Modelling & simulating microalgae production in an open pond reactor

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Abstract

Microalgae are thought to be one of the most promising source materials for biodiesel among a variety of other products. A large scale utilisation of their potential however remains unrealised as of now. One of the core areas in the microalgae to biodiesel field is the algae cultivation process. A variety of cultivation systems have been proposed, which can be divided into two classes closed photobioreactors and open pond reactors. The latter being the least expensive but also least efficient type. To analyse the performance of such an open pond system a mathematical model was constructed. Formulations for light and temperature dependent algae growth were taken from literature. Outdoor conditions were emulated by using meteorological data and sub models for light distribution and pond temperature. Simulations were done for different locations, mainly the Netherlands and Algeria. The growth behaviour of two microalgae species was simulated, namely *Phaeodactylum tricornutum* and *Thalassiosira pseudonana*. The simulations show that strong differences in daily and yearly biomass yields are present between different locations and also between different algae species. The model offers possibilities to optimize the cultivation process.
1 Introduction

The term microalgae is generally used to classify photoautotrophic organisms of microscopic size[1]. Photoautotrophic means that they fixate inorganic carbon and thus generate biomass by capturing light energy.

Microalgae have a unicellular or simple multicellular structure, with no differentiation into roots, stem or leaves, and vary in size from 1 to 50µm[1]. It is estimated that there are between 200,000 and 800,000 microalgae species of which only around 35,000 have been described so far[2], consequently they offer an tremendous potential with regard to biodiversity.

Cultivation of microalgae has emerged as a major point of interest in recent years, due to the diverse range of products microalgae can lead to. Microalgae are a good source for both pharmaceutical and food products because of the high content of valuable fatty acids (especially ω3-fatty acids), carotenes, vitamins, antioxidants and a variety of very specific compounds that can be found in several algae species. Microalgae can furthermore be used as feedstock in aqua- and agriculture[1, 3-6].

The main application of microalgae however is thought to be as a stock material for biofuel production on a large scale[2, 7, 8].

1.1 Biofuels from microalgae

The global demand for liquid fuels is expected to surpass supply by 2015[9-11], this encourages the search for alternatives. One of the alternatives are biofuels, fuels made from biomass, which are in principle everlasting and sustainable. Additionally biofuels ideally have a close to neutral CO₂ balance and are readily biodegradable making them an environment friendly replacement for traditional fuels.

The downside of biofuels is the high production cost which makes them yet economically unpractical. Biofuels, particularly those derived from terrestrial plants, furthermore require large areas of land to be produced and may stand in competition with traditional agriculture for land usage[12, 13].
The term biofuel includes a wide variety of products, ranging from solid biomass pellets to liquid biofuels or biogases, which can be generated from numerous stock materials[12], as can be seen in Figure 1.1.

Figure 1.1: Different types of biofuels.

Biofuels that stem from microalgae have several economical and ecological advantages over their counterparts derived from terrestrial plants.

Microalgae are basic in comparison to higher plants and therefore usually have fewer demands and can be grown under harsher conditions. They are furthermore able to reach higher lipid contents due to their simplicity, with oil contents of 20-50% per dry weight being found quite often and some species even reaching more than 70%[2]. High oil contents are especially desirable for biodiesel production. Microalgae have higher growth rates and very short harvesting cycles in comparison to higher plants as they have a higher photosynthetic efficiency, i.e. they can utilize more incoming light energy. This results in higher biomass yields and a more continuous and reliable overall process.

Another significant factor is the possibility to grow algae on land that is not suitable for traditional agriculture. Microalgae production facilities can be set up on arid, saline or generally infertile land, which resolves the issue of competition of crops for food production and crops for biofuel production.
Even though algae grow in an aqueous medium, they consume less freshwater than terrestrial crops. Cultivation of several microalgae species can also be conducted on pretreated wastewater or for marine species on ocean water, which in turn minimizes the consumption of freshwater and fertilizers even more. Sequestration of CO$_2$ from industrial waste streams can also be incorporated into the cultivation process.

Microalgae are a highly flexible source of raw material and can be used to produce a wide variety of biofuels ranging from biodiesel and bioethanol to H$_2$. Accumulating waste biomass could also be used to produce methane. The by far largest market however is biodiesel, accounting for 82% of the total biofuel production.

Despite all these advantages biodiesel production from algae suffers from a few issues that so far have prevented the realization of the technology on a scale of economic impact. The cultivation process is one of the areas still under considerable research, as higher productivities coupled to lower production costs would consequently lead to a lower priced end product, which would make it competitive with conventional fuels.

### 1.2 Microalgae cultivation

To date microalgae cultivation can essentially be carried out via 2 different systems: Open pond reactors and closed photobioreactors. The latter are usually found in the form of tubular reactors or flat panel reactors. Open pond reactors are also available in numerous designs, ranging from circular concrete ponds to natural lakes[1]. The most common form are raceway ponds, which are constructed visually resembling a racing track to form an endless loop. They are usually build by digging a shallow track (approximately 30cm deep) into the ground, lining is applied in form of thin long lasting PVC membranes. Mixing of raceway ponds is accomplished by paddlewheels, which create a depth gradient resulting in a steady flow through the loop[1]. A depiction of the most common photobioreactor- and open pond reactor types can be seen in Figure 1.2.
Open and closed systems exhibit different advantages and disadvantages[14] as can be seen in Table 1.1. Open ponds offer only low productivities compared to closed photobioreactors, because the growth conditions for microalgae can be optimized in closed systems. Open ponds are furthermore sensitive to ambient influences and contamination with other algae species or viruses. However their low construction costs combined with low maintenance demands and a high durability make them as of now the most applied system.

The proneness of open systems to contamination can be countered by using algae species that can either grow under saline, alkaline or acidic conditions or even by adopting species that are resistant to herbicides[15]. Though this reduces the number of applicable species greatly and excludes many species of high economic potential.
Table 1.1: Comparison of different characteristics between open and closed systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Closed photobioreactors</th>
<th>Open ponds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination area</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Light path</td>
<td>Small</td>
<td>Long</td>
</tr>
<tr>
<td>Productivity</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Biomass concentration</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Area requirements</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Water losses</td>
<td>Virtually none</td>
<td>High, due to evaporation</td>
</tr>
<tr>
<td>CO₂ losses</td>
<td>Low</td>
<td>High, direct exchange with ambient air</td>
</tr>
<tr>
<td>Contamination risk</td>
<td>Very low</td>
<td>High</td>
</tr>
<tr>
<td>Flexibility towards cultivatable species</td>
<td>No restrictions</td>
<td>Low, only selected species feasible</td>
</tr>
<tr>
<td>Design</td>
<td>Complex</td>
<td>Basic</td>
</tr>
<tr>
<td>Capital costs</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Intensive</td>
<td>Simple</td>
</tr>
<tr>
<td>Large scale realisation</td>
<td>Difficult</td>
<td>Possible</td>
</tr>
<tr>
<td>Process control</td>
<td>Good</td>
<td>Hard</td>
</tr>
<tr>
<td>Susceptibility to environment</td>
<td>Only dependent on available light</td>
<td>Very dependent on outdoor conditions</td>
</tr>
</tbody>
</table>

1.3 Challenges

To evaluate the large scale practicability of microalgae as a source for biodiesel, life cycle assessments (LCA) are carried out[16-21].

Apparent is that there is a large uncertainty attached to the productivity of algae cultivation plants, with estimates often assuming up to 25-30 g algal biomass m⁻² d⁻¹[16, 17, 22] for raceway ponds which would equal 90-110 t ha⁻¹ y⁻¹. Richmond on the other hand states that long-term productivity is usually around 12-13 g m⁻² d⁻¹ (44-47 t ha⁻¹ y⁻¹)[1]. Contradictory Wijfels et al. give an amount of 40-80 t ha⁻¹ y⁻¹[23] although for closed photobioreactors, which theoretically should have a higher productivity than raceway ponds. Wijfels et al. also voice the opinion that many published estimates are too high and lead to false assumptions and expectations[23]. Accurate estimates for algae production are furthermore increasingly important in the developing commercialisation of algae cultivation.

Location and algae species have a pivotal impact on the potential biomass production. This thesis aims at improving the accuracy of biomass yield predictions with regard to location, algae species and design parameters. Therefore algal biomass production in an open raceway pond is mathematically modelled and simulated. A basic computational model, based on elements found in literature is constructed and evaluated.

Mathematical models are an efficient way to improve the accuracy of biomass productivity predictions. They give the means to precisely estimate algal growth under specific
conditions, which is needed for a thorough LCA. Contrary to simple extrapolations from lab scale experimental reactors, simulations by models can be valid for a range of conditions. However they are still dependent on the quality of experiments, which are needed to describe the relations between different variables and to supply specific parameter values.

Moreover the impact of design parameters, i.e. the depth of the pond and the used biomass concentration, on algal growth is evaluated. This furthermore offers the possibility to optimize the cultivation process. The potential and behaviour of different algae species in such a system is also analysed.

Limitations and possible further improvements regarding the components used in the modelling process are also discussed.

2 System description

Algal biomass production is evaluated as a function of the available light energy and the temperature of the growth medium as can be seen in Figure 2.1. For the purpose of creating realistic outdoor conditions for simulation, models for light energy and temperature dependent on meteorological data are constructed. Environmental data was taken for three locations: Cabauw, the Netherlands, Carpentras, France and Tamanrasset, Algeria.

As can be seen from the Figure 2.1 the different influences of light and temperature are then combined to yield a model for algal growth, which is dependent on the algae species in use. Simulations are conducted for two algae species: *Phaeodactylum tricornutum* and *Thalassiosira pseudonana*, mainly because there is sufficient data for those two species available.

Other factors such as nutrient concentrations and pH are considered to be optimal at all times, as they can be regulated relatively easy in practice.

The reactor is assumed to be ideally mixed, i.e. temperature and biomass concentration are homogenous in the pond. Possible influences of shear forces, generated by mixing, on algal growth are not considered.
Figure 2.1: Schematic representation of the algorithm employed to compute algal biomass production in an open pond reactor.

2.1 Light

The amount of sunlight that reaches the surface of an open pond reactor is naturally dependent on the position of the reactor surface towards the sun. The position is influenced by the location of the reactor on earth (latitude and longitude), the earth’s movement around the sun (time of the year) and the earth’s rotation around its own axis (diurnal cycle).

Solar radiance can furthermore be obstructed by clouds or other particles present in the atmosphere, which obviously diminishes the amount of light falling on a surface[24].

Irradiance on a pond surface stems from two fractions, direct light and diffuse light. Direct light is solar radiation which reaches a surface under a specific angle of incidence without
encountering any obstacles in the atmosphere. Diffuse light is light that has been scattered by the atmosphere and light reflected from other objects, which thus falls on surface from a variety of directions.

Irradiance measurements for 2009, along with other meteorological data, are taken from the World Radiation Monitoring Center (WMRC) [25] [26] [27]. The radiation data provides measurements in intervals of 1 minute. These 1 minute intervals are transformed into 10 minute averages, to save computation time and because principally algae do not adapt so fast anyway. In the cases where during a day a prolonged period of data points are missing, the measurements of the whole previous day are taken as a replacement.

2.1.1 Reflection on the pond surface

Sunlight that reaches the surface of a pond is subject to reflection due to the transition between air and the culture medium. The amount of light that is reflected on the pond surface is determined by the difference in refractive indices of the media and the angle of incidence of a light beam. For the calculation of reflection the water surface is considered to be smooth.

Reflection on the surface can be described using the Fresnel equations[28]. These equations are dependent on the polarisation of the incoming light beam in relation to the surface (s- or p-polarised). As sunlight is unpolarised, i.e. it is s- and p-polarised in equal amounts, the individual reflection coefficients for both fractions are calculated and averaged to get the overall reflection coefficient.

Reflection coefficient of the s-polarised fraction:
Reflection coefficient of the p-polarised fraction:

\[
R_p = \frac{n_a \cdot \sqrt{1 - \left( \frac{n_a}{n_w} \sin \theta_\text{e} \right)^2} - n_w \cdot \cos \theta_\text{e}}{n_a \cdot \sqrt{1 - \left( \frac{n_a}{n_w} \sin \theta_\text{e} \right)^2} + n_w \cdot \cos \theta_\text{e}}
\]

Overall reflection coefficient:

\[
R = \frac{R_p + R_y}{2}
\]

Where \( n_a \) and \( n_w \) are the refractive indices of air and respectively water. \( \theta_\text{e} \) is the angle of incidence or in this case the zenith angle, the angle between the incoming sun ray and the vertical of the pond, the zenith.

The refractive index of the culture medium is assumed to be that of water, as the biomass concentrations are relatively low (<0.2 % w/w).

The reflection differs for direct light and diffuse light, as diffuse light reaches the pond surface from a variety of angles. The reflection for direct light changes with time as the position of the pond towards the sun changes and thus also the angle under which sun rays strike the surface.

The fraction of diffuse light that is reflected is approximated by using an equivalent angle for \( \theta_\text{x} \). The equivalent angle is an average of which has been found to be 60°[24]. The reflection of diffuse light is hence treated as that of direct light at a constant angle of incidence of 60°.

The angle of incidence for direct light on a horizontal surface \( \theta_\text{d} \) can be described by:

\[
\cos \theta_\text{d} = \cos \phi \cdot \cos \delta \cdot \cos \omega + \sin \phi \cdot \sin \delta
\]
Where $\varphi(\cdot)$ is the latitude of the reactor location, $\delta(\cdot)$ is the declination of the sun, i.e. the angle between the rays of the sun and the plane of the equator and $\omega(\cdot)$ is the hour angle, the angular displacement west or east of the local meridian due to the earth’s rotation on its axis[24].

$\delta$ varies during the course of a year between the two solstices (-23.45° ≤ $\delta$ ≤ 23.45°) and can be calculated by:

$$\delta = 23.45 \cdot \sin\left(\frac{360 \cdot (84 + N)}{365}\right)$$

Where $N$ is the day of the year.

The hour angle $\omega$ is related to the solar time and is an expression in angular units thereof. Solar time is a measurement of the apparent angular movement of the sun across the sky, noon in this timescale is the point when the sun crosses the local meridian.

Solar time can be calculated from the local time by using corrections for the difference in longitude from the local meridian and for deviations in the rotation of the earth:

$$t_{\text{sun}} = t_{\text{local}} + \frac{\lambda_{\text{local}} - \lambda}{60} + E$$

Where $t_{\text{sun}}$ is the solar time, $t_{\text{local}}$ is the local time, $\lambda_{\text{local}}(\cdot)$ is the local meridian, $\lambda(\cdot)$ is the longitude of the reactor location and $E(\cdot)$ is the correction factor for perturbations in the earth’s rate of rotation:

$$E = 229.2 \cdot (0.000075 + 0.001866 \cdot \cos B - 0.032077 \cdot \sin B - 0.0141 \cdot \sin 2B)$$

Where $B$ is the correction for the day of the year:
The hour angle $\omega$ is calculated from the solar time:

$$\omega = 15 \cdot \left( \frac{I_{\text{solar}}}{60} - 12 \right)$$

From the calculated $\theta_2$ for direct light and the assumed $\theta_2$ of 60° for diffuse light, the amount of light that enters the pond is calculated for both fractions using equations Error! Reference source not found.-Error! Reference source not found.. The amount of light that enters the pond as a function of time is then calculated by:

$$I_{\text{surface}}(t) = I_{\text{input}}(t) \cdot (1 - R)$$

Where $I_{\text{surface}}$(J m$^{-2}$ s$^{-1}$) is the fraction of light that is not reflected and $I_{\text{input}}$(J m$^{-2}$ s$^{-1}$) is the irradiance data for either direct or diffuse light. For the latter $I_{\text{input}}$ is equal to the data obtained from measurements. Whereas for direct light $I_{\text{input}}$ has to be calculated from the measured data using a correction factor as a consequence of the fact that the data stems from a rotating sensor. The sensor plate is set to follow the movement of the sun across the sky, so that the sun rays are always perpendicular to the sensor plate. The amount of light that would fall on a horizontal surface is then calculated using the theoretical angle of incidence $\theta_2$:

$$I_{\text{input direct}}(t) = I_{\text{measured direct}}(t) \cdot \cos \theta_2$$

Where $I_{\text{measured direct}}$(J m$^{-2}$ s$^{-1}$) is the data for direct irradiance obtained from measurements.
2.1.2 Light distribution in the pond:

Light that enters the reactor is considered to spread through the pond along its original path. The effect of light scattering by algae particles is assumed to nullify itself between different rays of light, as the algae concentration is homogenous in the pond. Shading by the reactor walls is neglected. A vertical light gradient in the pond is created by algal self shading. Self shading is a term for the absorption of light by algae cells, which then will not be available to algae in lower layers of the pond.

Light diffusion through a liquid influenced by absorption and scattering can be described as a function of biomass concentration and the light path, by the law of Lambert-Beer:

\[
I(t, C, d) = J_{\text{surf}}(t) \cdot e^{-\alpha C \cdot \rho d}
\]

Where \( I(\text{J m}^{-2} \text{ s}^{-1}) \) is the amount of light available at a certain depth \( d(\text{m}) \) and biomass concentration \( C(\text{kg m}^{-3}) \). The variable \( \alpha(\text{m}^{2} \text{ kg}^{-1}) \) is the absorption coefficient which is a specific parameter of the algae species used in the pond and \( \rho(\text{m}) \) is the path of the light.

Figure 2.2: Schematic representation of the changes of the sun lights way due to reflection and refraction. Also indicated is the vertical light gradient in the pond generated by algal self shading.

The effective path of light is computed from \( \theta_z \) and the depth of the pond \( d \):
Light that enters the water body is refracted, due to a change in optical densities between air and water. This phenomenon is described by Snell’s law:

\[
\frac{n_w}{n_a} \frac{\sin \theta_w}{\sin \theta_i} = \frac{n_i}{n_w}
\]

Where \( \theta_w \) is the angle of incidence of the refracted beam of light. For diffuse light \( \theta_i \) is once more considered to be \( 60^\circ \):

From \( \theta_w \) and the depth, the effective light path \( p \) is calculated[29] as it is visible from Figure 2.2:

\[
p(d) = \frac{d}{\cos \theta_w}
\]

Algae can only use the visible fraction of the light spectrum for photosynthesis. This fraction is therefore called photosynthetically active radiation (PAR) and accounts for around 43% of the total spectrum. Irradiance is furthermore converted to a photosynthetic photon flux density \( I_{PFD} (\mu\text{mol photons m}^{-2} \text{s}^{-1} \text{ or } \mu\text{E m}^{-2} \text{s}^{-1}) \), as photochemical reactions are based on the number of photons involved[1].

The light energy in \( \mu\text{mol photons m}^{-2} \text{s}^{-1} \) that is available for algal photosynthesis is hence:

\[
I_{PFD}(t, C_X, d) = 0.43 \cdot 4.57 \cdot f(t, C_X, d)
\]

### 2.2 Temperature
The temperature of a system significantly affects all biological and chemical reactions that it contains. As open pond reactors are especially susceptible to ambient conditions, a realistic temperature model is needed to accurately predict algae growth patterns.

A variety of approaches to model the temperature of ponds, swimming pools, lakes and similar systems have been published[30-36]. They all have in common that they are constructed around an energy balance for the system in question, which describes the thermal energy of the water body as the sum of different heat fluxes. However the description of these heat fluxes can vary quite a lot in terms of approach and complexity.

To model the fluctuating temperature of an open pond reactor five separate heat fluxes are considered (see Figure 2.3): Heating of the pond water due to incoming sun light, loss of energy due to the waters emission of radiation in the long wave spectrum, heat flux as a result of evaporation or condensation, heat exchange between the water body and the ambient air due to convection and also heat exchange among the pond and its surrounding soil layer due to conduction. This yields the following energy balance:

$$V_w \cdot \rho_w \cdot C_{p_w} \cdot \frac{dT_w}{dt} = Q_{\text{irradiance}} - Q_{\text{evaporation}} - Q_{\text{convection}} - Q_{\text{cond}}$$

Where $V_w$($m^3$) is the volume of the pond, $\rho_w$($kg \cdot m^{-3}$) is the density of the growth medium, $C_{p_w}$($J \cdot kg^{-1} \cdot \deg C^{-1}$) is the heat capacity of the growth medium, $T_w$(°C) is the temperature in the pond, $Q_{\text{irradiance}}$($W$) is the heating of the pond by sun light, $Q_{\text{radiation}}$($W$) is the heat loss of the pond by emission of radiation in the infrared region, $Q_{\text{evaporation}}$($W$) is the heat flux caused by either evaporation or condensation, $Q_{\text{convection}}$($W$) is the heat flux by convection and $Q_{\text{cond}}$($W$) is the heat exchange with the ground via conduction.
The volume of the pond is set to be constant at all times. This means that changes in the water volume due to mass transfer by evaporation or precipitation are considered to be balanced by an overflow/inflow system. Heat transfer on the basis of precipitation or the addition of growth medium is neglected. Algal respiration is also considered to have no effect on the temperature of the water. Furthermore any effect of the movement of the water due to mixing, on the different heat fluxes is not considered here but may play a significant role.

Meteorological data, including ambient temperature, dew point temperature, relative humidity, wind speed and pressure, was taken for Cabauw, the Netherlands and Tamanrasset, Algeria. The Cabauw measurements were again transformed into 10 minute averages from a 1 minute interval dataset, except for the dew point temperature, which is calculated from the relative humidity and the ambient temperature (see). Wind speed data for Cabauw was only available in form of daily average values. The wind speed dataset for Tamanrasset is comprised of 3 hour mean values. Both wind speed data sets are therefore interpolated to yield 10 minute averages.

2.2.1 Irradiance
The water inside the pond is heated by sun rays that strike the surface. All solar energy is considered to be converted into thermal energy when reaching the surface, except for the fraction of light that is used for photosynthesis by algae cells.

Warming of the pond by sunlight is therefore calculated by:

\[ Q_{\text{irradiance}} = A_{\text{surface}} \cdot I_{\text{heat}} \]

Where \( I_{\text{heat}}(W \text{ m}^2) \) is the irradiance that is not used for photosynthesis by algae:

\[ I_{\text{heat}} = I_{\text{surf}} - a_v E \cdot \mu \cdot C_x \]

\( a_v E(J \text{ kg algae}^{-1}) \) is the average energy content of the algae in the pond, \( \mu(s^{-1}) \) is the growth rate and \( C_x(\text{kg m}^{-3}) \) is the biomass concentration in the pond.

### 2.2.2 Evaporation and condensation

The energy flux between the pond and the ambient air as a result of evaporation or condensation is computed using a formula employed by Wooley et al.[35], which is supported by the findings of Sartori[37]. The equation is based on the difference of water vapour pressures between the ambient air and the saturated water body:

\[ Q_{\text{evaporation}} = A_{\text{surface}} \cdot h_{\text{evaporation}} \cdot (e_s - e_a) \]

Where \( h_{\text{evaporation}}(W \text{ m}^2 \text{ Pa}^{-1}) \) is the heat transfer coefficient due to evaporation, \( e_s(\text{Pa}) \) is the saturated water pressure at water temperature and \( e_a(\text{Pa}) \) is the water pressure of the air.

\( h_{\text{evaporation}} \) can be calculated by[35]:
Where \( u (\text{m s}^{-1}) \) is the wind speed.

\( e_s \) and \( e_a \) can be calculated using a formula developed by Bögel[38] using parameter values recommended by Buck[39]:

\[
\text{Equation 1: } e_s = 611.21 \cdot e^{\frac{17.58 \cdot T_s}{T_s - 273.16}}
\]

\[
\text{Equation 2: } e_a = \text{rh} \cdot 611.21 \cdot e^{\frac{17.58 \cdot T_a}{T_a - 273.16}}
\]

Where \( \text{rh} \) is the relative humidity.

Heat loss via evaporation is accordingly higher in areas with a dry climate, due to the greater difference between \( e_a \) and \( e_s \). Condensation can only occur under fairly humid conditions and if the ambient temperature \( T_a \) is higher than the water temperature \( T_w \).

### 2.2.3 Convection

Convection along the water surface is sometimes calculated to include the effect of evaporation, as convective heat transfer is caused by the motion of fluids or gases, which evaporation essentially is. In this case the term convection covers diffusion of molecules between ambient air and the water body, as well as forced convection induced by wind.

Wooley et al. link heat transfer by convection to heat flux by evaporation, via the ratio of Bowen[35]:

\[ Q_c = 
\]
Bowen developed a formula to calculate this ratio for changing environmental conditions[40]:

$$R_{\text{bowen}} = \frac{Q_{\text{convection}}}{Q_{\text{evaporation}}}$$

Where $C_{\text{bowen}}(\text{Pa \degree C}^{-1})$ is a constant, $P_a(\text{Pa})$ is the ambient pressure and $P_{\text{ref}}(\text{Pa})$, the reference pressure, is also a constant.

The energy flux by convection is then calculated by simply multiplying the Bowen ratio with the evaporative heat flux:

$$Q_{\text{convection}} = R_{\text{bowen}} \cdot Q_{\text{evaporation}}$$

### 2.2.4 Conduction

Conductive heat transfer is the transfer of thermal energy from a molecule to a neighbouring molecule due to an existing temperature gradient.

Heat transfer by conduction is calculated according to Fourier’s law:

$$Q_{\text{conduction}} = k \cdot A_{\text{ground}} \cdot \frac{T_w - T_{\text{ground}}}{x}$$

Where $k(\text{W m}^{-1} \text{\degree C}^{-1})$ is the thermal conductivity of the ground, $A_{\text{ground}}(\text{m}^2)$ is the area of the pond floor and walls, $T_{\text{ground}}(\text{\degree C})$ is the temperature of earth surrounding the pond and $x(\text{m})$ is the thickness of the surrounding soil layer.
The ground surface is calculated from the water surface area, the length of the pond walls and the depth of the pond:

\[ M_{\text{ground}} = A_w + 2 \cdot d \cdot \text{length} \]

The ground temperature is gathered from a 30min intervals dataset for Cabauw[41], where the temperature was measured at a depth of 50cm. In the case of Tamanrasset, for the lack of any data, a constant 15°C were assumed[42, 43]. The ground temperature is furthermore set to be independent of the pond temperature and to equal in all places surrounding the pond, i.e. there is no difference in between the temperatures of the pond walls and the pond floor. The thermal conductivity of the soil for Cabauw is established to be 0.601W m\(^{-1}\) °C\(^{-1}\)[44]. For Tamanrasset there was yet again no specific data available for \( k \). As the thermal conductivity could realistically lie anywhere inside 0.25 to 2 W m\(^{-1}\) °C\(^{-1}\), the value for Cabauw was also applied for Tamanrasset.

The influence of the thin PVC lining, that is used to cover the floor in practice, is also neglected.

### 2.2.5 Radiation

Every object with a temperature greater than the absolute zero emits thermal energy in the form of electromagnetic waves. The higher the temperature of the object the more energy is emitted. As a result the very same object or molecule is simultaneously reached by the radiation of other molecules. Heat is then transferred to objects with a lower temperature.

The energy exchange due to radiation between the surface and the sky is calculated as suggested by Hahne et al.[32] and Duffie and Beckman[24]:

\[ Q_{\text{radiation}} = A_{\text{surface}} \cdot \varepsilon \cdot \sigma \cdot \left( T_w^4 + 287.15 \right) - T_{\text{sky}}^4 \]
Where $A_{\text{surface}}$ (m$^2$) is the area of the pond surface, $\varepsilon_{\text{w}}$ is the emissivity of water in the infrared region, $\sigma$ (W m$^{-2}$ K$^{-4}$) is the Stefan-Boltzmann constant and $T_{\text{sky}}$ (K) is the equivalent sky temperature for clear sky days[24, 45]:

\[
(2.295)\ T_{\text{sky}} = (237.15 + T_a) \cdot [0.711 + 0.0056 \cdot T_{\text{dew}} + 0.000973 \cdot T_{\text{dew}}^2 + 0.00000841 \cdot T_{\text{dew}}^3]
\]

Where $T_a$ (°C) is the ambient temperature, $T_{\text{dew}}$ (°C) is the dew point temperature and $t_{\text{solar}}$ is in this case the number of hours that have elapsed since midnight. The effect of cloud cover is not included in the calculation of the sky temperature, due to lack of suitable data. However it should be noted that clouding increases the sky temperature and hence may have significant impact on the radiation flux.

For Cabauw, the Netherlands, no data was available for the dew point temperature. $T_{\text{dew}}$ is therefore calculated on the basis of the water pressure of the ambient air $e_a$ from equation Error! Reference source not found., using a rearranged version of equation Error! Reference source not found.:

\[
(2.302)\ T_{\text{dew}} = \frac{240.97 \cdot \ln \left(\frac{e_a}{611.21}\right)}{17.502 - \ln \left(\frac{e_a}{611.21}\right)}
\]

2.3 Algal growth

The growth rate of an algal cell is influenced by a variety of factors including light, temperature, nutrients and pH. These factors are commonly regarded as independent and the specific growth rate is then described as the product of all these influences:

\[
(2.313)\ \mu(t) = \mu_{\text{max}} \cdot f_1(t) \cdot f_2(t) \cdot f_{\text{UV}}(t) \cdot f_N(t) \ldots - r
\]
The specific growth rate is hereby described as the product of $\mu_{\text{max}}$ with a variable number of factors $f$ which all range from 0 to 1 ($0 \leq f \leq 1$) minus the respiration rate of the algae cells. If a factor is not considered in the calculation it is simply regarded as optimal and set to be 1.

A similar approach is chosen here, with available light energy and temperature being the factors that are examined. The difference in this work is that the factor temperature is also assumed to affect the respiration rate.

### 2.3.1 Growth rate as a function of light

Several extensive descriptions of the growth rate as a function of light have been proposed as reviewed by Zonneveld[46]. They are all based on photosynthesis-irradiance (PI) curves, but vary a lot with regard to in which variables these curves are expressed. While some simply use Steele’s equation in combination with light saturation as the only parameter, others have chosen for a mechanistic modelling approach to simulate the changes that occur within a cell. Complex mechanistic models may offer more accuracy in the predictions and can yield more information on the algal cell composition. However these models are limited by the quality of the experimental parameter measurements.

The mechanistic approach by Geider et al.[47], was chosen in this thesis simply because the variables that are used in their approach are commonly measured and because the article already provides a good set of parameter values.

Geider et al. link the photosynthetic activity of algae cells to the irradiance and the irradiance dependent chlorophyll a:carbon ratio. Chlorophyll a is one of the major light absorbing pigments found in the light harvesting apparatus of most photosynthetic organisms. Algae produce more chlorophyll at low light levels to compensate for the lower light intensity and vice versa chlorophyll a production is downregulated at high light intensities, where light saturation is already reached. Light saturation is caused by the fact that the rate of the CO$_2$ fixation process and especially that of key-enzyme RuBisCo is limited[48]. Therefore a theoretical surplus of cellular energy/electron carriers generated by additional light capturing could not be utilized by algae cells and is hence not promoted.

The equation developed by Geider et al. is:
\[ \mu_{\text{light}}(\text{d}^{-1}) = \frac{P_{S_{\text{max}}}^C}{1 - e^{-\frac{-\alpha I_{\text{FED}}}{P_{S_{\text{max}}}^C}} - r. \]

Where \( \mu_{\text{light}}(\text{d}^{-1}) \) is the light dependant growth rate, \( P_{S_{\text{max}}}^C \) is the carbon specific maximum rate of photosynthesis, \( a(\text{g C m}^2 \text{ mol photons}^{-1} \text{ g Chl a}^{-1}) \) is the initial slope of the PI curve, \( \phi(\text{g Chl a}^{-1} \text{ g C}^{-1}) \) is the chlorophyll a:carbon ratio in the algae cells and \( r(\text{d}^{-1}) \) is the respiration rate, which is a fixed constant in this case.

The carbon specific maximum rate of photosynthesis is calculated from the maximum growth rate and the respiration rate:

\[ P_{S_{\text{max}}}^C = \mu_{\text{max}} + r \]

Where \( \mu_{\text{max}}(\text{d}^{-1}) \) is the maximum growth rate, i.e. when all conditions are optimal.

The chlorophyll a:carbon ratio which is also dependent on the irradiance is computed from:

\[ \Theta = \frac{1}{1 + \frac{\Theta_{\text{max}} - \Phi_{\text{max}} - \alpha I_{\text{FED}}}{2 P_{S_{\text{max}}}^C}} \]

With \( \Theta_{\text{max}}(\text{g Chl a}^{-1} \text{ g C}^{-1}) \) as the maximal chlorophyll a:carbon ratio.
Figure 2.4: Growth rate $\mu_{\text{light}}(\text{d}^{-1})$ as a function of irradiance $I_{\text{PFD}}(\mu\text{mol photons m}^{-2}\text{ s}^{-1})$ for the microalgae *Phaeodactylum tricornutum*. All other growth affecting conditions are optimal.

The commonly observed effect of photoinhibition, which occurs when the photosynthetic apparatus is damaged by a too high light intensity, is not included in the formulation of Geider *et al.* and is not added here. Even though this effect has been recognized for quite some time, light dependant measurements of algae growth are often carried out under conditions that are not comparable to normal to sunlight in terms of intensity. Therefore a quantification of the effect is still difficult and hence not employed here.

### 2.3.2 Growth rate as a function of temperature

Similar to the light dependent growth rate, several equations have been proposed to model the effect of temperature on the growth rate[49],[50]. The greatest difficulty in describing the temperature dependence of growth is however not related to which formulation is used. Experimental measurements of this dependence are often carried out only in a fairly small range of temperatures and only few discrete points are examined, which leads to a large uncertainty attached to the parameters of the description.
In this work the non-linear model of Blanchard et al.[50] is used, as its asymmetric shape seems to represent the temperature dependent growth adequately. The model of Blanchard et al. is based on the optimal temperature, a value at which the growth rate is maximal, a lethal temperature, i.e. a temperature above which no growth can take place and a modulating constant.

$$\mu_{\text{temperature}} = \mu_{\text{max}} \left( \frac{T_{\text{tet}} - T_{\text{w}}}{T_{\text{tet}} - T_{\text{opt}}} \right)^{\beta} e^{-\beta \left( \frac{T_{\text{tet}} - T_{\text{opt}}}{T_{\text{tet}} - T_{\text{opt}}} - 1 \right)}$$

Where $T_{\text{tet}}$(°C) is the lethal temperature, $T_{\text{opt}}$(°C) is the optimal temperature and $\beta$ is the curve modulating constant.

Parameter values for $T. \text{pseudonana}$ were taken from Claquin et al.[51], however it should be noted that these parameters values are derived from measurements under non optimal light conditions, which may have an influence on the shape of the curve.

Parameter values for $P. \text{icornutum}$ were generated by fitting equation Error! Reference source not found.) to data obtained by Montagnes and Franklin[52] and William et al.[53] (see Figure 2.5).

![Figure 2.5: The maximal growth rate $\mu_{\text{max}}$ ($d^{-1}$) as a function of the Temperature(°C) for $P. \text{icornutum}$. The parameters of equation Error! Reference source not found.) are fit to experimental data from William et al.(stars) and Montagnes and Franklin(circles).](image-url)
### 2.3.3 Effective growth rate

As the temperature of the system influences all metabolic activities, the respiration rate will also be affected. The fact that both the photosynthetic rate and also the respiration rate are altered by the temperature leads to a formulation for the effective/apparent growth rate.

\[
\mu_{\text{effective}} = \mu_{\text{light}} \cdot \left( 1 - e^{\beta \left( T_{\text{opt}} - T\right)} \right)
\]

Where \( \mu_{\text{effective}} (d^{-1}) \) is the effective growth rate of the system at a certain depth.

### 2.3.4 Production

The accumulation of biomass in the pond is given by the following first order differential equation:

\[
\frac{dC_x(t)}{dt} = (\mu_{\text{effective}}(t, d) - D(t)) \cdot C_x
\]

Where \( D(d^{-1}) \) is the dilution rate, i.e. the rate of outflow of the reactor.

The dilution rate is set to be equal to the growth rate, so that the reactor operates in steady state therefore no change in biomass concentration occurs. This is done to bypass using an elaborate control function for the dilution rate. However it should be noted that such a control function could optimize productivity.

When the dilution rate is equal to the effective growth rate, the areal production as a function of time is calculated by integrating over the depth of the pond:
\[ Y_{\text{area}}(t) = 0.8 \cdot \int_{d}^{\text{d eff}} \mu_{\text{eff}}(t, d) \cdot C_{\text{b}} \cdot d d \]

Where \( Y_{\text{area}}(t) \) in kg biomass m\(^{-2}\) is the areal biomass production of the whole pond at a certain time. The factor 0.8 is added, because it is assumed that only 80% of a hectare would be actual water surface, while the rest would be covered by reactor walls and other units involved in the operation of such a plant.

To be able to compare the simulation results to literature data and life cycle analysis data, the areal productivity is transformed into a yearly productivity by integrating over the time span of one year:

\[ Y_{\text{yearly}} = 10 \cdot \int_{t_{\text{year}}}^{t_{\text{year}}} Y_{\text{area}}(t) \cdot dt \]

Where \( Y_{\text{yearly}} \) (t biomass ha\(^{-1}\) y\(^{-1}\)) is the biomass production of a open pond reactor plant in one year. The factor 10 is applied to transform kg m\(^{-1}\) into t ha\(^{-1}\).
3 Results and discussion

Algal biomass production was first simulated for the algae species *Phaeodactylum tricornutum*. Simulations were run at a constant optimal temperature and at a variable, ambient dependent temperature to illustrate the differences in biomass production. The simulations run at an optimal temperature were carried out for the Netherlands, France and Algeria. Simulations carried out with a variable temperature were done for the Netherlands and Algeria only, as there was not sufficient meteorological data available for France. These simulations were all done under non optimized conditions, with a pond depth of 0.3 m and a biomass concentration of 0.5 kg m\(^{-3}\). Pond depth and biomass vary significantly in literature\[1\], so that this standard, being a reasonable average, was chosen. Optimisation by variation of the pond depth and the biomass concentration was done subsequently. The same simulations were then conducted for the algae *Thalassiosira pseudonana*, to evaluate the influence of the algae parameters.

3.1 Light dependent biomass production

Algal biomass production solely dependent on the available light, i.e. at a constant optimal temperature, was simulated for three locations: Cabauw, the Netherlands, Carpentras, France and Tamanrasset, Algeria. The results of these simulations can be seen in Figure 3.1. The simulations were done under non optimised conditions (\(d=30\)cm, \(C_x=0.5\)kg m\(^{-3}\)) for the algae species *P. tricornutum*.

All three simulations showcase a clear correlation between the daily biomass production and the day length. This was expected as algal growth can obviously only be maintained under illumination. The pattern is clearer for the Netherlands and France, where there is a greater variation in day length between the different seasons of the year, which also leads to stronger variations in the daily biomass production in winter and summer. Conversely in Algeria where the day length difference during a year is maximal two hours, the daily biomass production is also fairly constant and larger variations are caused by other effects, i.e. clouding.

Higher peak values can be reached during the summer in the Netherlands and France, where the daily biomass production approximates 200 kg ha\(^{-1}\) d\(^{-1}\), while in Algeria the peak
values lie just above the 170 kg ha \(^{-1}\) d \(^{-1}\) threshold. This is a direct result of the longer illumination times in these regions. However during the winter months biomass production might even become negative. A loss of biomass occurs, as the biomass gains via photosynthesis throughout the day cannot compensate for respiratory losses during dark phases. This is most prominently visible for the Netherlands where biomass production would only be practical during a rather small time frame. Production in France would be affected similarly even though to a much lesser extent as the irradiance does not shrink as drastically during the winter as in the Netherlands. Low production values also occur in Algeria, but are limited to a few distinct days and are caused by clouding and thus low levels of direct radiation but not by low levels of total radiation, as can be seen in Figure 6.1 (appendix).

Striking is also that day by day variations in biomass production are far stronger pronounced in the Netherlands than in France or Algeria, this is probably a result of stronger weather variations and thus more cloud movement.

Compared to predicted biomass production in flat panel reactors from Slegers et al.[54], stronger day by day variations in biomass productivities are visible for all investigated locations, indicating, that the light levels are often inadequate to penetrate such a deep pond. Noticeable is also that open ponds are affected significantly more by phases of bad weather. Diffuse light cannot be utilised by open pond systems as much as by flat panel reactors, which is apparent from the gaps that can be seen in Figure 3.1 (C) during the Algerian summer. Remarkable is also that productivities are negative throughout the winter in the Netherlands and significantly lowered during the winter in France. However for flat panel reactors low or even negative productivities are limited to the Netherlands. For France production remains stable during the winter period albeit a bit lowered. The drop in average daily biomass production that can be seen in Algeria during the winter month for open ponds is also far less pronounced if not absent for a flat panel system. Flat panel reactors thus seem to offer a more continuous performance during the year. Algae could be grown over a longer period in the Netherlands and all year long in France at a reasonable level.

The yearly production increases with lower latitudes and is hence the highest for Algeria with 45 t ha \(^{-1}\) y \(^{-1}\), second highest for France with 34 t ha \(^{-1}\) y \(^{-1}\) and the lowest for the Netherlands with 19.2 t ha \(^{-1}\) y \(^{-1}\).
Figure 3.1: Irradiance dependent daily biomass production (kg ha\(^{-1}\) d\(^{-1}\)) and day length (h\(^{-1}\)) during the course of a year for three locations: (A) Cabauw, the Netherlands, (B) Carpentras, France and (C) Tamanrasset, Algeria. The algae species used in these simulations is \textit{P. tricornutum}. The depth of the pond is 30cm. The biomass concentration is constant at 0.5 kg m\(^{-3}\).

3.2 Biomass production influenced by temperature

To simulate realistic conditions that would be found when operating raceway ponds the effect of temperature on the biomass production was taken into account. The results of these simulations can be seen in Figure 3.2. Compared to the results found in the previous passage, it is noticeable that the daily biomass production values are principally lower, except for those times where the productivity was negative which are conversely generally higher. Lower productivities can be explained by the fact that non-optimal temperatures only have diminishing effects on the algae growth and never affect it positively. Higher productivities, on winter days are caused by the moderating effect of temperature on the respiration rate of algae cells. The influence of temperature is the most evident for the Netherlands, where during the winter period productivities are fluctuating around 0 kg ha\(^{-1}\) y\(^{-1}\) compared to -45 to -20 kg ha\(^{-1}\) d\(^{-1}\) as visible in Figure 3.1(A). During the summer the daily biomass production in the Netherlands is greatly decreased, quite often even by a value of up to 50 kg ha\(^{-1}\) d\(^{-1}\). This indicates that algae growth is very sensitive to temperature deviations.
Figure 3.2: Irradiance and temperature dependent daily biomass production (kg ha\(^{-1}\) d\(^{-1}\)) during the course of one year. The algae species used in these simulations is *P. tricornutum*, the pond depth is 30 cm and the biomass concentration is 0.5 kg m\(^{-3}\). (A) Cabauw, the Netherlands. (B) Tamanrasset, Algeria.

Figure 3.2 (B) shows that the daily biomass production is also universally lower in Algeria. However the difference between different seasons due to temperature is not as substantial as in the Netherlands. The productivity pattern itself is unlike in the Netherlands relatively unchanged. The winter period gets more pronounced due to disproportionately lowered productivities. The resulting pattern can be attributed to the fact that the daily deviations in pond temperature are also quite constant throughout the year. The daily average pond
temperature in Algeria fluctuates around 12-15°C, with the exception being the winter period where the temperatures are on average a bit lower. In the Netherlands on the other hand the pond temperature follows a typical four seasons pattern, as can be seen in Figure 3.3 and Figure 6.2 (appendix). A closer look at the pond temperature variations in Algeria, as shown in Figure 3.4, reveals that temperature changes during a single day are far more distinct than the variation in between different seasons. Figure 3.4 also provides a good explanation for the relatively low drop in productivity: the temperature is approaches the optimum during the day which promotes growth, while it is conversely relatively cold during the night, which in turn reduces respiratory biomass losses.

Figure 3.3: Average daily pond temperature(°C) over the period of one year. (A) Cabauw, the Netherlands. (B) Tamanrasset, Algeria.
Yearly biomass yields are 15.6 t ha\(^{-1}\) y\(^{-1}\) for the Netherlands and 35.8 t ha\(^{-1}\) y\(^{-1}\) for Algeria. The rather low drop in yearly biomass production in the Netherlands can be attributed to the fact that lower yields during the summer are offset by higher yields in the winter. Previously high respiratory losses are damped by low temperatures. Production nevertheless remains pointless in winter, as the yields are around 0 kg ha\(^{-1}\) d\(^{-1}\), so that production can best be halted completely during these periods.

The gap in yearly production for Algeria of nearly 10 t ha\(^{-1}\) y\(^{-1}\) between production as a function of varying light and production as a function of varying light and temperature, showcases that open ponds are very susceptible to varying temperatures. This can significantly reduce their production potential.
3.3 Effects of decision variables on biomass production

Yearly biomass production can be optimized by varying the depth of the pond and the biomass concentration, as to maximize the utilisation of the available light. Theoretically even daily biomass production could be optimised by controlling the dilution rate and thus also the biomass concentration. This would subsequently also lead to an improved yearly biomass yield.

Figure 3.5 shows a clear trend for the yearly biomass production as a function of pond depth and biomass concentration. For both the Netherlands and Algeria, yearly biomass production increases with higher biomass concentrations and lower depths. Reducing the depth however boosts the productivity only up to the point where all available light energy can be used. Further reduction of depth leads to the phenomenon that there are simply not enough algae cells to utilise all the available light energy. Vice versa lower yields at higher depths are due to an excess of algae cells in relation to the available sunlight.

The curves are sharper for higher biomass concentrations as small deviations in the pond depth logically have stronger effects on the total amount of algae compared to low biomass concentrations. The total amount of algae is crucial in determining whether there is too much or not enough light available, so that fluctuations thereof decide the productivity. Lower biomass concentrations thus might be beneficial to the productivity, despite leading to decreased maximum values, as slight fluctuations in the biomass concentration do not have such a strong impact. Low biomass concentrations are however less desirable for downstream processing as mentioned earlier.

The overall pattern is slightly shifted towards lower depths for the Netherlands in comparison to Algeria, as the total amount of available light is simply lower at higher latitudes. This is also confirmed by the significantly higher optimal values that are achievable in Algeria, which are directly related to the amount of usable light energy. The maximal yearly biomass production in Algeria can be more than double that of the Netherlands. In Algeria yearly yields can be up to 45.1 t ha\(^{-1}\) y\(^{-1}\) whereas in the Netherlands values of around 22.2 t ha\(^{-1}\) y\(^{-1}\) are achievable. This indicates how much the choice of location affects the production potential of an open pond reactor.
Figure 3.5: Yearly biomass production (t ha\(^{-1}\) y\(^{-1}\)) as a function of the pond depth (m) for varying biomass concentrations (kg m\(^{-3}\)). The algae species used in these simulations is *P. tricornutum*. (A) Cabauw, the Netherlands. (B) Tamanrasset, Algeria.

Figure 3.6 shows how daily biomass productions are affected by varying biomass productions. If the biomass concentration is below the optimum for a specific depth (see Figure 3.6 A) biomass yields as well as respiratory losses will be relatively low, leading to an even pattern. Higher biomass concentrations will raise daily biomass yields on those days.
where a surplus of light energy is available and will lower yields on those days where the sunlight was already insufficient. Raising the biomass furthermore eventually leads to a point where only more respiratory losses are promoted, as additional algae cells cannot be supplied with sunlight. In practice biomass concentrations therefore should be kept around the optimum for the given pond depth to maximize the productivity. The same effect is visible for the Netherlands as can be seen in Figure 6.3 (appendix).

Daily biomass yields under optimised conditions are shown in Figure 3.7. Noticeable is that the production levels are more even throughout the year for Algeria as compared to those under standard conditions (Figure 3.2 B). In the Netherlands the production pattern remains the same, while the yields are generally raised. In Algeria an average daily productivity of 12.4 g m$^{-2}$ d$^{-1}$ is achieved under these conditions, with peak values being lower than 15 g m$^{-2}$.
In the Netherlands this results in an average of 6.1 g m$^{-2}$ d$^{-1}$, but days with up to 20 g m$^{-2}$ d$^{-1}$ are possible in the summer. In literature a few comparable values can be found for *P. tricornutum* cultivation. Thomas *et al.*[55] report maximum values of 22 g m$^{-2}$ d$^{-1}$ for batch cultures in an flat panel like setup run in California. Ansell *et al.*[56] found yields of up to 8 g m$^{-2}$ d$^{-1}$ under fairly unfavourable conditions in outdoor tanks tested in England. Raymond[57] furthermore reports yields of 41 g m$^{-2}$ d$^{-1}$ for raceway ponds placed on Hawaii, the exact experiment setup could however not be reviewed. A comparison to these values seems to indicate that the models predictions are fairly low, this could however be caused by the non optimal dilution rate and the inclusion of the factor 0.8 in the computation of all areal productivities.

(A)

![Graph A](image1)

(B)

![Graph B](image2)
Figure 3.7: Daily biomass production for *P. tricornutum* over the period of one year for optimised conditions. (A) Cabauw, the Netherlands, the pond depth is 0.08 m and the biomass concentration is 1 kg m$^{-3}$. (B) Tamanrasset, Algeria, the pond depth is 0.1 m and the biomass concentration is 0.9 kg m$^{-3}$.

3.4 Differences in biomass production between two algae species

Similar simulations as those shown in the previous section were also carried out for *Thalassiosira pseudonana*, to evaluate the sensitivity of the system towards the influence of different algae species.

Figure 3.8: Daily biomass production (kg ha$^{-1}$ d$^{-1}$) over the period of one year for the algae *T. pseudonana*. The pond depth is 30cm, the biomass concentration is 0.5 kg m$^{-3}$. (A) Cabauw, the Netherlands. (B) Tamanrasset, Algeria.
*T. pseudonana* shows generally lower yields, in comparison to *P. tricornutum*. Light and temperature dependent biomass production under standard conditions (d=0.3 m, C<sub>x</sub>=0.5 kg m<sup>-3</sup>) are considerably lower as can be seen in Figure 3.8. The production pattern however remains essentially unchanged for both investigated locations. For those days where biomass production occurs, production levels are reduced by a value of around 90 kg ha<sup>-1</sup> y<sup>-1</sup> on average compared to *P. tricornutum*. *T. pseudonana* is furthermore affected by lower temperatures to a greater extent than *P. tricornutum*. This is apparent when surveying those days where negative productivities prevail, as the daily yields are closer to zero kg ha<sup>-1</sup> d<sup>-1</sup>, indicating that the respiration rate and thus also the growth rate are diminished greatly by the temperature term.

Yearly biomass productivities for the standard case are consequently also lowered to 7.3 t ha<sup>-1</sup> y<sup>-1</sup> for the Netherlands and accordingly 15.4 t ha<sup>-1</sup> y<sup>-1</sup> for Algeria. When optimizing the yearly biomass production for *T. pseudonana* by varying the depth of the pond and the steady state biomass concentration, it is noticeable that the optimum is shifted towards relatively low depths (see Figure 3.9). This can be explained by the high light absorption coefficient of *T. pseudonana*, which severely reduces the depth the sunlight can penetrate. This consequently leads to a larger dark area in the pond, where only respiration takes place, which reduces the overall biomass yield even more. From Figure 3.10 it can be seen that for a biomass concentration of 0.5 kg m<sup>-3</sup> for *T. pseudonana* sunlight will on average only reach water layers mere millimetres under the surface, while for *P. tricornutum* under equal conditions light penetration can be up to 8 cm on some days. This indicates that *T. pseudonana* can in practice only be grown in ponds with a maximum depth of 10 cm and then only at relatively low biomass concentrations. Closed photobioreactors are due to their minimised light path probably a much better choice for this algae species.
Figure 3.9: Yearly biomass production (t ha$^{-1}$ y$^{-1}$) as a function of the pond depth (m) for varying biomass concentrations (kg m$^{-3}$). The algae species used in these simulations is $T. pseudonana$. (A) Cabauw, the Netherlands. (B) Tamanrasset, Algeria.
However even under optimised conditions yearly productivities are considerably lower than those achievable for *P. tricornutum*, indicating that *T. pseudonana* simply does not offer the same potential for high biomass yields as *P. tricornutum*. Maximum values obtainable are 9.7 t ha$^{-1}$ y$^{-1}$ for the Netherlands and 19.4 t ha$^{-1}$ y$^{-1}$ for Algeria. Transformed into average daily biomass productivities this gives 26.6 kg ha$^{-1}$ d$^{-1}$ (2.7 g m$^{-2}$ d$^{-1}$) and 53.2 kg ha$^{-1}$ d$^{-1}$ (5.3 g m$^{-2}$ d$^{-1}$) respectively. These values are less than half of what is attainable when using *P. tricornutum*, showing that there can be vast differences between different algae species. A comparison between Figure 3.7 and Figure 3.11 shows that differences in daily biomass production can be as high as 100 kg ha$^{-1}$ d$^{-1}$ under optimised conditions.

Figure 3.10: Average irradiance (µmol photons m$^{-2}$ s$^{-1}$) as a function of depth over the course of one year for Cabauw, the Netherlands. The biomass concentration is 0.5 kg m$^{-3}$. (A) *P. tricornutum*. (B) *T. pseudonana*. 
Figure 3.11: Daily biomass production for *T. pseudonana* over the period of one year for optimised conditions. (A) Cabauw, the Netherlands, the pond depth is 0.04 m and the biomass concentration is 0.9 kg m$^{-3}$. (B) Tamanrasset, Algeria, the pond depth is 0.04 m and the biomass concentration is 1 kg m$^{-3}$. 
4 Conclusions

The results presented in the previous chapter imply that the potential algal biomass production in an open pond reactor is to a great extent dependent on which location is chosen. Productivities can potentially be doubled or halved depending on the choice of location. The same holds true for the choice of algae species, which also vastly influences the biomass production.

A relatively basic mathematical model as the one presented here, gives the possibility to significantly improve estimates used in life cycle assessments or commercial planning. A variety of realistic scenarios can be analysed using commonly available meteorological data and data gathered for the algae species of choice from experiments. This helps in verifying assumptions and in recognising of what is actually possible with this technology. The need for expensive trial systems is also reduced by more and more accurate predictions.

A model also offers the possibility of optimizing construction related parameters such as the depth of the pond before actually constructing it, as shown in section 3.3. An implementation of a control function for the dilution rate could also, besides enhancing the accuracy of the results, be used to improve the harvesting cycles of such a system.

As the efficiency of an open pond system is not only given by its biomass yield but is also dependent on its energy and water requirements, it might be vital to extent the model to include those factors. Energy requirements are also profoundly dependent on the post processing of the product stream generated by a pond reactor. Post processing is generally less energy intensive for higher biomass concentrations in the product stream, implying that high biomass yields are not always a guarantee for low production costs. For a thorough evaluation of the potential of an open pond reactor an inclusion of those factors is therefore necessary.

5 Acknowledgements

Foremost I would like to thank my supervisors Ellen Slegers and Ton van Boxtel for their indispensable guidance through this thesis project. I am also very grateful for the amount of work Ellen Selgers has invested into this project, preparing most of the datasets and providing a number of modules used in the model. I would also like to thank Peter van Beveren who supplied numerous very helpful suggestions and ideas for this work.
6 Appendix

6.1 Nomenclature

Table 6.1: Notation used in the description of the system.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
</tr>
<tr>
<td>a</td>
<td>Initial slope of the PI curve</td>
<td>g C m⁻² mol photons⁻¹ g Chl a⁻¹</td>
</tr>
<tr>
<td>avE</td>
<td>Average energy content of algal biomass</td>
<td>J kg algae⁻¹</td>
</tr>
<tr>
<td>B</td>
<td>Correction factor for the day of the year</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>C Bowen</td>
<td>Bowen constant</td>
<td>Pa ° C⁻¹</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific heat capacity</td>
<td>J kg⁻¹ ° C</td>
</tr>
<tr>
<td>Cx</td>
<td>Biomass concentration</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>d</td>
<td>Depth of the pond</td>
<td>m</td>
</tr>
<tr>
<td>D</td>
<td>Dilution rate</td>
<td>d⁻¹</td>
</tr>
<tr>
<td>E</td>
<td>Correction factor for perturbations in the earth's rate of rotation</td>
<td>min</td>
</tr>
<tr>
<td>e</td>
<td>Water vapour pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>h</td>
<td>Heat transfer coefficient</td>
<td>W m⁻² Pa⁻¹</td>
</tr>
<tr>
<td>I</td>
<td>Irradiance</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity</td>
<td>W m⁻¹ ° C⁻¹</td>
</tr>
<tr>
<td>Length</td>
<td>Length of the pond</td>
<td>m</td>
</tr>
<tr>
<td>n</td>
<td>Refractive index</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>N</td>
<td>Day of the year</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>p</td>
<td>Path of light</td>
<td>m</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>PS C</td>
<td>Carbon specific rate of photosynthesis</td>
<td>d⁻¹</td>
</tr>
<tr>
<td>Q</td>
<td>Heat flux</td>
<td>W</td>
</tr>
<tr>
<td>R</td>
<td>Reflection coefficient</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>r</td>
<td>Respiration rate</td>
<td>d⁻¹</td>
</tr>
<tr>
<td>R Bowen</td>
<td>Bowen ratio</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>Rh</td>
<td>Relative humidity</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>min or h (see subscript)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>° C (K for T sky)</td>
</tr>
<tr>
<td>u</td>
<td>Wind speed</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>m³</td>
</tr>
<tr>
<td>Width</td>
<td>Width of the pond</td>
<td>m</td>
</tr>
<tr>
<td>X</td>
<td>Thickness of the surrounding soil layer</td>
<td>m</td>
</tr>
<tr>
<td>Y</td>
<td>Biomass yield/Biomass production</td>
<td>See subscript</td>
</tr>
<tr>
<td>I PFD</td>
<td>Photon flux density</td>
<td>µmol photons m⁻² s⁻¹</td>
</tr>
<tr>
<td>Greek letters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>µ</td>
<td>Growth rate</td>
<td>d⁻¹</td>
</tr>
<tr>
<td>β</td>
<td>Modulation parameter of µ(T)</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>δ</td>
<td>Declination of the sun</td>
<td>°</td>
</tr>
<tr>
<td>ε&lt;w&gt;</td>
<td>Emissivity of water in the infrared region</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>Θ</td>
<td>Chlorophyll a: carbon ratio</td>
<td>g Chl a⁻¹ g C⁻¹</td>
</tr>
<tr>
<td>θ</td>
<td>Angle of incidence</td>
<td>°</td>
</tr>
<tr>
<td>λ</td>
<td>Longitude of the reactor location</td>
<td>°</td>
</tr>
<tr>
<td>λₘ</td>
<td>Local meridian</td>
<td>°</td>
</tr>
<tr>
<td>ρ</td>
<td>Density</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>σ</td>
<td>Stefan-Boltzmann constant</td>
<td>W m⁻² K⁴</td>
</tr>
<tr>
<td>φ</td>
<td>Latitude of the reactor location</td>
<td>°</td>
</tr>
<tr>
<td>ω</td>
<td>Hour angle</td>
<td>°</td>
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<table>
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<tr>
<th>Subscripts</th>
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<tr>
<td>a</td>
<td>Ambient air</td>
<td></td>
</tr>
<tr>
<td>areal</td>
<td>Areal productivity</td>
<td>kg m⁻²</td>
</tr>
<tr>
<td>conduction</td>
<td>Heat flux due to conduction</td>
<td></td>
</tr>
<tr>
<td>convection</td>
<td>Heat flux due to convection</td>
<td></td>
</tr>
<tr>
<td>dew</td>
<td>Dew point temperature</td>
<td></td>
</tr>
<tr>
<td>effective</td>
<td>Effective growth rate</td>
<td></td>
</tr>
<tr>
<td>evaporation</td>
<td>Heat flux due to evaporation/condensation</td>
<td></td>
</tr>
<tr>
<td>ground</td>
<td>Soil layer around the pond</td>
<td></td>
</tr>
<tr>
<td>heat</td>
<td>Fraction of irradiance that is considered to heat up the pond</td>
<td></td>
</tr>
<tr>
<td>input</td>
<td>Irradiance data</td>
<td></td>
</tr>
<tr>
<td>input direct</td>
<td>Irradiance data for the direct fraction of irradiance</td>
<td></td>
</tr>
<tr>
<td>irradiance</td>
<td>Heat flux due to irradiance</td>
<td></td>
</tr>
<tr>
<td>let</td>
<td>Lethal temperature</td>
<td></td>
</tr>
<tr>
<td>local</td>
<td>Local time</td>
<td></td>
</tr>
<tr>
<td>max</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td>measured direct</td>
<td>Radiation data for the direct fraction of light</td>
<td></td>
</tr>
<tr>
<td>opt</td>
<td>Optimal temperature</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>P-polarised fraction of light</td>
<td></td>
</tr>
<tr>
<td>radiation</td>
<td>Heat flux due to infrared radiation</td>
<td></td>
</tr>
<tr>
<td>ref</td>
<td>Reference pressure</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>S-polarised fraction of light</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>Saturated water vapour pressure</td>
<td></td>
</tr>
<tr>
<td>sky</td>
<td>Sky temperature</td>
<td>K</td>
</tr>
<tr>
<td>solar</td>
<td>Solar time</td>
<td></td>
</tr>
<tr>
<td>surface</td>
<td>Pond surface</td>
<td></td>
</tr>
<tr>
<td>w</td>
<td>Growth medium (water)</td>
<td></td>
</tr>
<tr>
<td>yearly</td>
<td>Yearly biomass production</td>
<td>t ha⁻¹ y⁻¹</td>
</tr>
<tr>
<td>z</td>
<td>Angle of incidence with regard to the zenith</td>
<td></td>
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### 6.2 Parameter values used in the calculations

Table 6.2: General parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Dimensions</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>n_a</td>
<td>1.000277</td>
<td>Dimensionless</td>
<td>[32]</td>
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<tr>
<td>n_w</td>
<td>1.333</td>
<td>Dimensionless</td>
<td></td>
</tr>
<tr>
<td>ε_w</td>
<td>0.96</td>
<td>Dimensionless</td>
<td>[32]</td>
</tr>
<tr>
<td>ρ_w</td>
<td>1000</td>
<td>kg m⁻³</td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>5.77*10⁴</td>
<td>W m⁻¹ K⁻¹</td>
<td></td>
</tr>
<tr>
<td>C_{p_w}</td>
<td>4180</td>
<td>Pa °C⁻¹</td>
<td>[35]</td>
</tr>
<tr>
<td>k</td>
<td>0.601</td>
<td>W m⁻¹ °C⁻¹</td>
<td>[44]</td>
</tr>
<tr>
<td>C_{bowen}</td>
<td>61.3</td>
<td>Pa °C⁻¹</td>
<td>[35]</td>
</tr>
<tr>
<td>P_{ref}</td>
<td>101325</td>
<td>Pa</td>
<td>[40]</td>
</tr>
<tr>
<td>A_w</td>
<td>8000</td>
<td>m⁻¹</td>
<td></td>
</tr>
<tr>
<td>length</td>
<td>2666.67</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>width</td>
<td>3</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>0.3</td>
<td>m</td>
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</tbody>
</table>

Table 6.3: Algae dependent parameter values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phaeodactylum tricornutum</th>
<th>Thalassiosira pseudonana</th>
<th>Dimensions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>10⁻⁵</td>
<td>10⁻⁵</td>
<td>g C m⁻² mol photons⁻¹ g Chl a⁻¹</td>
<td>[47]</td>
</tr>
<tr>
<td>avE</td>
<td>2.299*10⁶</td>
<td>2.299*10⁶</td>
<td>J kg algae⁻¹</td>
<td>[58]</td>
</tr>
<tr>
<td>r</td>
<td>0.05</td>
<td>0.05</td>
<td>d⁻¹</td>
<td>[47]</td>
</tr>
<tr>
<td>T_{let}</td>
<td>30.31</td>
<td>31.4</td>
<td>°C</td>
<td>[51-53]</td>
</tr>
<tr>
<td>T_{opt}</td>
<td>21.64</td>
<td>24.73</td>
<td>°C</td>
<td>[51-53]</td>
</tr>
<tr>
<td>α</td>
<td>75</td>
<td>269</td>
<td>m² kg⁻¹</td>
<td>[51, 59]</td>
</tr>
<tr>
<td>β</td>
<td>1.57</td>
<td>1.83</td>
<td>Dimensionless</td>
<td>[51-53]</td>
</tr>
<tr>
<td>Θ_{max}</td>
<td>0.08</td>
<td>0.08</td>
<td>g Chl a⁻¹ g C⁻¹</td>
<td>[47]</td>
</tr>
<tr>
<td>µ_max</td>
<td>1.39</td>
<td>3.28</td>
<td>d⁻¹</td>
<td>[47]</td>
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</table>

Table 6.4: Location dependent parameter values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cabauw, NL</th>
<th>Carpentras, FR</th>
<th>Tamanrasset, DZ</th>
<th>Dimensions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ</td>
<td>51.97</td>
<td>44.08</td>
<td>22.78</td>
<td>°N</td>
<td>[42, 43]</td>
</tr>
<tr>
<td>λ</td>
<td>4.93</td>
<td>5.06</td>
<td>5.51</td>
<td>°E</td>
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</tr>
<tr>
<td>λ_m</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>°E</td>
<td></td>
</tr>
<tr>
<td>T_{ground}</td>
<td>15</td>
<td></td>
<td></td>
<td>°C</td>
<td>[42, 43]</td>
</tr>
</tbody>
</table>
6.3 Complementary figures

Figure 6.1: Average direct and diffuse radiation (W m\(^{-2}\)) during the course of one year for Tamanrasset, Algeria.

Figure 6.2: Variations in pond temperature(°C) in Ca bauw, the Netherlands during the days of one year.
Figure 6.3: Daily biomass production (kg ha\(^{-1}\) d\(^{-1}\)) over the period of one year for a range of biomass concentrations. The algae species used *P. tricornutum*, the simulated location is the Netherlands and the applied depth is 0.3m. The biomass concentration was varied in steps of 0.1 kg m\(^{-3}\) from 0.1 to 1 kg m\(^{-3}\), respectively (A) to (J).
7 References


