Microalgae Biomass Potential in Europe

Land Availability as a Key Issue

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Microalgae are a promising option for sustainable biomass production in Europe. One important advantage of microalgae is that they can be cultivated on non-arable land and therefore do not contribute to an increase in unwanted land use change, particularly for the production of biofuels. The biomass potential of microalgae is limited, however, by the limited availability of such marginal land in densely populated Europe and by the slope of many of these areas or their status as protected areas. A GIS-based model was developed to assess this potential. A general result was that about 50 megatons (Mt) dry matter microalgal biomass could be produced annually in Europe. The by far largest part of this amount would come from the Iberian Peninsula. However, northern countries such as Sweden or the UK also show considerable potential.

1 Introduction

Microalgae are a promising option for sustainable biomass production. Microalgal biomass can be used for a broad range of purposes depending on the microalgae strain and the cultivation conditions. The main part of the biomass currently being produced is dedicated to health food products, feed for aquaculture or for the extraction of specialities such as astaxanthin[1] (Olaizola 2003). The objective of recent research and development efforts is to make microalgae biomass a feasible source for the production of bulk products such as biofuels and animal feed (Chisti 2007).

One major advantage over other traditional crops is that microalgae can be cultivated in technical systems and can, thus, be produced on non-arable land. The use of microalgal biomass for biofuel may therefore significantly reduce the food vs. fuel dilemma usually associated with other energy crops. Besides, microalgae have the potential to show much higher photoconversion efficiencies[2] (PCE) than higher plants. For microalgae a PCE of 5 % seems feasible (Stephens et al. 2010) whereas the PCEs of higher plants do not exceed 1 % (Walker 2009). Furthermore, the energetic use of algal biomass produced in the EU-27 countries could reduce their dependence on energy imports.

Although microalgae produce higher yields than other plants, huge areas of land will be needed to produce significant amounts of bulk products such as biofuels from microalgae. In densely populated Europe, the demand for so much land for this purpose is an important issue. To meet the goals of sustainability, large scale microalgae facilities covering many hectares of land will be limited to areas that are not yet used for other purposes and where this use will have a low impact on the landscape, soil, water balance and nature protection.

This article presents a model for assessing the resource potential of biomass from microalgae, taking account of anticipated yields and land availability. The model's parameter values were chosen for a closed photobioreactor (PBR) cultivation system. However, in principle, the model is applicable to open pond cultivation systems as well. The results of the model calculations are shown and discussed.

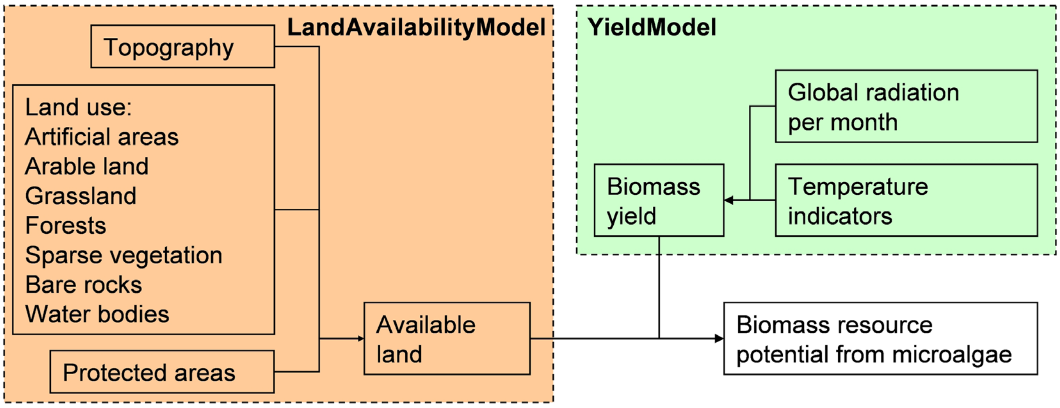
2 Assessing the Resource Potential

The resource potential is calculated as the sum of the yield on all available land. To reflect the spatial differences in yield and land availability, a GIS-based[3] model was developed and the appropriate geographic data sets were used. Figure 1 shows a flow diagram of the GIS model. It consists of two parts: the "YieldModel" for yield calculation and the "LandAvailabilityModel" for determining land availability. In the following, the two parts are described, including the assumptions made. The parameter values mentioned in the next two sections reflect a "projected realistic case", which is the default scenario for the model calculations.

2.1 Yield Calculation

In the "YieldModel", the yield in kg m^{-2} a^{-1} was calculated based on climate data for temperature and global radiation according to the following equation:

Fig. 1: Flow scheme of the GIS-based model developed for assessing the microalgae biomass resource potential



Source: Own compilation

$$\text{Yield} = \frac{\text{PCE}}{H_o} \cdot \sum_{m=1}^{12} \left(\prod_T I_{T,m} \cdot G_m \right)$$

Yield in $\text{kg m}^{-2}\ \text{a}^{-1}$

PCE : Conversion efficiency from global radiation to biomass

H_o : Calorific value of the biomass in MJ kg^{-1}

$I_{T,m}$: Different temperature indicators $\in \{0;1\}$ for a month m

G_m : Mean global radiation in a month m in MJ m^{-2}

As a general assumption for the yield calculation, the PCE was set to be independent of local conditions. Usually the PCE depends on the irradiation flux and is only constant under light-limiting conditions (Tredici 2010). High irradiation fluxes result in photosaturation or even photoinhibition, and the PCE declines. However, it is reasonable to assume a constant PCE when light-limiting conditions can be achieved by optimal process management (e.g. light-adapted mixing) and by choosing the optimal reactor design and algae strains for each site. A PCE of 5% was assumed for the yield calculation.

Several temperature indicators were used to decide whether a month is suitable ($I_{T,m} = 1$) for microalgae production or not ($I_{T,m} = 0$). The monthly mean temperature should not fall below 10°C and not exceed 35°C. In any one month, a daily minimum temperature of 0°C may not be undercut or a maximum temperature of 45°C may not be exceeded on more than 5 days, respectively. The temperature differences within one day may not exceed 20°C on more than 10 days in one month. These limits were chosen based on the comprehensive review on algal biology from the AQUAFUELS project (Aquafuels 2011).

The sum of the mean global radiation in all the suitable months was calculated and multiplied by the PCE. The biomass yield in $\text{kg m}^{-2}\ \text{a}^{-1}$ is obtained by dividing this value by the calorific value of the biomass H_o. For H_o a value of 20 MJ kg^{-1} was assumed according to Lehr and Posten (2009).

The GIS data on long-term mean, minimum and maximum temperatures with a spatial resolution of 0.25° were taken from the E-OBS dataset (Besselaar et al. 2011). Data on the long-term monthly mean global radiation with a spatial resolution of 1000 m were taken from the PVGIS project (Súri et al. 2007).

2.2 Determining the Availability of Suitable Areas

The LandAvailabilityModel is used to determine whether an area is suitable for the construction and operation of a microalgae plant or not. An area is designated suitable if

- its slope is suitable,
- it is non-arable land and not used for other purposes,
- it is not a protected area.

The slope is calculated using a digital elevation model (DEM) of the U.S. Geological Survey (USGS 2006) with a spatial resolution of 100 m. According to the U.S. DOE (2010), the maximum suitable slope for microalgae cultivation in open ponds is 5 % due to the high costs for site preparation and levelling of higher slopes. For closed PBRs a higher value might be still feasible since extensive site levelling can be assumed to be unnecessary for PBR construction. However, slope was limited to 8 % to assure the accessibility of the site, which excludes mountainous areas (simplified definition based on Blyth et al. 2002) from the analysis.

To identify available areas according to their current land use, the CORINE 2006 land cover raster dataset (EEA 2011) with a spatial resolution of 250 m was used. Missing data for Greece was taken from the CORINE 2000 dataset (EEA 2010). To avoid land use competition with food and feed production, agricultural areas were considered unavailable for algae production. According to the EU renewable energy directive (EU 2009), land with high carbon stocks and high biodiversity such as forests, scrublands, grasslands, and wetlands may not be used for biofuel production. These areas were consequently set to be unavailable for microalgae production as well. Also considered unavailable were areas already intensively used such as most artificial areas where space for large scale algae production facilities is very limited. Since only land-based cultivation systems were investigated for this work, bodies of water have not been considered for potential analysis. This leaves areas which are classified as "bare rocks" or "sparsely vegetated areas" for the construction of microalgae production facilities.

Since microalgae plants are technical systems, they might have a severe impact on the ecosystem. Land that is classified as a protected area according to the UNEP World Database on Protected Areas (IUCN, UNEP 2010) was thus generally set to be unavailable.

3 Results

The main results of the model calculations for the default scenario are depicted as a map in figure 2. The biomass resource potential for each EU-27 country is given in megatons (Mt) dry matter per year. Furthermore, yields in t ha^{-1} a^{-1} were calculated as mean values for each NUTS level 3 region[4], so that promising regions can be identified.

Table 1: Microalgae biomass yield potential of the top 10 European countries and area statistics

	*Available areas considering restrictions to**			*Yield potential*	
Country	*LU km²*	*LU + Slope km²*	*LU + Slope + PA km²*	*Mean yield** t ha^{-1} a^{-1}*	*Potential kt a^{-1}******
Spain	11,284	3,182	2,679	126	33,867
Sweden	10,524	3,568	2,263	22	3,092
Italy	8,583	373	255	102	2,438
Portugal	1,240	288	185	109	2,016
United Kingdom	4,002	747	386	35	1,352
France	8,408	322	145	88	1,268
Greece	1,991	158	127	104	1,203
Cyprus	141	84	75	149	1,109
Ireland	340	116	99	60	587
Germany	495	201	97	60	581
EU-27	54,926	10,136	6,655	78	49,171

* = LU: land use, PA: protected areas
** = mean yield calculated for available areas only
*** = kilotons per year

Source: Own compilation

The calculated yields range from 12 t ha^{-1} a^{-1} in boreal regions and the High Alps to 160 t ha^{-1} a^{-1} in southern Portugal (Algarve). On Sicily (Italy), on the Dodecanese (Greece) and in Andalusia (Spain), yields above 150 t ha^{-1} a^{-1} can be expected as well. Spain's biomass potential (34 Mt a^{-1}) is by far the highest, followed by Sweden (!), Italy, and Portugal. The total potential for Europe adds up to almost 50 Mt a^{-1} on about 6500 km² available cultivation land (see table 1).

Table 1 shows the results of the potential calculation and of area statistics for land availability for the 10 countries which contribute the most to the total biomass potential for the default case. Obviously, large countries with high biomass yields per hectare tend to have higher biomass potentials than small countries with low biomass yields (e.g. Spain vs. Ireland). However, at only 1.2 Mt a^{-1}, Greece's potential is relatively low despite the high biomass yields per hectare which could be achieved there. The low potential in France is surprising, too. Although there is a considerable amount of land in Greece that could be used for algae cultivation concerning land use restriction, over 90 % of this land is in mountainous areas and therefore unsuitable. In Italy and France, the situation is similar, and in France the availability restrictions due to protected areas also prove to be very important. Since Sweden has large areas of suitable land which are relatively flat and not protected, it contributes the second most to the biomass resource potential despite its low biomass yields per hectare. The outstanding high potential in Spain can be explained by the high yields and the huge barren or sparsely vegetated areas in which the slope in many cases is suitable and that are nature protected only in a few cases.

Sensitivity analyses have been performed to assess the importance of the reference period for the temperature data and to investigate how different values for the maximum suitable slope produce changes in biomass potential. In table 2, the results of these analyses are shown as the percentage deviation from the default "projected realistic case".

Changes in the reference period for the temperature data have only a small effect on total biomass potential. If the reference period covers the last 60 years, the biomass potential tends to be smaller than in the default case (a 40-year reference period). For the last 20 years, however, during which temperatures increased due to global warming, the potential is higher for every country. There is even an increase in potential greater than 20 % in Sweden, a country with a cold climate.

Different assumptions for the maximum suitable slope have a strong effect on the biomass

Table 2: Sensitivity analysis for the top 10 European countries (temperature and variation of the maximum suitable slope value)*

	Temperature data base period		*Maximum suitable slope*			
Country	*last 60 a*	*last 20 a*	*< 2 %*	*< 4 %*	*< 15 %*	*< 30 %*
Spain	-0.4	+2.4	-90.0	-60.4	+62.3	+123.2
Sweden	-15.3	+20.4	-68.7	-42.8	+47.9	+78.4
Italy	-0.4	+3.2	-84.5	-61.2	+129.7	+415.5
Portugal	+0.1	+6.4	-94.0	-70.7	+108.8	+212.7
United Kingdom	-1.0	+2.1	-88.7	-64.6	+104.5	+244.7
France	-1.4	+3.4	-92.4	-67.5	+166.6	+645.7
Greece	+0.6	+0.2	-92.2	-74.5	+193.7	+580.7
Cyprus	+0.5	+0.3	-86.5	-51.5	+32.9	+43.0
Ireland	-0.0	+0.9	-48.2	-29.3	+55.8	+138.4
Germany	+1.1	+1.1	-39.6	-15.4	+3.7	+5.7
EU-27	-1.3	+3.6	-86.4	-58.7	+72.8	+167.1

* = The results show the percentage deviation of the microalgae biomass potential in relation to the default case

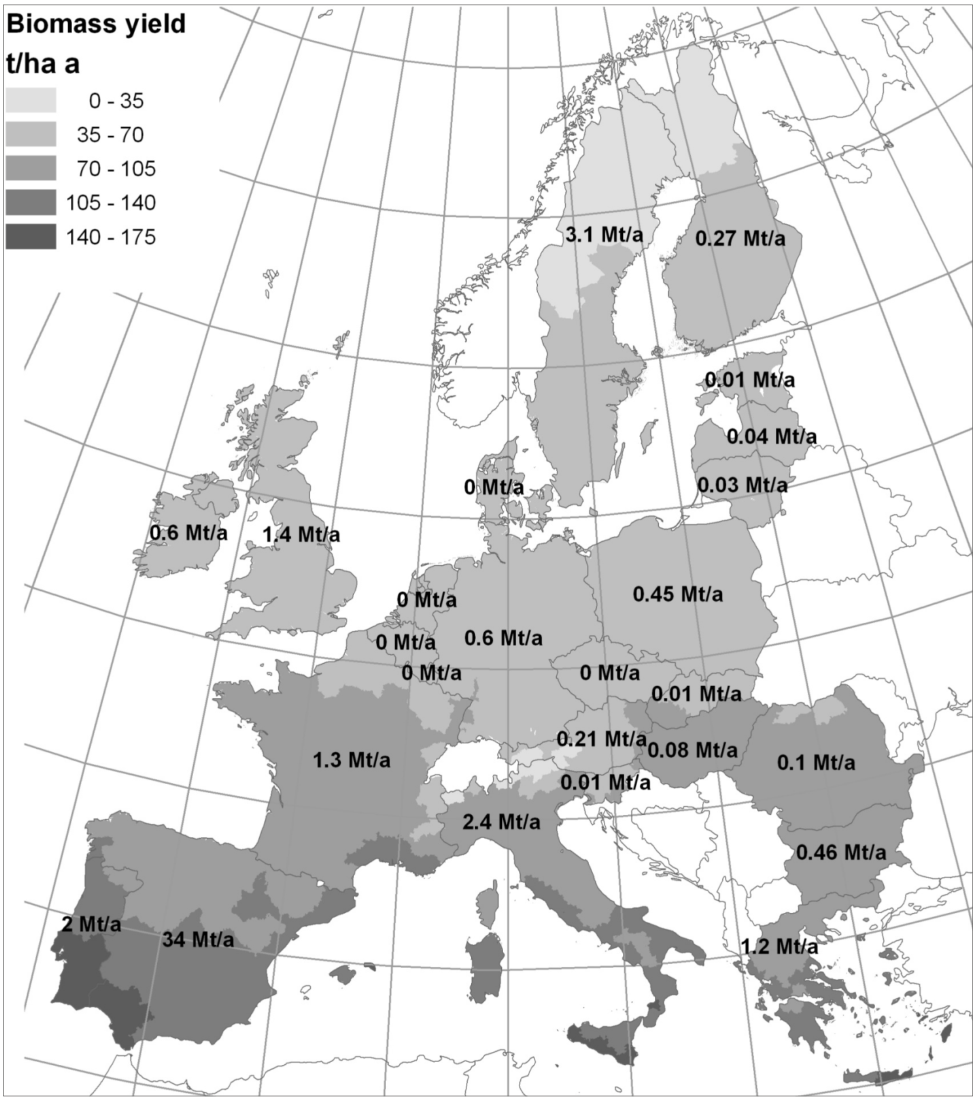
Source: Own compilation

resource potential as shown in table 2. Assuming slope values suitable for open pond construction (4 % and 2 %), the total potential and the potential in most countries are reduced by about 60 % to 90 %. Germany and Ireland are only slightly affected. On the other hand, allowing higher slopes for PBRs means that the biomass potentials would be much higher. This effect is particularly strong in France, Greece and Italy, where the biomass potential could be up to sixfold higher than in the default case. In Germany, the differences to the default case are very small because of the high importance of protected areas for the availability of land (see table 1).

4 Discussion

The considerable amount of about 50 Mt dry microalgal biomass per year can be produced on Europe's marginal land. In terms of energy content, this corresponds to 1 EJ. Although this is

Fig. 2: Map showing the microalgae biomass resource potential (for each EU-27 country in Mt a^{-1} and the mean biomass yield in t ha^{-1} a^{-1})



* = Biomass is given as dry matter; the mean biomass yield is calculated for the total country area.

Source: Own compilation

only a small portion of the overall European final energy consumption of 48 EJ in 2009 (Eurostat 2011), such a no-regrets biofuel strategy does not utilize arable land but can, on the contrary, give added value to otherwise unused land. In Spain, where most of the algal production potential is located, an innovative microalgae based industry could emerge, offering new chances for income in rural or abandoned areas. Besides, land use competition between biofuel and feed crops could be reduced because the protein-rich algal residues remaining after oil extraction could replace soybeans grown on arable land. The high protein content and quality of this material could pose a significant factor in feed production and replacing feed imports. In 2010, 30 Mt soybean meal were consumed in the EU (FEDIOL 2012), most of which was produced from imported soybeans or imported directly as meal.

The countries in Southern Europe show higher yields per hectare because of higher global radiation but also because temperature is one of the most important factors in microalgae production and determines the length of the production period. Although the effects of rising temperatures during the last 20 years on the biomass potential of microalgae are relatively low, they are discernible and might be stronger in the future if climate change continues. For northern countries such as Sweden, there might be new opportunities for the cultivation of microalgae in the future. Again, this can be a chance to return production value to marginal land. However, the low yields in the northern countries could limit these opportunities since low biomass yields result in higher production costs (Stephens et al. 2010). Thus, it is highly likely that only a small portion of Sweden's huge biomass potential will be exploitable in an economically viable way.

At the present, biomass production in PBRs is much more expensive and sophisticated than in ponds. However, open pond cultivation systems suffer from high water evaporation, low cell concentrations, low yield per hectare and contamination problems (Posten, Schaub 2009). The results highlight another weakness of open ponds, namely the need for relatively flat land. In Europe, this limits the biomass potential from open ponds to just a small fraction of that from closed PBRs. The development of PBRs suitable for areas with higher slopes than the assumed 8 % could further increase the potential.

The availability of suitable land turns out to be a crucial issue for the biomass potential of microalgae in Europe. It is a great advantage that microalgae are cultivated in technical systems which can be built on otherwise unused land and give added value to regions with a high percentage of such land. However, the premise that land use competition by biofuel production must be avoided significantly limits the amount of land available for microalgae production plants because only about 0.1 % of Europe's land area fulfils these criteria. In this regard, research and societal discussion are needed to learn if other areas, e.g. a small percentage of the so-called surplus grassland areas which are no longer needed for forage production (Rösch et al. 2009), could increase the amount of land available for microalgae cultivation. In principle, microalgae could also be produced in plastic bags floating in the sea, e.g. docked at offshore wind power plants, but so far no commercial production systems are available.

It is obvious that the availability of land is a major prerequisite, though not the only one, for commercial and socially acceptable microalgae cultivation. Due to the enormous productivity, there is a high demand for a low-cost supply of water and nutrients, such as CO_2, nitrate and phosphorus. Research on the availability of emissions from power and industrial plants (Skarka et al. 2011) and municipal waste streams for the nutrient supply (Yang et al. 2011) or the recycling of nutrients (Rösch et al. 2012) indicate that the issue of nutrient supply for large scale production of microalgal biomass could be solved in a sustainable manner.

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tected Areas Programme, UNEP-WCMC (http://www.protectedplanet.net) for providing data from the WDPA; and the EEA (http://www.eea.europa.eu/) for providing the CORINE datasets.

Notes

1) A carotenoid which is used as feed supplement in e.g. salmon farming to provide the red colour of the salmon meat.
2) Conversion efficiency of sunlight irradiation energy into energy content of the biomass.
3) Geographical Information System.
4) NUTS level 3 regions are the smallest spatial units according to the Nomenclature of Units for Territorial Statistics and correspond to the German districts.

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