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An assessment of the biological feasibility of an offshore macroalgal aquaculture system in the North Sea.

Master Thesis

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Abstract

An ever expanding global population has led to increased pressure on available land for food production. Thoughts are turning to the large expanses of space and resources available in the sea, in particular offshore areas. Macroalgae are an ideal solution due to their productivity, high nutritional value and use as a dietary protein substitute. This research has been conducted with Deltares and as a component of the MERMAID European Union initiative which aims to incorporate aquaculture into their designs for multi functional offshore platforms. This research aimed to determine the biological feasibility of an offshore macroalgal farm in the North Sea. To do so, we therefore assumed that macroalgae cultivated offshore would respond in a similar manner as when cultivated nearshore. Two species, *Laminaria digitata* and *Saccharina latissima* were studied in nine selected sites in the North Sea in monoculture and polyculture scenarios. These sites represented characteristic offshore areas of the North Sea and aquaculture sites in planning. The suitability of sites and the controlling factors to growth were studied with the generic integrated ecosystem model Delft3D. Results indicate offshore aquaculture systems to be biologically feasible based on macroalgal farming in the North Sea. *L. digitata* produced the largest biomass when grown in a monoculture and in a polyculture with an increase in total biomass production being observed in the polyculture scenario. The site that produced the largest biomass was Borssele which had one of the highest current velocities observed. A positive trend was found between current velocity, seawater temperature and maximum biomass produced. A relationship was found between the concentration of dissolved inorganic nitrogen (DIN) and phosphorous (DIP) throughout the year and the biomass produced at each site. The sites which produced the most biomass had a simultaneous increase in DIN, DIP and biomass between July and October. Therefore this research recommends that in order to achieve maximum biomass production, *L. digitata* and *S. latissima* should be grown in a polyculture. The current velocity, DIN and DIP concentrations and seawater temperature were found to be the main controlling factors to biomass production and should be considered when selecting a suitable offshore macroalgal site. This model can be used as a starting point to which additional modifications and data from test sites when available can be implemented into in order to bridge the gap between model output and reality. Despite this research concluding that it is biologically feasible for an offshore macroalgal farm, the feasibility of other aspects such as economic and social must also be accessed.

Keywords: macroalgae, offshore, commercial, biological, feasibility, nutrients, competition

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1. Introduction

1.1 Global perspective

From a global perspective the population is predicted to reach 9.3 billion by 2050 (United Nations, 2012). Rising incomes are associated with a higher standard of living which simultaneously increases the consumption of meat and fish. This leads to a rise in the number of conflicts of interest over land use. Thoughts are therefore turning towards utilising the resources and available area in the sea to meet this growing demand help achieve global food security. If at least the current level of global consumption of aquatic products is to be maintained there will need to be an additional 23 million tonnes of aquatic products available by 2020 (FAO, 2012). Meeting these additional demands will have to come from aquaculture.

Aquaculture is the fastest growing food production sector in the world with an average growth rate of 8.3% per annum. The rate of aquaculture growth is in fact faster than the pace of human population growth (1.6% per year) which according to the FAO is a crucial factor in securing global food security. However this expansion is slowing partly due to public concerns about the environmental impact, associated unsustainable practices and resulting fish quality (FAO, 2009; FAO, 2010). The optimal solution to address these public concerns is one which helps to secure global food security in a sustainable and environmentally friendly way whilst producing high quality products.

Macroalgae is one possible solution to address public concerns whilst helping to secure global food security. This is due to their high productivity which is as great as or greater than the most productive land plants whilst simultaneously not competing with terrestrial crops for land space and having cheaper system inputs than their terrestrial counterparts (Gao & McKinley, 1994). This high productivity can thus absorb large quantities of nitrogen, phosphorous and carbon dioxide whilst producing large amounts of oxygen (Fei, 2004). The carbon dioxide which is absorbed during the growth of the biomass is roughly equivalent to the amount of carbon dioxide released when the biomass is utilised or consumed – thereby returning the carbon dioxide to the atmosphere (Fei, 2004). This means that macroalgae could be approximately carbon neutral over its life cycle. However emissions are produced during the harvesting, refining and transporting of the macroalgae, with transporting emissions being especially high if it is cultivated offshore. Therefore the exact carbon dioxide life cycle emissions of commercially cultivating macroalgae offshore are not yet known (Fei, 2004). The emissions associated in particular with transport could be minimised if the transport was shared with other offshore ventures such as wind farms or other forms of

aquaculture, for example integrated multi trophic aquaculture (IMTA) (Reid *et al.*, 2010). IMTA involves cultivating numerous trophic levels such as shellfish and fish in close proximity. This results in a decrease in the total particulate matter (shellfish) and up to 90% of the inorganic nitrogen and phosphorous (by seaweed) realised from the fish farm culminating in a more environmentally friendly aquaculture system (Luning & Pang, 2003; Reid *et al.*, 2010 & Huo *et al.*, 2012).

Nonetheless how can these advantages of macroalgae help to secure global food security? Although not often promoted for their nutritional value, macroalgae are a highly nutritious, low calorific food group containing many vitamins, minerals, proteins and fibre (Pereira, 2011). Macroalgae can thus address the nutritional deficiencies of modern 'fast food' whilst being a dietary protein substitute to red meat and fish (Pereira, 2011). It has been calculated that an area of 180,000 square kilometres of seaweed farm growing sea lettuce (*Ulva lactuca*) could produce enough protein for the entire world population (Plant life, 2010).

In summary, macroalgae is a practical low cost (in terms of input) environmentally friendly solution to help solve the global food shortage. How this can be achieved from a local perspective will be further discussed below.

1.2 Local perspective

From a local perspective some countries are already making progress towards meeting these additional demands from aquaculture. For example, the Netherlands is at the forefront of increasing the productivity of terrestrial species with the world's highest productivity in the agri-food business with regards to production per acre (Nature Jobs, 2012). Now progress is being made towards expanding this productivity in an effective and sustainable manner to its near and offshore waters in the form of aquaculture.

Currently a pilot project in the Oosterschelde (Eastern Scheldt) is already underway with an offshore test site being constructed off the coast of Texel. These pilot projects are part of a European Union initiative known as the MERMAID project which is striving to develop concepts for the next generation of multi-purpose off-shore platforms that incorporate sustainable energy extraction and aquaculture (MERMAID, 2012). The current research is being undertaken as a component of the MERMAID project through an internship with one of the involved partners, Deltares which is a Dutch independent research institute in the field of water, subsurface and infrastructure (Deltares, 2012).

IMTA systems are the ultimate aim for the MERMAID project to incorporate within their multi-purpose off-shore platforms (MERMAID, 2012). However their pilot projects thus far are concentrating only on macroalgal growth, in particular offshore macroalgal growth which will be the focus of this research.

1.3 Offshore macroalgal aquaculture

Traditionally aquaculture is pursued on a land or nearshore basis. However there is growing public and scientific interest in the movement of these aquaculture systems offshore as this will increase the number of suitable sites whilst decreasing conflicts for alternative uses of nearshore areas such as for tourism or recreational fishing (Chavez-Crooker & Obrique-Contreras, 2010 & Klinger & Naylor, 2012). Currently there is no universally recognised definition for 'offshore aquaculture' because of differing environmental conditions found in every location, instead it is generally accepted that it is the movement of farm installations from nearshore sheltered environments to more exposed environments (Troell, 2009).

Currently there are no commercial offshore macroalgal farms. There is only a selection of nearshore experimental studies cultivating a commercially interesting macroalgae (*Saccharina latissima*) which focus on conditions to achieve maximum biomass yield (Peteiro & Freire, 2013; Peteiro & Freire, 2009; Peteiro *et al.*, 2006; Druehl *et al.*, 1988). These experimental sites are located in a variety of hydrodynamic and environmental conditions with some of the sites being in more exposed locations and therefore having conditions moderated by the open ocean and therefore more applicable for this project (Peteiro & Freire, 2013; Druehl *et al.*, 1988).

Although the movement of aquaculture offshore seems advantageous from some perspectives; the economic and biological feasibility of moving and maintaining aquaculture offshore is unknown. The economic feasibility includes the additional costs relating to the technical, logistical and infrastructural requirements of setting up and operating an aquaculture farm in a dynamic offshore environment (Buck & Buchholz, 2004). As the costs are expected to be high for such a venture it makes logical sense to utilise existing or projected offshore constructions (Buck & Buchholz, 2005). The attachment of aquaculture units to rigid platforms could prevent damage or loss of whole aquaculture units and in exchange these units can dampen the waves and thus their impact on the platform (Buck & Buchholz, 2005). An obvious type of offshore platform that could be combined with aquaculture is the many planned offshore wind farms in Europe which is in line with the aims of the MERMAID project (Buck & Buchholz, 2005).

There is little known about the biological feasibility of a macroalgal aquaculture system in an offshore context. Therefore, this study will focus on an assessment of the *biological feasibility* of an offshore aquaculture system in the North Sea.

1.4 Problem definition and research question

In relation to offshore macroalgal farms there are no commercial farms in place and only limited experimental trials. There is a gap in knowledge regarding the economic and biological feasibility of such a venture. This project aims to address part of this knowledge gap by focusing on the biological feasibility of an offshore system in the North Sea by answering the following research question:

Is it biologically feasible to exploit an offshore aquaculture system based on macroalgal farming in the North Sea?

This research question will be answered by the following sub-questions:

1. Which of the selected sites in the North Sea (if any) would be suitable location(s) for an offshore aquaculture system based on macroalgal farms?
2. What factors control the productivity of an offshore aquaculture system at the selected sites based on macroalgal farms in the North Sea?

These questions will be answered by using the generic integrated ecosystem model Delft3D GEM. This model is a primary production model which includes the BLOOM phytoplankton module that simulates algal growth under natural conditions. The model will be adjusted to simulate growth of the seaweed species of interest for commercial purposes. The involved processes and a model description will be discussed in more detail in the methods chapter.

Due to a lack of literature about offshore aquaculture the details relating to the offshore farms, sites and species selected for this project will be selected from literature and from discussions with experts in the field in order to produce the most realistic results possible. These will be discussed further in the next chapter on theoretical background.

2. Theoretical background

The aim of this chapter is to give the reader an overview of the relevant theoretical background for this research, particularly in reference to specific details in the main research question and sub-questions. This will be achieved by providing a description of how the various elements of this research were selected. These elements are the macroalgal species of interest (used for macroalgal farming in the main research question), potential offshore macroalgal farm sites (sub-question one) and determining the controlling and limiting factors for growth (sub-question two).

2.1 Selection of suitable macroalgal species

There are many factors that must be considered when selecting appropriate species for use within an offshore macroalgal system. These factors include the physical characteristics of the seaweed and intended application (Neori *et al.*, 2004; Chynoweth, 2002). For example, if the role is bioremediation then nutrient uptake and storage are important characteristics whereas if the role is value then quality of the tissue is an important factor. Ideally the selected species would be a native species suitable for large-scale commercial production with a high economic value, growth and nutrient uptake rates and therefore high bioremediation potential (Neori *et al.*, 2004; Chynoweth, 2002). Additionally and most importantly the species must have suitable characteristics to allow it to survive in a dynamic offshore environment. These include a high productivity in the prevailing climate, tolerance to a prolonged exposure at high intensities and an anchoring structure suitable for attaching to artificial substrates and fast nutrient uptake (Chynoweth, 2002).

Examples of species encompassing the aforementioned characteristics include *Laminaria digitata* (oarweed) and *Saccharina latissima* (seabelt, formerly *Laminaria saccharina*) which can be collectively referred to by their genus name *Laminarians* (Chynoweth, 2002). Suitability tests to select appropriate species for offshore aquaculture in the North Sea were conducted concluding that *S. latissima* would be a suitable species to culture (Pogoda *et al.*, 2011; Buck & Buchholz, 2004). *S. latissima* also has a flexible stipe which is thought would be advantageous in strong currents and high waves as it is capable of quickly re-orientating and thus becoming aligned with the new direction of current (Buck & Buchholz, 2005). However in an experimental study *L. digitata* was found to be more robust than *S. latissima* to the strong mechanical forces present in the sea (Buck & Buchholz, 2004). *L. digitata*'s robust nature lead an expert in the field to predict it would be the most suitable of the two species to cultivate offshore (Schipper, J., personal communication, 19-03-2013).

Additionally there is already a market for *Laminarians* due to the economic value associated with its chemical content, mostly iodine, alginate, laminaran and mannitol (Druehl, 1998; Hoppe, 1979) and its use as a food source (Saito, 1976). In recent years, many other applications for *Laminarians* have emerged such as animal feed, fertilizers, feedstock for biofuel production, and culture for bioremediation purposes (Bartsch *et al.* 2008; Peteiro & Freire 2013). Therefore *Laminaria digitata* and *Saccharina latissima* will be selected as the two study species within this project. Their physical characteristics and life histories will be discussed further in the next section.

2.1.1 Laminarians

Laminarians are slow growing brown macroalgae which inhabit temperate and polar regions, mostly in the northern hemisphere where it can be intensively grown in the temperate zone. The life history characteristics and optimum conditions for growth of this perennial species will be summarised below.

Laminarians have a prolonged period of growth from late spring until early summer due to utilisation of nutrients stored in late winter and early spring. A reduction in growth rates occurs during the summer when the carbohydrates produced during photosynthesis are stored. Decreased growth rates may also result in the facilitation of epiphyte growth which reduces or eliminates the supply of irradiance, carbon and nitrogen to the surface of the seaweed therefore decreasing productivity (Luning & Pang, 2003). Growth remains low during autumn and increases in mid-winter as the stored carbohydrates act as an energy source allowing for exploitation of the high levels of nutrients available in seawater during winter (Luning & Pang, 2003; Sjutun, 1993).

The optimum depth for *Laminarians* under natural growth occurs at a minimum depth of 5 meters below sea level with the maximum summer growth rate of *S. latissima* was found to occur at a depth of 9 meter (Reith *et al.*, 2005; Buck & Buchholz, 2004; Boden, 1979). However commercial growth requires growth at a depth of 1 m below the surface despite the growth rates at 1 and 3 m being found to be only 40% of the maximum growth rate (Boden, 1979; Schipper, J., personal communication, 19-03-2013; Buck & Buccholz, 2005). It must also be considered that in more turbid conditions the light will not penetrate the water column as deep as in calm conditions (Anthony *et al.*, 2004). The optimum sea water temperatures for growth is 10°C for *L. digitata* and whilst *S. latissima* has the broadest range of optimum temperatures from the genus *Laminaria* of 10-15°C (Reith *et al.*, 2005; Bolton & Luning, 1982; Druehl, 1988). These optimum growth temperatures fall within the average offshore North Sea temperatures of 6-15.5°C (Rijkswaterstaat, 2001).

However it must be considered that in a natural system the conditions are constantly fluctuating due to physical, chemical, environmental and social factors. Thus one or multiple factors may be determining or limiting to the macroalgae growth at certain points. These factors will be further discussed below.

2.2 Controlling factors to macroalgal growth

Macroalgal growth is controlled by a number of factors. These include physical (irradiance, temperature and current), biological (species, type of tissue, nutritional history, competition and predation) and chemical factors (ambient concentration, chemical species and internal nitrogen) (Troell *et al.*, 2003). The most important factors for controlling the growth rate will be discussed below.

2.2.1 Light

The most important factor for the growth of macroalgae growing in natural conditions has been determined as irradiance (Lobban *et al.* 1985; Boden, 1979). Light availability has been described as the most spatially and temporally variable factors (Delebecq *et al.*, 2012). Turbidity can account for up to 80% of the overall variation in benthic irradiance over a year (Anthony *et al.*, 2004) with reductions in seawater clarity reducing the production rate of *Laminaria* species (Delebecq *et al.*, 2012). However within this research, light is not expected to be a controlling factor for growth because commercially produced macroalgae sits near the water surface and therefore competition with suspended matter is eliminated (Los, H., personal communication, 12-6-2013).

2.2.2 Nutrients

The productivity of brown macroalgae in temperate marine environments has typically found to be limited by the supply of inorganic nitrogen (i.e. nitrate and ammonia) (Dugdale, 1967). The seasonal changes in the ambient nitrate (NO_3^-) concentration of sea water was found to be a major factor affecting the growth of populations of *Laminarians* (Davison & Stewart, 1984). Additionally there has been a significant relationship found between the growth rate of *L. digitata* and the availability of nitrogen (Kain, 1989). Therefore nitrogen is considered to be the primary limiting factor in marine waters however phosphorous may limit production in some systems and may also secondarily limit production in combination with nitrogen (Rabalais, 2002).

Nitrogen released into the environment from aquaculture and terrestrial farming has been found to be in the preferred form for seaweed growth which is ammonium (NH_3). Phosphorous from these

farms is generally released as dissolved phosphorous which in turn increases the concentrations of PO_4^{3-} which is in the form most suitable for growth (Troell *et al.*, 2003). Cultivated seaweed grows better in areas where nitrogen and phosphorous are in abundance however the seaweeds requirement for phosphorous are not as sensitive as they are to nitrogen (Fei, 2004). In order to understand how the released nutrients are taken up by the seaweed certain phrases should be explained. *Nutrient reduction efficiency* is the defined average reduction (%) in the nutrient concentration in water whereas *nutrient uptake rate* is defined as the amount of nutrients removed per unit area. Both of these concepts vary depending on the conditions of the system such as depth, light and macroalgal stocking density. High nutrient loads increase uptake rates however there is low efficiency whereas low nutrient loads have a higher efficiency but a lower uptake rate. In consideration of this, the optimal uptake and efficiency rates for an offshore aquaculture system would be produced through the manipulation of the seaweed species, density and harvesting frequency (Troell *et al.*, 2003).

2.2.3 Water Velocity

Water velocity substantially affects the macroalgal production, directly by increasing the availability of nutrients and carbon dioxide and indirectly by influencing most of the factors that determine their growth (Hurd, 2000). In general, the productivity of macrophytes seems to be higher at moderate levels of water velocity in comparison with slower water velocities as it enhances the nutrient uptake (Hurd, 2000; Neushul *et al.*, 1992). Additionally the exposure of high levels of water current or wave exposure is more stressful than beneficial as it often leads to the detachment or breakage of the seaweed (Hurd, 2000). This was found during an experimental study when there was a significant increase in the biomass yield of *S. latissima* at a more exposed site than a sheltered site on the N.W. coast of Spain (Peteiro & Freire, 2013). However other studies have shown that differences in water velocity have not altered the growth and production of *S. latissima* (Hurd, 2000).

2.2.4 Competition

Competition with one or more species can be a controlling factor for growth however the occurrence of multiple species in a natural system can also have other implications (Troell *et al.*, 2003). Polycultures in natural systems can have an increased total biomass that is higher than the best performing monocultures (Stachowicz *et al.*, 2008). This can be explained by the species within a polyculture being complementary in their use of different nitrogen forms. Therefore an increased

uptake of nitrate and ammonium is observed in comparison to the monoculture average is observed (Bracken & Stachowicz, 2006).

The controlling factors that have been selected to focus on within this project are nitrogen and phosphorous which are also the main limiting factors when considering seaweed growth (Troell *et al.*, 2003). Additionally temperature, water velocity and competition will be considered. As the controlling factors have been determined, the selection of the sites at which these will be studied will be described below.

2.3 Selection of potential farm sites

The nine potential seaweed farm sites which have been selected are situated in a range of locations (figure 3, page) within a variety of environmental conditions (table 1). These sites were selected due to a variety of reasons such as high nutrient concentrations and sites that have been already established as seaweed pilot projects or are in planning or have been proposed. The reason for the selection of each site will be discussed below followed by a short site description.

Table 1: Highlighting the environmental and hydrodynamic conditions at each of the selected sites. The seawater temperature, nutrient concentrations and current are the mean annual values.

Site	Depth (m)	Seawater temperature (°C)	Nitrate concentration (mg N/l)	Ammonium concentration (mg N/l)	Phosphate concentration (mg P/l)	Current velocity (m/s)
SW001	11	11.53	0.167	0.029	0.017	0.43
GR006	14	11.55	0.511	0.049	0.022	0.45
NW002	14	12.09	0.351	0.055	0.022	0.31
Texel	25	11.21	0.120	0.022	0.011	0.5
SW070	38	10.62	0.048	0.013	0.010	0.77
TS235	33	10.13	0.021	0.008	0.018	0.14
Borssele	26	11.25	0.047	0.015	0.009	0.74
Gemini	34	10.83	0.059	0.018	0.011	0.38
TS135	48	10.58	0.033	0.009	0.019	0.16

The sites which are also monitoring locations have abbreviated names which consist of the first two letters referring to a coastal location with the following numbers relating to the number of kilometres from the shore that the site is. Site SW001 sits 1 km from the mouth of the Eastern Scheldt and was selected as it is near to a current seaweed test site in the Eastern Scheldt

(Brandenburg, W., personal communication, 08-02-2013). The Texel site is 10 km off the island of Texel at the location where a pilot seaweed farm is being constructed as part of the MERMAID project (Schipper, J., personal communication, 19-03-2013). The Gemini site is located 70 km offshore from the island of Schiermonnikoog and the Borssele site is located 36 km offshore from the coast of Zeeland on the border with Belgium. The Borssele site is the site with the lowest modelled phosphate concentration in the reference run that was used as a starting point for the model (table 1). The Gemini and Borssele sites are planned offshore wind parks combining wind energy and aquaculture in multi-functional offshore platforms; the Gemini site is also a part of the MERMAID initiative (Schouten, J., personal communication, 07-06-2013; MERMAID, 2013). The SW070 is located 70 km offshore from the Eastern Scheldt whilst sites TS135 and TS235 are 135 km and 235 km respectively offshore from the island of Terschelling. SW070, TS135 and TS235 have been chosen because they are monitoring locations which represent different characteristic offshore areas in the North Sea (Schipper, J., personal communication, 19-03-2013 & Troost, T., personal communication, 02-03-2013). SW070 site has the fastest modelled current velocity whilst TS135 has the lowest modelled ammonium concentration and TS235 has the lowest modelled nitrate concentration. Finally NW002 is 2 km offshore from Noordwijk and GR006 is 6 km offshore from Goeree (Overflakkee). These sites were selected because of their mid and high nutrient concentrations with NW002 having the highest modelled ammonium concentration and GR006 having the highest modelled nitrate concentration and both sites having the highest phosphate concentration. The NW002 site also has the highest modelled sea water temperature. The hydrodynamic and environmental characteristics of each site are summarised in the table 1. This chapter has clarified some important elements required for answering the research question and sub questions. In the following chapter the method utilised will be described.

3. Materials & Methods

This chapter aims to provide the reader with an overview of the method used in this research to answer the research question. This will be achieved by providing a description of the model used (Delft 3D GEM), the relevant parameters and assumptions made within the model, the model adaptations and the type of analysis used on model output. To be able to implement seaweed culture in the Delft3D GEM model, a literature and expert survey was conducted.

3.1 The Delft3D GEM model

The biogeochemical transport model Delft3D GEM is a generic ecological modelling instrument that can be applied to any water system (fresh, transitional or coastal water). The model can calculate nutrient concentrations (nitrate, ammonium, phosphate, silica), dissolved oxygen and salinity, phytoplankton (diatoms, flagellates, dinoflagellates and *Phaeocystis*), and detritus. The Delft3D-GEM application for the North Sea is described in Blauw *et al.* (2009) and Los *et al.* (2008). Over the past few years, Delft3D-GEM has been thoroughly validated for the North Sea (Los and Wijsman, 2007; Los *et al.*, 2008; Los and Blaas, 2010). Also, an inter-model comparison showed that the model performance is in line with that of other biogeochemical flux models, with respect to both its behaviour under default conditions and its response to changes (Lenhart *et al.*, 2010). The model includes phytoplankton processes (BLOOM), mineralization in water and sediment, (de)nitrification, reaeration, sedimentation, resuspension and burial of phytoplankton and particulate organic matter; and extinction of light by suspended solids, organic matter, phytoplankton, and humic substances. The most relevant processes for this study, namely BLOOM are described below.

The phytoplankton module (BLOOM) is a module that simulates primary production, respiration and mortality of phytoplankton. Growth is calculated as a function of nutrients, light conditions and mortality. BLOOM can be used as part of an integrated modelling system whereby there is direct, internal communication between BLOOM and other modules (such as hydrodynamic and morphology).

Under default conditions in the North Sea model the total algal biomass generally consists of four defined phytoplankton groups, diatoms, flagellates, dinoflagellates and *Phaeocystis* with each having different resource requirements and ecological properties. Within each group, there are three phenotypes defined which can reflect adaptation to changing environmental conditions: energy-limited (E), nitrogen-limited (N) and phosphorous-limited (P) types (Los, 2009). The phenotypes reflect the state of the species and can change rapidly (with each cell division) if conditions change.

Using an optimization algorithm, the limiting resource is selected with the best set of phenotypes at each time step under the prevailing environmental conditions and species composition. Species composition on the other hand can only change due to growth and mortality. The time steps used in BLOOM for the ecological processes (i.e. cell division) are 24 hours (Los, 2009). The characteristics of the phytoplankton species are based on data collected over the years (Blauw *et al.*, 2009). For each type, there is a different conversion factor from carbon to chl *a* concentration (Los and Wijsman, 2007). The relevant nutrient changing processes in GEM are for nitrogen: nitrification, denitrification, uptake by phytoplankton and mineralization/respiration and for phosphorus phytoplankton uptake and mineralization/respiration (Blauw *et al.*, 2009).

Delft3D-GEM and BLOOM will be used as a basis for the alterations necessary to answer the sub-questions. Initially a stand-alone version of the BLOOM module was used as this has limited inputs in comparison to the 2D/3D models and only considers one location rather than the whole of the North Sea. Therefore the model runs are completed in a shorter time allowing for a faster understanding of the importance of the different parameters and the associated differences when parameters are altered. This was a useful stepping stone towards using the 2D model as they have comparable input files. Unfortunately the transition to the 3D model was considered too time consuming because of the increased time required for the 3D model runs and the limited time frame of this research. However it has been shown that although the 2D model is not as complex as the 3D that the output is accurate and credible and therefore suitable for applications such as this research (Los and Blaas, 2010.)

3.1.1 Schematization, hydrodynamics and model set-up

The modelling grid used in GEM for the North Sea is called the ZUNO-grid. This grid covers the southern North Sea and, formally, also the eastern English Channel, but in this research its domain will only be referred to as the former. The model grid consists of 4350 grid cells in the horizontal. The grid is variable, with a resolution ranging from 1x1 km at the continental coast to 20 by 20 km at the north-western boundary. The model set-up was initially chosen as 2D, because the North Sea is generally well mixed and depth effects are limited. The setup is similar to the model setup in Troost *et al.* (submitted). The model has a generic character, with a hydrodynamics model with an average yearly water transport, average silt concentrations, average temperature, average boundary conditions and a generic spring-neap cycle. Nutrient input was taken from 2007, the most recent year in the model of Troost *et al.* (submitted). The necessary adjustments to this setup to answer the research questions are described below.

3.2 Literature Review & Database

As *L. digitata* and *S. latissima* were selected as the species most suitable for survival in offshore North Sea conditions, a literature review was conducted on these species. Relevant characteristics and parameters for each species were collected for use as an input into the model and for the identification of realistic parameter ranges for each species. These parameters were collected for three categories: specific maximum growth and mortality rates, stoichiometry and chlorophyll a to carbon ratios. A description of the relevant model parameters for this study are summarised in table 2 a and b. Appropriate unit conversions were made and the output placed in a database. In order for these conversions to occur some assumptions had to be made. These will be summarised in the following section.

3.2.1 Assumptions

As there are no offshore macroalgal farms in existence, data availability is limited to monotrophic nearshore aquaculture systems and experiments and measurements conducted under natural and laboratory conditions. Therefore it must be considered that this research is assuming that macroalgae grown in commercial conditions offshore will respond in the same way to nearshore conditions. Whilst converting these nearshore values to the model unit some assumptions had to be made. There are three types (light, nitrogen and phosphorus-limited) within the model for each species that require allocated parameter values. It was therefore assumed that the three types would be allocated the same value unless there was sufficient reason to assume otherwise. Assumptions made in each of the parameter categories will be described below. Refer to tables 5 - 8 in the results section for the completed databases.

Specific growth and mortality rates - The reference temperature for model input is 0°C so it was of particular relevance that the sea water temperature was taken into account especially when considering specific growth rates. Some papers did not measure this variable and so the average sea water temperatures for an area during a particular time period were assumed using a relevant literature source (Government Laboratory, 2007; Wang *et al.*, 2007 & Jordan *et al.*, 1993). This assumption was also relevant for the specific mortality rate. An average of the literature values for specific growth rate over different temperatures was collected for each species to implement into the model (table 5). One paper was found per species in literature for the specific mortality rate (Gerard and Du Bois, 1988 & Chapman, 1984). Gerard and Du Bois (1988) studied the specific mortality for *saccharina* for two locations therefore an average was implemented into the model (table 6).

Chlorophyll a to carbon ratio - Only one study (Gerard, 1988) had all of the required variables to make the unit conversion to the model unit (g Chl g C⁻¹). These values were carbon content, dry content and weight to area ratio so this paper was chosen as a reference paper. The reference paper values were then used to convert the remaining values from literature into the model unit. Although these values were for *S. latissima* it was assumed that these values for conversion would also be similar for *L. digitata*. Light limited environments (E-type) are often associated with a higher chlorophyll a to carbon ratio (Gerard, 1988). As there were chlorophyll a to carbon values recorded for two locations for *L. digitata* the higher value was chosen for the light-limited conditions (E) and the lower value for the nutrient-limited conditions (N & P) (Delebecq, 2012). The Gerard & Du Bois (1988) values were chosen to represent *S. latissima* as there were also values for 2 locations which could replicate the difference seen in chlorophyll a concentrations in light limiting conditions (table 7).

Stoichiometry – No additional assumptions were required for the stoichiometry conversions. Connolly and Drew (1984) studied the stoichiometry of *L. digitata* and *S. latissima* at sites near and far (18 km) from a sewer over the course of one year. Nitrogen limiting conditions were found at the site 18 km away from the sewer hence this value relates to the nitrogen-limited type (N) in the model. It was assumed that these values would also reflect the phosphorous-limited type (P) as no data was available for such conditions. The near sewer measurements were associated with the light-limited type (E) (table 8).

The additional relevant parameters (in table 2a) including species-specific extinction coefficient and dry matter to carbon ratio which could not be found in literature were assumed to be same as a macroalgae species (*Ulva lactuca*). This species which has very different life history characteristics to *L. digitata* and *S. latissima* was inserted into the model growing under natural conditions during a previous project (DeGroot, 1992; Los 1999; Spiteri & Nolte, 2010). The final parameters used to implement into the model for each species are summarised in tables 9 & 10.

3.3 Model adaptations

Various adaptations were made to the model so that the research question could be answered. This included the implementation of the database values, insertion of the two seaweed species and potential offshore farm sites. Tables 2 a and b summarise the relevant model parameters, processes and terminology required for these alterations.

Table 2 a: description of relevant model parameters.

Parameter (abbreviation in model)	Unit	Description
DMCF	g DW g C^{-1}	Dry matter to carbon ratio.
NCR	g N g C^{-1}	Nitrogen to carbon ratio.
PCR	g P g C^{-1}	Phosphorous to carbon ratio.
SCR	g Si g C^{-1}	Silicon to carbon ratio.
ExtVL	$\text{m}^2 \text{g C}^{-1}$	Species specific extinction coefficient – Contribution of algae to light attenuation, for example by self-shading. The relationship between the growth rate and light intensity is determined by the frm curve (see below).
ChlaC	g Chl g C^{-1}	Chlorophyll a to carbon ratio.
PPMax	d^{-1}	Primary production - the rate at which a species captures and stores chemical energy as biomass at 0°C during a time step, i.e. the simple growth rate.
TcPMx	$^\circ\text{C}$	Temperature coefficient (dependency) for primary production.
TFPMx	-	Temperature curve for growth (0=linear, 1=exponential).
Mort0	d^{-1}	Specific mortality rate at 0°C .
TcMrt	-	Temperature coefficient (dependency) for mortality.
MResp	d^{-1}	Specific maintenance respiration rate at 0°C .
TcRsp	-	Temperature coefficient (dependency) for maintenance respiration.
Frm	-	Light response curve: a curve which is formulated from a table of growth efficiencies at different light intensities.

Table 2 b: description of relevant model processes and terminology.

Process/terminology (abbreviation in model)	Description
Inactive	An inactive substance is part of/attached to a segment and not subject to horizontal and vertical dispersion in the water column.
Active	An active substance is part/within the water column and is subject to horizontal and vertical dispersion, including transport between segments.
Ulvafix	The process of suspending a macroalgae species in the water column which links inactive and active parts of a macroalgae species.
SDmix	Indicates the position of the macroalgae in the water column.
Salinity dependent mortality rate	The rate at which an algae species dies at the prevailing salinity levels.

The macroalgal species *Ulva* was added into the model growing in its natural conditions on the sea floor (DeGroot, 1992; Los 1999; Spiteri & Nolte, 2010). In the model this is referred to as an inactive substance because it is attached to the sea floor and therefore not subject to vertical dispersion in the water column. However in this research *L. digitata* and *S. latissima* were added growing under commercial conditions. These species were implemented as active species because they will be able to vertically disperse within the water column (table 2 b). A process referred to as ‘Ulvafix’ was used to suspend the macroalgae in the water column, the use of this process allows an inactive substance to become active. A separate process known as ‘SDmix’ indicates the position of the macroalgae

growing in the water column (table 2 b). A value of 1.0 indicates that the species is evenly mixed throughout the water column whilst a value of 0.08 reflects that the species is mixed throughout the top 8% of the water column. Ulvafix and SDmix can be used simultaneously to restrict the macroalgae to grow within the top $1 \text{ m} \pm 0.20\text{m}$ of the water column to reflect commercial conditions (Schipper, J., personal communication, 19-03-2013; Buck & Buccholz, 2005). The latter was achieved by grouping sites with similar depths together and allocating one SDmix value per group (table 3). The model can only have one SDmix value for each species at a time therefore separate model runs were conducted for each SDmix group.

The only BLOOM parameter that allows for spatial variation is the salinity dependent mortality rate. To have the macroalgae exclusively growing at the selected sites in the North Sea this parameter was used. In all non-selected sites, the macroalgae were assigned very high mortality rates at the prevailing salinity levels. The light response curve shows the growth efficiencies of each species at different light intensities. These were constructed from literature values for each species using a program called Blefpro and implemented into the model (Han & Kain, 1996 & Fortes & Luning, 1980). As initial conditions, the outcome of a model run for each scenario was used, where the macroalgae concentrations were set manually to 0 again to simulate harvesting at the end of year. Each species of macroalgae was initially implemented alongside the four phytoplankton species, this allowed for observation of a macroalgae monoculture. Due to the maximum capacity for 5 species in the model, *phaeocystis* was removed so that both species could be implemented into the model together, allowing observation of a macroalgae polyculture.

Table 3: Highlighting the grouping of sites with similar depths.

Site	Depth (m)	SDmix	Depth of macroalgae growth in model (m)
SW001	11	0.08	0.88
NW002	14	0.08	1.12
R4GR006	14	0.08	1.12
Texel	25	0.04	1
TS235	33	0.03	0.99
Gemini	34	0.03	1.02
Borssele	36	0.03	1.08
SW070	38	0.03	1.14
TS135	48	0.02	0.96

Calibration of the biomass was conducted for each of the parameters to determine which (if any) the model was most sensitive to; the outcome was that maintenance respiration was the most sensitive parameter. This parameter was altered in order to reproduce realistic macroalgal biomass outputs from the model that reflected values found in literature (Peteiro & Freire, 2013; Peteiro & Freire, 2009 and Peteiro *et al.*, 2006) and from an expert in the field (Schipper, J., personal communication, 5-3-2013). These values are in the range for commercial growth between 50 g C m⁻² and 70 g C m⁻². A numerical optimisation program (solver) was used to determine temperature dependencies by using non-linear model fitting to the temperature-growth curves from literature. However after implementing the optimum temperature dependencies unrealistically low model outputs were recorded. These values were considerably outside of the range of values found in literature so it was decided to assume that the temperature dependencies were also the same as *Ulva lactuca*. After all of these changes were implemented the model output was validated by a seaweed modelling expert as there are no suitable literature values available for validation (Birkeland, M. J., personal communication, 25-6-2013).

3.3.1 Results analysis

This section contains a brief description of the analysis that was conducted on the results including the description of any relevant terminology required to understand the results. The model output was initially analysed with regards to the maximum biomass produced for every site in each scenario. Each site was ranked from the largest maximum biomass produced to the smallest. Analysis was conducted on each of the locations for each of the scenarios in relation to the total nitrogen and total phosphorous concentrations in the seawater and within the macroalgae. Total nitrogen refers to the nitrogen contained in detritus, phytoplankton, seaweed and nutrients (NH₄ and NO₃) whilst total phosphorous refers to the phosphorous contained in detritus, phytoplankton, seaweed and PO₄.

A program called ecoplot was used to analyse the limitations at each site. The limitations considered are energy, nitrogen, phosphorous, silicon, growth and mortality limitations. Growth and mortality limitations refer to the upper and lower limits to growth and mortality. Ecoplot only allows for analysis of the limitations in relation to the total number of algae within the model. In this case, that includes both the macroalgae and the phytoplankton. All of the sites were studied in relation to the biomass produced, mean annual seawater temperatures, mean annual ammonium, phosphate and nitrate concentrations and the mean current velocity to see if there were any apparent trends.

Additionally the development of dissolved inorganic nitrogen and phosphorous concentrations at each site were analysed.

4. Results

The aim of this chapter is to summarise the results found during this research. To determine if an offshore aquaculture system in the North Sea is biologically feasible a two-step process was implemented. Initially a literature review was conducted to establish a database from which values could be implemented into the model. Finally the values were implemented into the model. Therefore the results will be conveyed in two sections: database and model to reflect this process. The results acquired will be described in this chapter and discussed in the following chapter.

4.1 Database

A literature review was conducted to establish a range of realistic parameter settings for use within the model for each of the study species. The results from each category within the database will be briefly described followed by the parameters selected for implementation into the model.

The maximum specific growth rates of *L. digitata* were in the range of 0.006 d^{-1} to 0.12 d^{-1} whilst for *S. latissima* they were in the range of 0.011 d^{-1} to 0.18 d^{-1} (table 4). The average value of maximum specific growth rate for each species was calculated for all of the literature values found for each species. This average value was the specific growth rate that was implemented into the model (table 8 & 9). The specific mortality rate was 0.00254 d^{-1} for *L. digitata* found to be 0.00152 d^{-1} for *S. latissima* (see table 5). One specific mortality rate was found in literature for each species so this was these were the values selected (table 5).

There was a range of values found for stoichiometry for both species as they were measured along a gradient from an area beside a sewer to an area 18 km from the sewer (Connolly & Drew, 1984). The phosphorous concentrations for *L. digitata* ranged from 0.0016 g P/g C to 0.01 g P/g C whilst the values for *S. latissima* ranged between 0.0058 g P/g C to 0.0125 g P/g C . The range of nitrogen concentrations found for *L. digitata* ranged between $0.00016 \text{ g N / g C}$ to $0.00017 \text{ g N / g C}$ whilst the value for *S. latissima* for both near and far from the sewer was 0.0021 g N/g C (see table 6). The chlorophyll a to carbon ratio for *L. digitata* were found to be in the range of $0.002 \text{ g Chl g C}^{-1}$ to $0.006 \text{ g Chl g C}^{-1}$ whilst the range for *S. latissima* was between $0.007 \text{ g Chl g C}^{-1}$ and $0.04 \text{ g Chl g C}^{-1}$ (see table 7). The specific stoichiometry values and chlorophyll a to carbon ratios selected for implementation into the model are discussed in chapter 3.2.1 (page 17 & 18).

Calibration of the model parameters allowed for observation of the sensitivity of each parameter to change. The parameter that was most sensitive was found to respiration. Figure 2 highlights the

observed differences in biomass production in relation to a variety of respiration rates. The respiration rate of 0.002 d⁻¹ was chosen for implementation.

Table 4: Specific growth rate (d⁻¹) of *L. digitata* and *S. latissima* over a range of temperatures.

Reference	Maximum (d ⁻¹)	Minimum (d ⁻¹)	Notes
Creed (1998)	0.012 (7.1°C)	0.0002 (13.6°C)	<ul style="list-style-type: none"> No reference to temperatures so assumptions made using government laboratory (2007).
Pedersen <i>et al.</i> (2010)	0.006 (18°C)	Not measured	-
Bolton & Luning (1982)	0.10 (10°C)	0.045 (20°C)	Location Nova Scotia (Canada) Helgoland (Germany) Helgoland (Germany) Brittany (France) Isle of Man (UK) Espegrend (Norway)
	0.12 (10°C)	0.07 at 20°C	
	0.15 (10°C)	0.04 (0°C)	
	0.15 (10°C)	0.06 (0°C)	
	0.18 (16°C)	0.07 (0°C)	
	0.17 (11°C)	0.04 (0°C)	
Gerard & Bois (1988)	0.048 (7°C) (NY)	0.01(20°C) (NY)	<ul style="list-style-type: none"> New York (NY) Maine (ME)
	0.039 (7°C) (ME)	0.03 (18°C) (ME)	
Gerard (1988)	0.11 (13°C) (Turbid habitat)	0.055 (13°C) (deep habitat)	<ul style="list-style-type: none"> Water temperature range 8-18°C (assumed average temperature of 13°C).
Fortes & Luning (1980)	0.092 (15°C)	0.022 (0°C)	<ul style="list-style-type: none"> Sea water temperatures assumed from Wang <i>et al.</i>, 2007.
Broch & Slagstad (2012)	0.011 (13°C)	0.005 (5°C)	-

Table 5: Specific mortality rate (d⁻¹) for *L. digitata* and *S. latissima* at a range of temperatures.

Reference	Maximum (d ⁻¹)	Minimum (d ⁻¹)	Notes
Gerard & Du Bois (1988)	0.00057	0.002479	<ul style="list-style-type: none"> Average of values = 0.00152. Seawater temperature 3°C.
Chapman (1984)	0.00254	Not measured	<ul style="list-style-type: none"> At 4°C (assumed from Jordan <i>et al.</i> (1993)

Table 6: Stoichiometry values (g P / g C and g N / g C) for *L. digitata* and *S. latissima*.

Reference	Unit	Stoichiometry	Location	Notes
Connolly & Drew (1984)	(g P / g C)	0.00010	Near the sewer	<ul style="list-style-type: none"> N limited conditions occur 18km from sewer in summer. Assuming C-content from Gerard (1988)
		0.00006		
		0.00002	18km from the sewer	
		0.00001		
	(g N / g C)	0.00016	Near the sewer	
		0.00021		
0.00017		18km from the sewer		
		0.00021		

Table 7: Chlorophyll a to carbon ratios (g Chl g C⁻¹) for *L. digitata* and *S. latissima* over a range of temperatures.

Reference	Maximum (g Chl g C ⁻¹)	Minimum (g Chl g C ⁻¹)	Notes	
Delebecq (2012)	0.00328 (16.7°C)	0.00217 (13.3 °C)	Roscoff, France	<ul style="list-style-type: none"> Assuming C-content, dry content & weight : area ratio from Gerard (88) Additional recorded values for Roscoff: 0.00232 (10.7°C) and 0.00287 (12.7°C). Average of all Roscoff values: 0.00266 Additional recorded values for Wissant: 0.00476 (15.0°C) and 0.00693 (19.8°C). Average of all Wissant values: 0.00600
	0.00780 (13.3 °C)	0.00450 (6.7 °C)	Wissant, UK	
Davison <i>et al.</i> (1991)	0.03651 (15°C)	0.01141 (5°C)	<ul style="list-style-type: none"> Assuming C-content, dry content & weight : area ratio from Gerard (88) 	
Gerard (1988)	0.0434181 (Turbid)	0.0155458 (Deep)	<ul style="list-style-type: none"> Water temperature range 8-18 °C (assumed average temperature of 13°C) 	
Gerard & Bois (1988)	0.02946 (20°C acclimatised for one week)	0.00985 (8°C)	New York, USA	<ul style="list-style-type: none"> Additional recorded values for New York: 0.02101 (18°C) and 0.02306 (20°C acclimatised for three weeks). Average of New York values: 0.02084. Additional recorded values for Maine: 0.00682 (8°C) Average of values: 0.00792
	0.01107 (18°C)	0.00588 (20°C acclimatised for one week)	Maine, USA	
Heralt <i>et al.</i> (1997)	0.03498 (5°C)	-		

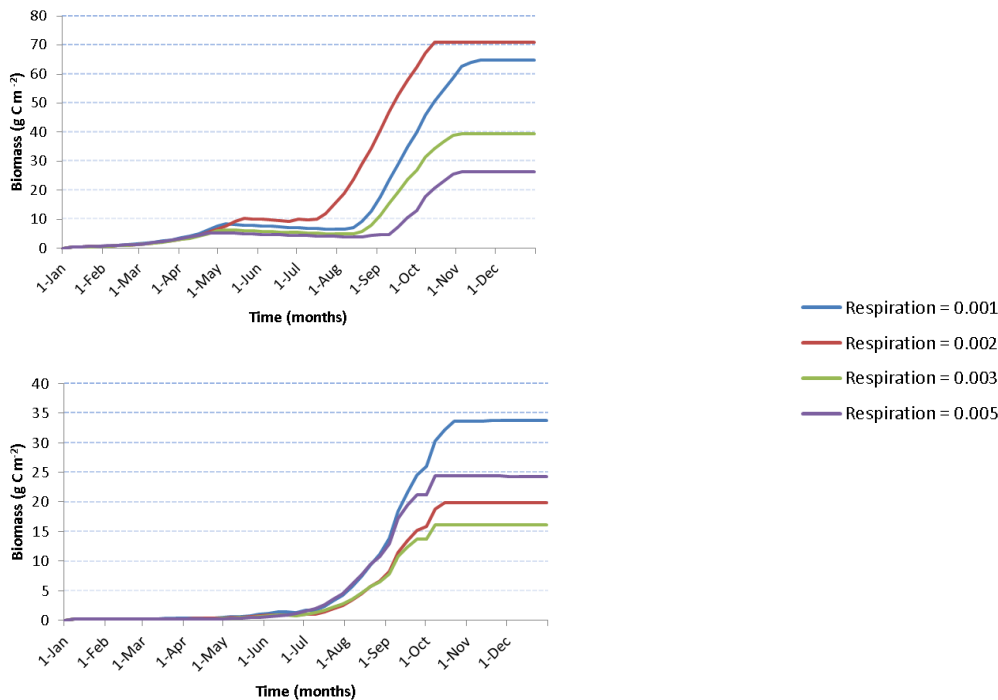


Figure 1: Biomass development (g C m⁻²) over the course of 2007 for *L. digitata* in relation to four respiration rates (d⁻¹).

4.1.1 Parameters implemented into model

The parameters selected from the database for implementation into the model have been summarised in table 8 & 9. Figure 3 shows the database values for specific growth rate in relation to the specific growth rate as calculated by the model for each species. When the average net growth rate for each of the species is calculated and compared, their growth rates at 0 °C are similar and both species growth rates reach an optimum with increasing temperature and then decrease. The optimum range for *L. digitata* is between 0 °C and 9 °C whilst the optimum for *S. latissima* is at 11°C.

Table 8: Summary of parameters and values used within the model for *L. digitata*.

Parameter (model abbreviation)	Value (per type)			Unit	Reference
	E	N	P		
Dry matter to carbon ratio (DMCF)	3.3	3.3	3.3	g DW g C ⁻¹	Suspended Ulva (Spiteri & Nolte, 2010)
Nitrogen to carbon ratio (NCR)	0.1590	0.1621	0.1621	g N/g C ⁻¹	Connolly & Drew (1984)
Phosphorous to carbon ratio (PCR)	0.0998	0.0156	0.0156	g P/g C ⁻¹	Connolly & Drew (1984)
Silicon to carbon ratio (SCR)	0.0	0.0	0.0	g Si/g C ⁻¹	Connolly & Drew (1984)
Species specific extinction coefficient (ExtVL)	0.248	0.248	0.248	mg m ²	Suspended Ulva (Spiteri & Nolte, 2010)
Chlorophyll a to carbon ratio (ChlaC)	0.600E-2	0.266E-2	0.266E-2	g Chl g C ⁻¹	Delebecq (2012)
Primary production at 0°C (PP _{max})	0.725E-1	0.725E-1	0.725E-1	d ⁻¹	Average value from Creed (1998), Bolton & Luning (1982) & Pedersen <i>et al.</i> , (2010).
Temperature coefficient for primary production (TCP _{max})	1.070	1.080	1.080	°C	Suspended Ulva (Spiteri & Nolte, 2010)
Temperature curve for growth; 0=linear & 1=exponential (TFP _{max})	1.0	1.0	1.0	-	Suspended Ulva (Spiteri & Nolte, 2010)
Specific mortality rate at 0°C (Mort0)	0.254E-2	0.254E-2	0.254E-2	d ⁻¹	Chapman (1984)
Temperature coefficient for mortality (TCMrt)	-25.0	-25.0	-25.0	-	Suspended Ulva (Spiteri & Nolte, 2010)
Specific maintenance respiration at 0°C (MResp)	0.2E-1	0.2E-1	0.2E-1	d ⁻¹	Calibrated within this research.
Temperature coefficient for maintenance respiration (TCRS)	1.066	1.066	1.066	-	Suspended Ulva (Spiteri & Nolte, 2010)
Light efficiency curve (frm)	-	-	-	-	Han & Kain (1996)

Table 9: Summary of parameters and values used within the model for *S. latissima*.

Parameter (model abbreviation)	Values (per type)			Unit	Reference
	E	N	P		
Dry matter to carbon ratio (DMCF)	3.3	3.3	3.3	g DW g C ⁻¹	Suspended Ulva (Spiteri & Nolte, 2010)
Nitrogen to carbon ratio (NCR)	0.2027	0.1996	0.1996	g N/g C ⁻¹	Connolly & Drew (1984)
Phosphorous to carbon ratio (PCR)	0.0561	0.0125	0.0125	g P/g C ⁻¹	Connolly & Drew (1984)
Silicon to carbon ratio (SCR)	0.0	0.0	0.0	g Si/g C ⁻¹	Connolly & Drew (1984)
Species specific extinction coefficient (ExtVL)	0.248	0.248	0.248	mg m ²	Suspended Ulva (Spiteri & Nolte, 2010)
Chlorophyll a to carbon ratio (ChlaC)	0.2084E-1	0.792E-2	0.792E-2	g Chl g C ⁻¹	Gerard & Du Bois (1988)
Primary production at 0°C (PP _{max})	0.53E-1	0.53E-1	0.53E-1	d ⁻¹	Average value from Gerard & Du Bois (1988), Bolton & Luning (1982), Broch & Slagstad (2012) & Gerard (1988)
Temperature coefficient for primary production (TCP _{max})	1.070	1.080	1.080	°C	Suspended Ulva (Spiteri & Nolte, 2010)
Temperature curve for growth; 0=linear & 1=exponential (TFP _{max})	1.0	1.0	1.0	-	Suspended Ulva (Spiteri & Nolte, 2010)
Specific mortality rate at 0°C (Mort0)	0.152E-2	0.152E-2	0.152E-2	d ⁻¹	Gerard & Du Bois (1988)
Temperature coefficient for mortality (TCMrt)	-25.0	-25.0	-25.0	-	Suspended Ulva (Spiteri & Nolte, 2010)
Specific maintenance respiration at 0°C (MResp)	0.2E-1	0.2E-1	0.2E-1	d ⁻¹	Calibrated within this research.
Temperature coefficient for maintenance respiration (TCRS)	1.066	1.066	1.066	-	Suspended Ulva (Spiteri & Nolte, 2010)
Light efficiency curve (frm)	-	-	-	-	Fortes & Luning (1980)

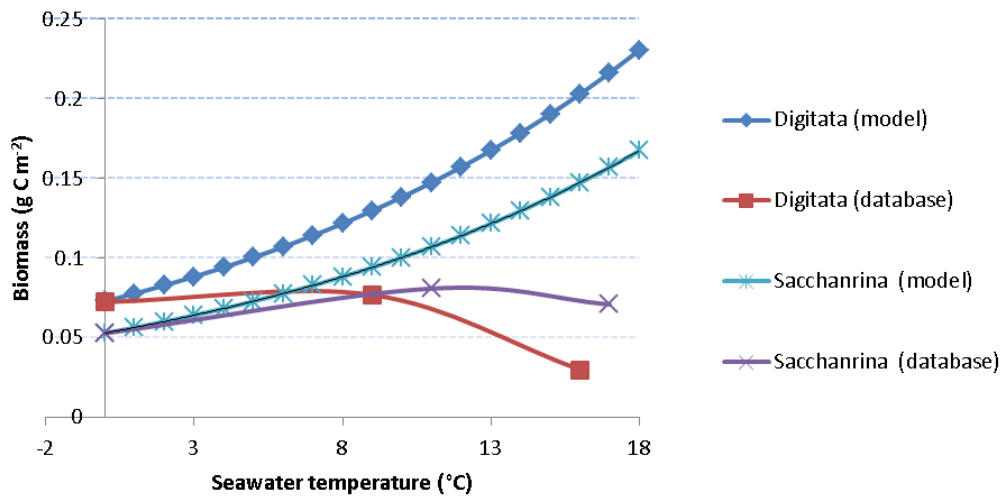


Figure 2: Average net growth rates for *L. digitata* and *S. latissima* over a range of temperatures as calculated in the database and in the model.

4.2 Model

4.2.1 Biomass production

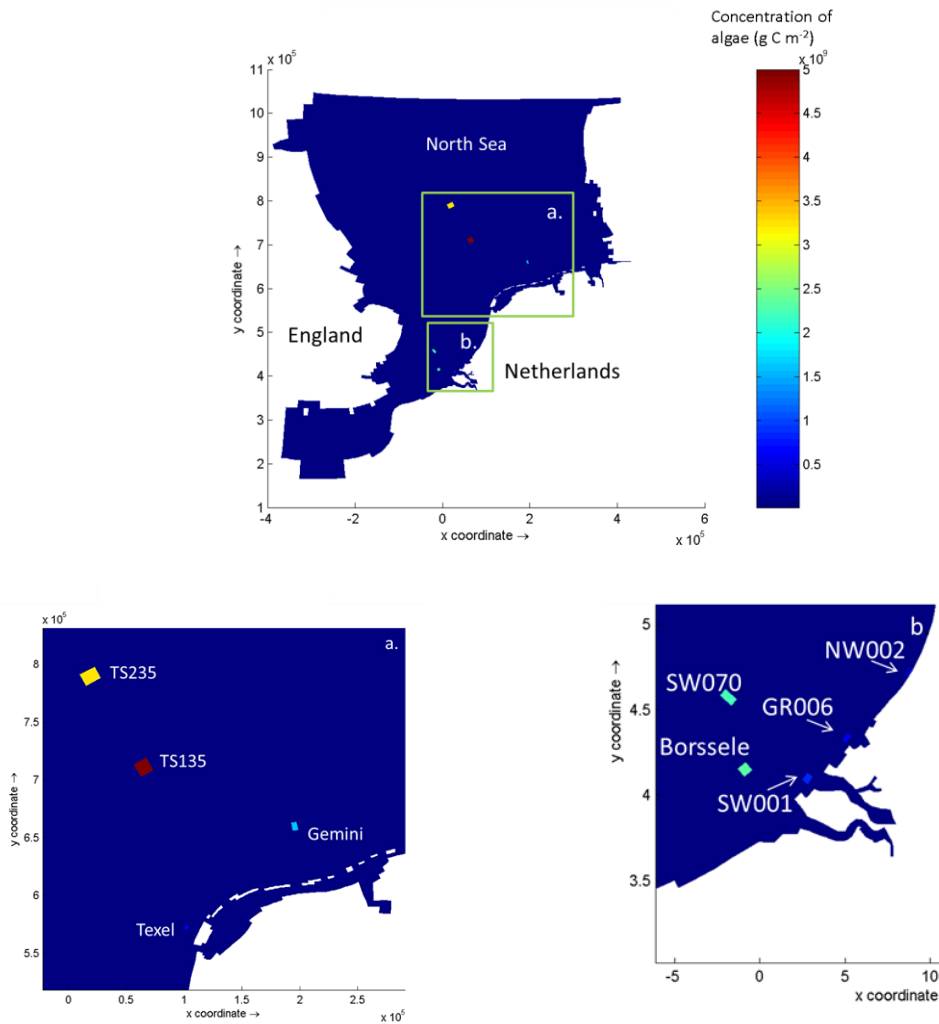


Figure 3: The model domain with macroalgae growing at the sites.

The two species, *L. digitata* and *S. latissima*, were added into the model both within a monoculture and a polyculture to observe the differences in the behaviour of each of these species in offshore North Sea conditions. Figure 3 shows macroalgae growing in some of the potential sites. The maximum biomass produced for *L. digitata* and *S. latissima* at each site in the three scenarios is summarised in table 10. The range of maximum biomass was between 13 g C m⁻² and 72 g C m⁻². In general it was observed that when grown separately *L. digitata* produces a larger biomass than *S. latissima* at all of the sites (table 10). More biomass was produced in the polyculture scenario than was produced in either of the monocultures.

To establish how productive each of the sites was, they were ranked according to maximum biomass produced (see table 11). It was found that the order of ranking in terms of maximum biomass produced for the scenarios with *L. digitata* growing in a monoculture and a polyculture was the same. The order of ranking for the scenarios where *S. latissima* was grown in a monoculture had five of the nine sites at the same rank as the other scenarios. The largest biomass produced for both the scenario growing *L. digitata* in a monoculture and in a polyculture was found at the Borssele site with biomasses of 72.10 g C m⁻² and 71.72 g C m⁻² respectively. The Texel site was ranked second and the Gemini site third. Whereas for the scenario growing *S. latissima* in a monoculture Texel was the site ranked first with 58.66 g C m⁻² biomass with Borssele ranked second and Gemini third (see table 11).

Table 10: Maximum biomass produced (g C m⁻²) for *L. digitata* and *S. latissima* for different scenarios at all of the sites modelled.

Site	Maximum biomass (g C m ⁻²)						
	<i>L. digitata</i> (monoculture)	<i>S. latissima</i> (monoculture)	<i>L. digitata</i> & <i>S. latissima</i> (polyculture)				
			<i>L. digitata</i>	<i>S. latissima</i>	Total (polyculture)	% <i>L.</i> <i>digitata</i>	% <i>S.</i> <i>latissima</i>
SW001	42.54	32.07	31.22	16.02	47.24	66	34
GR006	49.58	33.73	35.78	19.10	54.88	65	35
NW002	19.80	13.22	17.24	9.90	27.14	64	36
Texel	67.43	58.66	41.85	24.01	65.86	64	36
SW070	61.61	48.08	39.55	22.33	61.88	64	36
TS235	34.29	27.17	31.71	13.22	44.93	71	29
Borssele	72.10	48.82	48.29	23.43	71.72	67	33
Gemini	61.99	48.70	39.98	22.65	62.63	64	36
TS135	42.89	34.36	32.37	16.26	48.63	67	33

Table 11: Showing the rank assigned to each site in each scenario in relation to the maximum biomass produced (g C m^{-2}) (1 represents the largest biomass and 9 represents the smallest biomass).

Rank in terms of maximum standing stock (g C m^{-2})		<i>L. digitata</i> (monoculture)	<i>S. latissima</i> (monoculture)	<i>L. digitata</i> & <i>S. latissima</i> (polyculture)
Largest biomass	1	Borssele	Texel	Borssele
	2	Texel	Borssele	Texel
	3	Gemini	Gemini	Gemini
	4	SW070	SW070	SW070
	5	GR006	TS135	GR006
	6	TS135	GR006	TS135
	7	SW001	SW001	SW001
	8	TS235	TS235	TS235
Smallest biomass	9	NW002	NW002	NW002

4.2.2 Biomass development

The pattern of biomass development throughout the year was similar for the three scenarios (figure 4 a, b and c). The development for all three scenarios produces a similar pattern with slow growth until May when the amount of biomass levels off and then exponential growth occurs between mid-July and mid-October. As Borssele was the site with the largest biomass for two of the three scenarios so it will be the focus for further analysis. The seawater temperature for the Borssele site was found to be warmest throughout the summer months (July, August and September) and in October this temperature begins to decrease (figure 5). This decrease coincides with when the biomass in each scenario levels off. However the seawater temperature could not explain the decrease in total biomass seen in the scenario with both species growing together. This trend is observed for all of the sites (appendix A). Additionally it was observed that the two defined types (light-limited and nutrient-limited) were not distinctively different. Therefore analysis of the results will only account for each species and not the associated types.

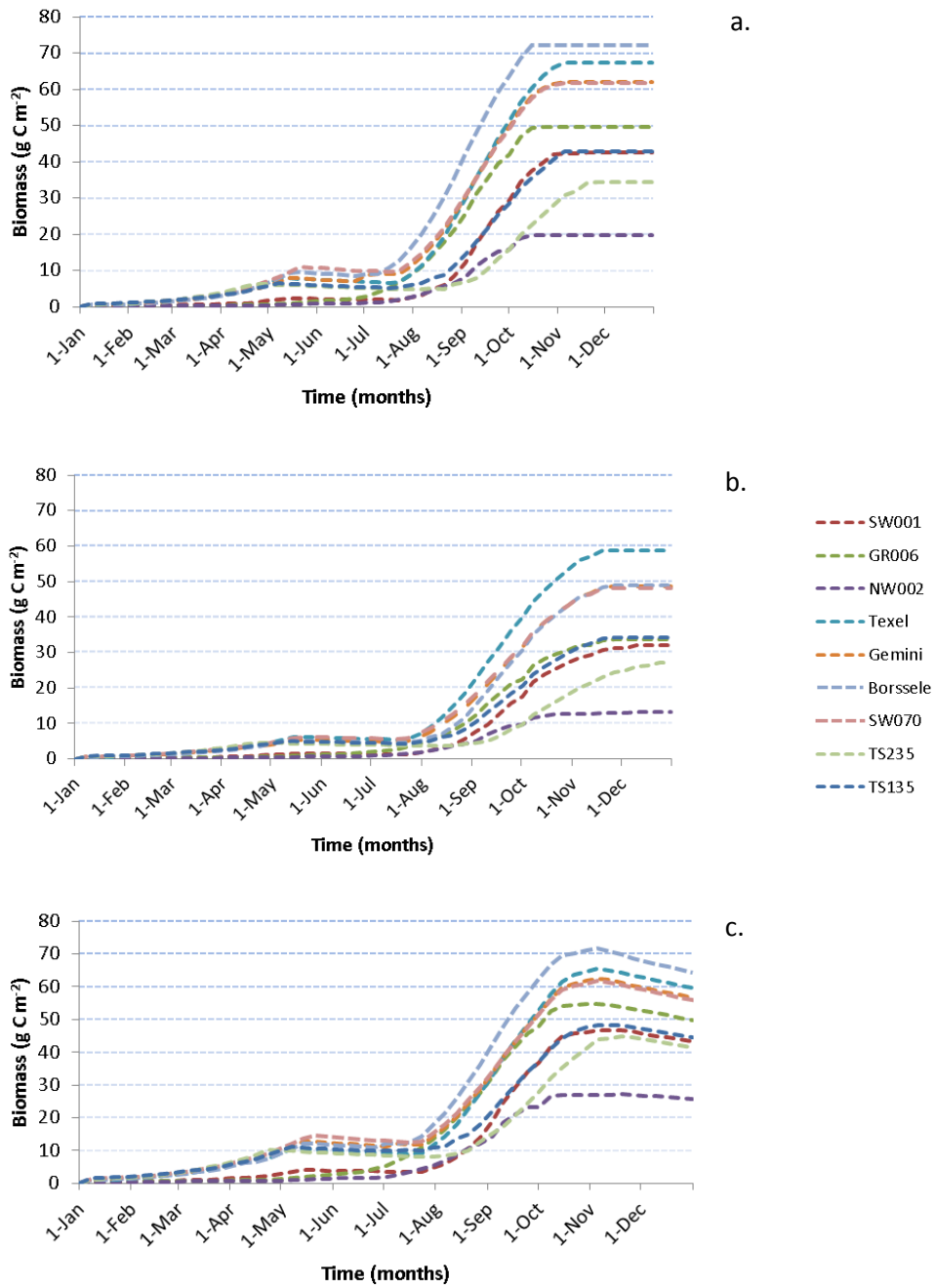


Figure 4: Biomass development (g C m⁻²) throughout the course of 2007 for the *L. digitata* monoculture (a), the *S. latissima* monoculture (b) and the polyculture (c).

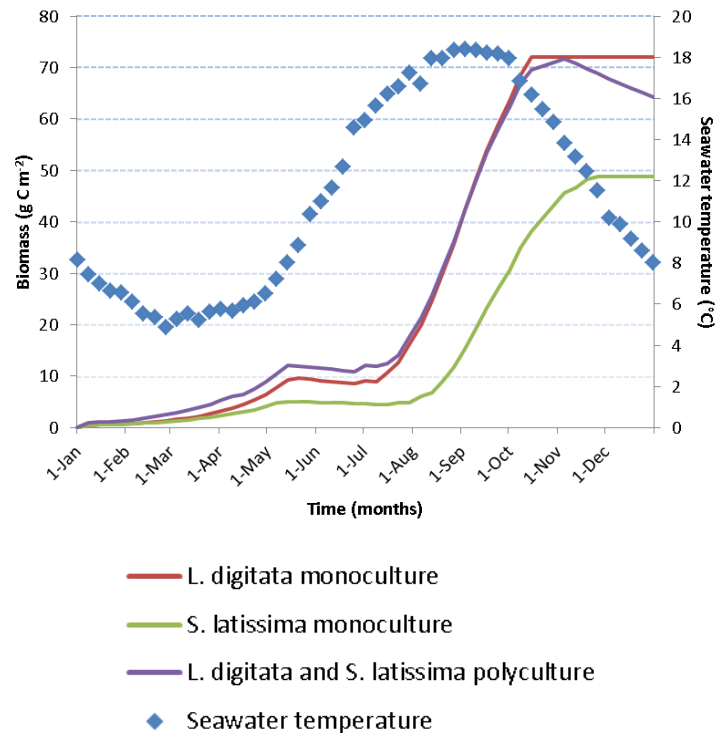


Figure 5: Biomass development (g C m^{-2}) throughout the course of 2007 for the three scenarios in relation to the seawater temperature ($^{\circ}\text{C}$).

The total nitrogen concentration and total phosphorous concentrations at the Borssele site are shown in figure 6 a and b. Each total contains the concentration of each nutrient in the detritus, macroalgae, phytoplankton and nutrients in the sea water. The pattern observed reflects the pattern of macroalgae biomass development throughout the year. The nitrogen and phosphorous contained within the seaweed at the Borssele site is also shown (figure 7 a and b). It is observed that the total nitrogen and phosphorous concentrations are predominantly made up of the macroalgae. Within the scenario growing both species together there is a decrease in nitrogen and phosphorous for *L. digitata*, there is no pattern observed for *S. latissima*. However this decrease in biomass was not found to be related to a nutrient limitation (figure 8). Only growth and mortality limitations occur at this later stage of the year implying that the macroalgae are growing to the best of their ability. The limitation plot considers limitations for all five species within the model including the phytoplankton and macroalgae species. The limitations for the remaining sites can be seen in appendix B. The development of these species throughout the year shows most of the phytoplankton biomass to develop between April and September (figure 9). This time period relates to the second and third quarter of the year in the limitation plot when there are nutrient limitations. These are likely to be related to the phytoplankton growth because it is during the time period when the macroalgae still have small biomasses. The mortality limitation in the final part of the year could also be related to the phytoplankton as their biomass decreases to 0 by the end of November (figure 9).

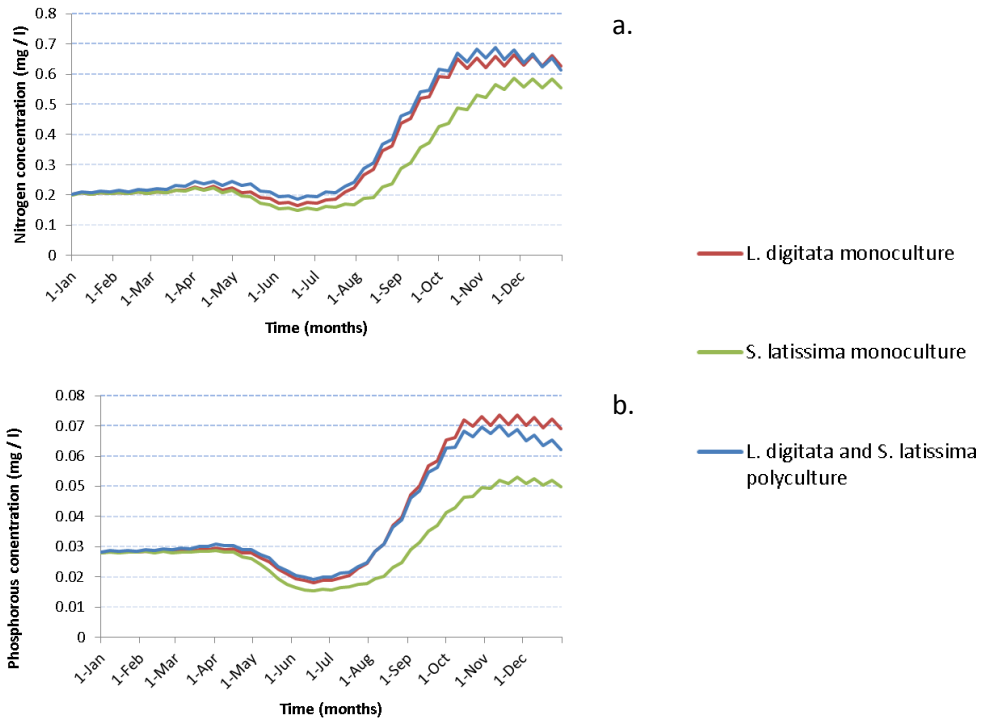


Figure 6: Total nitrogen concentration (a) and total phosphorous concentration (b) over the course of 2007 for the three scenarios at the Borssele site.

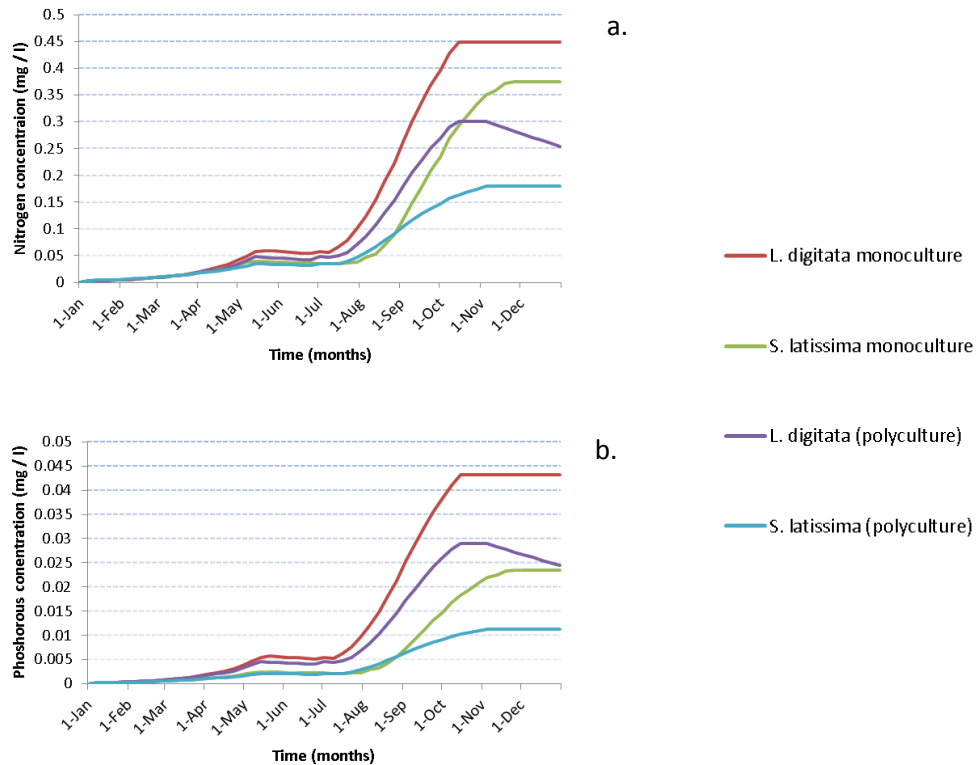


Figure 7: Concentration of nitrogen (a) and phosphorous (b) in the macroalgae growing over the course of 2007 in the three scenarios at the Borssele site.

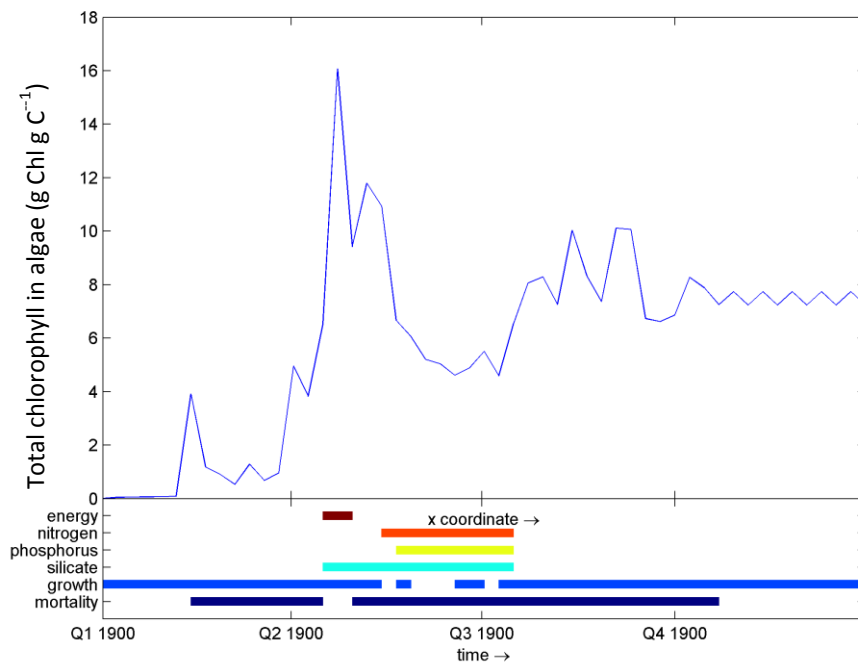


Figure 8: Limitation plot for the algae (phytoplankton and macroalgae) growing at the Borssele site throughout 2007 in relation to the total chlorophyll in algae (g Chl g C^{-1}). Q relates to a quarter of a year.

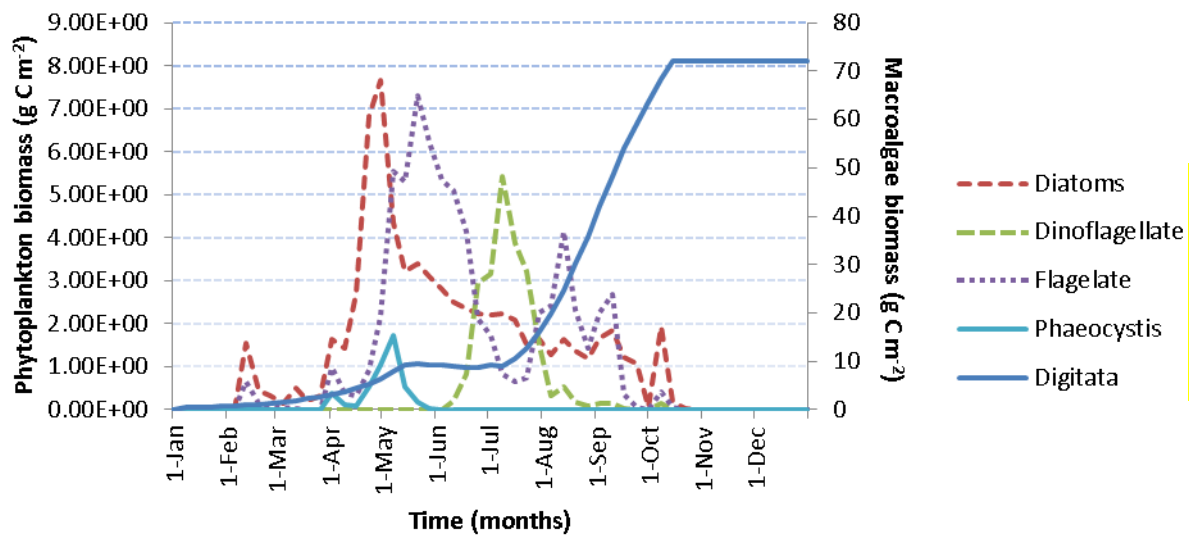


Figure 9: Biomass development (g C m^{-2}) over the course of 2007 for *L. digitata*, diatoms, flagellates, dinoflagellates and *Phaeocystis* over the course of 2007.

4.2.3 Controlling factors for biomass growth

To establish if there was a relationship between nutrients, which are the dissolved inorganic nitrogen (DIN) and phosphorous (DIP) concentrations, and the production of biomass, the development of DIN and DIP throughout the year was observed. The sites with the largest biomass production (Borssele, Texel, Gemini and SW070) followed a similar pattern for DIN and DIP concentrations throughout the year (figure 10a). Both concentrations simultaneously increase from mid July to mid October of both concentrations reflects the increase in biomass at these sites, as shown in figure 10a for Borssele. However for the remaining sites producing less biomass this simultaneous increase was not observed. This increase in DIP during summer is observed in the NW002 site (ranked 9th out of 9) however the DIN concentration despite increasing simultaneously with the DIP concentration decreases rapidly again (figure 10b). When the mean DIP and DIN concentration for the summer period (June July and August) of exponential growth was related to the seawater temperature at each site there was a trend observed, in particular for DIP (figure 11 a & b). The DIN and DIP trends for the remaining sites can be seen in appendix C.

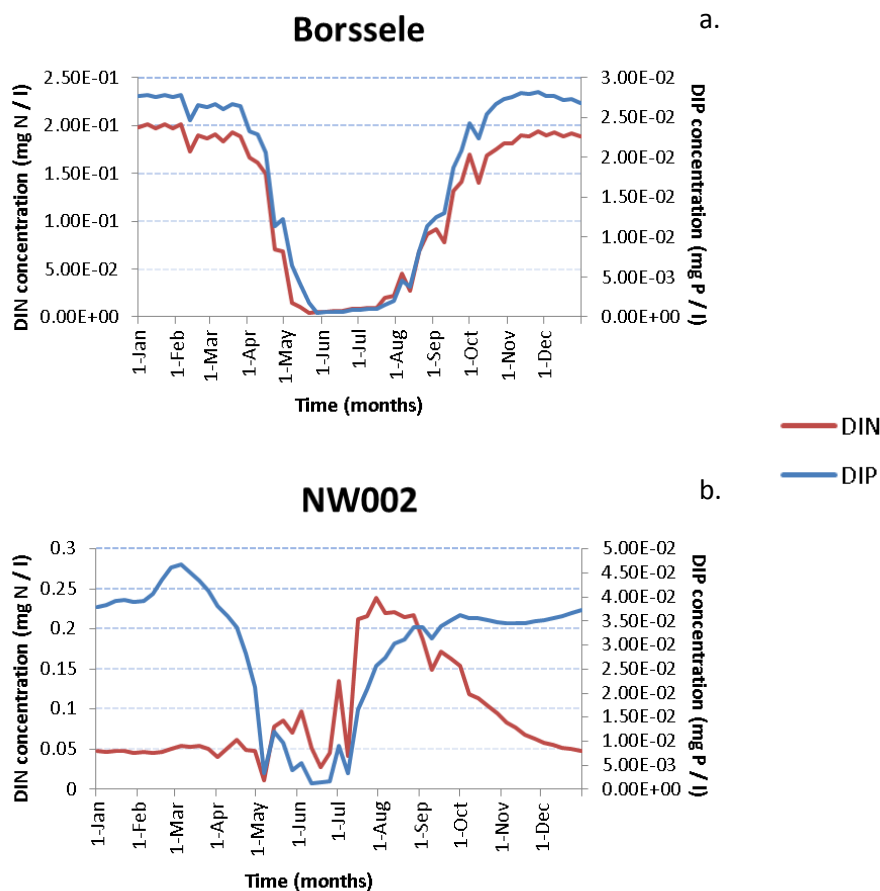


Figure 10: Development of dissolved inorganic nitrogen (DIN, mg N / l) (a) and dissolved inorganic phosphorous (DIP, mg P / l) (b) throughout the course of 2007 for Borssele and NW002.

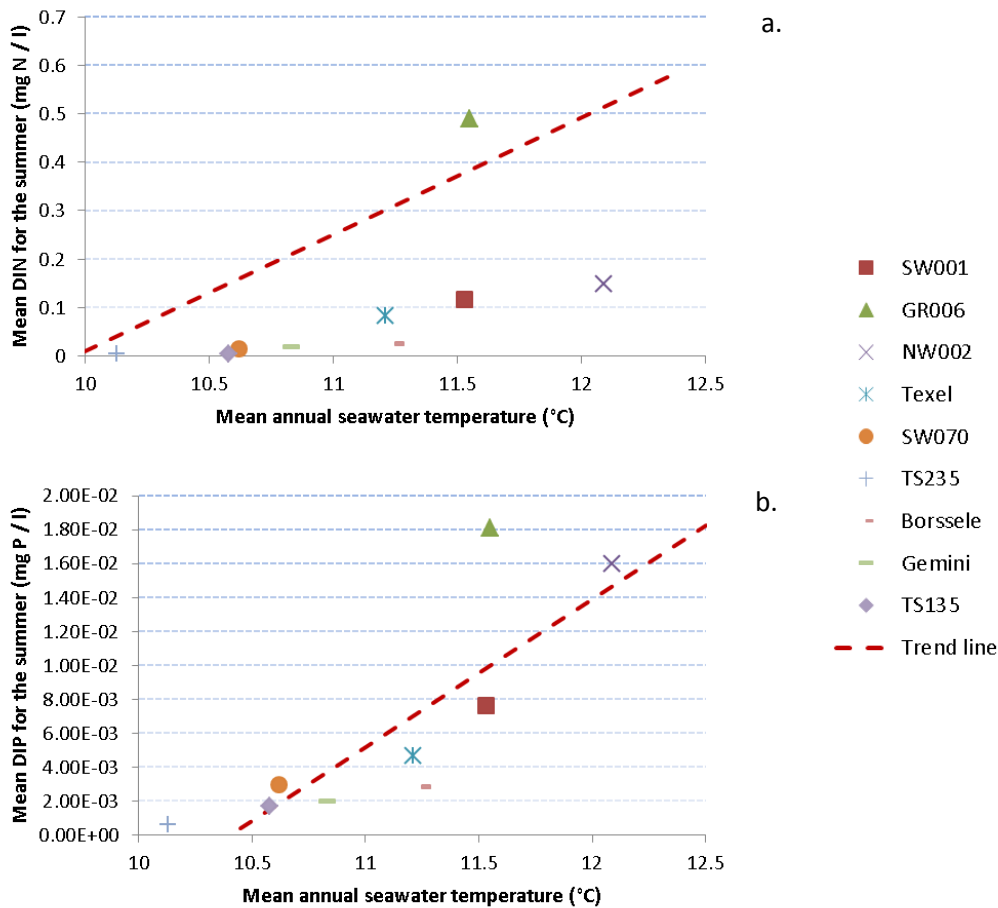


Figure 11: Mean annual DIN (a) and DIP (b) (mg N / l and mg P / l) in relation to the mean annual seawater temperature at each of the sites.

To establish which factors were the controlling factors for growth of the macroalgae the nutrients (NH_4 , NO_3 and PO_4), current velocity and temperature were analysed. A positive linear relationship was found between the mean annual current velocity at each site and the biomass produced (figure 12 a). Borssele had the second fastest current out of all of the sites and produced the largest biomass for two of the scenarios. Three of the top four biomass producing sites have the three fastest current velocities.

Second order polynomial relationships were observed for the mean PO_4 concentrations, mean annual seawater temperature and the mean NH_4 concentrations and in relation to the maximum amount of biomass produced at each site. Each of these factors was found to show an optimum, within which the top four sites for all scenarios fall within. The optimum mean annual phosphate concentration in seawater range was from 0.0157 mg/l to 0.0175 mg/l (figure 12 b). The mean annual temperature optimum was found to be in the range of 10.6°C and 11.3°C (see figures 12 c). An optimum mean annual ammonium concentration in seawater was observed in the range of 0.0142 mg/l to 0.0258 mg/l (see figures 12 d). In contrast NW002, the site producing the least biomass

did not fall within these optimum ranges, it had the slowest current velocity, the highest phosphate concentration, the second highest ammonium concentration and the warmest seawater temperature. No relationship was found between the mean NO₃ concentration in the water and the biomass produced (figure 12 e). The figures show the results for *L. digitata* although the same trend was seen for *S. latissima* (appendix D). The implications of the results from the database and the model will be interpreted and discussed in the following chapter.

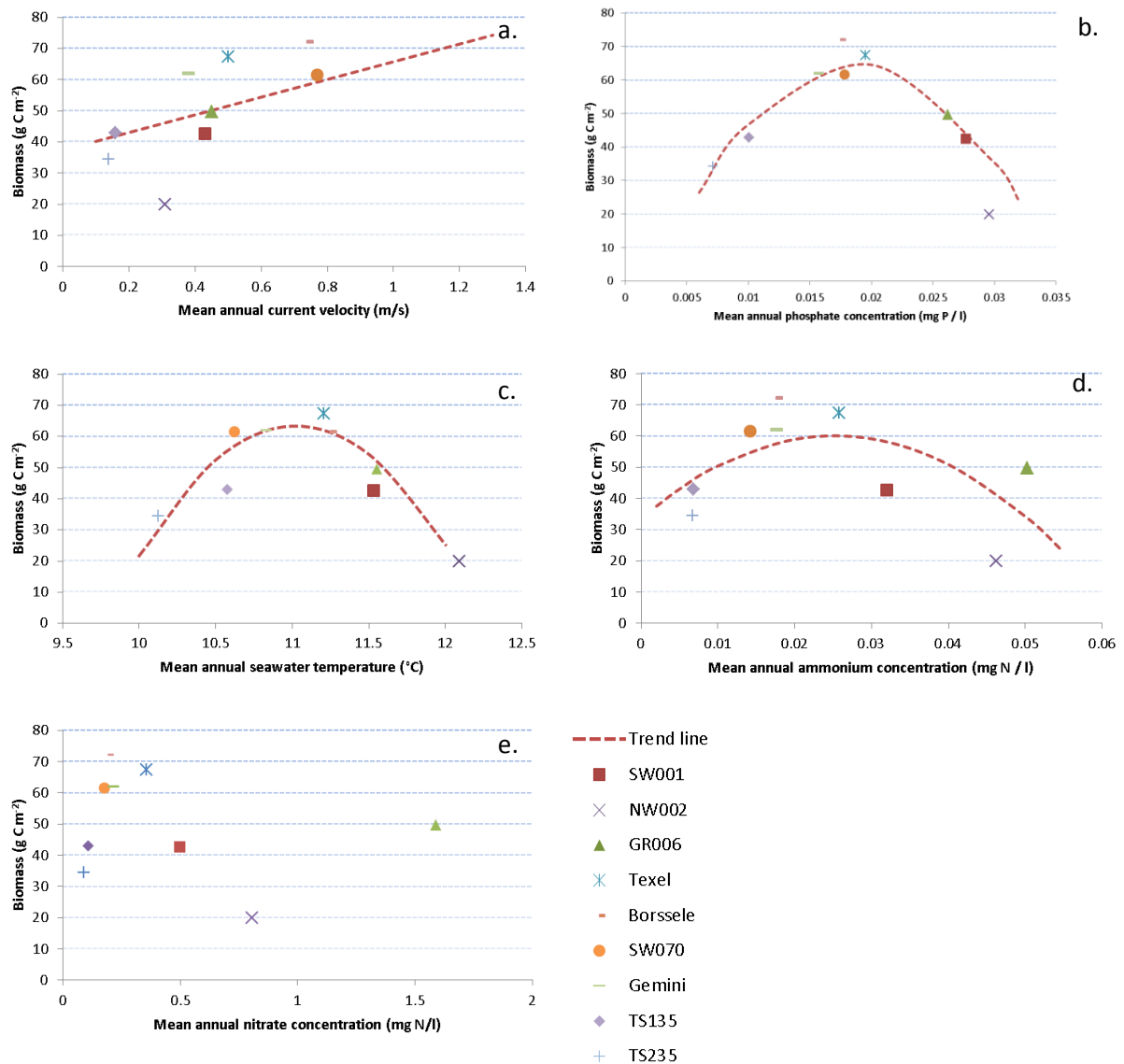


Figure 12: *L. digitata* biomass produced (g C m⁻²) over the course of 2007 at all of the sites in relation to the:
a. mean annual current velocity (m/s) $y = 55.023x + 26.527$, $R^2 = 0.5067$.
b. mean annual phosphate concentration (mg P / l) $y = -289856x^2 + 10257x - 26.568$, $R^2 = 0.8858$.
c. mean annual seawater temperature (°C) $y = -39.839x^2 + 878.25x - 4776.9$, $R^2 = 0.8044$.
d. mean annual ammonium concentration (mg N / l) $y = -56606x^2 + 2813x + 27.498$, $R^2 = 0.4626$.
e. mean annual nitrate concentration (mg N / l)

5. Discussion

The aim of this research was to determine if it is biologically feasible to exploit an offshore aquaculture system based on macroalgal farming. The results indicate that it is biologically feasible to exploit such a system offshore in the North Sea. The monoculture and polyculture scenarios growing *L. digitata* and *S. latissima* showed varying amounts of biomass production. *L. digitata* was found to be the species that produced the most biomass at all of the sites. For instance the Borssele site has the most biomass produced when *L. digitata* was grown in a monoculture or alongside *S. latissima* in a polyculture. The Texel site has the most biomass production for *S. latissima* growing in a monoculture. Moreover, an increased total biomass was found for the polyculture scenario and although this is consistent with literature this trend could not be understood by analysis. A relationship was found between the dissolved inorganic nitrogen and dissolved inorganic phosphorous concentrations throughout the year and biomass production. Positive trends were observed the mean annual current velocity, mean seawater temperature and the maximum biomass produced at each site. These results will be further discussed below.

5.1 Biomass production

The range of maximum biomass produced for the selected sites in the model are consistent with the values found in literature (Peteiro & Freire, 2013; Peteiro & Freire, 2009 and Peteiro *et al.*, 2006) and from an expert in the field (Schipper, J., personal communication, 5-3-2013). Commercial macroalgae production should produce biomass in the range of 50 g C m⁻² and 70 g C m⁻², with the model values being between 13 g C m⁻² and 72 g C m⁻² (table 10). The model output was additionally validated by a seaweed expert due to the lack of any data for use in validation (Birkeland, M. J., personal communication, 25-6-2013). *L. digitata* was found to be the species which produced the most biomass at all of the sites in all of the scenarios (table 11). This can be explained by the model parameter for rate of primary production being higher for *L. digitata* than *S. latissima*. This result is in accordance with the opinion of an expert in the field (Schipper, J., personal communication, 19-03-2013). Experimental studies concluded *L. digitata* to be more robust than *S. latissima* to the strong mechanical forces in the offshore sea (Buck & Buchholz, 2004). However, other studies found *S. latissima* to be the more suitable species for culturing offshore due to its physical characteristics. For example, its flexible stipe leading to its selection after suitability tests as an appropriate offshore species (Pogoda *et al.*, 2011; Buck & Buchholz, 2004). Nonetheless characteristics such as robustness and a flexible stipe are beyond the scope of the model.

5.2 Biomass development

The development of macroalgal biomass has a different development pattern than the phytoplankton (figure 9). In general, the phytoplankton bloom in spring when there is an abundance of sun and nutrients leading to a peak in June when nutrient recharge is not sufficient and therefore becomes limiting. The biomass decreases until October during the time when the macroalgae biomass is increasing exponentially. During the winter the biomass decays and the nutrients are released and in spring the cycle begins again (Los, 2009). This can be explained by a lower phytoplankton growth rate than macroalgae, different nutrient requirements for growth and a difference in temperature dependency within the model (Los, 2009).

With regards to the development of macroalgae within all three scenarios a similar pattern of development is observed. There is slow growth until May when the amount of biomass levels off and then exponential growth occurs between mid-July and mid-October (figures 4 a-c). This increase in biomass coincides with the increase in seawater temperature which is in the range of optimum growth temperatures observed for each species in literature (Reith *et al.*, 2005; Bolton & Luning, 1982; Druehl, 1988). When the seawater temperature begins to decrease in mid-October, the amount of biomass starts to level off (figure 5, appendix A). However for the polyculture scenario a peak is reached and then the biomass decreases for the remainder of the year (figure 4 c). Again, a temperature dependency was found, since nutrient limitation could not explain this (figure 8, appendix B).

The pattern of biomass development contrasts with the pattern of *L. digitata* and *S. latissima* biomass development in natural systems. Under model conditions growth in biomass occurs when there are suitable growing conditions, such as sufficient light and nutrient concentrations. In natural systems, both species have the ability to store nutrients in late winter and early spring. This storage of nutrients allows for a prolonged period of growth from late spring until early summer, a reduction in growth rate in summer, low growth rates in autumn which increase again in mid-winter (Luning & Pang, 2003; Sjutun, 1993).

In the polyculture scenario there was a larger total biomass produced than when the species were grown as monocultures (table 10). A trend in the model was present, which could not be understood using analyses. This could be due to a model artefact whereby under growth limited conditions in the model the total biomass increases with the number of species present in the model. Nonetheless this trend of an increased biomass in polycultures in comparison to the best performing monocultures has also been observed in natural systems (Stachowicz *et al.*, 2008). In natural systems

this can be explained by the species within a polyculture being complementary in their use of different nitrogen forms. Therefore an increased uptake of nitrate and ammonium within a polyculture in comparison to the monoculture average is observed (Bracken & Stachowicz, 2006). However this was not observed within the polyculture scenario in the model. Under the BLOOM default settings there is a preference for ammonium for all of the species; however this preference was not implemented in this research.

The site with the most biomass produced for the two scenarios growing *L. digitata* in a monoculture and with *S. latissima* in a polyculture was Borssele with 72.10 g C m⁻² and 71.72 g C m⁻² respectively produced (table 10). Texel produced the most biomass for the scenario growing *S. latissima* alone with 58.66 g C m⁻² whilst the site that produced the least biomass for all three scenarios was at NW002 with a range of 13 to 27 g C m⁻² (table 10). Surprisingly the top three sites for all scenarios were sites that are already in the process of having macroalgal farms constructed there. This difference in biomass at each site can be related to the relationship observed between the maximum biomass and the concentrations of dissolved inorganic nitrogen (DIN) and phosphorous (DIP) at each site (figures 10 a-b). The sites that produced the most biomass had similar patterns of development of DIN and DIP concentrations throughout the year, for example Borssele (figure 10 a). The increase from mid July to mid October of both concentrations reflects the increase in biomass at these sites. This increase was reflected in NW002 for the concentration of DIP but not for the DIN concentration as this concentration peaked in June and decreased for the remainder of the year (figure 10 b). The trends for the remaining sites can be observed in appendix C. In literature, a significant relationship between the growth rate of macroalgae and the availability of nitrogen has been observed (Kain, 1989). A positive trend was found between the mean summer DIN and DIP concentrations in relation to the mean annual seawater temperature which indicates temperature dependency (figures 11 a - b).

5.3 Controlling factors for biomass growth

A positive linear relationship was found for all scenarios between the mean annual current velocity of a site and the maximum biomass produced (figure 12 a, appendix D). This trend implies that with higher current velocities there will be an increased biomass with Borssele producing the highest biomass and penultimate fastest current velocity. Additionally three of the top four producing biomass sites have the top three fastest current velocities (figure 12 a, appendix D). Higher water velocities result in a more constant supply of nutrients which could then increase biomass production. This has been demonstrated in literature by Hurd (2000) who showed that water velocity increases the macroalgae production rate by increasing the uptake of nutrients and carbon

dioxide and by influencing the factors that determine growth in macroalgae. The productivity is higher at moderate levels of water velocity in comparison with slow velocities (Peteiro & Freire, 2012; Hurd, 2000; Neushul *et al.*, 1992). However a moderate level in this sense refers to 0.03 m/s whilst the sites studied have a current velocity in the range of 0.16m/s to 0.77 m/s (Peteiro & Freire, 2012). Positive trends were also observed between the maximum biomass and the mean seawater temperature with the top biomass producing sites for all of the scenarios being within a small range (figure 12 c, appendix D). This range is within the optimum range of temperatures stated in literature (Reith *et al.*, 2005; Bolton & Luning, 1982; Druehl, 1988). There was also a trend observed between the mean annual phosphate and ammonium seawater concentrations of each site and the maximum biomass produced (figure 12 b & d, appendix D). Both of these trends in nutrient concentrations also produced small optimum ranges. These trends were unexpected and imply that with increasing nutrient concentrations productivity would continue to decrease until the macroalgae population reached 0. This is in contrast to the relationship found in literature between the growth rate of a macroalgae and the availability of nitrogen (Kain, 1989). This trend could be indirect and caused by temperature since a positive relationship was found between temperature and DIN and DIP concentrations (figure 11 a and b, appendix C).

5.4 Limitations

A major limitation within this study has been a lack of data for macroalgal growth and limited data for nearshore macroalgal growth. Therefore a major assumption within this research was that the selected study species would react in a similar manner to offshore conditions. Until the experimental sites that are currently in planning and the proposed sites for the future are constructed and tested there is no way to test if this assumption is correct. This additionally has an impact on the definition of the characteristics for the light-limited, nitrogen-limited and phosphorous-limited types within the model as there was not sufficient information to clearly define each type. Therefore instead of three types a light-limiting type and a nutrient-limited type were defined.

This research has provided preliminary findings which can be used by experts in the field and policy makers who are planning future test sites or offshore platforms. This research can provide them with an overview of which of the selected sites are suitable locations for a macroalgal farm and which environmental and hydrodynamic conditions should be considered when selecting a site. The model can continue to be updated in the future with the results from the test sites to provide a more detailed overview. This can allow for continual improvement and modifications within the model to provide results which are as close to reality as possible.

5.5 Recommendations

Although this research has provided preliminary guidance for experts in the field and policy makers about expected biomass production at a variety of sites, it must be remembered that these values are based on a number of assumptions. Due to a lack of any offshore aquaculture farms, it was assumed that the macroalgae would respond to offshore conditions in the same way that they respond to nearshore. Nonetheless once a test sites is in use data can be collected and implemented into the model. The output of which could then be compared to this research to see were the similarities and differences are.

In the future this model can be used as a base model from which modifications and additional processes could be implemented to make the model output more realistic. This could include extending the process of flexible stoichiometry that could allow nutrients to be stored during certain times of year so that the growth periods and storage periods of nutrients for the macroalgae could be more realistic. The model time frame could also be ran from autumn to autumn to more accurately represent the commercial macroalgae calendar rather than a calendar year. The implementation of macroalgae predators could allow for consideration of the broader foodweb rather than focusing solely on the trophic level of interest. Additionally a harvesting function could be implemented to determine the best time of year to harvest the biomass.

In the context of the MERMAID program and goals, modules containing shellfish and fish could be implemented to replicate integrated multi trophic aquaculture. A more refined model with a finer scale grid and finer hydrodynamics could help produce more realistic results. The seaweed could then be modelled on a smaller scale than at grid segment size allowing for a closer representation of reality, such as the use of ropes to cultivate seaweeds on.

6. Conclusion

In summary, model assessments indicate that it is biologically feasible to exploit an offshore aquaculture system based on macroalgal farming in the North Sea. We found that *L. digitata* produced the highest biomass, both when grown in a monoculture and together with *S. latissima* in a polyculture. However when grown in a polyculture the total maximum biomass produced was higher than either of the species grown in monoculture. A relationship was found between the concentration of dissolved inorganic nitrogen and phosphorous concentrations throughout the year and the biomass produced at each site. Positive trends were found between the biomass produced and the mean current velocity and mean annual temperature. Therefore this research recommends that in order to achieve maximum biomass production, *L. digitata* and *S. latissima* should be grown in a polyculture. The current velocity, dissolved inorganic nitrogen and phosphorous concentrations and the seawater temperature were found to be the controlling factors to biomass production and should be considered when selecting suitable offshore macroalgal sites in the North Sea. This model can be used as a starting point to which additional modifications and data from test sites when available can be implemented into in order to bridge the gap between model output and reality. However in order for an offshore macroalgal farm to be successful, the feasibility of other aspects such as economic and social must also be accessed.

7. Acknowledgements

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9. Appendices

9.1 Appendix A

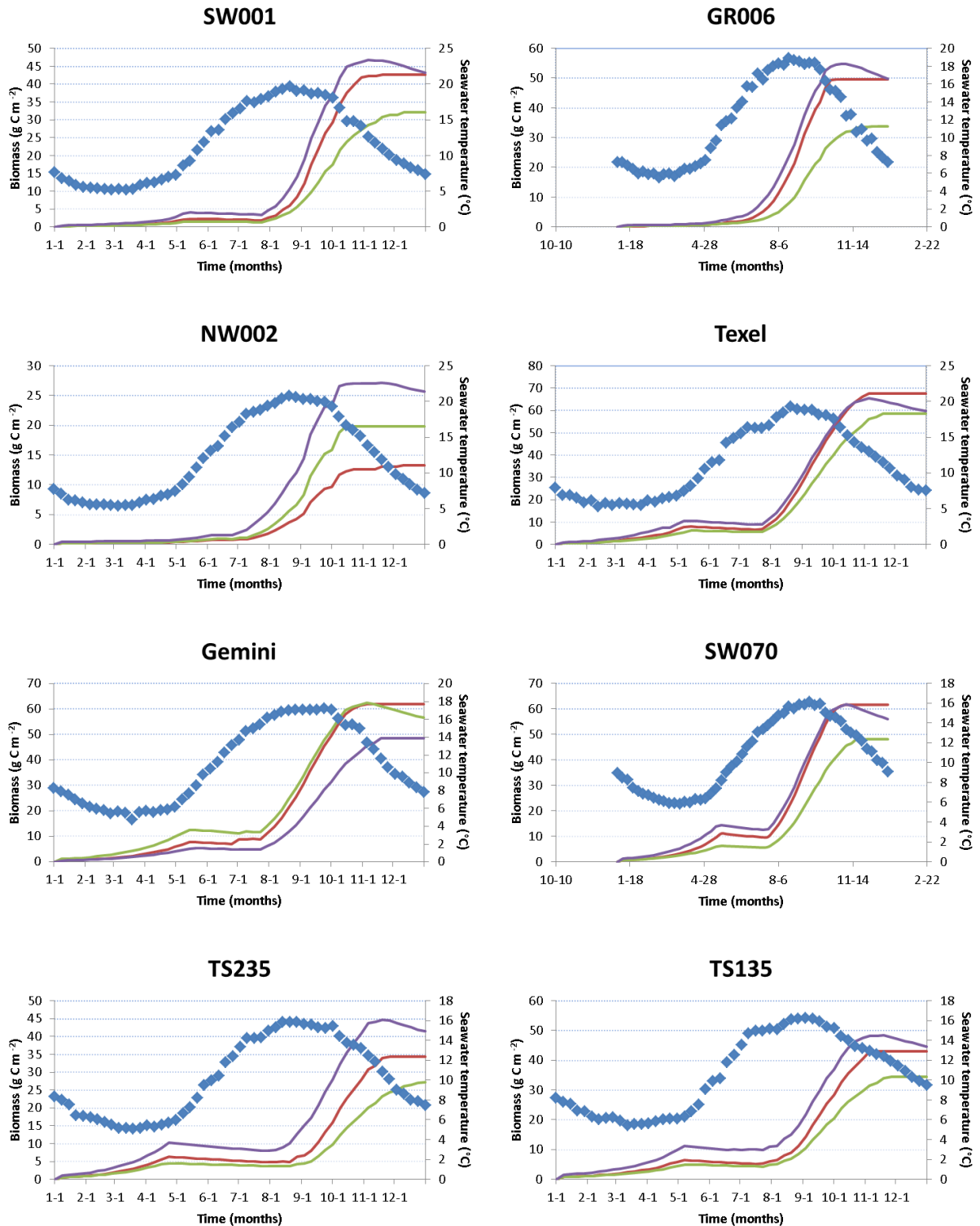
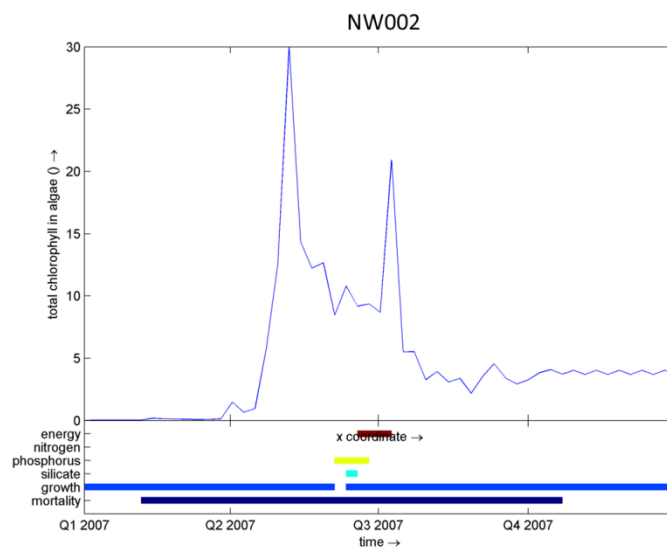
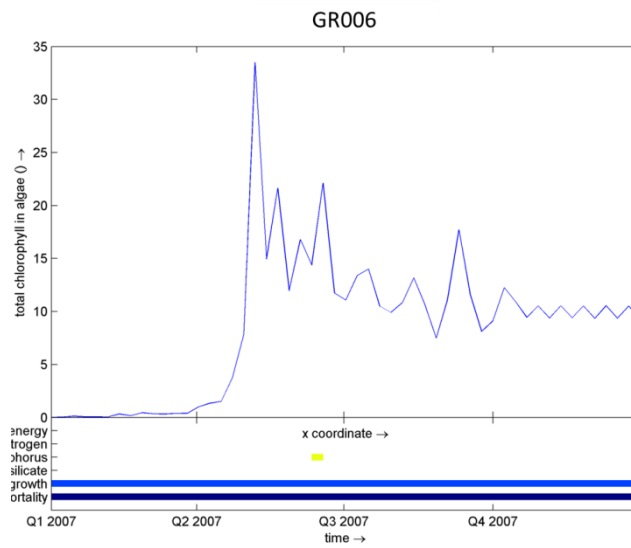
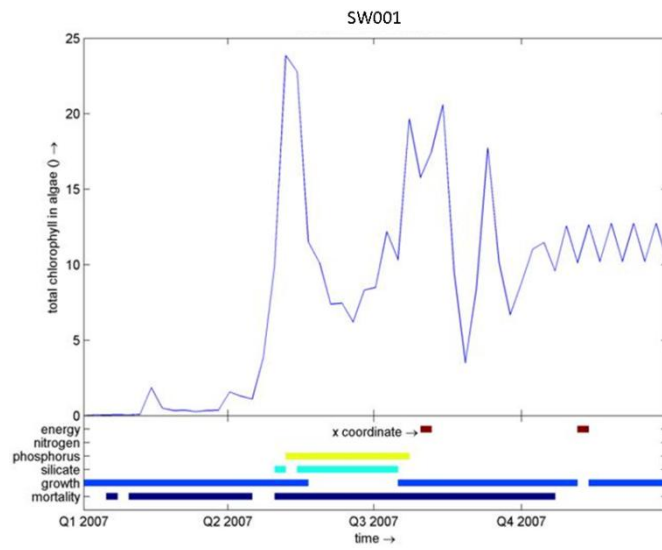
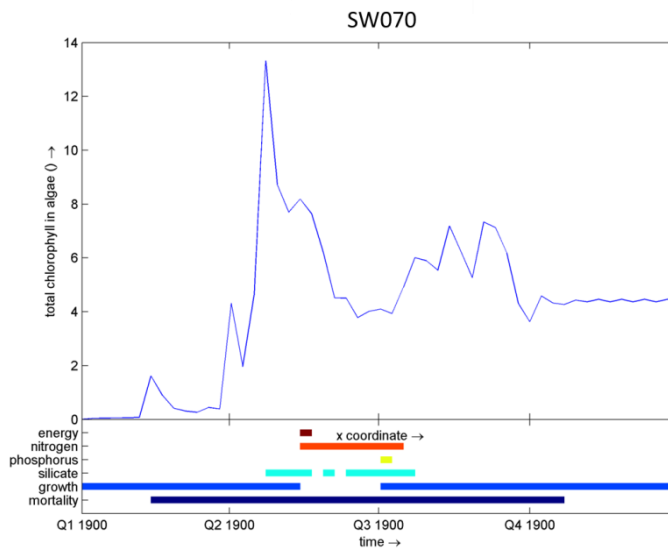
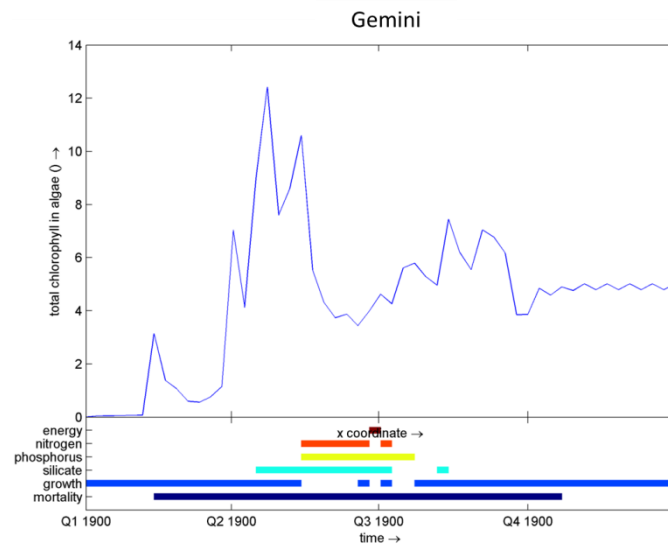
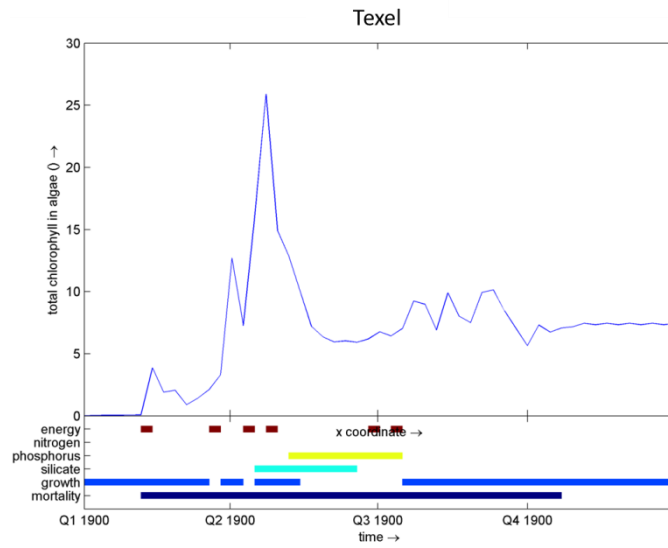


Figure: Biomass development (g C m⁻²) throughout the course of 2007 for the three scenarios for each site in relation to the seawater temperature (°C). The equivalent plot for Borssele is on page 31. Red represents *L. digitata* monoculture, green is *S. latissima* monoculture, purple is the polyculture and blue is the seawater temperature.

9.2 Appendix B





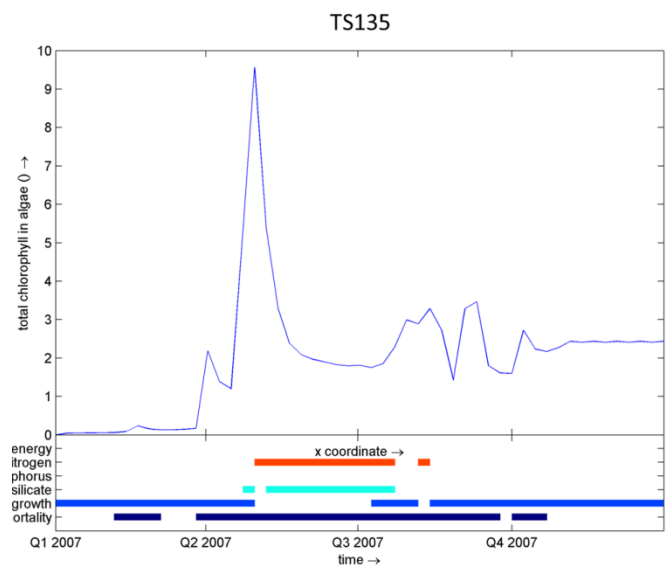
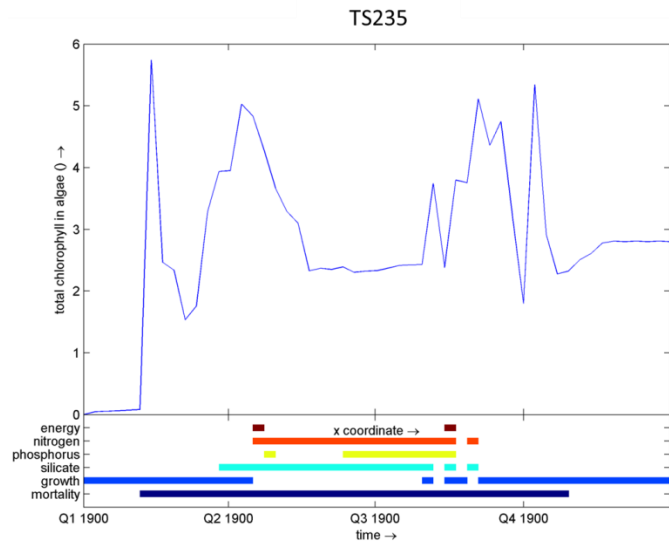


Figure: Limitation plot for the algae (phytoplankton and macroalgae) growing at each of the sites throughout 2007 in relation to the total chlorophyll in algae (g Chl g C^{-1}). Q relates to a quarter of a year.

9.3 Appendix C

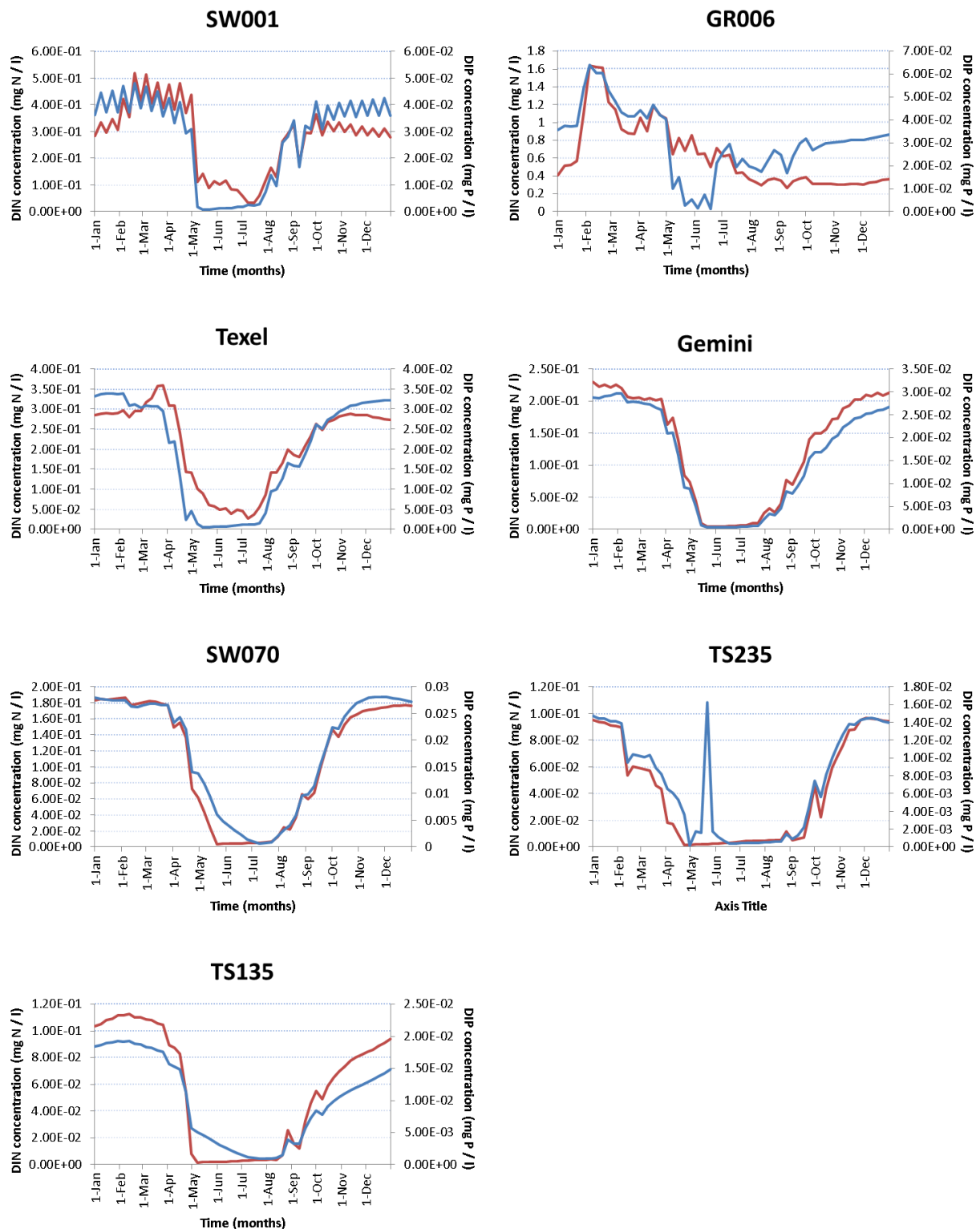


Figure: Development of dissolved inorganic nitrogen (DIN, mg N / l) is represented in red and dissolved inorganic phosphorous (DIP, mg P / l) is represented in blue throughout the course of 2007 for each of the sites. The figures for Borssele and NW002 are on page 35.

9.4 Appendix D

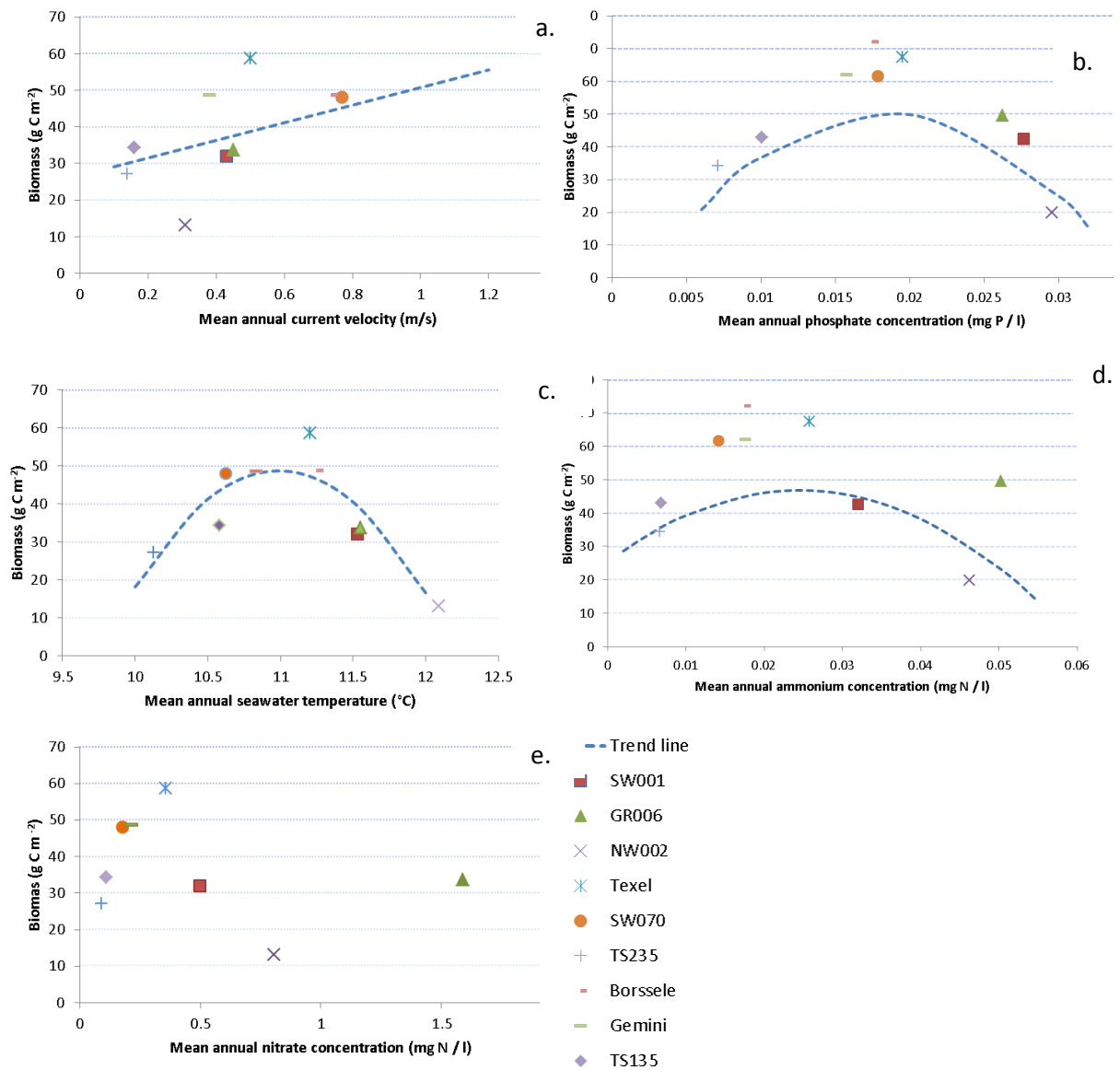


Figure : *S. latissima* biomass produced (g C m^{-2}) over the course of 2007 at all of the sites in relation to the:

- mean annual current velocity (m/s) $y = 37.61x + 22.098$, $R^2 = 0.3551$.
- mean annual phosphate concentration (mg P / l) $y = -230748x^2 + 8682.3x - 16.979$, $R^2 = 0.6746$.
- mean annual seawater temperature ($^{\circ}\text{C}$) $y = -31.303x^2 + 687.88x - 3730.3$, $R^2 = 0.7934$.
- mean annual ammonium concentration (mg N / l) $y = -40549x^2 + 2037.9x + 34.269$, $R^2 = 0.3295$.
- mean annual nitrate concentration (mg N / l)