted in Figure 17 and Figure 18. Individual farm results are given in Appendix B.3: Terschelling 50 km and Appendix C.3: Terschelling 50 km.

The frond area and dry weight have a growing pattern similar to the growth of the seaweed at the Noordwijk 20 km and Noordwijk 70 km farm. This growing pattern is elaborated upon in 3.2.1.1.

The nutrient uptake rates of the Terschelling 50 km seaweed also follow trends similar to the other farming sites. The values of the nutrient uptake rates are slightly higher than the Noordwijk 70 km farm, which is likely due to the slightly higher nutrient concentrations and current speed (see Figure 17-B, C and E). The higher nutrient concentration is likely due to the shorter distance to shore compared to the Noordwijk 70 km farm (Lubsch, 2020). The higher current speed is caused by the fact that the Terschelling 50 km farm is located at a position where current velocity is generally higher during the cultivation season (see Figure 23).

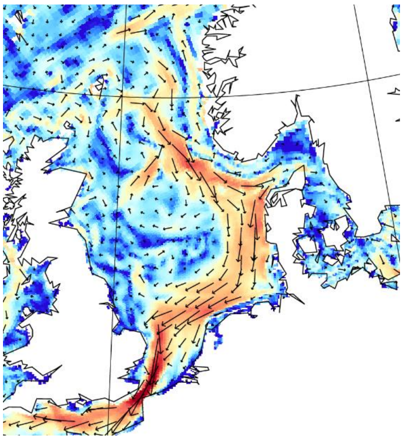


Figure 23: Empirical Orthogonal Functions analysis of the North Sea general circulation in winter (Mathis, 2015)

The carbon, nitrogen and phosphorus content follow similar trends to the other farms; see 3.2.1.1 and 3.2.1.2 for more information.

3.2.1.4 Analysis of nutrient dynamics and growth, Walcheren 20 km

The model results for the Walcheren 20 km farm are presented in Figure 17 and Figure 18. In-depth graphs are found in Appendix B.4: Walcheren 20 km and Appendix C.4: Walcheren 20 km.

The frond area of the seaweed at the Walcheren 20 km site follows a growing pattern similar to the other farming site; a steep increase from January to April and a stabilisation from May to June. The dry weight follows a similar pattern until May as well. However, it shows a significant decrease in June. The environmental variables of the Walcheren 20 km site in June show some variation when compared to the other farms:

- The water temperature is relatively high (15.9 °C);
- The nitrate concentration increases significantly from May to June (1.08 to 3.15 μmol L^{-1});
- The phosphate concentration increases from May to June (0.14 to 0.19 μmol L^{-1})

The loss of biomass compared to the other locations is likely a combined result of these factors. Considering Equation 4, the specific growth rate decreases significantly as a result of the high temperature. Combined with the increased respiration (resulting from the high temperature), this may result in loss of carbon storage and, thus, biomass. The slight increase in acidity of the water (due to heightened nitrate and phosphate levels) in itself is not a problem; the nutrient levels are much higher during the winter, as seen in Figure 17-B and C. However, the increased eutrophied water, combined with the heightened temperature, seems to result in biomass loss.

3.2.2 Analysis of harvest

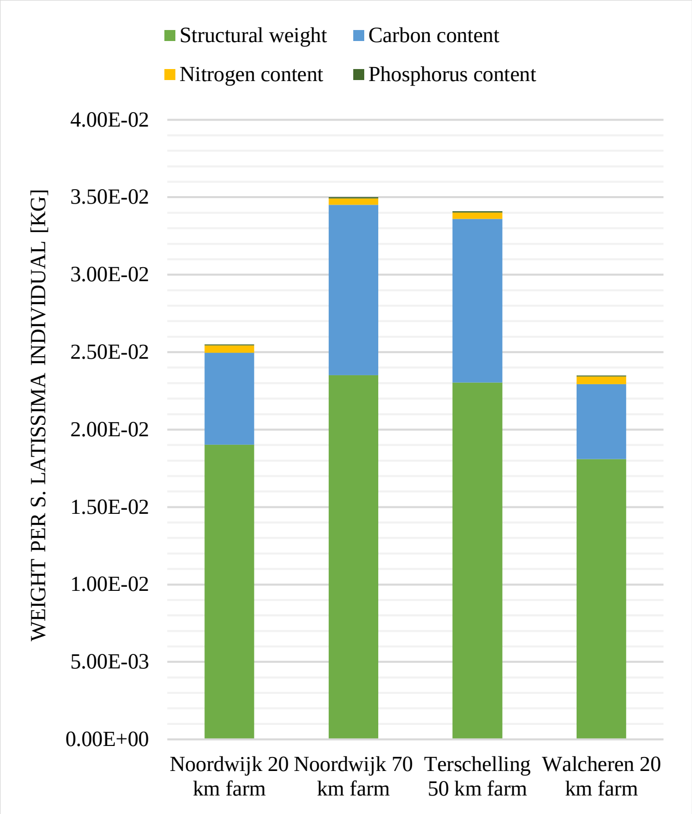
In the following section, the ideal harvest moment is discussed. In addition, the harvest per farm and differences in the harvest composition are analysed. The harvest results are found in Table 6 to Table 9. The composition of the harvested seaweed per farm is illustrated in Figure 24. In-depth information about the harvest is given in Appendix C: In-depth model results - Harvest.

Firstly, for all farms except the Walcheren 20 km farm, the dry weight and carbon content increase until the end of June. Although the harvesting of large-scale farms is likely to happen over several days, it is assumed that it takes place in one day for simplicity. If the cultivator wishes to maximise the dry weight and the total amount of carbon at the Noordwijk 20 km, Noordwijk 70 km, and Terschelling 50 km farms, harvesting on 30 June would be optimal. At the Walcheren 20 km site, the dry weight and the total amount of carbon are maximised by harvesting on 30 May.

Secondly, Figure 18-E illustrates that the total amount of sequestered nitrogen peaks on 30 March at all modelled farms. At the Noordwijk 20 km farm, the amount of sequestered nitrogen remains relatively high during the whole month of April. In conclusion, if the cultivator wishes to maximise nitrogen sequestration, the harvest should occur on 30 March at the Noordwijk 70 km, Terschelling 50 km, and Walcheren 20 km farm. Harvest at the Noordwijk 20 km farm should take place during April to maximise nitrogen sequestration.

Thirdly, suppose the cultivator wishes to maximise phosphorus sequestration. In that case, harvesting should occur on March 30 at all modelled farms (Figure 18-F), as the total amount of sequestered phosphorus is highest at this moment for all farms.

Concluding, the moment at which the highest revenue can be generated (highest amount of dry weight per square meter of farm) is June 30 for the Noordwijk 20 km, Noordwijk 70 km, and Terschelling 50 km farm. For the Walcheren 20 km farm, the highest revenue can be generated on May 30. However, the amount of sequestered nitrogen and phosphorus is highest on March 30 at all farms. The cultivator should keep in mind that if the seaweed is harvested on June 30, the amount of sequestered nitrogen and phosphorus has decreased by an average of 23% and 12%, respectively, compared to March 30.



Farm	Noordwijk 20 km farm	Noordwijk 70 km farm	Terschelling 50 km farm	Walcheren 20 km farm
Phosphorus content [%]	0.29	0.23	0.23	0.32
Nitrogen content [%]	1.81	1.18	1.21	2.06
Carbon content [%]	23.3	31.4	31.0	20.6
Structural weight [%]	74.6	67.2	67.6	77.0
Dry weight [kg]	$25.5 * 10^{-3}$	$35.0 * 10^{-3}$	$34.1 * 10^{-3}$	$23.5 * 10^{-3}$

Figure 24: Composition of harvested seaweed per farm (per S. latissima individual, harvested on June 30)

As illustrated in Figure 24, the Noordwijk 70 km harvest has the highest yield and carbon content. The Terschelling 50 km farm harvest has a slightly lower yield and a slightly lower carbon content. These deviations can be explained by the slightly higher temperature at the Terschelling 50 km farm, which causes higher respiration rates (see Figure 18-H). For a more detailed explanation, see 3.1.1. Although the nitrogen and phosphorus content of the Noordwijk 70 km and Terschelling 50 km farm are slightly lower than the farms situated closer to the coast (Noordwijk 20 km en Walcheren 20 km), the total amount of bioextracted nitrogen and phosphorus is larger due to the higher yield.

3.3 Impact assessment

In addition to the bioextraction potential of offshore *S. latissima* cultivation in MUPS, it is essential to consider the local marine environment's local ecological carrying capacity. Any use of an ecosystem leads to changes; however, these changes need to stay within acceptable levels. In the following section, the effect of the different cultivation scales and farms on the local nutrient levels is estimated.

Nitrogen and phosphorus are generally considered limiting nutrients when seaweed is cultivated in an open system. As the ocean acts as a natural sink for atmospheric CO_2, carbon is typically not a limiting nutrient in seaweed's growth and carrying capacity (Lubsch and Lansbergen, 2020). Therefore, only nitrogen and phosphorus are considered in the calculations.

The calculations in this section are based on a significant amount of assumptions. Firstly, the Dutch part of the North Sea has been divided into several inflow areas based on the distance from the shore. The inflow areas and their distance from shore are illustrated in Figure 25. Average nitrate and phosphate concentrations were extracted from the WaterInfo database for each inflow area. From these concentrations, a diffusion pattern was established. According to the CBS (2018), 281 million kilograms of nitrate and 12 million kilograms of phosphate flow to the North Sea via the Dutch rivers every year. It was assumed these amounts are distributed among the inflow areas according to their diffusion pattern. Secondly, this assessment has not included deposition, stratification, tidal action, circulation patterns, currents, and nutrient uptake from other organisms. Finally, it was assumed that the seaweed is cultivated in one continuous field instead of being divided into separate plots. Considering these assumptions, it should be noted that these calculations are a highly simplified version of reality and only serve as an indicative assessment. The results of the assessment are given in Figure 26 to Figure 29, Table 10, and Appendix E:

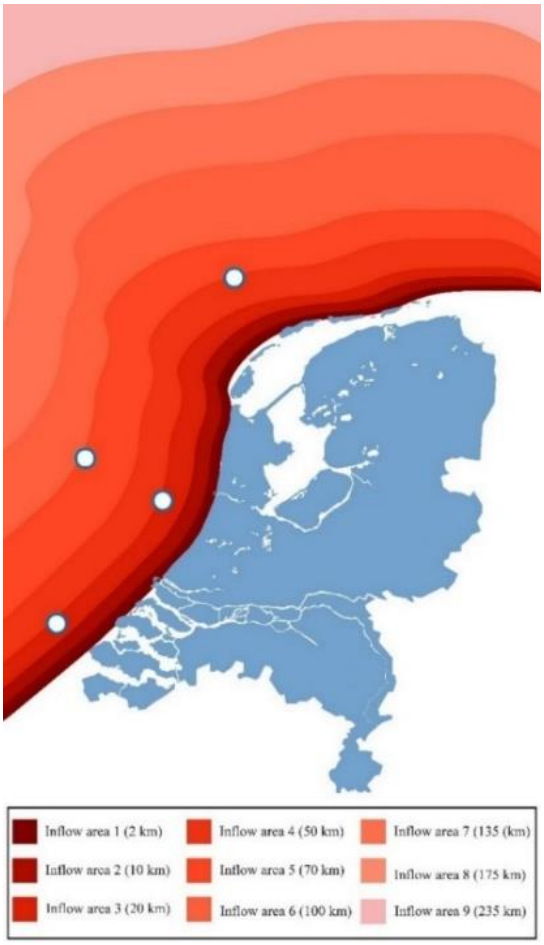


Figure 25: Division of the North Sea into inflow areas, depending on the distance from shore

Nitrate

The impact of a cultivation season of scenario 1 and 2 on the local nitrate stocks are rather significant, as seen in Figure 26 and Figure 27. The impact on each farm can be seen in Appendix E: Ecological carrying capacity. The impact is relatively minimal during the first months (October to February). The highest nitrate depletion is recorded at the Noordwijk 70 km farm (1.4% of the locally available nitrate). However, from March to June, the locally available nitrate starts depleting at a growing rate. This can be explained by the increasing nitrogen level in the seaweed tissue (Figure 18). During the spring and summer, nitrate levels are naturally low in the North Sea. Therefore, the local nitrate depletion is highest in the last month for all farms. The lowest depletion (29.3%) is recorded at the Walcheren 20 km farm (Figure 26). The highest depletion (42.3%) is seen at the Noordwijk 70 km farm (Figure 27).

Phosphate

As seen in Figure 28 and Figure 29, the impact on local phosphate levels is minimal. The impact on each farm can be seen in Appendix E: Ecological carrying capacity. During the first months (October to February) the largest depletion rate is recorded at the Noordwijk 20 km farm, showing depletion of 0.001% of the local phosphate stock. During the last month, the depletion of phosphate is highest for all farms. The marine environment of the Walcheren 20 km shows the smallest decrease in phosphate: 0.00332%. Noordwijk 20 km shows the largest decrease in phosphate levels: 0.00475%.

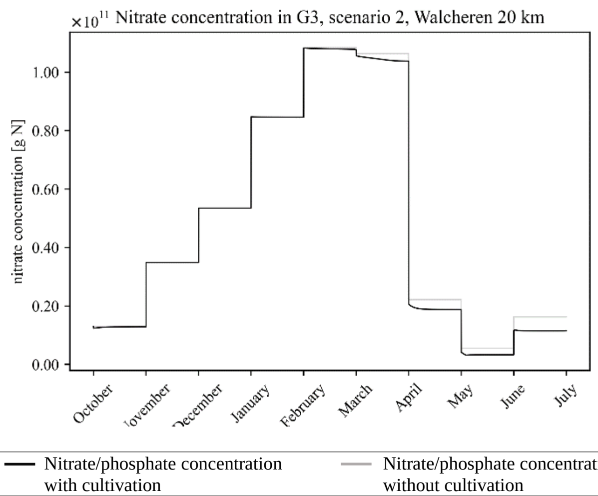


Figure 26: Impact on local nitrate concentrations for Walcheren 20 km farm, scenario 2

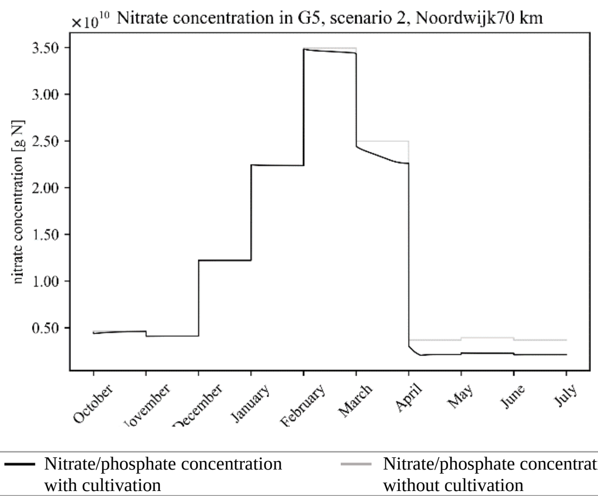


Figure 27: Impact on local nitrate concentrations for Noordwijk 70 km farm, scenario 2

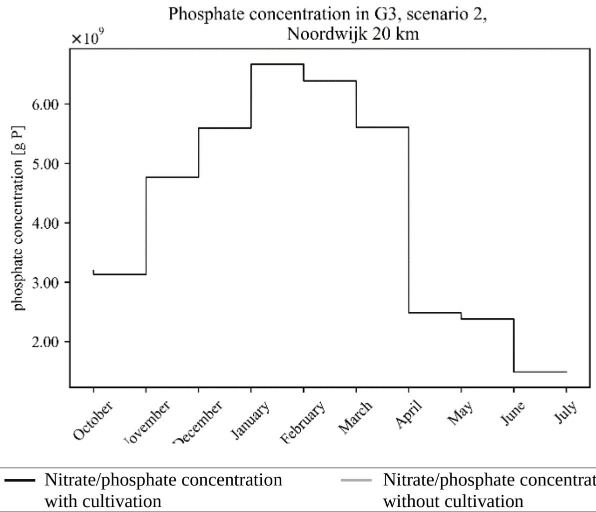


Figure 28: Impact on local phosphate concentrations for Noordwijk 20 km farm, scenario 2

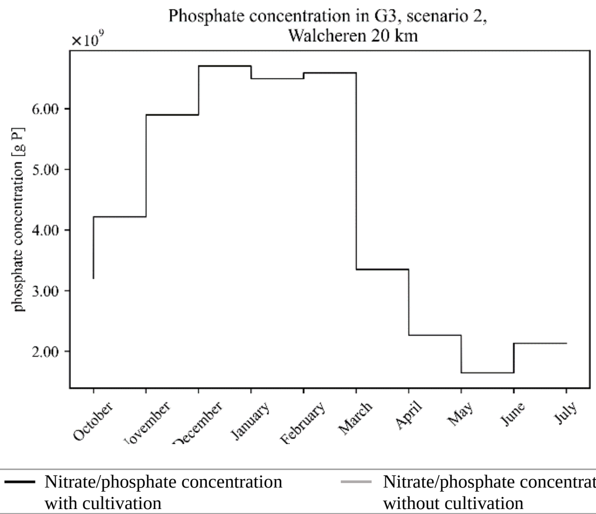


Figure 29: Impact on local phosphate concentrations for Walcheren 20 km farm, scenario 2

Farm	Scenario 1: uptake of local nitrate stock [%]	Scenario 1: uptake of local phosphate stock [%]	Scenario 2: uptake of local nitrate stock [%]	Scenario 2: uptake of local phosphate stock [%]
Noordwijk 20 km farm	28.5	0.00362	35.2	0.00475
Noordwijk 70 km farm	34.3	0.00299	42.3	0.00392
Terschelling 50 km farm	34.2	0.00355	42.0	0.00465
Walcheren 20 km farm	23.7	0.00253	29.3	0.00332

Table 10: Decrease in local nitrate and phosphate stocks per scenario and farming location

In conclusion, from this indicative assessment, it becomes clear that offshore cultivation of the *S. latissima* in the North Sea could result in significant nitrate depletion. As nitrate levels decrease when moving further from shore (Lubsch, 2020), the depletion and, therefore, the risk of detrimental ecological effects seem more significant when moving further from the coast. This phenomenon can be seen in Table 10. Furthermore, this indicative assessment illustrates that phosphate depletion does not seem to be a risk in the offshore cultivation of the *S. latissima* in the North Sea. The rate of phosphate depletion does not seem to show a correlation with the distance from the coast. Based on these findings, recommendations are made, which are found in the chapter Recommendations.

3.4 Validation of model

To gain a better understanding of the reliability of the model, the results are validated by comparing them to literature. In the following section, the model results are compared to several other measurements and models that are used to predict the growth and nutrient dynamics of the *S. latissima*. Deviations or similarities in trends and values are analysed, and possible explanations for variations are elaborated upon.

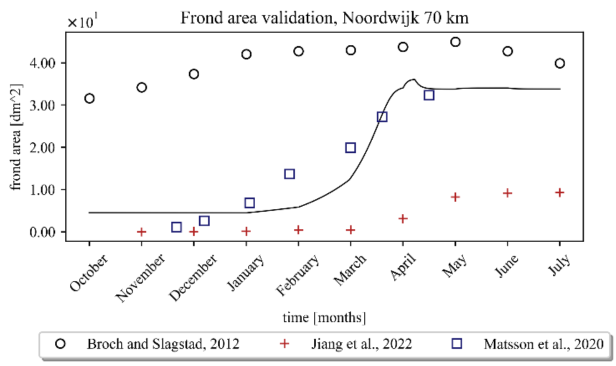


Figure 30: Validation of frond area; comparison with modelling results from Broch and Slagstad (2012) and Jiang et al. (2022)

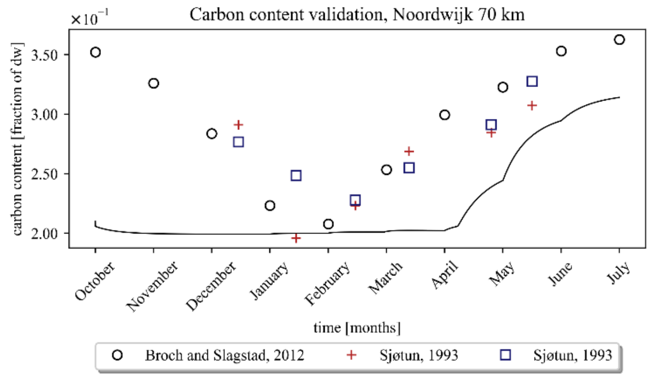


Figure 31: Validation of carbon content; comparison with Broch and Slagstad (2012) and Sjøtun (1993)

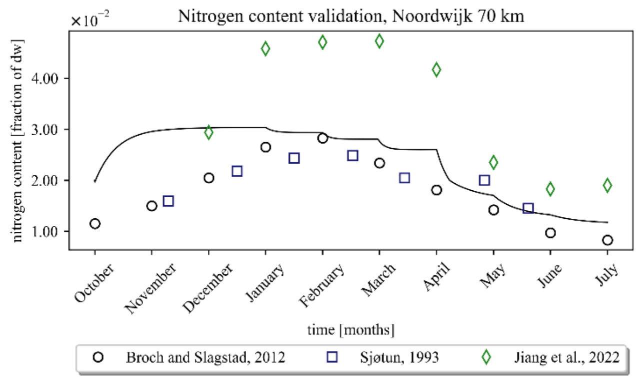


Figure 32: Validation of nitrogen content; comparison with Broch and Slagstad (2012) and Sjøtun (1993)

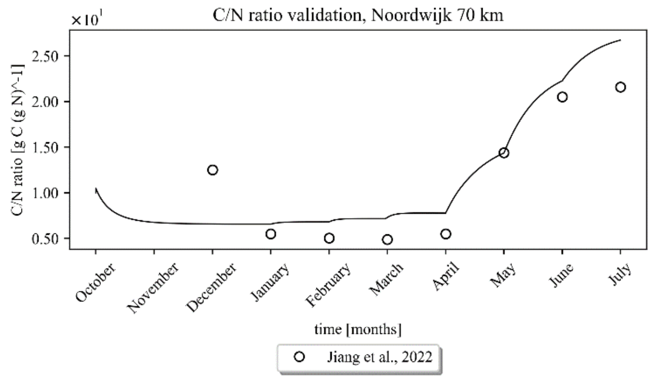


Figure 33: Validation of C/N ratio: comparison with Jiang et al., 2022

Seaweed generally has large variations in chemical compositions and growth rates, depending on location- and season-dependent variables (Van Hal et al., 2014). Therefore, when the chemical composition and growth are compared to other studies, several factors should be taken into account:

- The location- and season-dependent environmental variables;
- The deployment time;
- The harvest time;

To compare the studies fairly, the locations, deployment and harvest period of the compared studies are given in Table 11.

Study	Location	Deployment time	Harvest time
Broch and Slagstad (2012) - Model	Western Norway	August	-
Sjøtun (1993) - Observations	Western Norway	August	-
Jiang et al., 2022 - Model	Eastern Scheldt, the Netherlands	November 2009	June 2010
Matsson et al., 2020 - Observations	Tromsø, Norway	November 2012	May 2013
Ohtake et al., 2020 – Observations	Arikawa bay, Japan	December 2017	February 2019

Table 11: Location, deployment time, and harvest time of validation studies

First, the frond area is compared to modelling results from Broch and Slagstad (2012), Jiang et al. (2022), and Matsson et al. (2020). In Figure 30, it can be noticed that the individual studies have a high level of variability in values. The study from Broch and Slagstad has a fairly high and stable frond area. This stable and high value is likely caused by the fact that the seaweed in this study is not harvested. Therefore, the seaweed grows continuously throughout the season. The seaweed loses some biomass at the end of the growing season but does not have to start from sporophytes in October. Jiang et al. (2022) modelled the seasonal growth and carrying capacity of the *S. latissima* in the Eastern Scheldt. As seen in Figure 30, the values of the frond area are significantly lower than the results of this study. The model by Jiang et al. was run for a farm in the Eastern Scheldt, a coastal bay in the Netherlands. Coastal systems have different environmental variables than offshore systems. The model by Jiang et al. had significantly lower temperatures in the winter months, a lower current speed, and higher turbidity. These factors combined could be the cause of the deviating numbers from this research. The values from this study seem to be comparable to the observations performed by Matsson et al. (2020). Although the values of other studies somewhat deviate from the results of this thesis, there are similarities in trends. The frond areas in the compared studies remain stable until December and show – similar to this study – a significant increase between December and May.

In Figure 31, the model results for the carbon content are compared to studies by Broch and Slagstad (2012) and Sjøtun (1993). The carbon content of this study follows somewhat similar trends to the compared studies; a speak in October, a gradual decrease until January, and an increase from April to June. The peak in October, however, is moderately lower, and the increase in carbon content commences later. Several factors could cause these deviations. First, Norway's irradiance along the entire coast is slightly lower than in the Netherlands from October to January (Solcast, 2022). Lower irradiance results in slightly lower photosynthetic activity and would therefore cause a lower carbon content. However, the seawater temperatures in Norway are significantly lower (~3°C lower) in Norway compared to the Dutch part of the North sea (Broch and Slagstad, 2012; Höhn et al., 2017; Rijkswaterstaat, 2022) from October to January. The lower temperatures are beneficial for the growth and carbon content, as respiration rates decrease as a result of this. Therefore, the higher carbon content in the results of Broch and Slagstad (2012) can be explained by the lower seawater temperatures in Norway.

The nitrogen content of this study is compared to research from Broch and Slagstad (2012) and Sjøtun (1993) in Figure 32. All compared studies show a peak during the winter months (December to March), as nitrate concentrations peak during this period. During the spring bloom, nitrogen content gradually decreases in all studies. As seen in Figure 32, the nitrogen content values of the studies by Broch and Slagstad and Sjøtun are relatively lower. An explanation for this could be that eutrophication levels in the North Sea are significantly higher than in the Norwegian Sea, where the compared studies were carried out (see Figure 34). In opposition to the results from Broch and Slagstad and Sjøtun, the study by Jiang et al. (2022) shows a relatively late peak with high values. As this study was carried out in the Eastern Scheldt, nutrient concentrations are significantly higher than the offshore concentrations at the Noordwijk 70 km farm. Furthermore, the model of Jiang et al. was run from November to June instead of October to June, which could cause a later peak in nitrogen content. The later deployment time could also be the cause of the relatively late starting peak (December) in Figure 33.

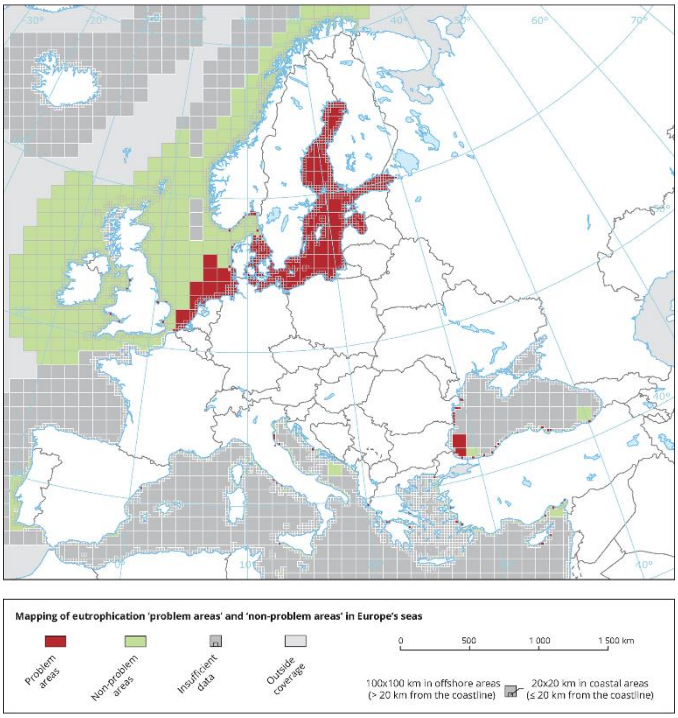


Figure 34: Map of eutrophication in European seas (European Environment Agency, 2020)

Literature on seasonal phosphate content and phosphate uptake rates of the *S. latissima* is very scarce. In a study by Lubsch and Timmermans (2018), the DIN- and DIP-uptake rates of young sporophytes of the *S. latissima* and *L. digitata* under fully controlled laboratory conditions. However, the uptake rates were only measured *during* the first three weeks of growth. The DIP-uptake rates are depicted in Figure 35. In these figures, it can be observed that the DIP-uptake rate of young *S. latissima* peaks during the first week of deployment, after which it gradually decreases. This trend is similar to the results of this study.

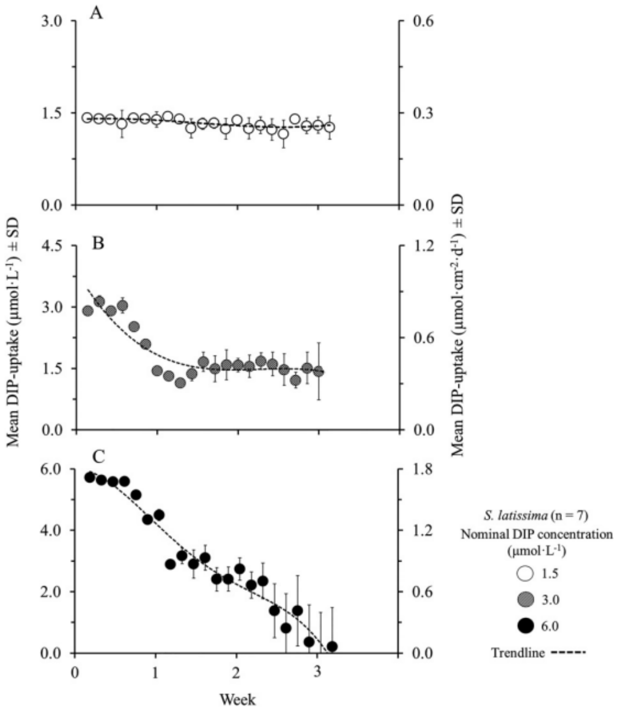


Figure 35: Mean DIP-uptake of young S. latissima (Lubsch and Timmermans, 2019)

A limited amount of studies have been performed on the P-uptake rates of other seaweed species. Ohtake et al. (2020) have conducted measurements on the phosphorus demand and uptake of the *S. macrocarpum* in Arikawa bay, Japan. As seen in Figure 36, phosphorus uptake peaks after deployment and gradually decreases during winter (December to March). During spring and early summer, the uptake gradually increases. These trends are similar to the results of this study.

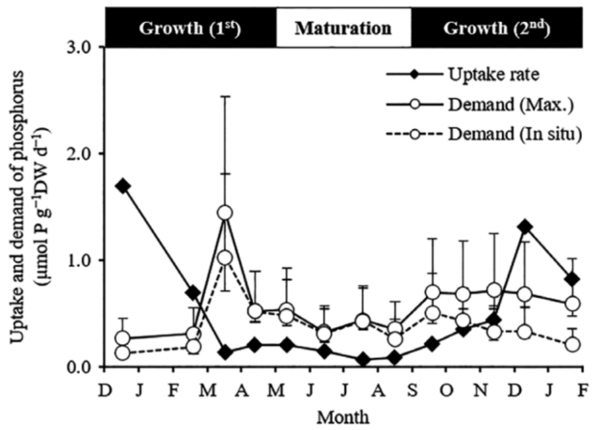


Figure 36: Uptake rate, maximum and in-situ demands for P of Sargassum macrocarpum (Ohtake et al., 2020)

Finally, the nutrient contents of the seaweed during the harvest period are compared to other measurements and models. In Table 12, this study's results are compared with the nutrient contents of other studies. Concluding, the model was evaluated as functional and sufficiently accurate from this analysis. The values for the evaluated parameters have been shown to lie within the range of comparable studies and experimental data. The trends portrayed by the generated model results can be explained and found in comparative studies. Outliers in these results can be explained by the differentiating framework conditions of the studies (temperature, location, irradiance, harvesting time, etc.). Therefore, the model as it was set up can be utilised for the purpose it was intended for; to simulate and compare conditions, nutrient dynamics, and growth in different farming locations in the North sea.

Study	Location	Carbon content [%dw]	Nitrogen content [%dw]	Phosphorus content [%dw]
Schoenmakers (2022)	Noordwijk, the Netherlands, 20 km from shore	23.3	1.81	0.29
Schoenmakers (2022)	Noordwijk, the Netherlands, 70 km from shore	31.4	1.18	0.23
Schoenmakers (2022)	Terschelling, the Netherlands, 50 km from shore	40.0	1.21	0.23
Schoenmakers (2022)	Walcheren, the Netherlands, 20 km from shore	20.6	2.06	0.32
TNO (n.d.)	Port A'bhuiltin, Scotland	24.0	2.63	-
TNO (n.d.)	Port A'bhuiltin, Scotland	25.3	2.66	-
TNO (n.d.)	Scheveningen, the Netherlands	29.4	3.87	-
Jiang et al. (2022)	Eastern Scheldt, the Netherlands	35.1	1.93	-
Marinho et al. (2015)	Horsens Fjord, Denmark	-	1.24	0.17
Matsson et al., 2020	Norwegian coast	-	1.8	-
Ometto et al., 2018 -	Trondheim, Norway		3.8	0.24
Pechsiri et al., 2016	Tjärnö, Sweden		1.6	0.24

Table 12: Validation of harvest results

3.5 Sensitivity analysis

In the following section, a sensitivity analysis is performed to determine the degree to which changes in the input values for a particular variable affect the model's output. The model is run again on the basis of the three following scenarios: (1) a marine heatwave; (2) a particularly cloudy cultivation season; (3) decreased eutrophication in the North Sea.

3.5.1 Sensitivity analysis 1: marine heatwave

Due to anthropogenic global warming, extreme events involving ocean temperature, such as marine heatwaves (MHWs), are anticipated to occur more frequently in the future decades (Jacox et al., 2022). MHWs, which are extended episodes of abnormally warm water temperatures, pose a serious threat to marine ecosystems and their ability to function. Previous research demonstrated indications of, amongst other detrimental effects, decreased nutrient uptake with rising temperature in *F. spiralis* and *S. latissima* (Topinka 1978; Gerard 1997). As Sen Gupta et al. (2020) described, an MHW can be subdivided into four categories, depending on the increase in surface water temperature:

- Moderate (1 < T <= 2);
- Strong (2 < T <= 3);
- Severe (3 < T <= 4);
- Extreme (T >= 4).

MHWs affect wind speeds and current speeds as well (Sen Gupta et al., 2020). Jiménez et al. (2011) researched that wind speeds can be reduced by up to 22% during an MHW. A literature study did not provide insights on the exact effects of MHWs on current speeds, and it is therefore assumed that current speeds are reduced by 22%, as well.

Lastly, MHWs can also decrease marine nutrient levels due to increased phytoplankton growth (Jacox et al., 2015; Roleda and Hurd, 2019; Hayashida et al., 2020). According to Wyatt et al. (2022), MHWs can decrease marine nutrient levels by up to 30%.

The adjusted parameters for the marine heatwave sensitivity analysis are displayed in Table 13. This sensitivity analysis assumes that the marine heatwave starts in February; at this point, the parameters gradually begin to adjust. The parameters reach their maximum adjustment value in April. This sensitivity analysis is performed on the Walcheren 20 km farm, as this is the farm that reaches the highest water temperatures. Examining a further increase in temperature could provide valuable insights. It is assumed that the seaweed is harvested on 30 June (similar to the harvest date used in section 3). The results from this sensitivity analysis on the Walcheren 20 km farm are displayed in Figure 37 to Figure 40. All graphs can be found in Appendix D.1: Sensitivity analysis 1: Marine heatwave**.**

Parameter	Adjustment
Temperature	+ 4 [°C]
Current speed	- 22 [%]
Nitrate concentration	- 30 [%]
Phosphate concentration	- 30 [%]

Table 13: Adjusted parameters for sensitivity analysis 1: marine heatwave

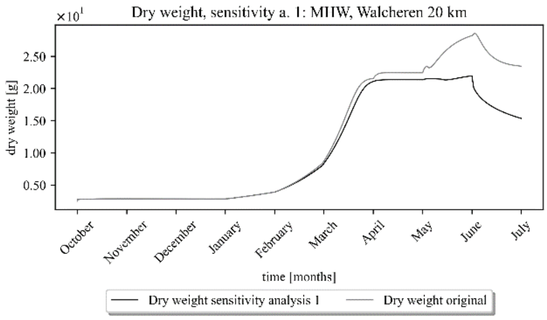


Figure 37: Dry weight, sensitivity analysis 1: MHW, Walcheren 20 km farm

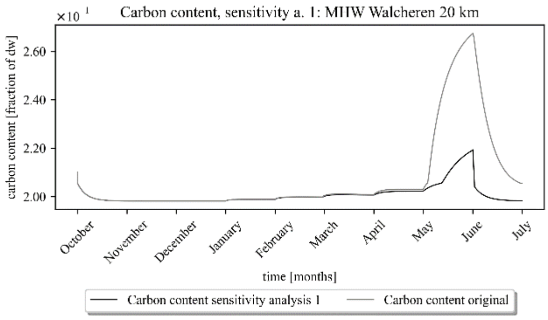


Figure 38:Carbon content, sensitivity analysis 1: MHW, Walcheren 20 km farm

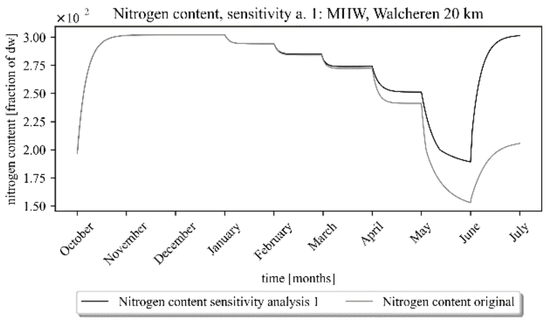


Figure 39: Nitrogen content, sensitivity analysis 1: MHW, Walcheren 20 km farm

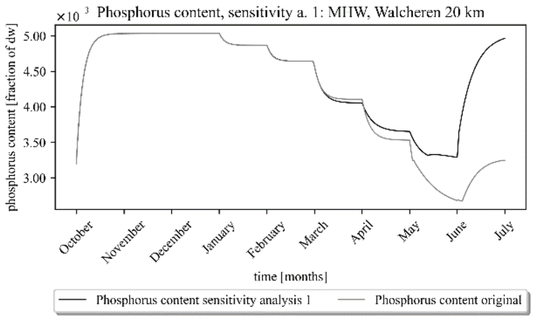


Figure 40: Phosphorus content, sensitivity analysis 1: MHW, Walcheren 20 km

Measurand	Value	Unit
Dry weight	1.07	[kg]
Total bioextracted carbon	0.21	[kg]
Total bioextracted nitrogen	0.032	[kg]
Total bioextracted phosphorus	0.0053	[kg]

Table 14: Dry weight and the total of bioextracted nutrients per square metre at Walcheren 20 km during a marine heatwave

Adjustment of the parameters results in changes in various nutrient and growth dynamics. Firstly, as seen in Figure 37, the dry weight increases gradually from January onwards. However, from April to June the dry weight decreases, indicating the mortality of biomass. This phenomenon is demonstrated by Equation 4. At temperatures above 15 °C, the growth rate of the *S. latissima* decreases drastically. As explained in 3.2.1.2, high temperatures (> 15 °C) result in low growth and high respiration rates. This causes a decrease in biomass, and a lower (± 35%) yield, compared to normal variables. In addition, the high respiration rates also cause a lower carbon content (Figure 38). An interesting result is displayed in Figure 39 and Figure 40. The nitrogen and phosphorus contents of the seaweed do not gradually decrease until harvest, but show a peak in June. As seen in Appendix D.1: Sensitivity analysis 1: Marine heatwave, the nutrient uptake rates are only slightly lower than in the normal situation. As the total dry weight reduces, the relative nutrient content is higher than in a normal situation. Comparing the results in Table 14 to the normal situation described in 3.1.2.4, the total bioextracted carbon, nitrogen and phosphorus is 37%, 4% and 0.1% lower, respectively. Therefore, it can be concluded that a heatwave has detrimental effects on the nutrient bioextraction potential of the *S. latissima*.

3.5.2 Sensitivity analysis 2: cloudy cultivation season

One of the parts of the earth-atmosphere system that is currently poorly understood is clouds and their effects on irradiance. Measuring their radiative characteristics remains a challenge. In this second sensitivity analysis, the effects of a cloudy year on the nutrient dynamics and growth of the *S. latissima* are analysed.

Several studies have been conducted seeking to measure the effect of clouding on solar radiation. Extremely heavy clouding can reduce solar radiation by up to -400 W/m^2 (Tzoumanikas, 2016). This could result in a decreased irradiance of 100% during winter and up to 50% during spring and summer. As it is not likely that heavy clouding occurs 100% of the cultivation, it is assumed that heavy clouding will take place 75% of the time. The adjusted parameters are displayed in Table 15. No unambiguous data has been found on the exact effects of heavy clouding on the surface temperature in the North Sea. It is assumed that a particularly cloudy cultivation season results in a 20% decrease in temperature. The results of this sensitivity analysis on the Noordwijk 20 km farm are displayed in Figure 41 to Figure 44. All graphs of this sensitivity analysis are given in Appendix D.2: Sensitivity analysis 2: cloudy cultivation season.

Parameter	Adjustment
Irradiance	-75% during winter -37.5% during spring and summer
Temperature	-20% during the entire cultivation season

Table 15: Adjusted parameters for sensitivity analysis 2: cloudy cultivation season

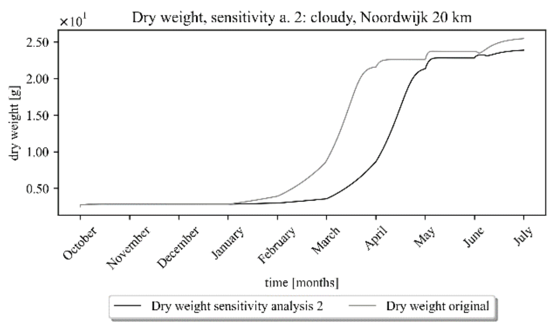


Figure 41: Dry weight, sensitivity analysis 2: cloudy cultivation season, Noordwijk 20 km farm

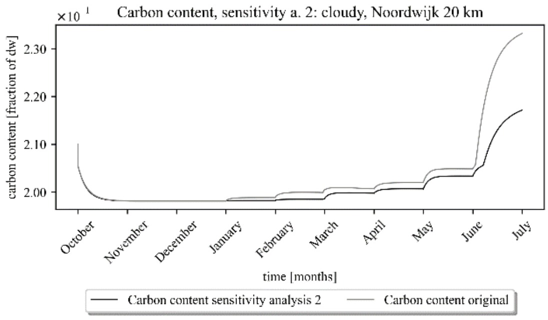


Figure 42: Carbon content, sensitivity analysis 2: cloudy cultivation season, Noordwijk 20 km farm

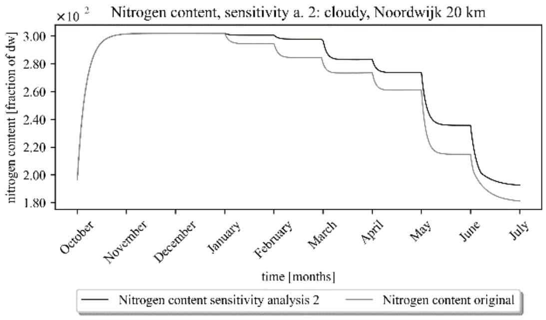


Figure 43: Nitrogen content, sensitivity analysis 2: cloudy cultivation season, Noordwijk 20 km farm

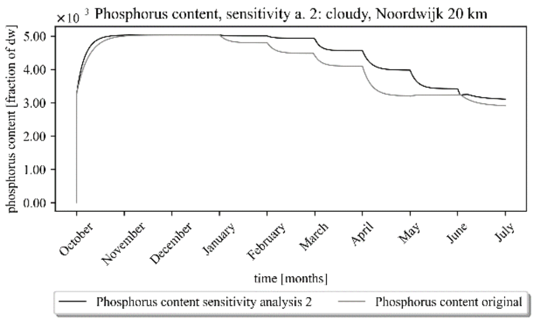


Figure 44: Phosphorus content, sensitivity analysis 2: cloudy cultivation season, Noordwijk 20 km farm

Measurand	Value	Unit
Dry weight	1.67	[kg]
Total bioextracted carbon	0.36	[kg]
Total bioextracted nitrogen	0.032	[kg]
Total bioextracted phosphorus	0.0052	[kg]

Table 16: Dry weight and the total of bioextracted nutrients per square metre at Noordwijk 20 km during a cloudy cultivation season

Comparing Figure 41 to Figure 44 with the modelling results of a 'normal' situation in 3.1.1.1 and 3.1.2.1, it becomes clear that a cloudy year affects the carbon content to a large extent and the nitrogen and phosphorus dynamics to a lesser extent. As photosynthetic activity is low during winter, the effects of clouds are minimal during this period. However, photosynthetic activity is decreased by up to 34% during spring and summer. The reduced gross photosynthesis during a cloudy cultivation season results in a lower carbon content (21.7%). In addition, a cloudy year results in a lower amount of bioextracted carbon (13% less than in a normal situation). Therefore, it can be concluded that a cloudy year (lower irradiance and lower water temperature) has minimal effects on the bioextraction potential of nitrogen and phosphorus but has a detrimental impact on the bioextraction of carbon.

3.5.3 Sensitivity analysis 3: decreased nitrate levels

The Dutch government has been working to put measures in place since the 1990s to reduce the country's carbon footprint and nitrogen emissions. Numerous strategies have been effective in cutting nitrogen emissions across various businesses and sectors (Backus, 2017). The agricultural sector, however, has fought the government's strategies for years. Since the government and environmental organizations had hoped that nitrogen emissions in the Dutch agricultural sector would decline at a faster rate, the cabinet moved to enact stricter regulations for farmers back in 2019. The new imposed measures differ per province (Figure 45), but should result in an average nitrogen emission reduction of 40% by 2030 (NOS. 2022). The decrease in nitrogen emissions by the Dutch agricultural sector can be achieved by, e.g., the following actions:

- Investing in sustainable technologies
- Implementing circular agricultural technologies
- Modifying the farm's business strategies
- Moving houses
- Quit farming

The Dutch agricultural section has a share of 45% of the national nitrogen emissions (RIVM, 2021). Providing that the measures are successfully implemented, the national nitrogen emissions should be reduced by 18% by 2030.

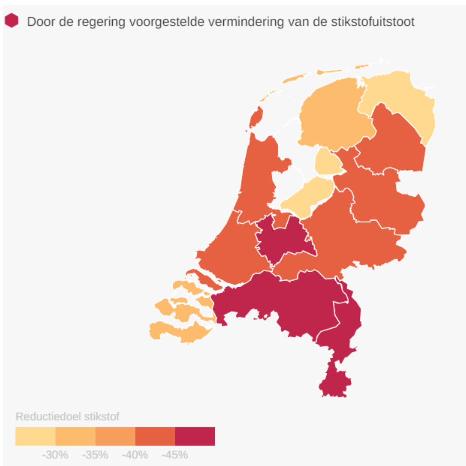


Figure 45: Government-proposed reduction in nitrogen emissions for Dutch agriculture (AD, 2022)

A reduction in nitrogen emissions will, evidently, affect the nitrogen outflow of Dutch rivers and, therefore, the nitrogen levels in the North Sea. The Netherlands has a share of ±37% of the total nitrogen deposition via rivers to the Dutch part of the North Sea (De Klein, 2007). Assuming a reduction of 18% of the total nitrogen emission results in a similar decrease in the total deposited nitrogen via rivers, the total nitrogen outflow of the Dutch rivers will decrease by 7%.

In this third sensitivity analysis, the effect of the Dutch nitrogen measures on the nutrient dynamics and growth of seaweed at the Noordwijk 70 km farm is analysed. It is assumed that a reduction of 7% of the nitrogen outflow also results in a 7% decrease in nitrate levels in the Dutch part of the North Sea. The adjusted parameters are displayed in Table 17. This sensitivity analysis is performed on the Noordwijk 70 km farm, as this is the farm with the lowest nitrate concentrations. Examining a further decrease in nitrate concentrations could provide valuable insights. The results of this sensitivity analysis are displayed in Figure 46 to Figure 49.

Parameter	Adjustment
Nitrate concentration	-7% during entire cultivation season

Table 17: Adjusted parameters for sensitivity analysis 3: decreased nitrate levels

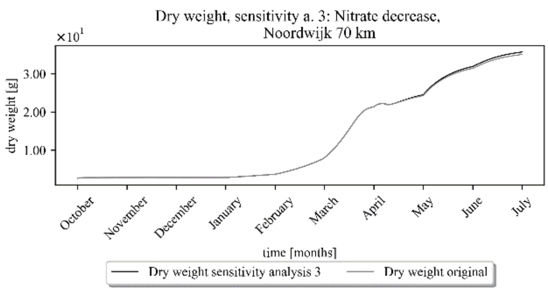


Figure 46: Dry weight, sensitivity analysis 3: decreased nitrate levels, Noordwijk 70 km farm

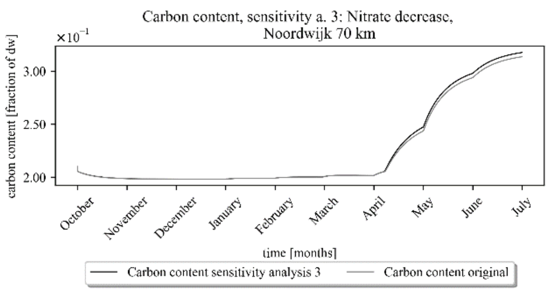


Figure 47: Carbon content, sensitivity analysis 3: decreased nitrate levels, Noordwijk 70 km farm

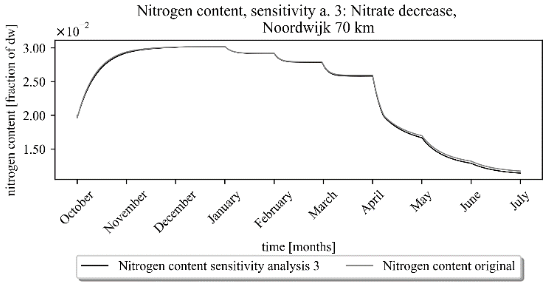


Figure 48: Nitrogen content, sensitivity analysis 3: decreased nitrate levels, Noordwijk 70 km farm

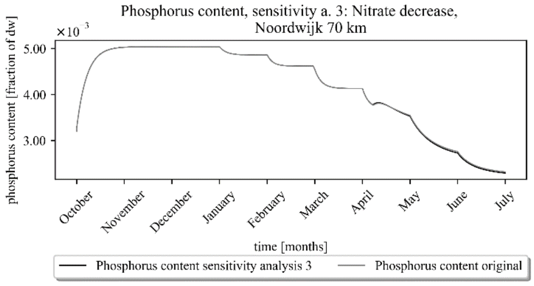


Figure 49: Phosphorus content, sensitivity analysis 3: decreased nitrate levels, Noordwijk 70 km farm

Measurand	Value	Unit
Dry weight	2.45	[kg]
Total bioextracted carbon	0.76	[kg]
Total bioextracted nitrogen	0.028	[kg]
Total bioextracted phosphorus	0.0057	[kg]

Table 18: Dry weight and the total of bioextracted nutrients per square metre at Noordwijk 70 km during a cultivation season with decreased nitrate levels

Comparing the results in Figure 46 to Figure 49 with the results of a ‘normal’ situation in 3.1.1.2 and 3.1.2.2, it can be seen that a decreased nitrate concentration has minimal effects on the nutrient dynamics and growth of the Noordwijk 70 km seaweed. The trends in growth and nutrient contents are similar. However, the values of the yield and total bioextracted nutrients differ slightly. The dry weight of the seaweed has decreased by 1.8%. Furthermore, the total amount of bioextracted carbon, nitrogen, and phosphorus decreased by 3%, 0.9%, and 0.2%, respectively. This appears to be a minimal difference. However, this could result in large differences in yield and bioextracted nutrients at larger scales. For scenario two, this could result in a decreased yield of 16 million kilogram dw. The decrease in dry weight and bioextracted nutrients is likely due to a deficiency in nitrate. As seen in Equation 2 and Equation 8, the uptake of nitrate results in the creation of biomass. A decreased nitrate concentration results in a lower specific growth rate, obstructing the carbon and phosphate uptake. Therefore, it appears that a decreased nitrate concentration resulting from the nitrogen measures of the Dutch government could result in a slightly lower yield and bioextraction potential of the seaweed at the Noordwijk 70 km farm. It should, however, be noted that this assessment is a highly simplified version of reality.

3.5.4 Conclusion sensitivity analysis

This sensitivity analysis was conducted to identify how much variations in the input values for specific scenarios affect the results for the mathematical model that is used in this research. The results of the calculations with adjusted parameters have been shown to generate foreseeable results. Differences in the results can be explained by the adjusted parameter conditions. Therefore, the model as it was set up can be evaluated as robust and utilised for its intended purpose.

4. Discussion

This study aims to quantify critical nutrient flows of seaweed cultivation in MUPS, and assess the impact on the local marine environment. Moreover, this study aims to translate the quantified nutrient flows into ecosystem services. Furthermore, this study seeks to examine what role monitoring systems can play in seaweed cultivation in MUPS at the North Sea. Merging these separate research topics, this study seeks to investigate whether ecosystem services can be established through macroalgae cultivation in the North Sea, using nutrient analyses and monitoring technologies. In the following section, uncertainties and limitations in the nutrient model and in achieving the research aim mentioned above are discussed.

4.1 Uncertainties and limitations

The mathematical model used in this research is based on the model of Broch and Slagstad (2012) and therefore uses the same assumptions, which result in similar limitations. Broch and Slagstad (2012) were the first to develop a dynamic bioenergetic model with the aim of optimising the aquaculture production of *S. latissima*. The model has been well-validated (Broch et al., 2013; Strong-Wright and Taylor, 2022) but has several uncertainties and limitations. In the following section, these uncertainties and limitations are elaborated upon.

Several variables that could impact the results have not been considered in this mathematical model. First, the salinity of the substrate has not been included. As studied by multiple scholars, salinity can greatly impact the growth rate of various types of macroalgae (Martins et al., 1999; Reis, 2011; Karsten, 2012). This variable has not been included in the study due to the lack of quantitative data. Secondly, a variable that has not been included in the model is the morphology of the *S. latissima* fronds. However, there is evidence that the morphology of the fronds may not influence nutrient uptake rate, growth rate, and erosion (Hurd et al., 1996; Gerard et al., 1987; Sjøtun, 1993). Lastly, the model has not included several other environmental variables, such as oxygen content, pH, water depth, and wave action (Engledow and Bolton, 2003; Ateweberhan, 2015). These variables have been proven to have an impact on the growth rate of seaweed but have not been included in this model due to a lack of quantitative data.

Aquaculture of the *S. latissima* is known to discharge POM and DOM, which partly consists of DOC, DON and DOP. As discussed in 1.3.2, the exact quantities and effects of DOM discharge at a large scale are still subject to research. The release of DOC has been partly covered by Equation 11 and Equation 12. However, the release of DON and DOP has not been included in this mathematical model. DOC, DON and DOP discharge have not been included in this model due to a lack of information on the precise functioning of these dynamics. Including these dynamics could result in deviations in the carbon, nitrogen and phosphorus pool in the tissue of the seaweed. Moreover, the inclusion of these dynamics in the model could provide more information on the ecological effects of seaweed aquaculture on the marine environment.

This research has dealt with several data availability limitations. Firstly, macroalgae are known to take up dissolved organic nitrogen and phosphorus (DIN and DIP, respectively) during their growth (Young, 2016; Lubsch and Timmermans, 2019). DIN consists of nitrate to a large extent, and ammonia and nitrite to a lesser extent. DIP consists of phosphate to a large extent, and phosphoric acid and hydrogen phosphate to a lesser extent. In this study, only nitrate and phosphate have been included due to a lack of quantitative data on the farming locations. Incorporating ammonia, nitrite, phosphoric acid, and hydrogen phosphate may result in slightly higher substrate nutrient concentrations, which may benefit the nutrient concentrations of the seaweed. Secondly, no hourly or daily data was available for the following environmental variables: water temperature, water current speed, and substrate nitrate/phosphate concentrations. The WaterInfo database only provided one to two measurements per month per year. Therefore, the environmental variables of 5 cultivation seasons have been averaged over a whole month (see 2.1.1.5). This has resulted in a step-profile in the environmental variables. Incorporating hourly or daily measurements for the environmental variables could result in more extreme growth or nutrient dynamics fluctuations within one month. Thirdly, no data on the irradiance levels at the different farming locations is available. Therefore, it was assumed that the irradiance are equal at every farming location. In reality, the irradiance levels deviate per location in the North Sea (Knibbeler, 2019). Incorporating deviating irradiance levels per farm would result in differing photosynthetic activity and possibly in more significant differences in yield and bioextracted nutrients per farm.

The mathematical model used in this thesis assumes that the seasonal growth of the *S. latissima* is partly forced by changes in day length (Equation 5). Some studies suggest that changes in day length influence the growth rate; however, this has not been validated yet (Barsch et al., 2008). The growth rate's forces may also result from variations in genetics, environmental variables, or geographical conditions (Broch and Slagstad, 2012). Several investigations have measured that growth rates of the *S. latissima* reach their maximum and minimum during the peak and trough of day lengths, respectively (Brinkhuis et al., 1987; Sjøtun, 1993). The timing of reproduction also seems to be timed (during the autumn equinox). Therefore, it is likely that the force behind the growth rate is the change in day length.

An offshore cultivation system will most likely be used for several growing seasons, growing different types of seaweed in one year (Van der Molen et al., 2018). This will increase the viability of deploying a costly, large-scale macroalgae farm. The mathematical model used in this thesis runs over the course of one cultivation season for one macroalgae species due to time constraints. Running the model for multiple years and multiple macroalgae species could provide valuable insights into the long-term ecological effects of intensive, large-scale seaweed farming. However, it remains challenging to estimate precisely how much of the marine zone is impacted by seaweed farming because it is dynamic in both location and time (seasonal and between years) (Eggertsen and Halling, 2021). Developments in mathematical models, data availability, and measurements may provide further insights into this.

The impact assessment in 3.3 is based on a significant amount of assumptions. Several factors have not been included, such as stratification, tidal action, circulation patterns, currents, and nutrient uptake from other organisms. Therefore, this study should only serve as an indicative assessment.

In conclusion, this study is based on a fair number of assumptions discussed above. Therefore, all results of this study should only serve as an indicative and exploratory assessment of offshore seaweed cultivation in MUPS at the North Sea. It is recommended that the nutrient bioextraction potential and impact be assessed in more advanced models, accompanied by data retrieved from monitoring technologies discussed below.

5. Monitoring technologies

In the following sections, options for monitoring technologies for large-scale seaweed farming are discussed.

5.1 Monitoring technologies

Innovative macro algae production strategies, including strain development, harvesting, shipping, and processing, are needed to optimise offshore aquaculture. The offshore aquaculture system may make use of novel engineering and material solutions, robotic and autonomous technology, as well as sensing and monitoring tools. New approaches, such as remote and automated monitoring, will be even more crucial for offshore areas (Siddiqui et al., 2019).

Frequent monitoring of offshore seaweed cultivation areas could offer several benefits. Firstly, in-person monitoring could be unpractical due to distance from shore, risk for personnel, required output volume, and high operational expenditures. Monitoring technologies could provide a solution for these issues. Furthermore, frequent monitoring could aid in the early detection of diseases (Kambet et al., 2020), "crop-to-wild" gene flow (Loureiro et al., 2015), toxins, or other unwanted conditions (Makkar et al., 2016), which could benefit yield and crop quality. Moreover, frequent monitoring could help detect potentially harmful interactions with the marine environment, such as plankton, benthic species, and other epifauna and megafauna species (Campbell et al., 2019). Additionally, the present boat-centric approaches use fossil fuels, which add to pollution and global warming (Thomas et al., 2021). Using automated or remote monitoring technologies could lower the carbon footprint of these operations. Lastly, to maximise productivity, the crop should be harvested as soon as it reaches the ideal size. On the sea belt, overgrown plants could shatter and drift away. The more frequently the monitoring occurs, the quicker issues can be solved, crop growth can be forecasted, and harvesting can be organised to maximise output and profitability. (Mahalik and Kim, 2014).

Although remote and automated monitoring of seaweed cultivation has numerous advantages, putting it into practice can pose several challenges. These difficulties can arise in the form of navigation, control, technology, perception, and planning. The problems are mainly caused by limited underwater sensing options and the offshore domain's erratic and harsh dynamics (Stenius et al., 2022). These difficulties could be partially solved by implementing high-grade navigation and sensory technologies. However, deploying expensive technology with advanced sensors may not be feasible for the large farming scales described in this thesis, as it would not be cost-effective yet (Stenius et al., 2022). Hence, deploying more cost-effective monitoring options, such as smart buoys, small AUVs, remotely operated vehicles (ROVs), small unoccupied aircraft vehicles (sUAS) or autonomous and unoccupied surface vehicles (ASVs and USVs, respectively), may be more attractive. An overview of the CapEx, OpEx, monitoring time, and the required amount of units per scenario is given in Table 20.

5.1.1 Smart buoys

Buoys are essential to most common seaweed cultivation systems, as they ensure the cultured ropes stay elevated near the water surface (see Figure 50). However, these buoys can also be fitted with sensors to provide information about, e.g., wave height, salinity, water quality, and current speed. The servers and communications technology capabilities are growing quickly, making it possible to carry out communication and data mining tasks rapidly. However, the most efficient method for deploying and operating sensory buoys is still subject to research (Samuel and Favitri, 2021).

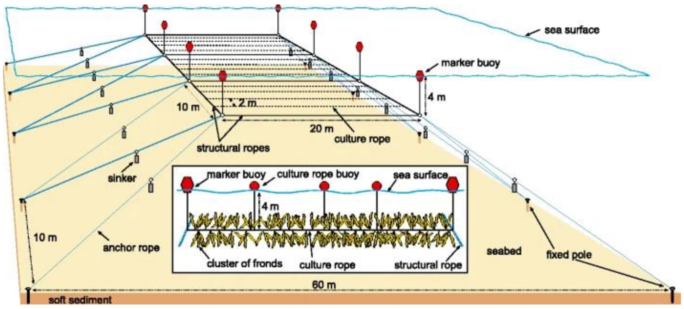


Figure 50: Typical open-water cultivation system using buoys (Peteiro et al., 2014)

Although literature is scarce, several designs and approaches to measure water parameters through smart buoys have been developed. One example of a design is a smart boy developed by Samuel and Favitri (2021). In this study, the authors have used an Internet of Things (IoT) approach to create a low-cost autonomous buoy that measures salinity, temperature, dissolved oxygen, irradiance, nitrate level, wind speed and direction, pH, and GPS. The study concluded that the development and implementation of a low-cost autonomous buoy could, in fact, be achieved. The monitoring system could provide valuable real-time and verifiable data, which could lead to optimised harvesting, seaweed quality, location selection, selling value, and area inspection/cleaning (Samuel and Favitri, 2021).

The CapEx and OpEx of smart buoys are highly dependent on the types of integrated sensors, the intensity of usage and depreciation. In a study by Greene (2019), a TEA and LCA were performed on a smart buoy monitoring system in an offshore macroalgae biorefinery scenario. The study estimated that the manufacturing costs of a typical smart buoy would be around 10,000 USD, and the maintenance costs amount to 1% of the total CapEx of the buoy spent annually. Each data transmission (per buoy) would cost 0.08 USD. Finally, a logistical staff member would be needed to monitor the farm for 40 hours per week, at 20 USD h^{-1} (Greene, 2019). A summary of the associated costs can be found in Table 20.

Performing measurements on a seaweed farm using smart buoys could entail several advantages. Firstly, as buoys float on the surface, they are capable of performing measurements on both the air and the water. Furthermore, as smart buoys stay in the water for extended periods, they can constantly transmit real-time data. In addition, there is no need for a vessel and crew to reach the site to perform measurements. Moreover, the design is relatively incomplex, and they can be fitted with a wide variety of sensors. Lastly, as the top of these tools is buoyant on the water, they can be equipped with solar panels. This would make it possible to perform measurements for even more extended periods.

The deployment of smart buoys can also pose several disadvantages and challenges. First, smart buoys are installed at a static position on the farm and cannot move. Therefore, they can only collect data from a single location. Furthermore, as these buoys are buoyant, they can only collect data from the surface. However, smart buoys do seem to have potential for a low-cost and low-maintenance monitoring tool to inspect environmental variables for extended periods (Greene, 2019).

5.1.2 Remotely operated vehicles

An ROV can be described as an underwater device that moves with the aid of thrusters and is connected to a cable that runs to the surface and transmits a video stream or other data. ROVs have been used for myriad applications, such as recovering bombs, offshore oil industry development, subsurface archaeology, and various types of aquaculture.

ROVs also have a wide variety of benefits in seaweed aquaculture. Firstly, they can be quickly deployed due to their relative ease of use. Furthermore, most ROVs require minimal maintenance due to their robust design and can remain underwater for hours on end. Additionally, ROVs have a high level of manoeuvrability and can therefore inspect hard-to-reach areas. ROVS can be equipped with various sensors for data collection. Lastly, with a CapEx of around 5,000 EUR, ROVs (without sensors) are relatively low (Bas Binnerts, pers. comm., July 19, 2022).

Figure 51: The TNO BLUEROV2 (TNO, 2022)

Utilising ROVs in an aquaculture context also has several disadvantages and challenges. Firstly, the deployment of the ROV is limited, as it is attached to a tether. In addition, deploying a fully functional vessel to anchor the ROV throughout the measurement period takes significant effort and money (Johnsen et al., 2013). Furthermore, the external thruster motors can interfere with sensory and imaging potential, especially when the ROV is close to soft-bottom seafloor (Johnset et al., 2013).

A vessel and crew must be transported to the location for the ROV to be deployed at an offshore seaweed farm. Transporting a seaweed vessel and crew to an offshore location has a daily cost of 3,000 EUR (Droog, 2021). The labour costs of harvesting are estimated to be 360 EUR per hectare (Van den Burg et al., 2016), and it is assumed that these costs are similar for monitoring activities. Considering these costs, the total OpEx of monitoring a high-value chemicals farm would amount to 157,500 EUR. An overview of the associated costs, required time, and amount of required units per scan is displayed in Table 20.

5.1.3 Small autonomous underwater vehicles

Traditionally, AUVs have been large, expensive and complex. However, smaller AUVs (up to 2 metres) are becoming more widely available in recent years. Together with improved machine learning-based image processing, this could indicate potential developments in subsurface monitoring capabilities (Kato, 2013; Fedorov et al., 2017; Manley and Smith, 2017). Optimising and combining these monitoring technologies could result in a valuable system for monitoring offshore aquaculture.

Smaller AUVs come with various advantages compared to the typical larger ones. Firstly, small AUVs typically have a lower CapEx and OpEx than larger AUVs. Furthermore, they can be launched by hand and can easily manoeuvre through the seaweed farm. These factors make small AUVs generally more attractive for seaweed monitoring.

As the market for AUVs has rapidly expanded in recent years, various innovative designs have been developed (Manley and Smith, 2017). An example of the design of a small AUV can be seen in Figure 52. AUVs can be mounted with a variety of sensors. Sonar, magnetometers, fluorometers (chlorophyll sensors), dissolved oxygen sensors, conductivity, temperature, depth sensors, pH sensors, GPS sensors, and turbidity sensors can all be included in sensor packages (Elias and Alderton, 2020). Due to their wide variety of applicable sensors, AUVs are used in myriad operations. Typical applications of AUVs include research purposes (e.g., ocean mapping, measuring environmental characteristics), commercial purposes (e.g., oil and gas exploration, locating plane- and shipwrecks), and military purposes (e.g., surveillance and anti-submarine warfare).

Figure 52: Layout of a typical small AUV (Manley and Smith, 2017)

In the future, these AUV systems may even be further optimised by implementing a submerged base where AUVs can dock, recharge, and communicate data. A docking system would mean the long-term presence of AUVs, which could aid in nearly constant data collection of farm parameters. However, these systems are still a hypothetical scenario. AUVs are currently deployed by hand, after which they follow an inspection plan set up by the operator (see Appendix F: AUV operator plan) and return to the deployment point.

Although the advantages of AUV monitoring in a seaweed farm are numerous, there are also several challenges. Firstly, reliable detection of varying macroalgae sizes remains a difficulty. Furthermore, manoeuvrability through seaweed and culture lines can be challenging, as tissue can obstruct the propulsion mechanism (see Figure 53). Moreover, since acoustics-based sensors typically make up the majority of the AUV's onboard sensors for mapping, navigation, and underwater communication, these systems must be reliable enough to run concurrently without interfering with one another. As many advanced sub-systems operate in the AUV's small, encapsulated space, noise, interference, and other disturbances may result in decreased data robustness (Stenius et al., 2022). Finally, although sensing technologies have developed rapidly in recent years, most difficulties in sensing are tied to the physical medium and are therefore difficult to resolve (Petillot, 2019). The wide variety of R&D directions has shown the relevance, potential, and significance of AUV technology in monitoring seaweed. Future technological developments should increase the technology readiness level of this monitoring strategy.

Although smaller AUVs have a relatively lower price than larger models, the CapEx are still quite high. The cost of a model with minimum hardware (without sensors) could range between 30,000 and 100,000 EUR. However, if a mid-range AUV were to be equipped with high-end navigation sensors, low-light cameras, and communication capabilities, this price could go up to between 250,000 and 500,000 EUR. High-end AUVs equipped with high-end tools could amount to 1,000,000 EUR (Bas Binnerts, pers. comm., July 19, 2022). Literature on the OpEx of AUVs is scarce. The OpEx highly depend on the types of used sensors, distance from shore, and monitoring times. Schofield et al. (2007) estimated that the communication and navigation costs of an AUV amount to 180 EUR day^{-1}. Considering the average speed of an AUV is 2 ms^{-1}, (Wynn, 2014; OceanScan MT, n.d.; Bas Binnerts, pers. comm., July 21, 2022), an entire seaweed farm for high-value chemicals (scenario 1) can be monitored in 1 day by 23 AUVs. The OpEx (including vessels and crews would amount to 149,030 EUR per scan. An overview of the costs is given in Table 20.

Figure 53: Seaweed tissue stuck in propulsion mechanism of AUV (TNO, 2022)

5.1.4 Autonomous and unoccupied surface vehicles

Autonomous surface vehicles (ASVs) or unoccupied surface vehicles (USVs) are vessels that operate on the water surface. ASVs operate autonomously, while USVs are remotely controlled by an operator on land or aboard another vessel. An example of a USV is given in Figure 54.

Figure 54: An unoccupied surface vehicle (Seabed, n.d.)

ASVs and USVs can offer various benefits when deployed to monitor seaweed aquaculture. Firstly, as these vehicles operate on the water surface, they can carry out measurements in both water and air. In addition, they can be equipped with solar panels. Furthermore, ASVs and USVs have a high level of manoeuvrability and speed, typically have a robust design, and can carry out measurements for extended periods of time.

While the deployment of ASVs and USVs for monitoring seaweed aquaculture can be beneficial for the reasons above, there can also be several disadvantages and challenges. The main disadvantage is that camera footage of the seaweed can only be taken from the surface and could therefore miss valuable information relative to monitoring systems that can come closer. Although this issue can be partially solved by integrating sidescan or acoustic sonars, combining the two adjacent image data (sonar and camera) would be most valuable (Kato, 2013).

The CapEx of ASVs and USVs are average compared to other monitoring devices. A web search concluded that prices of minimum hardware of ASVs and USVs range between 5,000 and 50,000 EUR. Including sensors (such as camera, sonar and water quality sensors), the price could go up to 250,000 - 500,000 EUR. The OpEx are expected to be similar to ROVs; these costs are discussed in more detail in 5.1.2.

According to Mousazadeh et al. (2017), unoccupied surface vehicles can reach speeds of 0.2 to 0.8 ms^{-1}, depending on the state of the sea. As hydrodynamic forces are typically high offshore, the speed is expected to be on the lower end of this range. This could result in a high duration of monitoring times. Moreover, the high hydrodynamic forces on the surface could result in the loss or damage of the vehicle. These factors could make ASVs and USVs a less attractive option compared to other monitoring strategies.

5.1.5 Small unoccupied aircraft systems

In contrast to aquatic monitoring devices, daily monitoring of offshore farms using sensors mounted to aerial devices also seems to be a promising technique (Bell et al., 2020). Small unoccupied aircraft systems (sUAS) carrying light optical sensors can conduct monitoring operations on canopy area, tissue nitrogen content, and density. Airborne footage can therefore provide valuable information to farmers.

SUAS have been widely accepted in agriculture (Mogli and Deepak, 2018; Ahriwar et al., 2019), but the advantages of using them in aquaculture also seem promising for several reasons. Firstly, consumer-grade sUAS equipped with optical sensors are relatively inexpensive and can provide footage with high spatial resolution. Furthermore, the manoeuvrability and speed of sUAS are exceptionally high, and they are relatively easy to use. These factors, together with developments in aerial sensory technologies, could make sUAS a competitive player in the seaweed monitoring market.

Deploying sUAS to monitor seaweed farms could also have some drawbacks. Similar to ASVs and USVs, sUAS can only extract data from an aerial perspective. Water in the North Sea is rather turbid (Fettweis et al., 2003), which could hamper extracting valuable data from this data. Aerial footage can be complemented with, for example, photoacoustic sonar systems (see Figure 55). These technologies are, however, still under development. Another major drawback is that it is difficult for sUAS to conduct measurements on water quality, as they do not come into contact with the water. Some projects and patents that explore this capability are pending (Bambanikos, 2016; Koparan, 2018), but these technologies are not yet common practice.

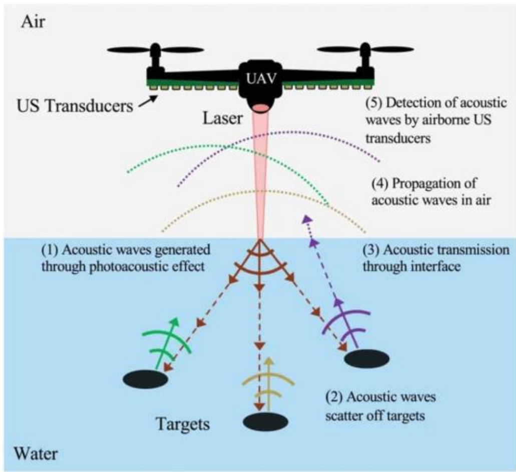


Figure 55: The Photoacoustic Airborne Sonar System (PASS) (Fitzpatrick et al., 2020)

As mentioned previously, the CapEx of consumer-grade sUAS are relatively low. A web search concluded that the CapEx of sUAS vary between 5,000 and 20,000 EUR per vehicle, with optical sensors included. However, the OpEx of sUAS monitoring in large-scale cultivation areas could quickly add up. The number of images that compose the mosaick of a cultivation area of 50 ha is 1,000. The price of acquisition, georeferencing, orthorectifing, and image processing amount to 5,300 EUR in an agricultural context (Matese et al., 2015). Translating to a large-scale farm, this means that a mosaick of the total cultivation area of a high-value chemicals seaweed farm (scenario 1) would amount to 150,000 images. The total OpEx per scan is estimated to be 201,225 EUR. Although technological developments could improve the high OpEx, the high costs of current sUAS could make it an unattractive monitoring option for large-scale seaweed cultivation.

5.1.6 Satellites

The public availability of satellite data has been drastically improved in recent years due to the democratisation of this information by parties like Google Earth Engine (Gorelick et al., 2017). The increase in sensor sensitivity and pixel resolution by multispectral satellite systems has improved the reliability of this data. Therefore, satellites have the potential to provide detailed information about the state of the seaweed farm.

Satellites have myriad applications and could also be beneficial in monitoring large-scale seaweed farms for various reasons. First of all, satellite data has extensive areal coverage. Using satellites could thus be a promising solution for monitoring large-scale seaweed farms (Bell et al., 2020). Another significant benefit is that operations like Google Earth Engine have made this data publicly available. The processing of the satellite footage is cloud-based. These factors mean that the CapEx and OpEx of this type of monitoring would be very limited compared to competing monitoring technologies.

Using satellites for seaweed monitoring could entail several disadvantages and challenges. The main disadvantage is that the monitoring would occur through a third party. This would imply that monitoring occurs when a third party chooses to take the imagery rather than when the seaweed cultivator believes it would be most beneficial (Bell et al., 2020). Another drawback is the spatial resolution of satellite images. Although the resolution and quality of these images have drastically improved in recent years, footage from submerged monitoring systems or sUAS still provides more detailed data (Bell et al., 2020).

As mentioned previously, the CapEx and OpEx of using satellites for monitoring seaweed farms are relatively limited. According to Matese et al. (2015), the costs of acquisition, georeferencing, orthorectification, and image processing an area of 50 ha amounts to 2,650 EUR in an agricultural context. Translating this to a seaweed farm for high-value chemicals, the total OpEx would come down to 21,853 EUR per scan. This is relatively low compared to other monitoring techniques.

5.2 Sensors

The monitoring technologies discussed in section 5.1 can be fitted with a wide variety of sensors. The following section discusses the opportunities and challenges of these sensory technologies. Laboratory-type analysis equipment has been excluded from this discussion, as these are too costly and vulnerable to be integrated into offshore monitoring devices.

Several key parameters for the growth of seaweed have been discussed in section 2.1.1, where the mathematical model used in this study is elaborated upon. However, as the mathematical model is a simplification of reality, the sensors used by the monitoring technologies on a 'real-life' seaweed farm need to scan supplementary parameters. These parameters and their significance are listed in Table 19. A list of potential sensor types and names that can monitor these parameters is given in Appendix I: Potential sensor types for measuring key parameters. This list is merely a selection of the available sensors; a multitude of sensors could potentially be applied in remote and autonomous monitoring devices.

Using sensors in offshore conditions could entail several challenges. Firstly, long-distance data transfer from the sensors to the land is not feasible; as a result, data transfer has to be established via the air (Kool and Bernard, 2019). Transmitting the data to a nearby smart buoy, which can then broadcast the information to the land, might be a solution. Secondly, a challenge of working in salt water under offshore conditions is the corrosion of sensory instruments. Therefore, corrosion-resistant materials are recommended in the sensors (Kool and Bernard, 2019). In the Dutch North Sea, unprotected steel can corrode up to 0.18 [mm] annually (Momber, 2011). However, as the sensors are currently not likely to be deployed for longer than a couple of days during the cultivation season, corrosion is unlikely to cause significant issues. Thirdly, biofouling (the growth of organisms on undersea instruments and other surfaces) remains a challenge in marine sensory technologies (Delauney et al., 2010). This issue especially occurs during the spring bloom, as the number of micro-organisms in the seawater is higher during this period. Biofouling can quickly form, degrade data quality, and even render sensors completely worthless (Lehaitre et al., 2008). It is therefore recommended that cultivators use solutions that minimise biofouling, such as wipers, chemical biocides, or UV/ultrasonic antifouling devices. Finally, some of the parameters depicted in Table 19 (e.g., nitrate/ammonium, phosphate) are relatively difficult and expensive to measure, while others (e.g., temperature) are less complicated and affordable. This difficulty is primarily due to the salty, harsh conditions at offshore locations.

Parameter	Importance
Dissolved Oxygen (DO)	Influences seaweed respiration
Dissolved Carbon Dioxide (DCD)	Essential in photosynthesis to absorb DCD and grow biomass.
Turbidity	Seaweed is vulnerable to high turbidity caused by terrigenous material that can induce ice formation
Temperature	Temperature has a strong effect on seaweed metabolism, enzyme functioning, and reproduction
Salinity	Salinity can adversely impact seaweed growth, particularly if it drops rapidly. A salinity of 33 – 35 psu is usually optimal
Flow rate	Too high or low flow can reduce growth rates
pH	No clear conclusions can be made because macroalgal responses appear to be highly species-specific
UVA + B radiation	UV (A+B) radiation damages proteins and leads to radical oxygen formation
Phosphate	Seaweed absorbs P as a nutrient. Needed for all growth processes and metabolism
Nitrate / Ammonium	Needed for chlorophyll, DNA, and protein production. Seaweed can store excess N in cellular reserves
Chlorophyll	Seaweed uses chlorophyll a and b to convert the sunlight into energy
Storms	Seaweed farms are vulnerable to bad weather and can result in severe losses
Solar radiation	Sunlight is needed for photosynthesis, but excess light can damage seaweed
Currents	Currents carry nutrients and homogenise the water

Table 19: Key sensing parameters and importance of seaweed cultivation sensory technologies (TNO, 2022)

5.3 Discussion

The monitoring techniques and sensors discussed in 5.1 and 5.2 have a unique set of advantages, disadvantages, and associated costs. In the following section, these factors are weighed and discussed. An overview of the associated CapEx, time per scan, the required amount of units, and the total OpEx of the discussed seaweed monitoring techniques is given in Table 20. The calculations are found in Appendix H: Estimation of required time, amount of units and associated costs of monitoring technologies.

Considering the advantages, disadvantages, and possibilities of each monitoring technique (see 5.1) and the associated costs (see Table 20), some technologies appear to be a better fit for large-scale offshore seaweed cultivation. Smart buoys appear to be a good fit to measure environmental variables, such as, e.g. nitrate/phosphate levels, irradiance, current speed, and pH for large-scale offshore cultivation. To ensure the integrity of the data, precautions must be taken against corrosion and biofouling. The design of smart buoys is generally simple, resulting in a relatively low CapEx and OpEx. In addition, it is generally not necessary to deploy a moving vehicle to measure environmental variables, making a static device like a smart buoy a fitting and relatively inexpensive choice. However, the static position of a smart buoy is a limitation in monitoring the seaweed. A dynamic device would be a better fit to monitor the growth of the seaweed, as these devices can move around the culture lines. Therefore, a monitoring device that can move around underwater (ROV or AUV) would be an adequate option to monitor growth and infrastructure. Both types of devices offer the required capabilities to measure growth. However, AUVs currently have a significantly higher CapEx, which could make this a less attractive option compared to ROVs for some cultivators. ROVs and AUVs generally have the same capabilities, so the choice between the two techniques depends on the cultivator's preference, the OpEx, the gains in terms of data, and the monetary resources. These monetary resources of the cultivator are partly fueled by the policy and subsidy climate discussed in 6.1. The available funds for seaweed cultivation are also highly dependent on the motives of the cultivator; research-based cultivation is more likely to receive EU funds than profit-driven cultivation (Jan Wilco Dijkstra, pers. comm., August 17, 2022). A cultivator could seize this opportunity to employ AUVs by acquiring research funds, thereby having the first access to better data and contributing to seaweed aquaculture's development in general.

The potential revenues of large-scale offshore cultivation should be kept in mind when considering the associated costs of various monitoring technologies. Certified European seaweed can reach retail prices up to 15 EUR/kg dw (Droog, 2021). If a successful harvest ($9.06 * 10^8$ kg dw) of a scenario 2 seaweed farm at the Noordwijk 70 km farm is sold for this retail price, an income of 13.6 billion EUR could be generated. It is assumed this farm conducts a daily smart buoy check, a monthly AUV check during the entire cultivation season, and four additional scans (for example, after storms) to check the infrastructure (Julia Wald, pers. comm, August 22, 2022). The total OpEx of these monitoring sessions would amount to about 2% of the potential revenue from seaweed. The total CapEx of these monitoring systems would amount to around 9% of the revenue of one cultivation season.[1] Although there are many other associated costs (such as harvesting and transporting the seaweed, establishing a seaweed value chain, and employing a crew), the CapEx and OpEx of these monitoring systems in large-scale seaweed cultivation appear to be financially viable.

Although monitoring techniques are improving, interpreting the data of large-scale seaweed farm monitoring remains a time-intensive task due to the large amount of acquired information (Agarwala, 2021). The use of Artificial intelligence (AI) could aid in lowering labour and time intensity. AI has been successfully tested to monitor aquatic ecosystems, such as coral reefs and submerged seaweed habitats (Keilaris et al., 2019; Gonzalez-Rivero et al., 2020). However, as using AI in a marine monitoring context is a relatively young and complex technology, several challenges such as overreliance on historical data in machine learning models, the complexity of marine ecosystems, the timescales of ecological effects, and increased cybersecurity risks remain (Nishant et al., 2020). In a future scenario, in which AI is more common and commercially available for seaweed monitoring, the amount of scans and labour could be decreased. OpEx and CapEx could be lowered (lower amount of devices and scans required) as a result, increasing the financial viability of marine monitoring systems. In addition, as the European seaweed industry is still young, research is key. When the industry gradually moves from research to exploitation, measurements of environmental variables can be minimised, and inspections with the goal of maximising output can be implemented.

	CapEx per unit (mid-range model incl. sensors) [EUR]	Estimated time per scan [h] Amount of units [-]	Estimated time per scan [h] Amount of units [-]	Total OpEx per scan [EUR]	Total OpEx per scan [EUR]
		Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
Smart buoy	10,000	1 hour, 825 units	1 hour, 73,800 units	1,092	26,923
ROV	5,000	24 hours, 23 units	48 hours, 1,067 units	157,500	13,293,000
AUV	250,000 – 500,000	24 hours, 23 units	48 hours, 1,067 units	149,040	13,285,080
ASV/USV	250,000 – 500,000	24 hours, 80 units	120 hours, 1,424 units	157,500	13,419,000
sUAS	5,000 – 20,000	24 hours, 4 units	24 hours, 342 units	201,225	17,205,400
Satellite	0	1 hour, 1 unit	1 hour, 1 unit	21,852.50	1,955,700

Table 20: Estimation of CapEx, time per scan, required amount of units and total OpEx of various seaweed monitoring technologies

[1] It must be noticed that to create a market to take off the amount of seaweed as considered for scenario 2, significant cost reductions in seaweed cultivation need to be realized, which would also lead to a lower market price and lower revenue. Although the cost of monitoring could drop, it is likely that the share of monitoring costs is likely a low estimate with the calculations in this section.

6. Ecosystem services

Ecosystem services are referred to as the benefits that humans depend on, consciously or unconsciously, directly or indirectly. They are provided by functioning natural or engineered ecosystems.

For millennia, especially after industrialisation, the main themes of human-nature relations have been centred around linear resource abstraction and waste creation. This linear economy has caused multiple complex environmental problems and deteriorated ecosystems. In return, these disturbances have threatened both the quantity and the quality that ecosystem services provide to the human world.

It is essential to create eco-industrial synergies that are focused on environmental sustainability and can produce goods for people without harming the environment. These engineered ecosystem services can be developed in a way that they can restore ecosystem health. As discussed in the previous chapters, seaweed cultivation has the potential to do this, as it transforms excessive dissolved carbon, nitrogen and phosphorus into versatile biomass.

Even though the offshore cultivation of seaweed can provide numerous benefits to ecosystems and the human world, several challenges remain. In the European context, these challenges to establishing these ecosystem services are twofold: (1) the European and Dutch policy climate; (2) barriers in technology (Marianne Thomsen, pers. comm., July 24, 2022). These challenges are elaborated upon in the following sections, and potential remedies are discussed. In conclusion, the social costs of carbon and nitrogen are discussed, and the possible role offshore seaweed cultivation could play in this is elaborated upon.

6.1 The European and Dutch policy climate

The growth of the European seaweed market is fueled partly by national and EU policy initiatives to promote aquaculture. Current offshore cultivation systems and infrastructure require considerable investments. Economies of scale are needed to reduce those expenses. However, the majority of new businesses lack the resources to fund research and development. To provide a catalytic function, the government (European or Dutch) is required.

The EU has enacted several policies to ensure the sustainability of seaweed aquaculture. The relevant policies applying to offshore seaweed aquaculture that are currently in effect are listed in Table 21, along with a short description. It should be noted that although several legislations apply to the production of seaweed, there are currently no specific European policies that directly apply to seaweed aquaculture. Modernisation of these policies may be required. Analysing the policies in Table 21, it becomes clear that the main challenges in regard to seaweed aquaculture have to do with the potential environmental effects, which need to be adequately assessed. Furthermore, the connections and relationships between the European laws and regulations pertaining to seaweed cultivation and food safety need to be highlighted. Unambiguous and cogent governance in European legislation may support the sector's growth (Barbier et al., 2019).

EU Policy	Description
Maritime Spatial Planning Directive (MSPD) 2014/89/EU	Each EU Member State must have Maritime Spatial Plans (MSP) to promote sustainable economic development and ecological conservation. The growth of seaweed aquaculture must be founded on effective space management and encouraging maximum output with minimal environmental damage. Furthermore, these operations must be coordinated with other maritime operations (Barbier et al. 2019).
Habitats Directive (92/43/EEC)	The development of aquaculture should guarantee the protection of natural habitats and biodiversity.
The Environmental Impact Assessment Directive 2011/92/EU	Before engaging in seaweed aquaculture, public and private ventures permitted by the state must first perform an environmental impact assessment.
The Regulation on Organic Production 2018/848/EU	This policy defines the production guidelines for algae, including the collection of natural stocks as well as their cultivation, and applies several restrictions on organic production and product labelling. Furthermore, it implies that only nutrients found naturally in the environment or from organic aquaculture animal production—preferably nearby as part of an IMTA system—shall be used in organic macroalgae cultivation at sea.

Table 21: Current EU policies regarding offshore seaweed cultivation

In addition to the EU laws regarding the cultivation of seaweed, several initiatives stimulate the production of seaweed. Firstly, the UNITED project seeks to enhance multi-use aquaculture in the European seas. The project reflects the European Commission’s long-term strategy to stimulate sustainable growth in the maritime industry. Working with several European partners, such as North Sea Farmers and TNO, the UNITED project aims to

- implement five multi-use pilots, demonstrating the viability and transition of technological, regulatory, economic, social, and environmental solutions for multi-use aquaculture;
- enable large-scale marine space multi-use by launching pilots in the marine setting (UNITED, 2020; North Sea Farmers, n.d.);

Another project, called KELP-EU, aims to kick-start macroalgae production in Europe. The project, which runs from 2021 to 2023, evaluates the life cycles of seaweed-based products along with their social influence on coastal communities and other factors. The findings are used to create and implement commercialisation schemes (KELP-EU. 2022). Another initiative is the EU4Algae platform. The stakeholder platform EU4Algae aims to encourage consumers and businesses in the EU to use algae for nutrition and other uses and hasten the establishment of a European algae sector. Furthermore, the platform, which also acts as an information hub, seeks to stimulate interaction and collaboration between European algae stakeholders such as cultivators, manufacturers, suppliers, consumers, NGOs, and researchers (European Commission, 2022). Finally, the consortium SeaMark aims to establish the groundwork for a completely new European maritime industry to satisfy the rising demand for seaweed and draw more investments and subsidies. In addition, to add to the body of evidence supporting large-scale seaweed farming as a biological and nutrient bioextracting tool, SeaMark measures the ecosystem services offered by seaweed farms (WUR, 2022). Although some initiatives and subsidies are available for seaweed cultivators in the nursery phase, the need for more grants and more favourable policies is essential for the European seaweed sector to take off. Currently, the key challenge in developing more beneficial regulations is the uncertainty of the environmental effects of large-scale seaweed cultivation (Marianne Thomsen, pers. comm., July 14, 2022).

In the upcoming decades, the North Sea will be exploited more intensively for commercial purposes due to the restricted space and capacity of industrial systems on land (Van den Burg et al., 2016). This will influence future marine environmental policy. Mutual coordination and legislation are necessary due to the increasing pressure at sea. In addition to the European laws, some Dutch policies have been implemented to ensure safe and sustainable seaweed cultivation. The main legislations controlling seaweed production are the Water Acts, Fisheries Acts, and Environment Acts (Trui, 2017). However, as seaweed cultivation is a relatively novel venture in the Netherlands, policies are still developing.

The Dutch seaweed industry comprises a sizable number of start-ups and an increasing number of established businesses taking up seaweed development. Similar to the EU initiatives for novel seaweed farmers, some national subsidies and initiatives have been implemented. Firstly, the TKI regulation aids starters by funding 30% of the activities carried out at research institutions, such as the TNO maritime department (Rijkswaterstaat, 2022). This subsidy for research activities only helps to a certain degree, as start-ups still have to invest the remaining 70%, which is often a sizeable sum (Marnix Krikke, pers. comm., 2020). Furthermore, the “Waddenfonds” (English: mudflats fund) subsidises several (coastal) seaweed cultivation projects (Waddenfonds, n.d.). Lastly, there is a multitude of Dutch initiatives researching the ecological effects of large-scale seaweed cultivation, such as Wageningen University & Research, TNO, NIOZ, and North Sea Farmers. However, despite the funds, policies and initiatives mentioned above, seaweed cultivators face many difficulties. One of these difficulties is acquiring permits, which is often a struggle for seaweed cultivators. This is primarily due to the licensing authority's occasionally poor understanding of seaweed production, the lengthy application process, and occasionally a lack of clarity. Furthermore, the legislation regarding seaweed cultivation is often considered too strict, and decision-making is too protracted, obstructing the sector's expansion. In addition, subsidies for start-ups are generally considered to be difficult to acquire and insufficient. (Van der Swam, 2017). Lastly, several subsidies, such as the “SDE++“ regulation, have been established for terrestrial initiatives that aim to develop CO_2-reducing technologies. However, no subsidies are available for aquaculture initiatives that reduce anthropogenic emissions. The avoided social costs through carbon and nitrogen sequestration of large-scale seaweed cultivation (see 6.3) should be considered by regulators. In conclusion, the current Dutch policy regarding seaweed is developing a more favourable climate, but novel companies in this sector still face many difficulties.

As discussed above, Dutch starters and researchers urgently call for a more favourable policy and subsidy climate in the Netherlands (Van den Burg, 2016; Van Swam et al., 2017). To improve this climate, new policies must place a strong emphasis on market expansion and greater sales. The success of start-ups increases along with the market and sales. In addition, the input of entrepreneurs is crucial when creating new legislation. Moreover, reserving space for sustainable cultivation areas is essential for scaling up, market expansion, and investor interest. Lastly, additional research into the ecosystem services offered by seaweed cultivation and its nutrient bioextraction potential may provide the seaweed industry with a solid foundation (Van den Burg, 2016).

Finally, geopolitical risk has increased and taken over the financial markets, particularly the commodity markets, as a result of the crisis between Russia and Ukraine. Commodity prices spiralled due to this conflict, which was already jarred by pandemic-related supply disruptions (Wang et al., 2022). The prices of commodities such as gold and crude oil are susceptible to geopolitical risks. The impact on commodity prices has been amplified by the fact that Russia and Ukraine are two key producers and exporters of commodities such as natural gas, crude oil, aluminium, and wheat. In order to address energy security, all EU member states have opted for nuclear or renewable energy (Brodny et al., 2021). Countries that invest in increasing the capacity of local renewable energy sources to meet a larger portion of their energy needs will subsequently import lower amounts of fossil fuels and will be able to become less reliant on foreign energy sources. However, diversification of these renewable energy sources is vital in securing energy supplies (Pacesila et al., 2016). The production of biofuels using marine biomass could provide numerous advantages and could play a key role in meeting future energy demands (Pablo et al., 2020). Therefore, it is essential for regulators to consider current geopolitical risks and diversification of renewable energy sources when formulating new subsidies and policies for seaweed cultivation.

6.2 Barriers in technology

For future applications of seaweed in MUPS, additional studies are required regarding several aforementioned barriers (See 1.3.1). So far, only a few offshore farms have been built specifically for seaweed production. Some potential designs and initiatives are discussed in 1.3.1. The designs seem promising; however, only a few European pilots have been launched so far. The main barrier in the development of offshore aquaculture technology is the harsh environment and strong hydrodynamic forces (Buck et al., 2018). Furthermore, the integration with offshore wind farms should be done in a way that (1) the risk of damage to the structures is minimised, and (2) the seaweed farm and wind turbines are still accessible for operation and maintenance activities. Although various initiatives are exploring designs in which the above-mentioned factors are taken into account, an optimised design remains a challenge. Hence, the optimal method for offshore seaweed cultivation in MUPS is still subject to research.

As discussed in chapter 5, in-person monitoring also poses challenges in seaweed cultivation in MUPS. Therefore, remote and automated monitoring technologies could provide a solution. A future scenario could even be that remote vehicles are further developed to include harvesting and preservation activities (Bas Binnerts, pers. comm. 2022). However, as analysed in more detail in 0, monitoring technologies are still developing and relatively expensive. More R&D and further development of these remote sensing technologies are a part of the ongoing endeavour to optimise offshore seaweed cultivation in MUPS.

Another challenge in large-scale offshore seaweed cultivation is the short-term, high-capacity requirement per harvesting location. Due to the limited harvesting capacity per vessel, this may lead to challenges in terms of logistics and infrastructure (Blikra et al., 2021). This challenge may be overcome by the development of remote harvesting vehicles (Bas Binnerts, pers. comm. 2022) or the implementation of mobile harvesting and preprocessing vessels (Blikra et al., 2021).

In conclusion, the potential of offshore seaweed aquaculture seems promising. However, there are several technological barriers which need to be addressed in order to make it feasible. There are currently a number of pilots in effect that aim to prove the feasibility of offshore seaweed aquaculture. However, future R&D and development of optimised technologies are needed to create more financially viable options for offshore cultivators.

6.3 The social costs of carbon, nitrogen and phosphorus

Anthropogenic activities have increased the amount of nitrogen and atmospheric CO_2 by ~100% and ~40%, respectively, compared to preindustrial levels (Stocker et al., 2014). This massive anthropogenic modification of the global N- and C-cycles results in a multitude of social costs. Amongst other effects, the buildup of C, N, and P in the environment is linked to decreased air and water quality, acidification of soil and water, biodiversity loss, stratospheric ozone depletion, and climate change (Townsend et al., 2003; Galloway et al., 2008; Rea et al., 2012). Remediation measures such as underground carbon storage and wastewater cleaning are largely government-funded (Georges, 2009). Sequestration of C, N, and P by versatile biomass such as seaweed could decrease excessive nutrients in the marine environment and, therefore, the associated costs of these remediation measures.

Monetising C- and N-related social costs is complicated and dependent on many factors, such as the magnitude, location, and distribution of the C- and N-emissions. Various studies have attempted to assess the social costs of C- and N-buildup in the environment. Keeler et al. (2016) estimated the social cost of terrestrial carbon emissions to be ~0.038 EUR/kg. Furthermore, Keeler et al. (2016) have assessed the social costs of various N-forms. The average social cost for terrestrial N emissions was set to ~15 EUR/kg N. Lastly, according to Sena et al. (2020), the social cost of terrestrial P emissions amounts to 30.35 EUR/kg P.

From the assessment in this study, it becomes clear that offshore seaweed cultivation in MUPS has a significant potential for nutrient bioextraction. The results demonstrated that up to $2.84*10^{8}$ [kg] of carbon could be bioextracted at a farm producing seaweed for a fuel biorefinery (scenario 2) 70 km from shore at Noordwijk. Furthermore, it was calculated that up to $1.25*10^{7}$ [kg] of nitrogen could be bioextracted at a farm producing seaweed for a biorefinery for fuels, 20 km from the coast at Walcheren. Compared to the yearly nitrogen outflow through the Dutch rivers, large-scale seaweed cultivation has the potential of sequestering ~4% of the nitrogen outflow. Finally, $2.10 *10^{6}$ [kg] of phosphorus can be bioextracted if a scenario 2 farm is built at Noordwijk, 70 km from shore. Compared to the yearly phosphorus outflow through the Dutch rivers, large-scale seaweed cultivation has the potential of sequestering ~17% of the phosphorus outflow. Translating the social costs mentioned above to the amount of sequestered C, N, and P in chapter Results & Analysis could result in significant numbers. For example, the amount of sequestered carbon of a scenario 2 seaweed farm at the Noordwijk 70 km farm could result in decreased social costs of almost 11 million EUR. The nitrogen sequestration at a scenario 2 farm with a relatively high nitrogen content, such as the Walcheren 20 km farm, could reduce social costs by almost 188 million EUR. Lastly, translating the social costs of phosphorus to a scenario 2 farm at Noordwijk 70 km, the avoided social costs come down to 63.7 EUR. Regulators should consider these significant sums of avoided social costs when formulating new policies and subsidies for seaweed cultivation. The avoided social costs discussed above were compared to the potential revenues of the seaweed cultivation mentioned in section 5.3. For carbon, nitrogen and phosphorus, the avoided social costs amounted to 0.08%, 1.4%, and 0.5%, respectively, of the potential revenues. With an expected future reduction in seaweed cultivation costs and, thereby, seaweed costs, this contribution could increase but will most likely only remain a minor one.

Policymakers will consider various aspects to justify legislations in which cultivators are compensated for seaweed cultivation and the resulting avoided social costs. In relation to this study, the effectiveness and quantification possibilities of ecosystem services are the most relevant. Considering the effectiveness, studies like the one performed in this thesis provide insights into the behaviour of the nutrient dynamics. For example, this study shows that nutrient removal is taking place to the largest extent in a limited timeframe. This is beneficial for an improved understanding of the behaviour of the nutrient dynamics that result in ecosystem services. However, further research is needed to explore the impact on aquatic flora, fauna, biodiversity, and the local marine ecosystem. Concretisation of the quantifications of bioextracted nutrients is essential in the formulation of policies. Although mathematical models and monitoring technologies are effective in understanding the behaviour of the dynamics through the cultivation season, these approaches are less suitable for the concretisation of the quantifications of bioextracted nutrients for accounting purposes, i.e. translating nutrient capture into financial benefits of some kind. Mathematical models are frequently based on a fair number of assumptions, and monitoring technologies are more suitable for measuring growth and environmental conditions. Therefore, considering the quantification possibilities, the bioextracted nutrients would best be measured through laboratory measurement of the nutrient content of the seaweed, combined with registration of the amount of seaweed produced.

7. Conclusion

This research aimed to assess the critical nutrient flow of seaweed farming in MUPS and evaluate the effects on the North Sea's nutrient environment. Additionally, this study studied and compared monitoring technologies and assessed the most effective ways to employ monitoring systems for growing seaweed in MUPS at the North Sea. Furthermore, this study assessed ways in which the ecological effects of seaweed can be translated into ecosystem services. Finally, the results of this study are combined to assess whether it is possible to establish ecosystem services through large-scale offshore seaweed cultivation in the North Sea using monitoring technologies and nutrient analyses.

The main research question of this study was: *"Can ecosystem services be established through large-scale offshore macroalgae cultivation in MUPS at the North Sea, using nutrient analyses and monitoring technologies?"*

To answer the main research question, three sub-questions were introduced and answered in this research. In the following section, each sub-question is discussed and answered. Concluding, the main research question is elaborated upon and answered.

The first sub-quesiton of this study was: *"What is the impact of macroalgae cultivation in MUPS at the North Sea on the marine nutrient cycles in the vicinity?"*. To answer this sub-question, a mathematical model was developed based on the model for calculating the growth and nutrient dynamics of the *S. latissima* by Broch and Slagstad (2012). The model was run over one cultivation period (October to June), using environmental variables from four offshore wind park locations. The following two cultivation scales were modelled at each farming location: (1) a farm producing seaweed for high-value chemicals (4.1 km^2), and (2) a farm producing seaweed for a biorefinery for fuels (369 km^2). Subsequently, the nutrient uptake dynamics of carbon, nitrogen, and phosphorus were assessed, and the impact on the local nutrient stocks.

From the model results, it becomes clear that offshore seaweed cultivation in MUPS has a significant potential for nutrient bioextraction. The results demonstrated that up to $2.84*10^8$ [kg] of carbon could be bioextracted at a farm producing seaweed for a fuel biorefinery 70 km from shore at Noordwijk. Furthermore, it was calculated that up to $1.25*10^7$ [kg] of nitrogen could be bioextracted at a farm producing seaweed for a biorefinery for fuels, 20 km from the coast at Walcheren. Compared to the yearly nitrogen outflow through the Dutch rivers, large-scale seaweed cultivation has the potential of sequestering ±4% of the nitrogen outflow. Finally, $2.10 *10^6$ [kg] of phosphorus can be bioextracted if a scenario 2 farm is built at Noordwijk, 70 km from shore. Compared to the yearly phosphorus outflow through the Dutch rivers, large-scale seaweed cultivation has the potential of sequestering ±17% of the phosphorus outflow.

Analysing the model results for the bioextraction potential of offshore cultivated seaweed in MUPS at the North Sea (summarised in Table 22), it becomes clear that the yield and the carbon content from the farms located further from shore (Terschelling 50 km and Noordwijk 70 km) are higher. This is likely caused by the relatively lower and more stable temperature – which is beneficial for the growth and carbon uptake – at the farms situated further from the coast. On the other hand, the nitrogen and phosphorus content at the farms located relatively closer to the shore is higher due to the higher nutrient concentrations. In conclusion, the bioextraction potential of large-scale offshore cultivated *S. latissima* in the North Sea seems promising, and could sequester significant amounts of anthropogenic emissions.

Farm	Yield [kg dw m^{-2}]	Carbon content [%]	Nitrogen content [%]	Phosphorus content [%]
Noordwijk 20 km	1.78	23.3	1.81	0.29
Noordwijk 70 km	2.46	31.4	1.18	0.23
Terschelling 50 km	2.39	31.0	1.21	0.23
Walcheren 20 km	1.64	20.6	2.06	0.32

Table 22: Summary of model results for yield and nutrient content

In addition to the nutrient bioextraction potential, the impact on the local marine nutrient stocks was assessed. The results for the local nutrient depletion per farm are displayed in Table 10. As carbon uptake is seldom a limiting nutrient in the growth of the *S. latissima*, it was not included in the indicative impact assessment. From the results, it can be concluded that the nitrate supply may become limiting in the large-scale offshore cultivation of *S. latissima* in the North Sea. The seaweed at the Noordwijk 70 km and Terschelling 50 km farms may deplete up to ±42% of the local nitrate stock during the last months of the cultivation season, which may induce unforeseen changes in the local marine environment. The nitrate depletion of the farms that are relatively closer to the coast (Noordwijk 20 km and Walcheren 20 km) seems to be less significant. The phosphate uptake of the local stocks did not seem to cause significant depletion. Hence, it can be concluded that phosphate is not a limiting nutrient in offshore cultivation of the *S. latissima* in the North Sea. The nitrate uptake of large-scale offshore cultivation seemed to have the potential of depleting the local stocks, which could induce unforeseen effects on the marine ecosystem. Further research using hydrodynamic nutrient models and an ecological assessment of the changes in nitrate stocks are recommended. The impact on aquatic flora, fauna, and biodiversity should be included in this assessment.

The sub-question *"What role can a monitoring system play in seaweed cultivation in MUPS at the North Sea?"* was answered by an extensive literature study and expert interviews. In this analysis, the advantages, disadvantages and associated costs of various monitoring technologies were discussed. A number of monitoring technologies, such as sUAS, satellites, and ASVs/USVs, do not appear to provide the features an offshore farm requires. Due to their high OpEx, inadequate monitoring capabilities, insufficient manoeuvrability, or potential for equipment loss, these choices are likely not appealing to offshore cultivators. Other monitoring technologies, such as AUVs, ROVs and smart buoys, are considered more attractive for large-scale offshore cultivators. AUVs and ROVs have great potential for detailed local inspection of the seaweed and infrastructure with the aid of camera and sonar equipment. Innovations such as smart buoys seem to have the potential for a low-cost and low-maintenance monitoring tool, to inspect environmental variables for extended periods. The role of the smart buoy could be to inspect environmental variables such as salinity, temperature, dissolved oxygen, irradiance, nitrate/phosphate levels, wind speed and direction, and pH. Harsh offshore conditions, which could cause corrosion and biofouling, should be considered in the design of the sensors. AUVs and ROVs could be used for detailed local inspection of the crops and infrastructure, which is especially attractive in the current early stage of the industry, where cultivation methods are being developed, and local effects are still being understood.

The sub-question *"In what ways can the ecological effects of seaweed cultivation in MUPS at the North Sea be translated into ecosystem services?"* was answered by an extensive literature study and expert interviews. Several challenges and opportunities in the Dutch and European climate were discussed. The challenges to establishing ecosystem services are twofold: (1) the current European and Dutch policy climate; and (2) barriers in technology. Firstly, the main challenges in the policy climate in regard to seaweed aquaculture have to do with the potential environmental effects, which need to be adequately assessed. Furthermore, although some initiatives and subsidies are available for seaweed cultivators in the nursery phase, the need for more grants and more favourable policies is essential for the European seaweed sector to take off. Currently, the key challenge in developing more beneficial regulations is the uncertainty of the environmental effects of large-scale seaweed cultivation. Moreover, C, N, and P sequestration of offshore large-scale cultivation could result in avoided social costs of up to ~11 million, ~188 million, and ~64 million EUR, respectively. These avoided social costs should be considered in the policy climate in the formulation of a mechanism to create benefits from these social costs. In order to translate the avoided social costs through nutrient extraction into legislation and compensation, the nutrient content of seaweed would best be measured through laboratory measurement of the nutrient content of the seaweed, combined with registration of the amount of seaweed produced. In addition, advanced nutrient models and monitoring technologies are needed to fully grasp the nutrient dynamics and their effects on the local marine environment. Secondly, the technological challenges lie mostly in designing cultivation systems that can withstand the harsh offshore environment, synergise with wind turbines, and maximise yield and financial viability. There are currently a number of pilots in effect that aim to prove the feasibility of offshore seaweed aquaculture. However, future R&D and development of optimised technologies are needed to create more financially viable options for offshore cultivators.

By combining the sub-questions, the main research question *"Can ecosystem services be established through large-scale offshore macroalgae cultivation in MUPS at the North Sea, using nutrient analyses and monitoring technologies?"* is answered. Offshore seaweed cultivation in MUPS at the North Sea has a significant potential of nutrient bioextraction. However, during the last months of cultivation, nitrate depletion could occur, of which the ecological effects are unknown. The main barrier in macroalgae cultivation in the Dutch and European climate – the uncertainty of detrimental ecological effects – could be solved in part by providing the seaweed industry with a solid foundation on the nutrient bioextraction potential and impact of offshore seaweed cultivation. Nutrient analyses, like the one performed in this paper and the implementation of monitoring technologies can be a building block in a better understanding of the nutrient dynamics of large-scale offshore macroalgae cultivation and, thereby, the establishment of ecosystem services.

8. Recommendations

This section presents recommendations for policy, industry, and further research based on the conducted analyses, discussions, and subsequent findings and conclusions.

8.1 Recommendations for further research

As this study is based on a significant amount of simplifications and assumptions, the results should be interpreted as exploratory and indicative. The aim of the model was to provide an initial indication regarding the potential of offshore seaweed cultivation in varying situations. Therefore, the assumptions and simplifications were made with this goal in mind. This should be taken into consideration when applying this research and model for a different purpose. Hence, several recommendations were formulated for future research.

The analysis of the modelled results showed that nitrate might be a limiting nutrient in the large-scale offshore cultivation of *S. latissima*. Based on this study, it is difficult to say if nitrate depletion causes any short- and long-term ecological effects in this context. Therefore, it is recommended to research whether the nitrate depletion resulting from the offshore seaweed cultivation scales discussed in this study causes ecological effects, and if these are beneficial or detrimental.

A multitude of studies suggests the capability of seaweed to sequester or sediment significant amounts of carbon through the release of POM and DOM. In this study, the carbon sequestration capabilities of seaweed have been analysed. The results seem promising; however, sedimentation through the release of POM and DOM specifically has not been included in this research. Further research on the carbon sedimentation potential of large-scale offshore seaweed cultivation could provide a more comprehensive understanding of the associated ecological effects.

This study found that a low-cost, optimised design for offshore seaweed cultivation still needs further improvement due to the harsh offshore environment. To make offshore cultivation more financially viable for farmers, low-cost designs are key, especially on large-scale farms. Therefore, a third recommendation is to engage in further R&D for large-scale, low-cost, low-maintenance offshore cultivation systems.

Finally, estimating precisely how much of the offshore zone is impacted by seaweed farming remains challenging since this is dynamic in both location and time (seasonal and between years). As this first exploratory study showed promising potential in yield and nutrient bioextraction potential of offshore seaweed cultivation, it would be interesting to perform more advanced assessments in biogeochemical models, such as the ERSEM-BFM model. In addition, as the study performed for this thesis contained several assumptions regarding the input data, it is recommended that these advanced assessments use improved location-dependent variables as input data (ideally hourly-based data). Furthermore, as it is likely that farming activities take place over several cultivation seasons with multiple seaweed species, it is recommended to include more seasons and species in this assessment. In addition to conducting analyses by means of more advanced nutrient models, it is recommended that large-scale offshore cultivation pilots will be monitored and analysed.

TNO is actively developing TEAs and LCAs for seaweed farming. To apply the results of nutrient analyses in these assessments, these results must be unambiguously quantifiable. As the results of this exploratory study are preliminary, it is not recommended to use the results in the TEAs and LCAs, for the time being. Developing advanced biogeochemical models, as discussed above, combined with improved data and real-time monitoring, could result in more unambiguously quantifiable results. The mathematical model and results of this study can be used as a basis for advanced models. Furthermore, this study can be used for public relations purposes, provided it is mentioned that these results are preliminary. Finally, this study and the accompanied mathematical model can be used for preliminary site selection and investigations of offshore seaweed farms.

This extensive research discussed above, in combination with real-time data, could lead to a better understanding of the ecological effects of large-scale offshore seaweed cultivation and, subsequently, to a solid foundation for the *raison d'être* of the seaweed industry.

8.2 Recommendations for policy and industry

Based on the exploratory study performed in this paper, several recommendations are formulated for the industry and government. This exploratory study concluded that offshore seaweed cultivation in MUPS has a significant potential for nutrient bioextraciton and yield in the North Sea. Consequently, it is advised that regulators further exploit the notion of offshore seaweed cultivation in the National Climate Agreement, provided that an additional study is conducted on strategies for minimising the risk of nitrate depletion. Furthermore, it is encouraged that entrepreneurs in the seaweed industry are included in the formulation of new, unambiguous legislation. These new policies must place a strong emphasis on market expansion, greater sales and reserving space for sustainable offshore cultivation.

In this study, it was found that the main barrier in the formulation of more favourable policies and subsidies in Europe is uncertainty about the ecological impact. As discussed previously, extensive monitoring and research on nutrient dynamics using advanced models could provide a more comprehensive understanding of the behaviour of the nutrient dynamics. Although mathematical models and monitoring technologies are effective in understanding the behaviour of the dynamics through the cultivation season, these approaches are less suitable for the concretisation of the quantifications of bioextracted nutrients for accounting purposes, i.e. translating nutrient capture into financial benefits of some kind. Therefore, considering the quantification possibilities, the bioextracted nutrients would best be measured through laboratory measurement of the nutrient content of the seaweed, combined with registration of the amount of seaweed produced. It is recommended that the findings of these studies are used in the formulation of a subsidy based on nutrient bio-extraction in the North Sea, similar to the SDE++ regulation on land. The avoided social costs resulting from nutrient sequestration by seaweed should be considered by regulators when formulating subsidies. Furthermore, it is suggested that current geopolitical risks and diversification of renewable energy sources, which are essential in securing future energy demands, are considered when formulating new subsidies and policies for seaweed cultivation. The consideration of the factors mentioned above by regulators could decrease the high barrier for start-ups and companies to apply for and be granted subsidies so that they can create a foothold in this new industry. This way, research projects can greatly contribute to the further implementation of seaweed cultivation in the near future.

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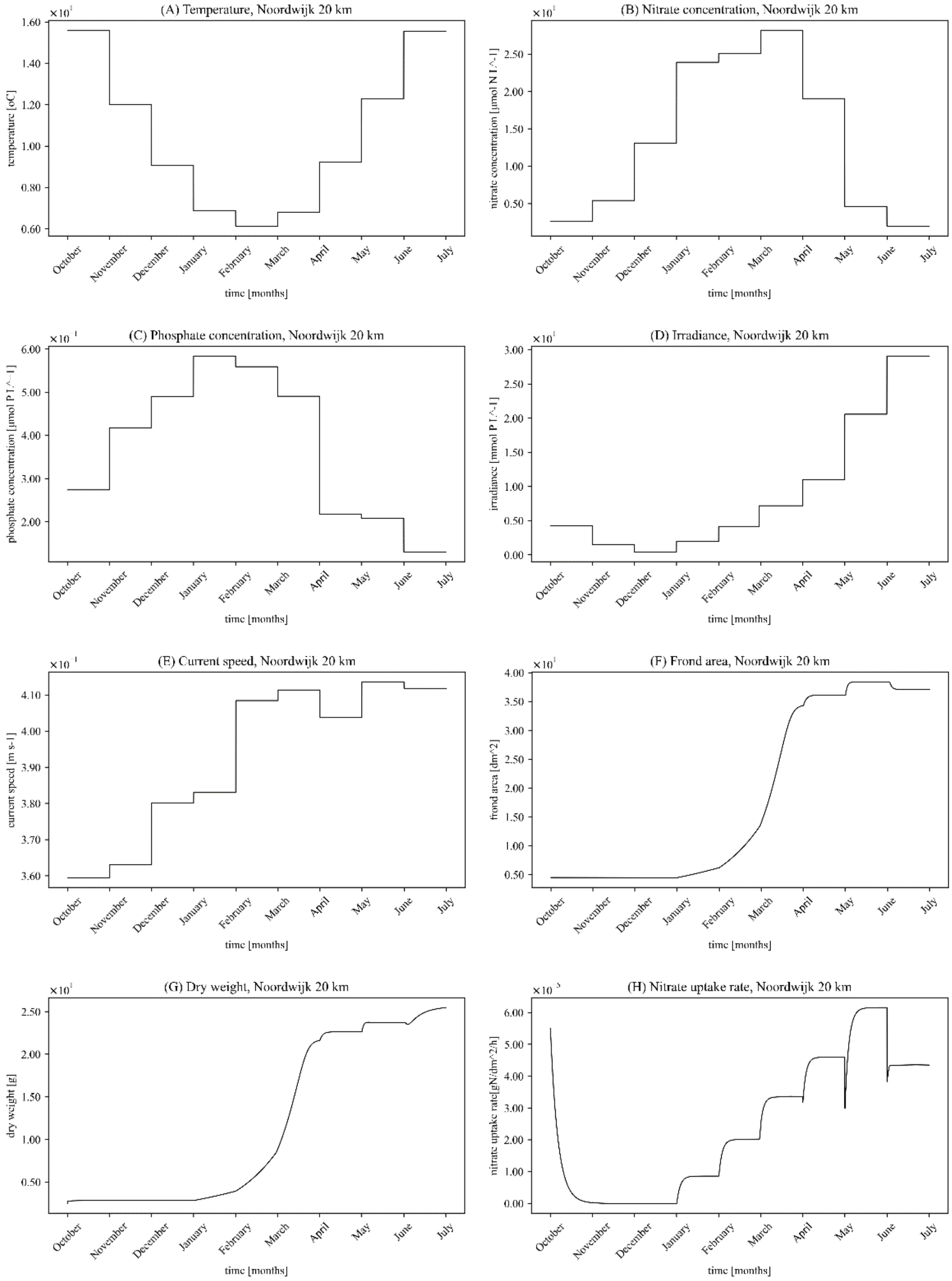
Appendix A: Nutrient dynamics and growth per farm

Appendix A.1: Noordwijk 20 km



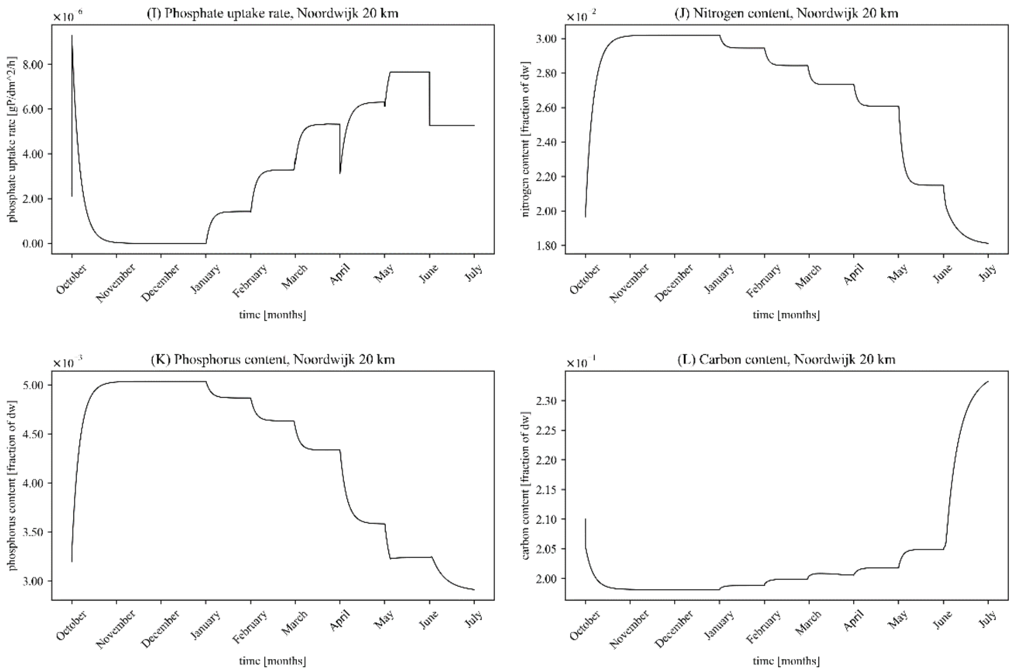


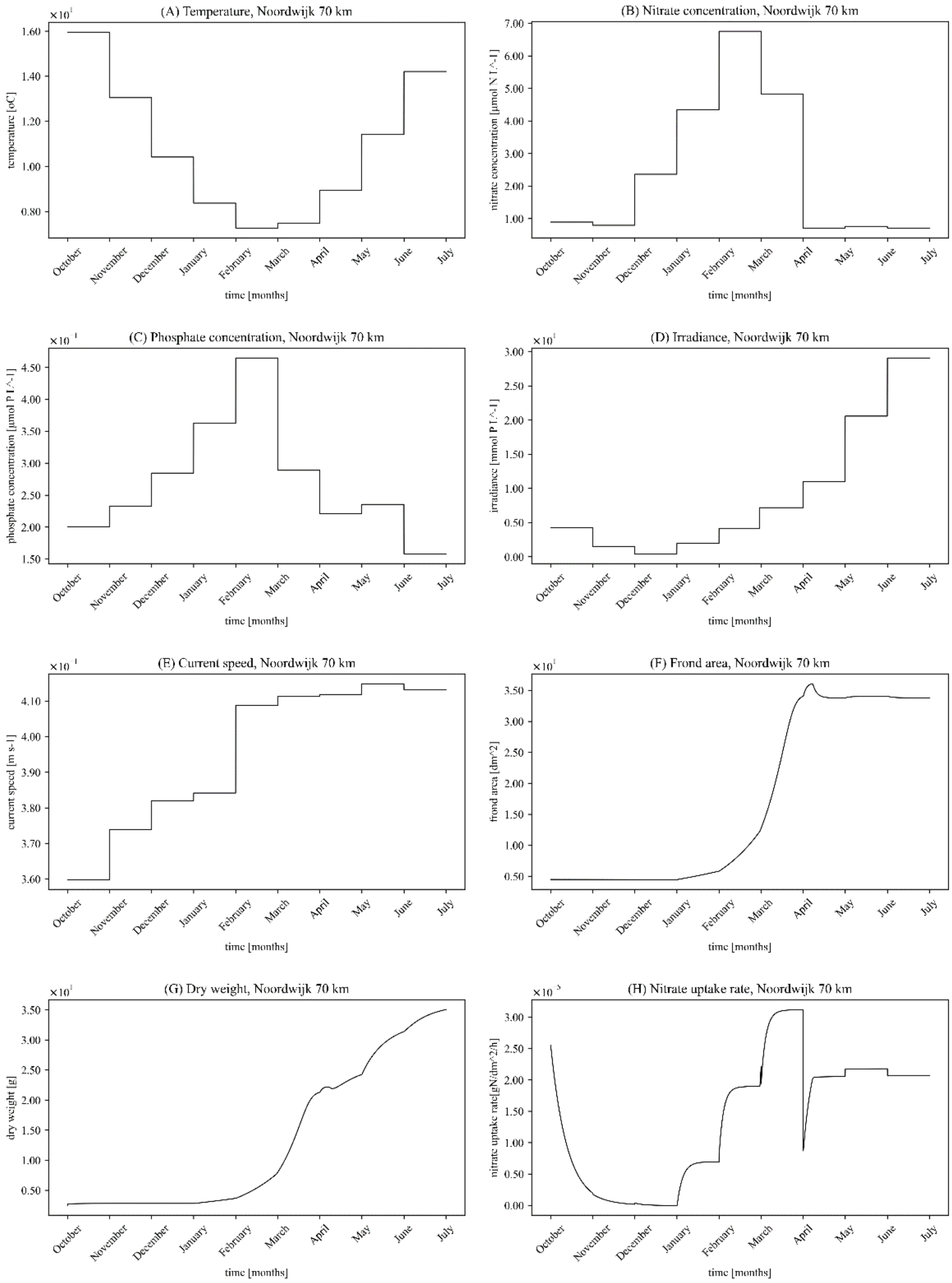
Figure 56: Model results for Noordwijk 20 km offshore seaweed farming location. Results are given per seaweed unit of the S. latissima. (A) Temperature; (B) nitrate concentration; (C) phosphate concentration; (D) irradiance; (E) current speed; (F) frond area; (G) dry weight; (H) nitrate uptake rate; (I) phosphate uptake rate; (J) nitrogen content; (K) phosphorus content; (L) carbon content.

Click to go back to Nutrient dynamics and growth, Noordwijk 20 km

Click to go back to Harvest results, Noordwijk 20 km

Click to go back to Analysis of nutrient dynamics and growth, Noordwijk 20 km

Appendix A.2: Noordwijk 70 km



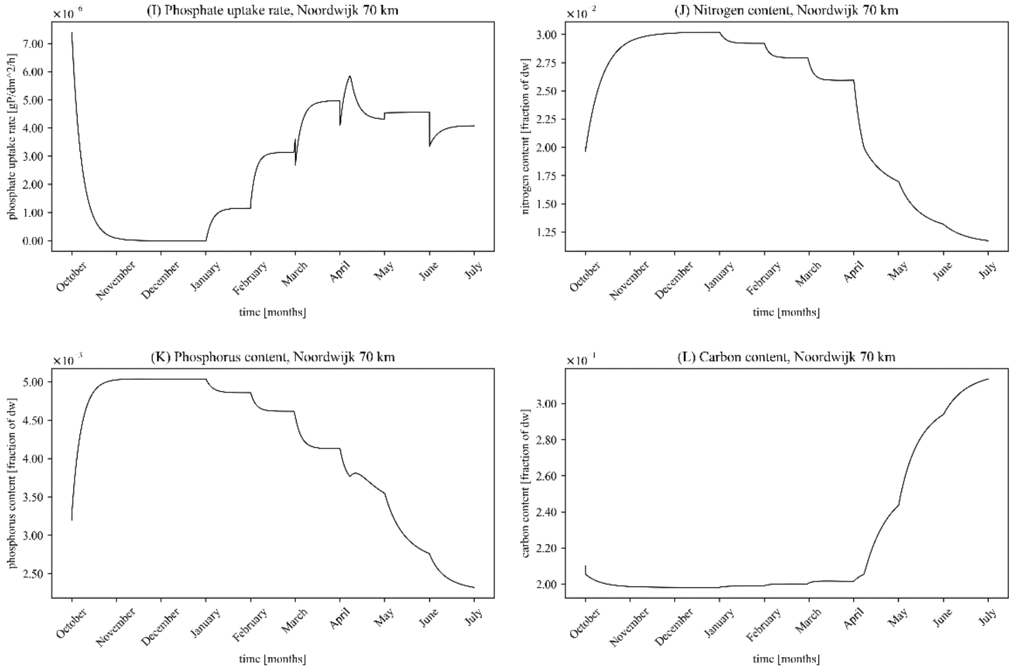


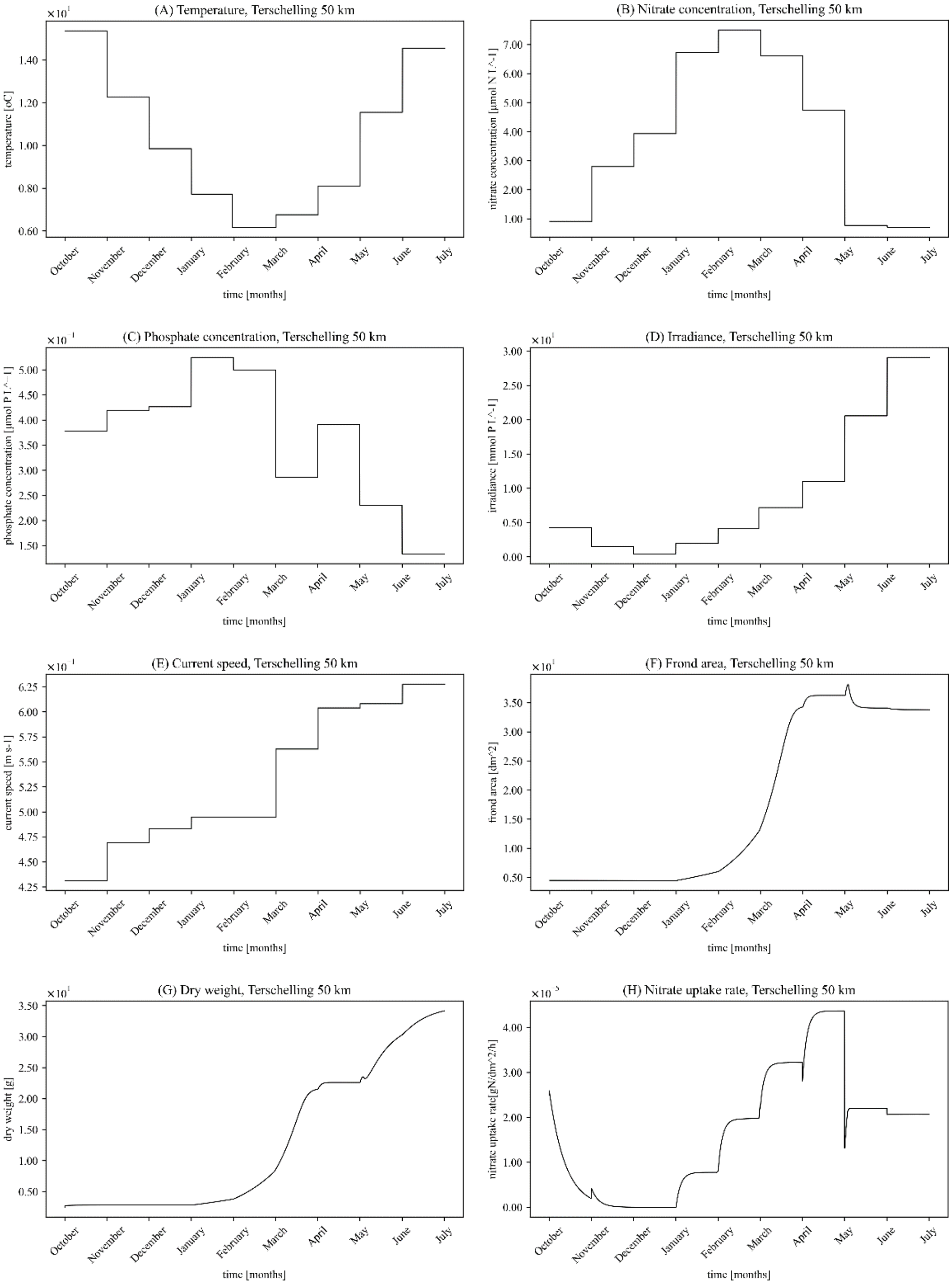
*Figure 57**:** Model results for Noordwijk 70 km offshore seaweed farming location. Results are given per seaweed unit of the S. latissima. (A) Temperature; (B) nitrate concentration; (C) phosphate concentration; (D) irradiance; (E) current speed; (F) frond area; (G) dry weight; (H) nitrate uptake rate; (I) phosphate uptake rate; (J) nitrogen content; (K) phosphorus content; (L) carbon content.*

Click to go back to Nutrient dynamics and growth, Noordwijk 70 km

Click to go back to Harvest results, Noordwijk 70 km

Click to go back to Analysis of nutrient dynamics and growth, Noordwijk 70 km

Appendix A.3: Terschelling 50 km



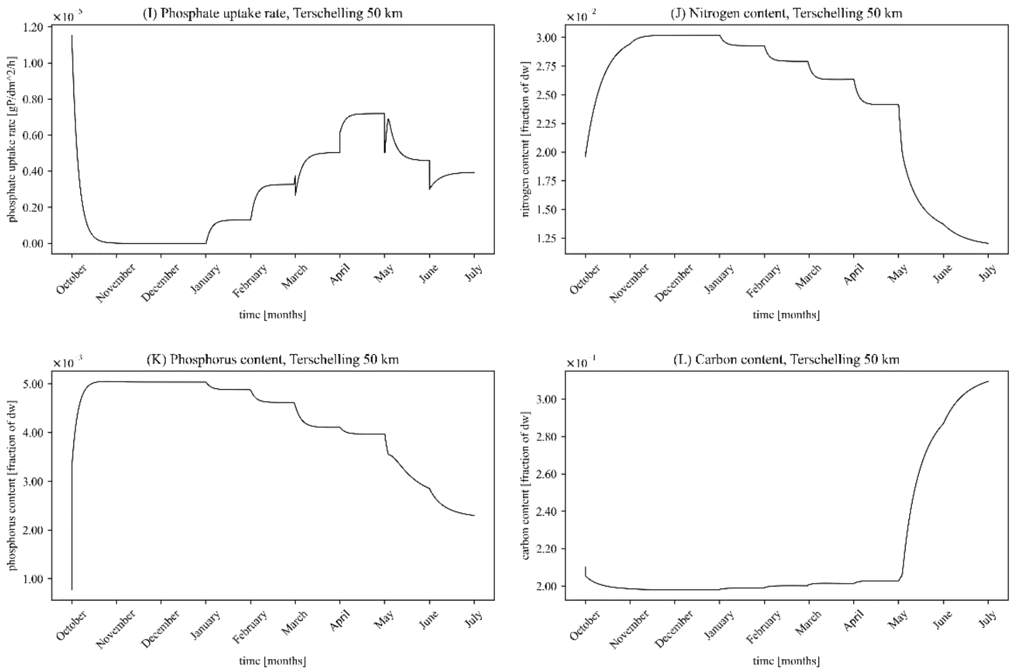


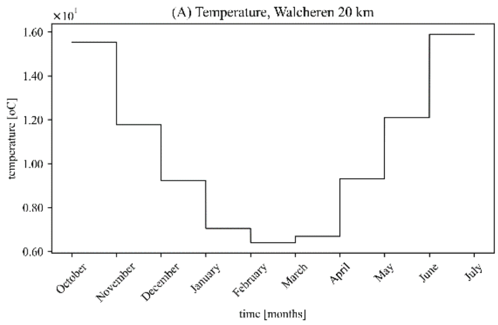
Figure 58: Model results for Terschelling 50 km offshore seaweed farming location. Results are given per seaweed unit of the S. latissima. (A) Temperature; (B) nitrate concentration; (C) phosphate concentration; (D) irradiance; (E) current speed; (F) frond area; (G) dry weight; (H) nitrate uptake rate; (I) phosphate uptake rate; (J) nitrogen content; (K) phosphorus content; (L) carbon content.

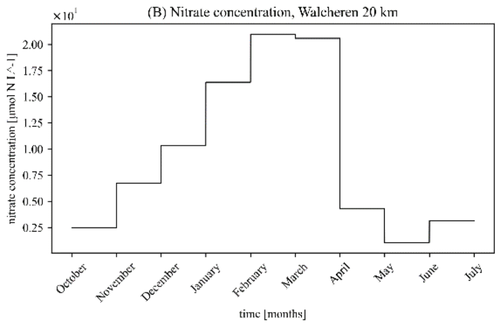
Click to go back to Nutrient dynamics and growth, Terschelling 50 km

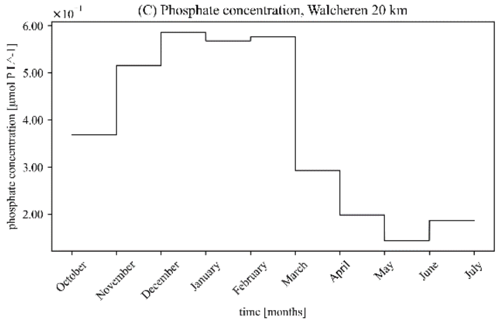
Click to go back to Harvest results, Terschelling 50 km

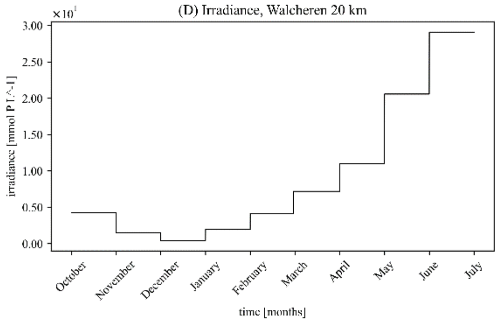
Click to go back to Analysis of nutrient dynamics and growth, Terschelling 50 km

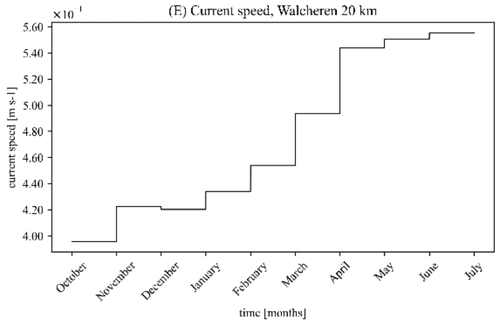
Appendix A.4: Walcheren 20 km

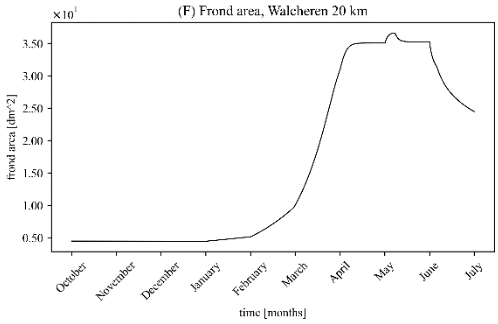


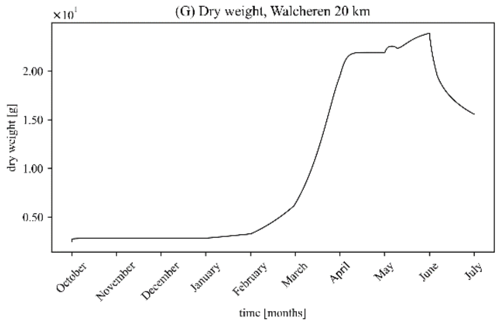


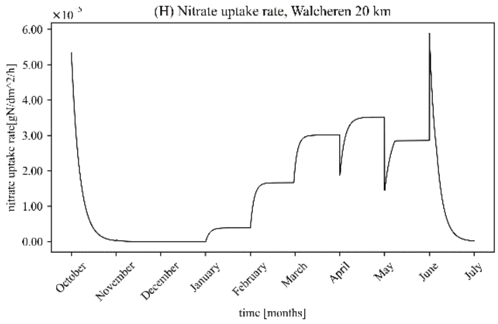












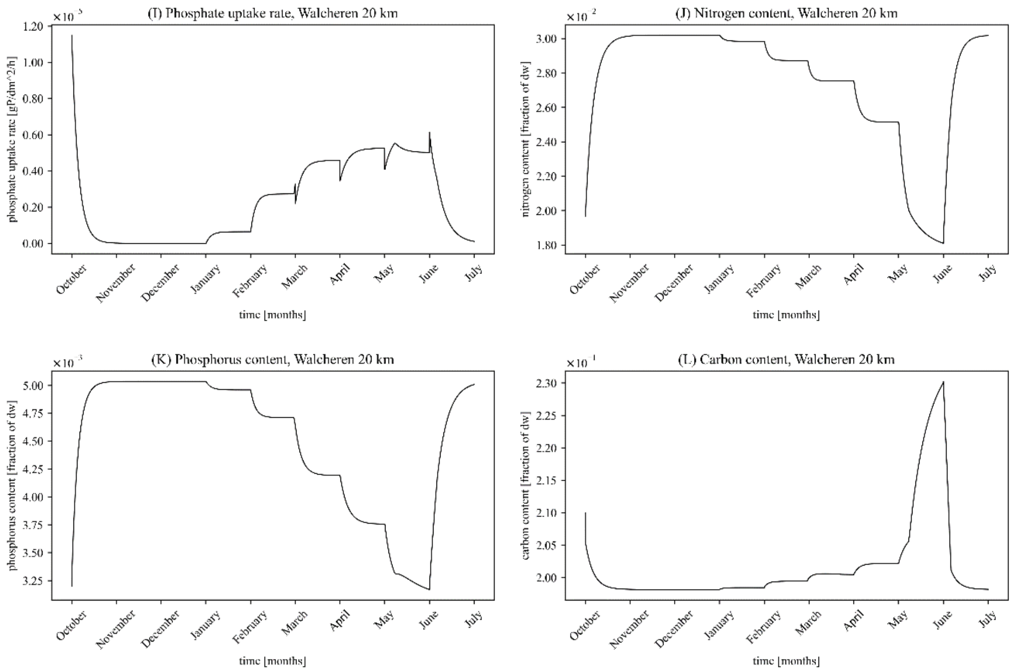


Figure 59: Model results for Walcheren 20 km offshore seaweed farming location. Results are given per seaweed unit of the S. latissima. (A) Temperature; (B) nitrate concentration; (C) phosphate concentration; (D) irradiance; (E) current speed; (F) frond area; (G) dry weight; (H) nitrate uptake rate; (I) phosphate uptake rate; (J) nitrogen content; (K) phosphorus content; (L) carbon content.

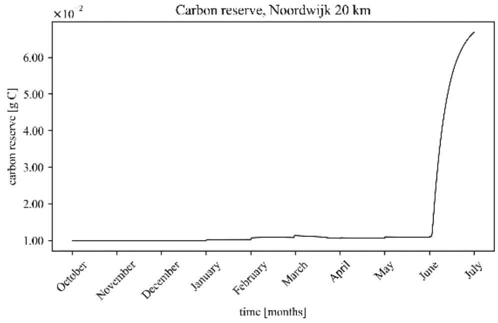
Click to go back to Nutrient dynamics and growth, Walcheren 20 km

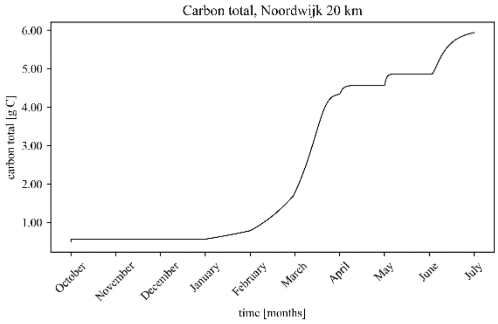
Click to go back to Harvest results, Walcheren 20 km

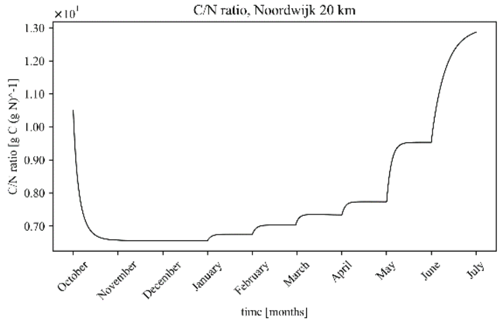
Click to go back to Analysis of nutrient dynamics and growth, Walcheren 20 km

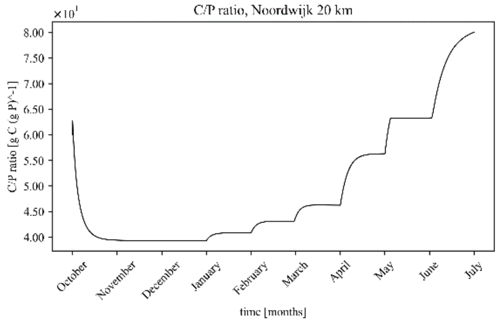
Appendix B: In-depth model results - Nutrient dynamics and growth

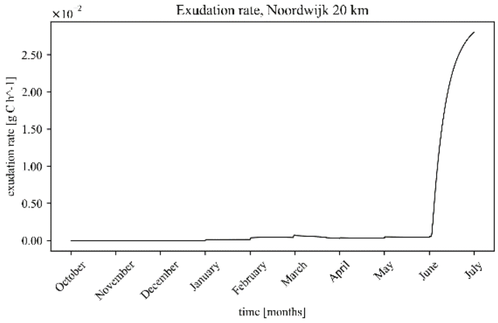
Appendix B.1: Noordwijk 20

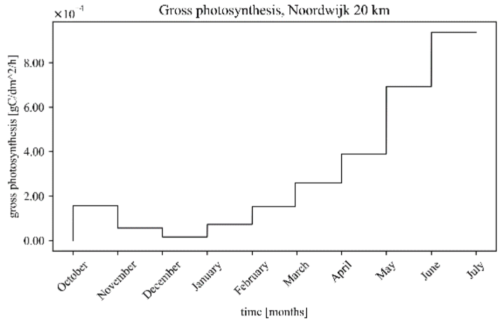


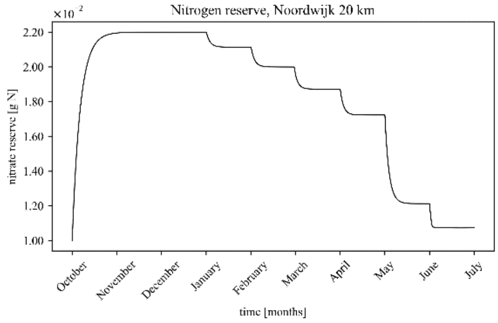


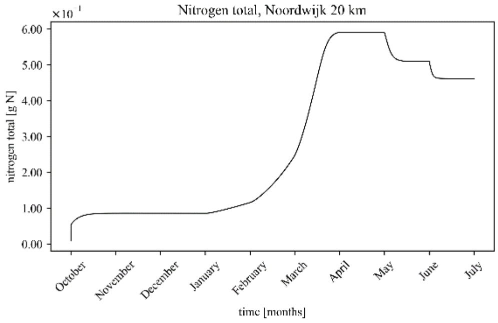


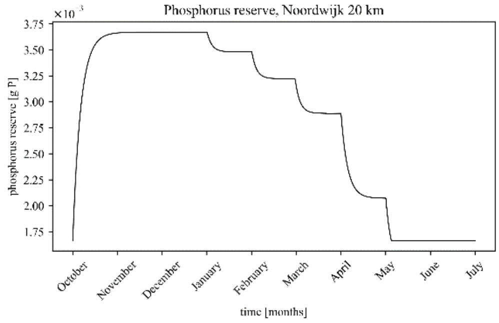


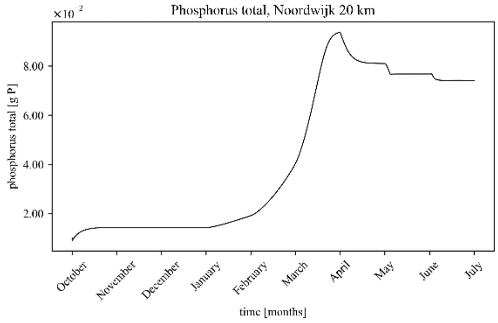


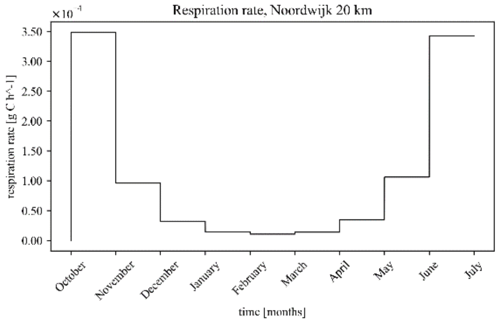


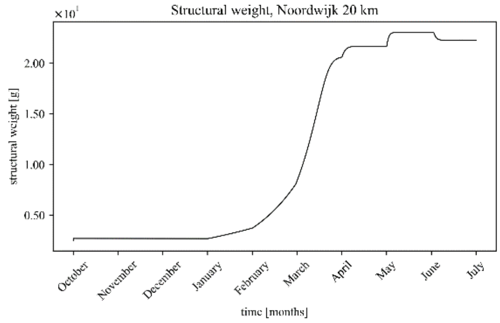






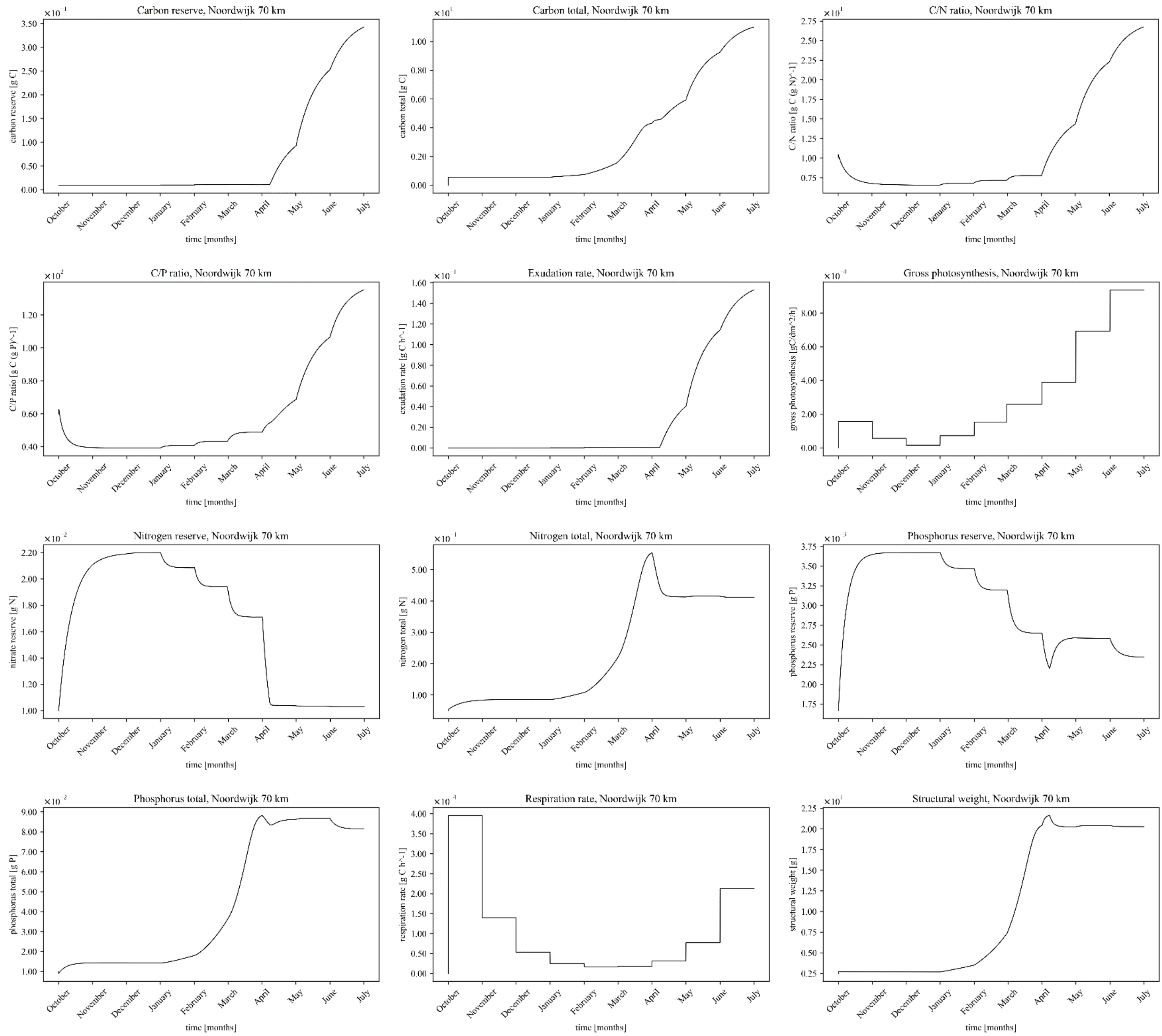






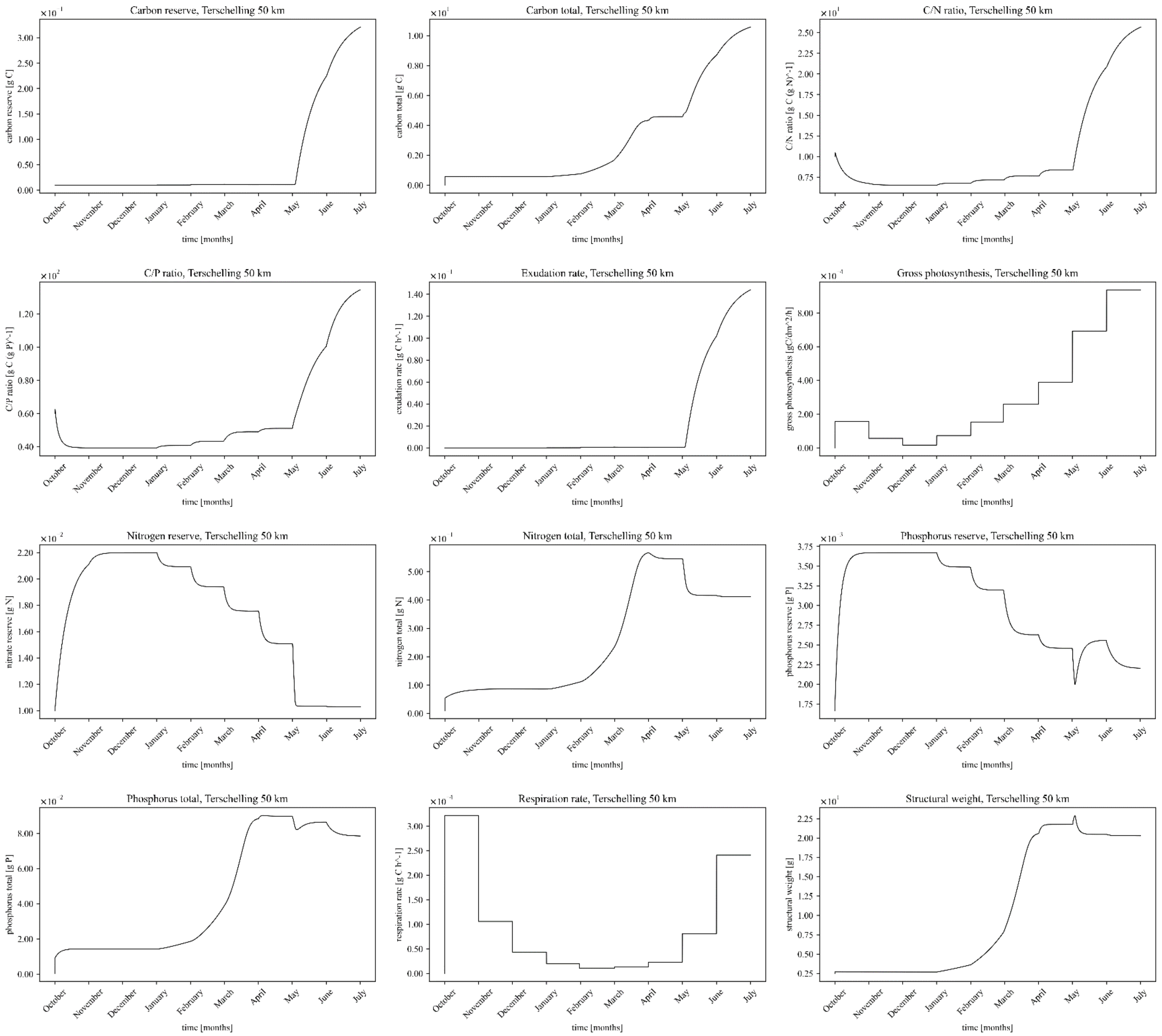
Go back to Nutrient dynamics and growth, Noordwijk 20 km

Appendix B.2: Noordwijk 70 km



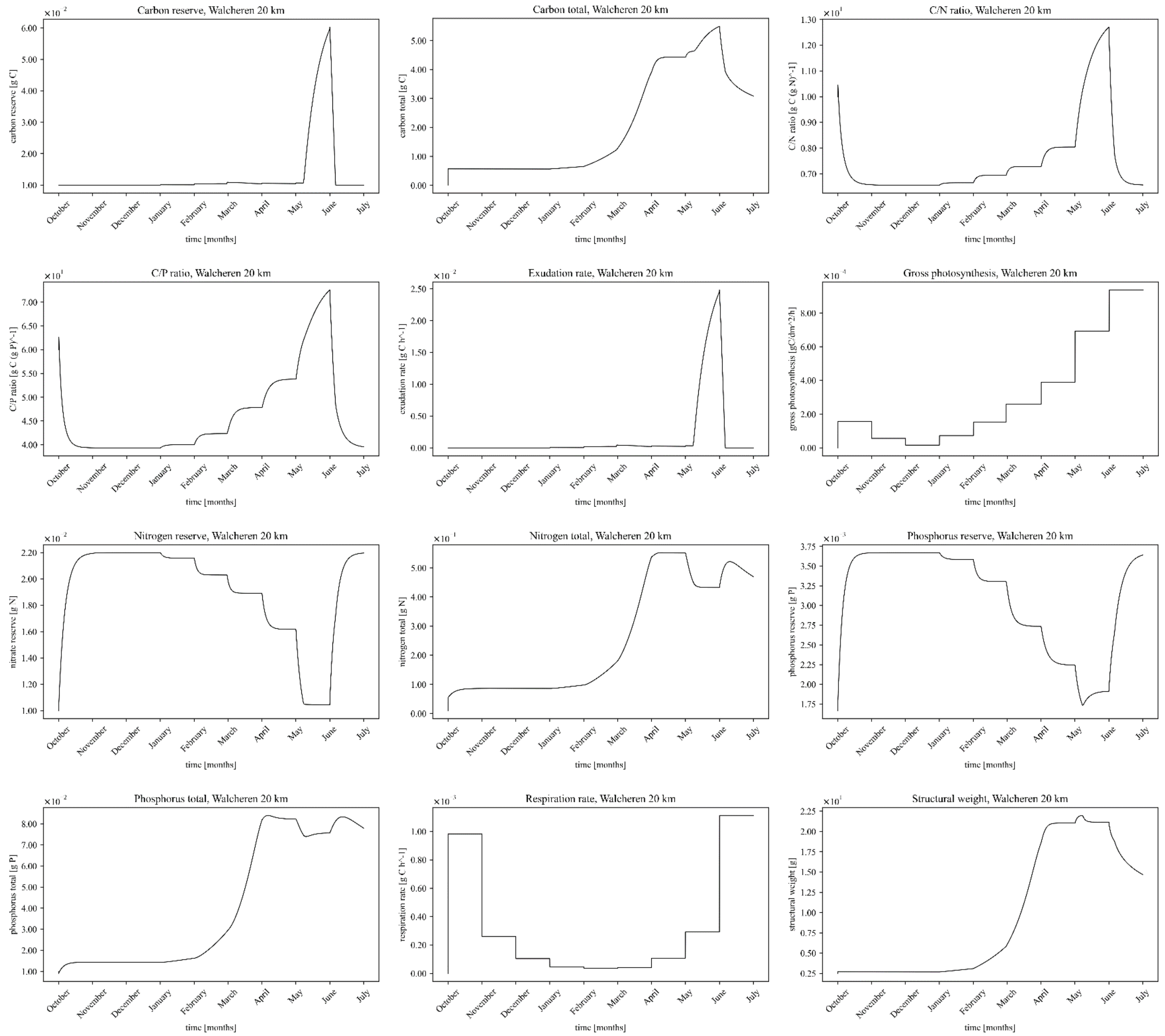
Go back to Nutrient dynamics and growth, Noordwijk 70 km

Appendix B.3: Terschelling 50 km



Go back to Nutrient dynamics and growth, Terschelling 50 km

Appendix B.4: Walcheren 20 km



Go back to Nutrient dynamics and growth, Walcheren 20 km

Appendix C: In-depth model results - Harvest

Appendix C.1: Noordwijk 20 km

	Value per individual	*Unit*
Frond area	37.10	[dm^2]
Structural weight	$22.26 * 10^{-3}$	[kg]
Carbon reserve	$6.69 * 10^{-5}$	[kg]
Nitrogen reserve	$1.07 * 10^{-5}$	[kg]
Phosphorus reserve	$1.67 * 10^{-3}$	[kg]
Carbon content	23.3	[%]
Nitrogen content	1.81	[%]
Phosphorus content	0.29	[%]
C:N ratio	12.9	[-]
C:P ratio	80.1	[-]

Appendix C.2: Noordwijk 70 km

	Value per individual	*Unit*
Frond area	33.81	[dm^2]
Structural weight	$20.29 * 10^{-3}$	[kg]
Carbon reserve	$3.42 * 10^{-4}$	[kg]
Nitrogen reserve	$1.03 * 10^{-5}$	[kg]
Phosphorus reserve	$2.35 * 10^{-6}$	[kg]
Carbon content	31.40	[%]
Nitrogen content	1.18	[%]
Phosphorus content	0.23	[%]
C:N ratio	26.7	[-]
C:P ratio	135.18	[-]

Appendix C.3: Terschelling 50 km

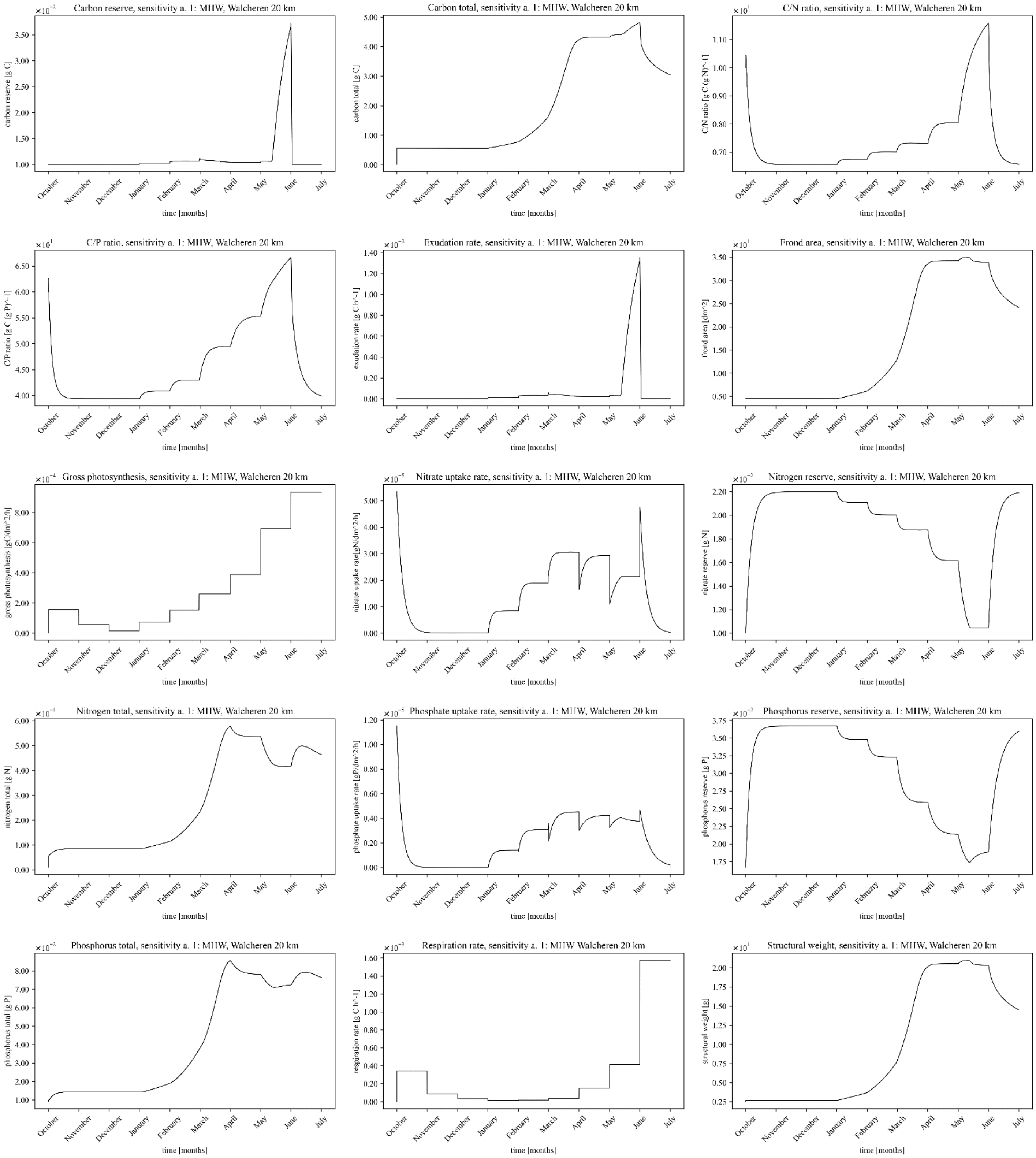
	Value per individual	*Unit*
Frond area	33.81	[dm^2]
Structural weight	$20.29 * 10^{-3}$	[kg]
Carbon reserve	$3.21 * 10^{-4}$	[kg]
Nitrogen reserve	$1.03 * 10^{-5}$	[kg]
Phosphorus reserve	$2.21 * 10^{-6}$	[kg]
Carbon content	30.98	[%]
Nitrogen content	1.21	[%]
Phosphorus content	0.23	[%]
C:N ratio	25.7	[-]
C:P ratio	134.6	[-]

Appendix C.4: Walcheren 20 km

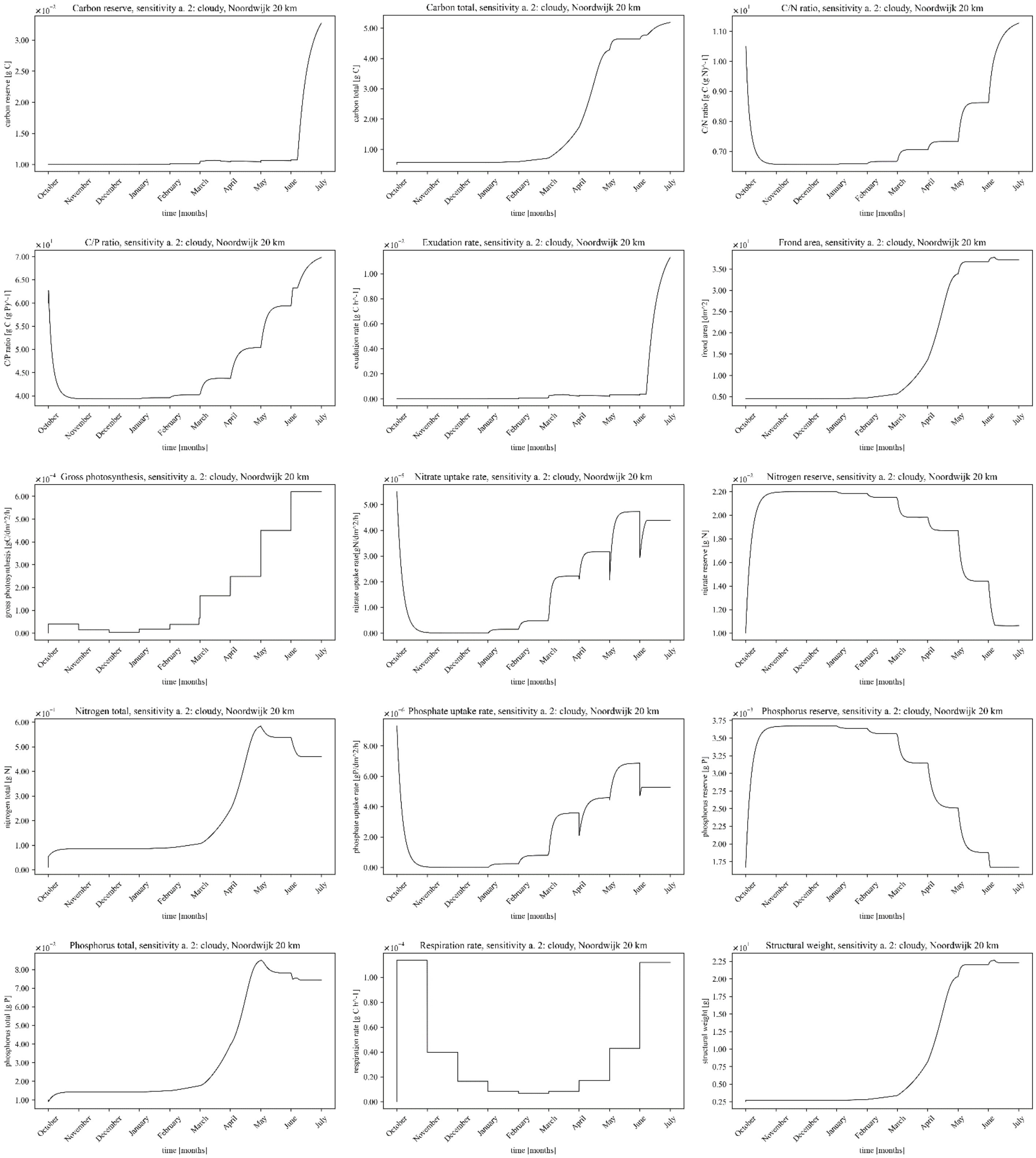
	Value per individual	*Unit*
Frond area	38.13	[dm^2]
Structural weight	$22.88 * 10^{-3}$	[kg]
Carbon reserve	$1.11 * 10^{-5}$	[kg]
Nitrogen reserve	$1.11 * 10^{-5}$	[kg]
Phosphorus reserve	$1.67 * 10^{-6}$	[kg]
Carbon content	20.57	[%]
Nitrogen content	2.06	[%]
Phosphorus content	0.32	[%]
C:N ratio	9.99	[-]
C:P ratio	63.3	[-]

Appendix D: Sensitivity analyses

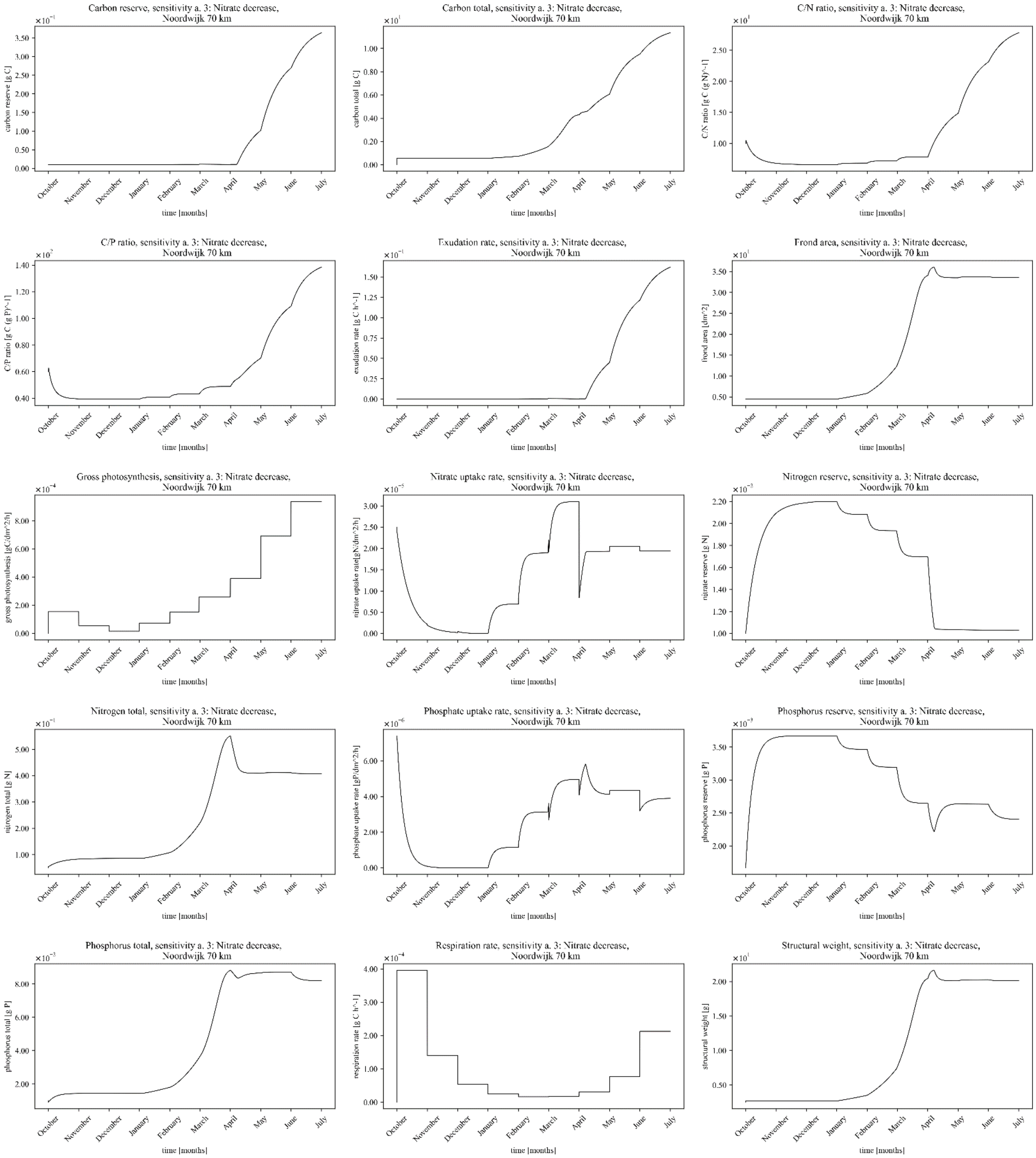
Appendix D.1: Sensitivity analysis 1: Marine heatwave



Appendix D.2: Sensitivity analysis 2: cloudy cultivation season



Appendix D.3: Decreased nitrate levels



Appendix E: Ecological carrying capacity

Appendix E.1: Calculations of ecological carrying capacity

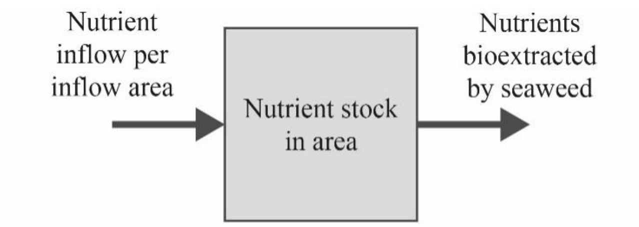
Inflow nitrate: 281,000,000,000 [g] yr^{-1}

Inflow phosphate: 12,000,000,000 [g] yr^{-1}

N inflow per inflow area: Total inflow * distribution factor

- ➔ It was assumed the seaweed grows to a blade length of 5 [m]

Inflow per scenario: Inflow per m3 * 5 * cultivation area



Nutrient stock with cultivation: Nutrient stock already present in water + nutrient inflow – nutrient uptake of seaweed

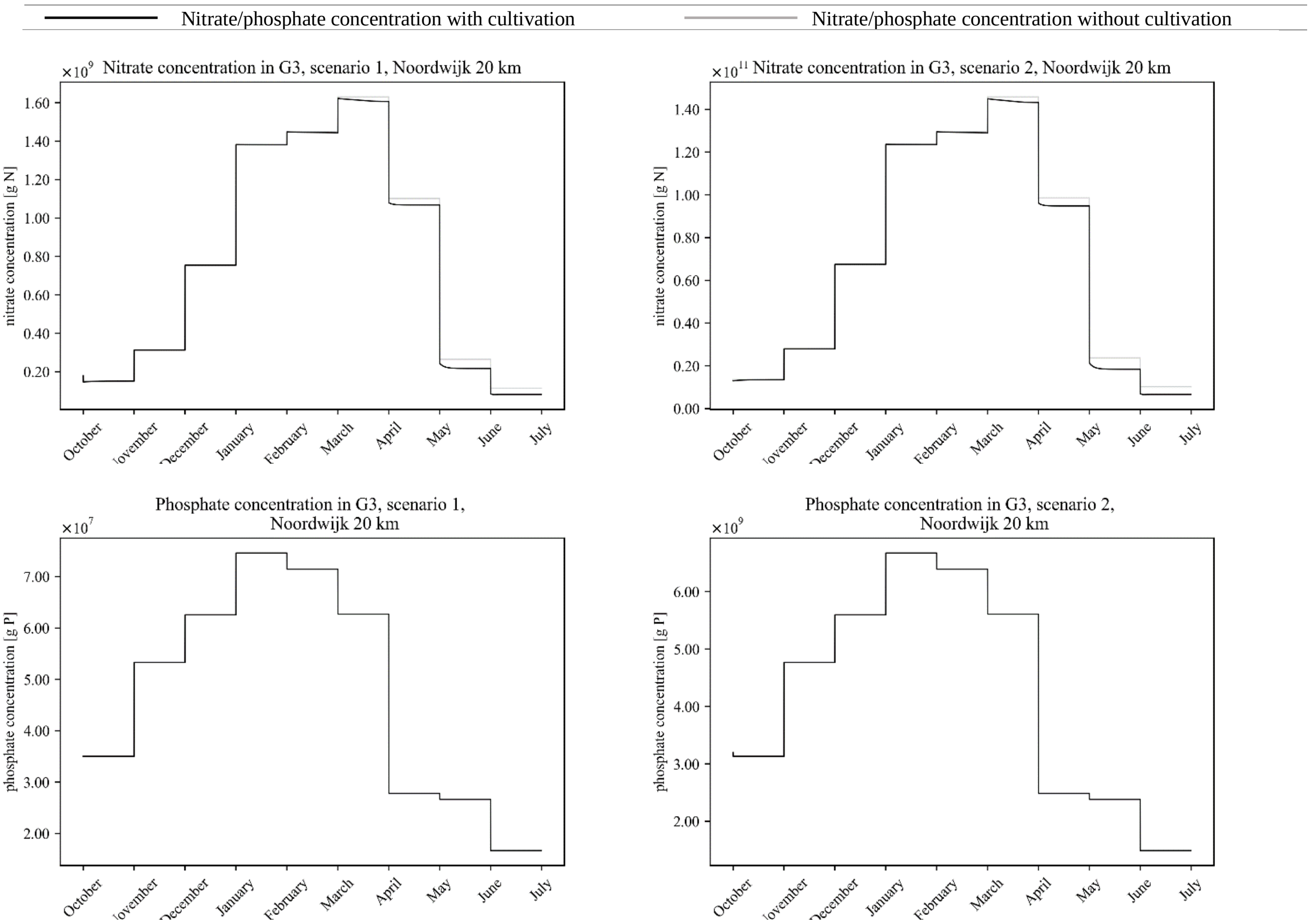
Nitrate

	2 km	10 km	20 km	50 km	70 km	100 km	135 km	175 km	235 km
Average	0.371	0.3135	0.2175	0.146333333	0.1345	0.127	0.125	0.078	0.075
Distribution factor	0.233651727	0.197438858	0.136979112	0.092159127	0.084706623	0.079983206	0.078723628	0.049123544	0.047234177
Inflow per gradient [g]	65656135195	55480319093	38491130471	25896714601	23802561142	22475280781	22121339351	13803715755	13272803611

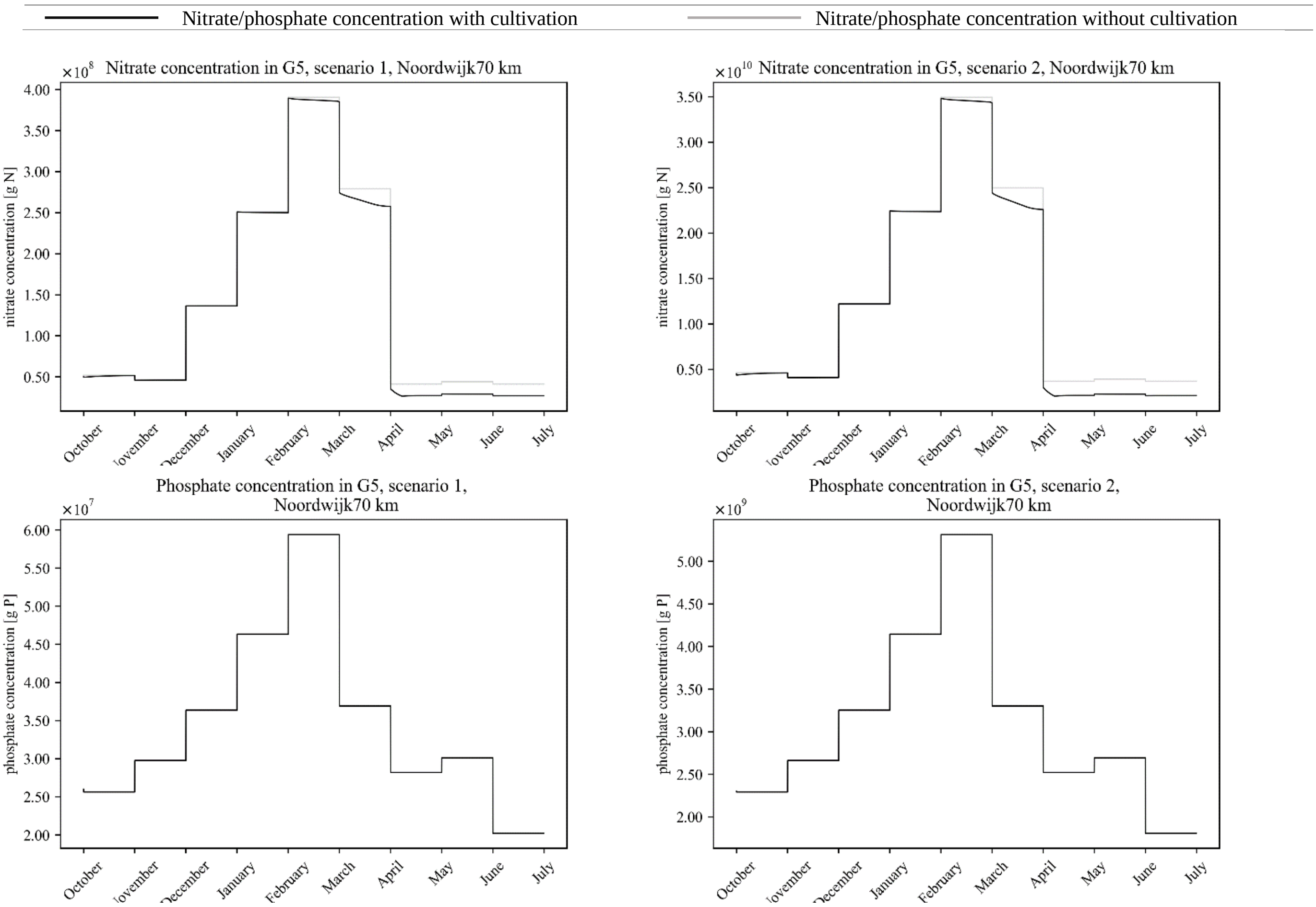
Phosphate

	2 km	10 km	20 km	50 km	70 km	100 km	135 km	175 km	235 km
Average	0.023	0.0185	0.0145	0.013	0.012	0.011	0.009	0.004	0.003
Distribution factor	0.212962963	0.171296296	0.134259259	0.12037037	0.111111111	0.101851852	0.083333333	0.037037037	0.027777778
Inflow per gradient [g]	2555555556	2055555556	1611111111	1444444444	1333333333	1222222222	1000000000	444444444.4	333333333.3

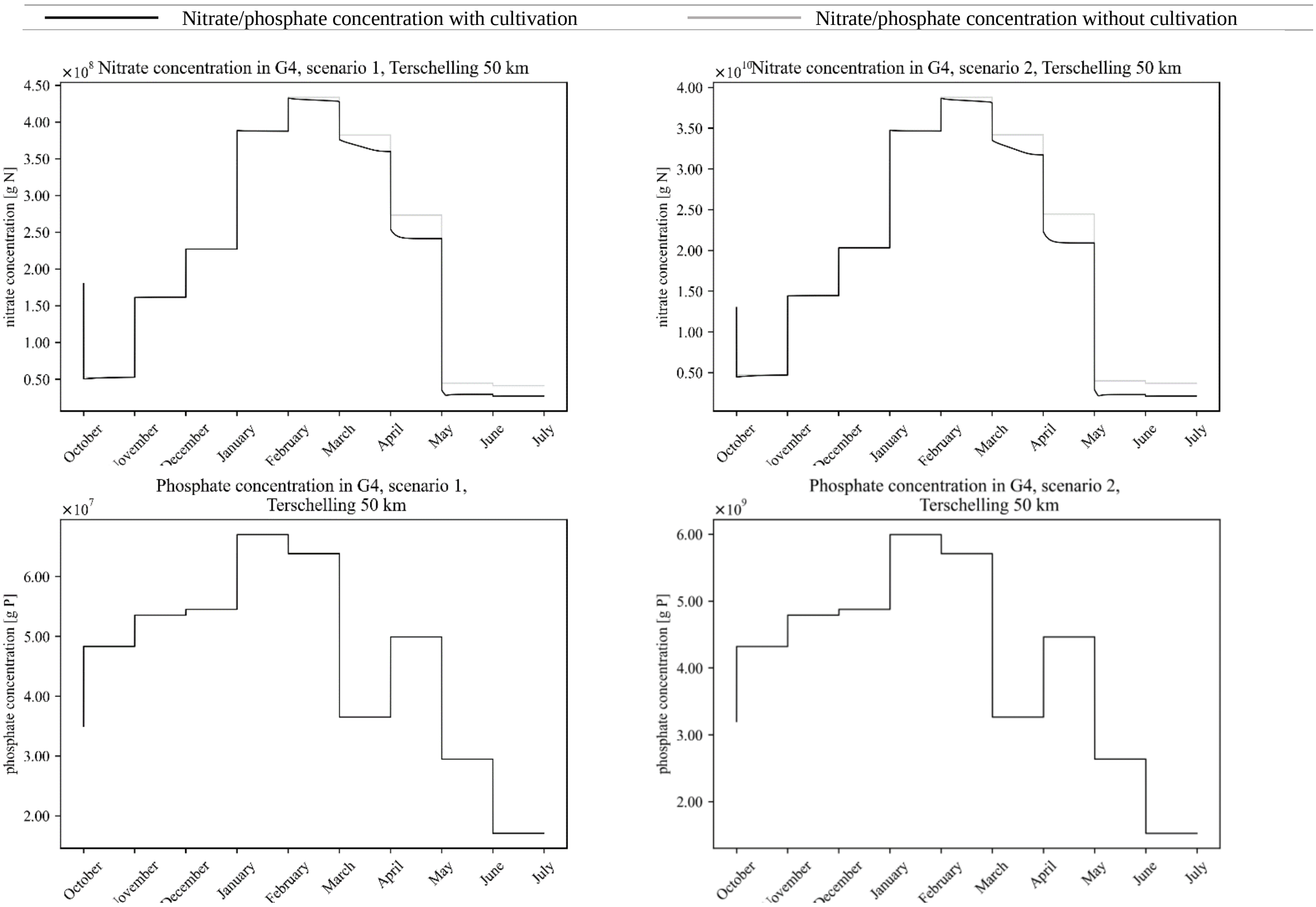
Noordwijk 20 km farm



Noordwijk 70 km farm

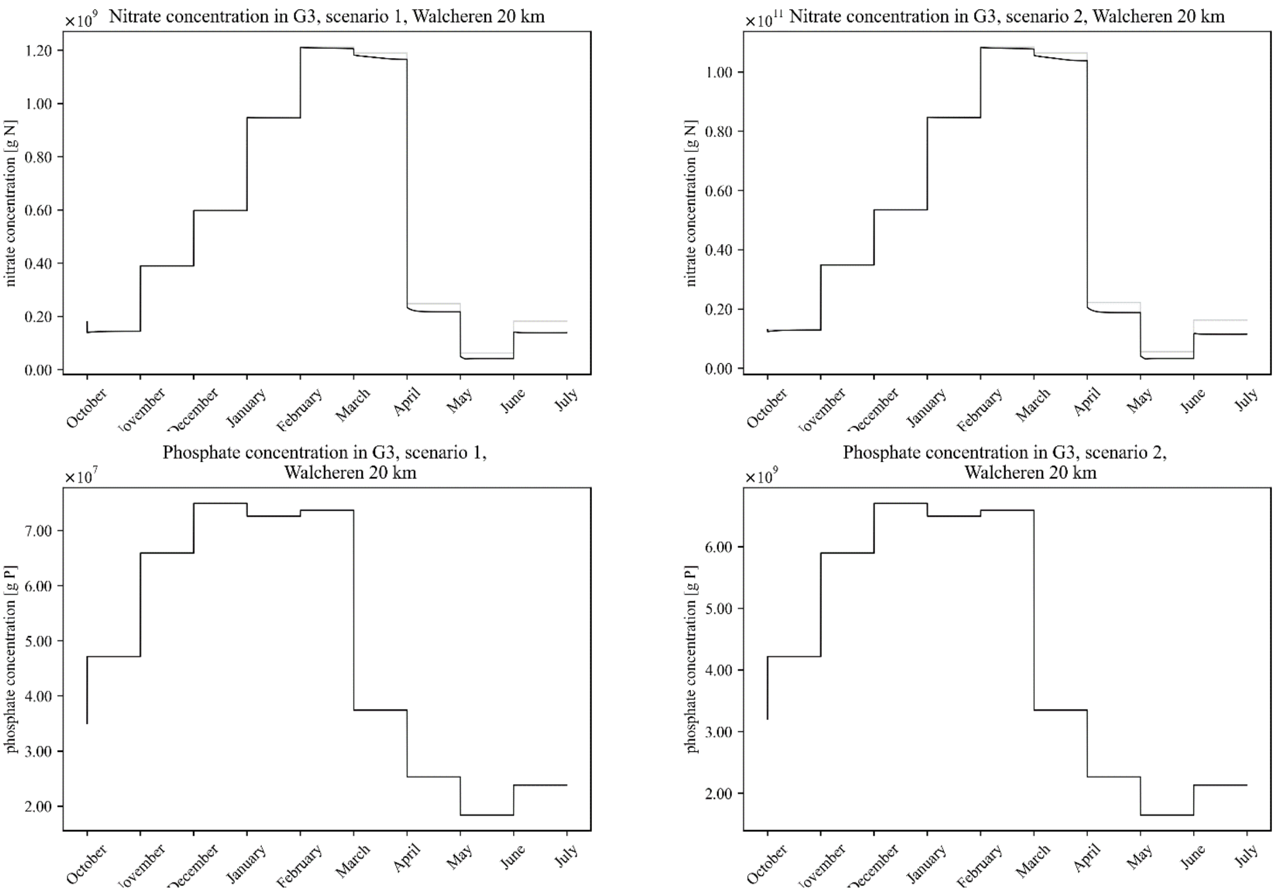


Terschelling 50 km farm



Walcheren 20 km farm

Nitrate/phosphate concentration with cultivation — Nitrate/phosphate concentration without cultivation



Appendix F: AUV operator plan

“The steps of a typical plan set up by the operator prior to launch are:

1. Vehicle is launched, and a GPS fix is acquired.

2. The AUV mission is started and the vehicle follows a plan to reach the farm’s vicinity.

3. The AUV circles around the farm, using sidescan sonar to detect buoys and construct a relative-to-AUV map of the farm.

4. Move to the beginning of the seaweed line, using the constructed map.

5. Start surveying the line according to the previously constructed map.

6. Transition to line-following once some of the lines have been detected using the sidescan sonar.

7. At end of the line execute a 180 turn to position the AUV on the other side of the line (between two lines now).

8. Follow the line using the previous detections of the first line seen from the first side and known prior line spacing until sufficient detections of the next line are found.

9. Repeat from (6) until complete.

10. Once all lines are surveyed, finish the planned mission and return to base.” (Stenius et al., 2022)

Appendix G: Maximal photosynthetic rate

The maximal photosynthetic rate is dependent on the temperature and is calculated according to the following equations:

$$P_S = \frac{\alpha\, I_{sat}}{\ln\left(1 + \frac{\alpha}{\beta}\right)}$$

Equation 23: Maximal photosynthetic rate 1

$$P_{max} = \frac{\alpha\, I_{sat}}{\ln\left(1 + \frac{\alpha}{\beta}\right)} \left(\frac{\alpha}{\alpha + \beta}\right) \left(\frac{\beta}{\alpha + \beta}\right)^{\beta/\alpha}$$

Equation 24: Maximal photosynthetic rate 2

$$P_{max}(T) = \frac{(P_1\ \exp\left(\frac{T_{AP}}{T_{P1}} - \frac{T_{AP}}{T}\right)}{1 + \exp\left(\frac{T_{APL}}{T} - \frac{T_{APL}}{T_{PL}}\right) + \exp\left(\frac{T_{APH}}{T_{PH}} - \frac{T_{APH}}{T}\right)}$$

Equation 25: Arrhenius law for maximal photosynthetic rate

In the formulas above, I_{sat} denotes the irradiance at which the photosynthetic rate is maximum. The variable β is calculated with the bisection method, using a start value of $1 * 10^{-9}$. β is used to equate Equation 24 and Equation 25, and is then used in Equation 10.

Appendix H: Estimation of required time, amount of units and associated costs of monitoring technologies

Smart buoy

CapEx	10,000 [EUR] per unit (Greene, 2019)
Estimated time per scan	Assumed to 1 [h]
Amount of units	1 culture line = 500 [m] (Bak et al., 2018) Scenario 1: 825 culture lines (Assumed 1 smart buoy is used per 10 culture lines) Scenario 2: 73,800 culture lines (Assumed 1 smart buoy is used per 10 culture lines)
Total OpEx	1% of OpEx (converted from $year^{-1}$ to day^{-1}) + 0.08 [EUR] per transmission per buoy + processing costs (40 hrs * 20 [EUR])

ROV

CapEx	5,000 [EUR] per unit (Bas Binnerts, pers. comm., July 19, 2022).
Estimated time per scan	Average speed of ROV: 2 ms^{-1} (Bas Binnerts, pers. comm., July 19, 2022). Required time for scenario 1 for 1 unit: 23 days Required time for scenario 2 for 1 unit: 2,135 days
Amount of units	Required time for a scan converted to acceptable timespan scenario 1: 23 units in 24 hours Required time for a scan converted to acceptable timespan scenario 1: 1,067 units in 48 hours
Total OpEx	Scenario 1: Vessel costs 3 working days (3 * 8 [hrs]) = 9,000 [EUR]. Labour costs per ha = 360 [EUR] Scenario 2: Vessel costs 6 working days = 18,000 [EUR]. Labour costs per ha = 360 [EUR]

AUV

CapEx	250,000 – 500,000 [EUR] per unit (Bas Binnerts, pers. comm., July 19, 2022).
Estimated time per scan	Average speed of AUV: 2 ms^{-1} (Bas Binnerts, pers. comm., July 19, 2022). Required time for scenario 1 for 1 unit: 23 days Required time for scenario 2 for 1 unit: 2,135 days
Amount of units	Required time for a scan converted to acceptable timespan scenario 1: 23 units in 24 hours Required time for a scan converted to acceptable timespan scenario 1: 1,067 units in 48 hours
Total OpEx	Scenario 1: Vessel costs 3 working days = 9,000 [EUR]. Navigational costs per UAV per day: 180 [EUR] Scenario 2: Vessel costs 6 working days = 18,000 [EUR]. Navigational costs per UAV per day: 180 [EUR]

ASV-USV

CapEx	250,000 – 500,000 [EUR] per unit (Bas Binnerts, pers. comm., July 19, 2022).
Estimated time per scan	Average speed of ASV: 0.6 ms^{-1} (Mousazadeh et al., 2017) Required time for scenario 1 for 1 unit: 80 days Required time for scenario 2 for 1 unit: 7,118 days
Amount of units	Required time for a scan converted to acceptable timespan scenario 1: 80 units in 24 hours Required time for a scan converted to acceptable timespan scenario 1: 1,424 units in 120 hours
Total OpEx	Scenario 1: Vessel costs 3 working days = 9,000 [EUR]. Labour costs per ha = 360 [EUR] Scenario 2: Vessel costs 15 working days = 45,000 [EUR]. Labour costs per ha = 360 [EUR]

sUAS

CapEx	5,000 – 20,000 [EUR] per unit (Web search)
Estimated time per scan	Average speed of sUAS: 12.5 ms^{-1} (DelAir, n.d.) Required time for scenario 1 for 1 unit: 4 days Required time for scenario 2 for 1 unit: 342 units
Amount of units	Required time for a scan converted to acceptable timespan scenario 1: 4 units in 24 hours Required time for a scan converted to acceptable timespan scenario 1: 342 units in 24 hours
Total OpEx	Scenario 1: Vessel costs 3 working days = 9,000 [EUR]. Labour costs per ha = 360 [EUR]. Processing costs: 5,300 [EUR] per 50 [ha] (Matese et al., 2015) Scenario 2: Vessel costs 3 working days = 9,000 [EUR]. Labour costs per ha = 360 [EUR]. Processing costs: 5,300 [EUR] per 50 [ha] (Matese et al., 2015)

Satellite

CapEx	0 [EUR] (No capital expenditures needed, as not satellite is purchased)
Estimated time per scan	Assumed to 1 [h]
Amount of units	1 satellite needed to capture images
Total OpEx	Processing costs per 50 [ha] = 2,650 [EUR] (Matese et al., 2015)

Appendix I: Potential sensor types for measuring key parameters

The following list was (for the most part) provided by Karla Dussan (Scientist at Biobased and Circular Technologies, TNO).

Biodiversity

Parameter	Sensor name	Sensor type
Algae-values (biofoul)	Phantom Pro 3 drone	Remote sensing (drone)
	GoPro Hero 4	
Invasive species	eDNA	DNA metabarcoding
Algae-values (biofoul)	DJI R-G-B/NIR-R-G	AUV(aerial)
Algae-values (biofoul)	OOI SD2000/USB4000	Spectroradiometer
Algae-values (biofoul)	Sentinel-1 A/B	Microwave satellite
Algae-values (biofoul)	Landsat TM+ETM/OLI	Optical satellite
Algae-values (biofoul)	GaoFen-1 WVF	Optical satellite
Algae-values (biofoul)	Sentinel-2 A/B	Optical satellite
Algae-values (biofoul)	MODIS terra/aqua	optical satellite

Seabed

Parameter	Sensor name	Sensor type
Depth	Dual-frequency Side-Scan Sonar	Depth sensor
Image	Electronic Still Camera (ESC) with 200 Watt-Sec Strobe Lighting	Camera
Depth	Multibeam Profiling Sonar	Depth sensor
Sediment	Sub-Bottom Profiling Sonar	
Image	Inocturn HI QE	Photography
Algae-values (biofoul)	MicaSense RedEdge-M multispectral camera	Multispectral Camera
Turbidity		

Water quality

Parameter	Sensor name	Sensor type
Dissolved Oxygen	Advant EDGE	DO sensor
Dissolved Oxygen	Process Instruments (PI)	DO sensor
Dissolved Oxygen	PreSens	DO sensor
Dissolved Oxygen	Hanna Instruments	DO sensor
Dissolved Oxygen	Omega	DO sensor
Temperature	Various sensors available	Thermometer
Salinity	BOQU	Salinometer
Irradiance	LI-192 Underwater Quantum Sensor	Solar irradiance meter
Current direction	MODEL6526	Current meter
Current velocity	MODEL6526	Current meter
pH	Ultra Tough pH/ORP Smart Sensors	pH-meter
Nitrate / ammonium	OTT HydroMet Aquams INNOVASEA SensorTips XylemAnalytics	Photometer
Phosphate	UWM phosphate sensor	Photometer