

A Site Selection Model to Identify Optimal Locations for Microalgae Biofuel Production Facilities in Sicily (Italy)

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Abstract

The lack of sustainability and negative environmental impacts of using fossil fuel resources for energy production and their consequent increase in prices during last decades have led to an increasing interest in the development of renewable biofuels. Among possible biomass fuel sources, microalgae represent one of the most promising solutions. The present work is based on the implementation of a model that facilitates identification of optimal geographic locations for large-scale open ponds for microalgae cultivation for biofuels production. The combination of a biomass production model with specific site location parameters such as irradiance, geographical

constraints, land use, topography, temperatures and CO₂ for biofuels plants were identified in Sicily (Italy). A simulation of CO₂ saved by using the theoretical biofuel produced in place of traditional fuel was implemented. Results indicate that the territory of Sicily offers a good prospective for these technologies and the results identify ideal locations for locating biomass fuel production facilities. Moreover, the research provides a robust method that can be tailored to the specific requirements and data availability of other territories.

Keywords: Biofuels, Microalgae, Geographic Information System, Sicily.

Nomenclature

Variable	UOM	Description
T	[°C]	Average yearly Temperature
S	%	Slope of terrain
A	[m]	Altimetry of terrain
BM _{production}	[kg/m ² /year]	Microalgae productivity
MO _{production}	[l/m ² /year]	Lipid productivity from microalgae
η _{transmission}	Unitless index	Efficiency of light transmission to micro algae
η _{Capture}	Unitless index	Efficiency of conversion of Incident sunlight to biomass in micro algae
η _{Light distribution}	Unitless index	Optical light distribution efficiency
η _{Land use}	Unitless index	Land use efficiency
η _{Photo synthetic}	Unitless index	Photosynthetic efficiency
η _{Photo utilisation}	Unitless index	Fraction of captured photons utilised by microalgae
E _{Microalgae}	[MJ/kg]	Total energy stored in biomass
E _L	[MJ/kg]	Lipids energy fraction
E _P	[KJ/kg]	Proteins energy fraction
E _C	[MJ/kg]	Carbohydrates energy fraction
f _L	Unitless index	Microalgae lipid fraction usable for biodiesel
f _P	Unitless index	Microalgae protein content fraction
f _C	Unitless index	Microalgae carbohydrate content fraction
ρ _L	[kg/l]	Density of lipids usable for conversion to biodiesel
H _s	[Wh/m ² /year]	Total solar irradiance falling on a horizontal surface
PAR _{Component}	Unitless index	Photo synthetically active radiation of sun
α	Unitless index	Light absorption coefficient of micro algae.
r	Unitless index	Fraction of energy consumed by respiration in microalgae
I _s	[μmole/m ² /s]	Saturation light photosynthetic photon flux density (PPFD) on microalgae
I _i	[μmole/m ² /s]	Incident light photosynthetic photon flux density (PPFD) incident on microalgae

INTRODUCTION

The uncertainty about the energy production in the world, the insufficient reserves of oil non-renewable energy, and the environmental consequences of the massive use of fossil fuels and their increasing prices, are among the primary reasons that induce the modern community to find alternative solutions to the use of oil [1]. In this context, many renewable energy sources have been investigated and, among them, significant attention is focused on the production of biodiesel as substitute for diesel derived by fossil hydrocarbons [2]. The energy produced with biomasses and in particular by the combustion of biodiesel is considered a cleaner alternative thanks to their low pollutant emission, and above all, the zero balance of carbon dioxide [3]. The CO₂ emitted during the combustion of biodiesel is the same that was absorbed during the growth of the plants whereby it was produced annulling in this way the overall calculation. This does not mean that the use of biodiesel eliminates CO₂ emissions but only that the CO₂ generated by the combustion is renewable at 95% while the remaining 5%, due to non-biogenic components, is not renewable. Nevertheless, there are some problems resulting from the cultivation of plants which are the raw material for this process. What is mentioned above would assume a social value if the raw material for the production of biodiesel was cultivated in barren wastelands or deserts, but as it often happens, the cultivation takes the place in areas that already contribute to carbon dioxide absorption from the atmosphere [4]. The production processes described above could easily be integrated with energy plants necessary for the same process, by using renewable sources such as wind power plants [5, 6] or photovoltaic plants [7, 8]. This makes the whole biodiesel production process clean and with zero or near zero greenhouse gases emissions. Therefore this source is particularly attractive for the promotion of the environmental sustainability and directly applicable to the reduction of problems associated with air pollution caused by vehicular traffic in urban areas [9, 10]. The use of biomasses from several sources for the energy production constitutes one of the key strategies by which the European community means to reduce its dependence on imported oil and derived products in middle and long term. In application of the Directive 2009/28/CE about renewable energies promotion, each State has to reach some goals by the year 2020. In particular, the Directive mandates that the proportion of consumptions consumption from non-renewable sources used for transportation should be reduced to at least 10% of the total consumption. According to [11] considering the current state of the technical development of the use of renewable sources in transports, this goal could be reached only through a massive use of biofuels. The most modern and commercial biofuels usually derive from short-rotation dedicated crops. Some of these crops, such as oilseed and sugarcane, are very competitive for biofuels production but they would be in "competition" with food crop production. A viable alternative is microalgae that could be an important component of the future biofuels mix. Algae are plant-like, largely photosynthetic, and could be grown in diverse habitats with fresh or salt water. Their use for biofuels production offers a sustainable alternative to other crops that compete for limiting resources such as fresh water [12, 13]. Currently, the production of biofuels from microalgae is still not competitive

with fossil fuels in terms of costs [14, 15]. As a result, new technologies are under investigation with the aim at reducing costs [16, 17]. Usually, the production of microalgae for biodiesel is conducted with open pond cultivation systems that require large amounts of water [13]. However, this critical issue is compensated by the fact that microalgae cultivations may grow with saline water in lands not suitable for other agricultural crops. A crucial factor affecting profitability of microalgae biofuel production is still the relative price of crude oil. Also if new technologies for biofuel conversion from microalgae [18, 19] are under investigation there is very little that can be done currently to improve microalgae productivity in terms of lipids conversion. What could be done to make this energy conversion system more competitive is to analyze a strategic selection of cultivation locations taking into account climate conditions, geographical constraints and other resources.

For cost-effective cultivation of microalgae, a suitable climate with high annual solar irradiation and an optimum temperature range that allows year-round microalgae growth at high productivity levels is critically important [20]. Therefore, in order to achieve high productivity and lipid content, the selection of locations for microalgae cultivation considering the optimum climatic conditions as well as available resources and CO₂ is of crucial importance. The objective of this applied study was to develop and test a modelling approach to find optimal locations for a microalgae biofuel cultivation facility. The mathematical model was implemented in a GIS environment [21-22].

BIOFUELS, MICROALGAE AND ENVIRONMENTAL ASPECTS

Biofuels are natural products usable for transport and heating [23]. The use of these fuels for these applications has been regulated with minimum requirements in the two European Directives: UNI 10946 and UNI 10947. Biofuel use presents some advantages in comparison with traditional fossil fuels, especially in terms of environmental sustainability. The emissions of pollutants are particularly low with a reduction of approximately 78% for CO₂ [24] and about 68% for particulate matters [25]. Therefore it may be inferred that the use of biofuels does not significantly contribute to the emissions of gases responsible for atmospheric greenhouse effect because they give back to atmosphere almost the same amount of CO₂ absorbed by crops during their life cycle. What it is important to consider in any case is that biofuels derived from cultivation can be in competition with food production and, with the aim at avoiding discrepancies, the European community has established a maximum of 7% of the contribution of biofuels produced by food crops with the Directive 2015/1513. For this reason the use of microalgae for biofuels production is of crucial importance.

Microalgae are microorganisms that usually grow rapidly in several pedoclimate conditions. The most common species are green algae (*Chlorophyta*) and diatoms (*Bacillariophyta*) [26-27]. Literature is full of research that highlight the advantages of using them for biodiesel production in comparison with other available feedstocks [28-29]. They are easy to cultivate,

without any particular attention, and above all, using water unsuitable for other crops or human consumption. Moreover, they can be cultivated almost anywhere, requiring only sunlight and some simple nutrients [30]. Another important aspect that has to be taken into account is their growth rates; microalgae usually present growth rates higher than other conventional cultivations such as agricultural crops, aquatic plants or conventional forestry. This implies they need less area than other biofuels of agricultural origin to obtain similar results

[31]. A typical microalgae-to-biofuel production chain consists of growth (cultivation), harvesting and dewatering of the algal biomass, and finally extraction of the lipids and conversion to fuel. There are two main types of microalgae cultivation systems: open ponds and closed photobioreactors [32], with open ponds the most widely used system for commercial large-scale outdoor microalgae cultivation [33]. This research focuses on selection of microalgae cultivation sites using the *raceway open pond method*.

STUDY AREA

Sicily, the biggest island in the Mediterranean sea, with a total surface of about 25.000 km² extends in latitude from 36° to 38° North and in longitude 12° to 15° East. It is located as shown in Fig. 1. The orography varies consistently: the northern part is mainly mountainous, the center-southern is collinear; the eastern zone is volcanic while the rest of the island is characterized by the presence of plateaus. Most of Sicily is characterized as hilly (62%) while 24% is mountainous and 14% is flat. The variety of Sicily's landscapes creates heterogenous climatic condition but, the island as a whole is defined in the Köppen macroclimatic classification system as a region of humid-temperate climate type C (the coldest month presents temperature in the range from -3°C to 18°C). The climate of the northern and eastern coasts is generally mild during the winter and hot during the summer with yearly means of 18 °C. The southern coasts and the inlands experience the influence of warm African winds with a torrid summer climate

[34]. The inner mountainous areas present a colder climate, characterized by thermal excursions and frequent rainfalls during winter months. The rains of Sicily are not copious with general yearly means less than 700 mm, concentrated between the late autumn and the early spring. The southern and western parts are particularly dry and also some valleys of the inner zones isolated by mountains which limits the marine influences, where annual rainfalls are very low, less than 500 mm, while the African influences are very strong [35]. The Tyrrhenian and Ionian coasts of Sicily are more rainy with annual quantities exceeding 800 mm and can be greater than 1000 mm at higher elevations, where during the winter season there are usual heavy snowfalls. The predominant winds are Mistral and Sirocco, but the Libeccio is also frequent during the middle seasons and Tramontane in winter. These winds are responsible for the heavy rains and sudden drops in temperatures. The predominant vegetation is Mediterranean characterized by Oaks, laurels, Arbutus and olives [36]. There are also tropical essences such as prickly pears, fat plants, palms, while wetter areas with altitudes over 1000 m are characterized by oak, beech, and maple forest. Some

particularly arid areas present typical aspects of the steppe with meadows characterized by an alternation of fat plants and evergreen shrubs.



Figure 1. Geographical location of Sicily.

DATA COLLECTION

The model was built in a GIS environment using data classified in 4 main domains: land use, topographical, CO₂ emissions, and climatic.

Land use data

In order to classify the territory for suitable lands for *raceway open ponds* microalgae production systems a prior analysis of political, geographical and agricultural constraints is necessary. Thanks to raster and vector data from “Geoportale Regione Siciliana-Infrastruttura dati territoriali – S.I.T.R.” and open data provided from the “OpenStreetMap (OSM)” project the territory of reference was classified according different land use typologies such as urban, industrial, agricultural lands, natural reserves and parks, etc. The popular nomenclature of the CORINE dataset from the European Environmental Agency was used to classify land use.

Topographical data

Previous studies for locating open pond microalgae production facilities have suggested slopes ranging from 1% to 10% are viable [37, 38]. With limited justification for any specific value within this range, the current model considered areas with ≤5% slope based on the median value observed in similar studies. In addition to slope, altitude can be a key factor in the growth of at least microalgae. According to [39] it was set at least a altitude of 500 m a.s.l in order to not compromise the growth of the plants. All topographic variables were extracted from a digital elevation model (DEM) with a 30m spatial resolution. The raw data was provided from “Geoportale Regione Siciliana-Infrastruttura dati territoriali – S.I.T.R.”.

CO₂ emissions data

CO₂ represents an essential nourishing element for microalgae. Moreover, the production of biofuels contributes to reduce the emission of CO₂ in air. Thanks to “Covenant of Mayors” [40] initiative it was possible to download data about CO₂ emissions for each municipality of Sicily for 2011 as a reference year. These data were analysed and geo-referenced in order to test the results of the model.

Climatic data

Important climatic variables that were integrated in the model included average yearly temperature T [°C] and the irradiation H_s [Wh/m²/year]. The growth of microalgae decreases at lower temperatures while its production is directly proportionally with irradiation. Average temperatures were calculated from a set of 79 meteorological stations (see Fig. 2). These data were furnished for 2015 as a reference year from “Servizio Informativo Agrometeorologico Siciliano (SIAS)”. In order to obtain a continuous map these point data were converted to a 30m resolution surface using Inverse Distance Weighted (IDW) interpolation, a technique widely used in applications like this [41-42].

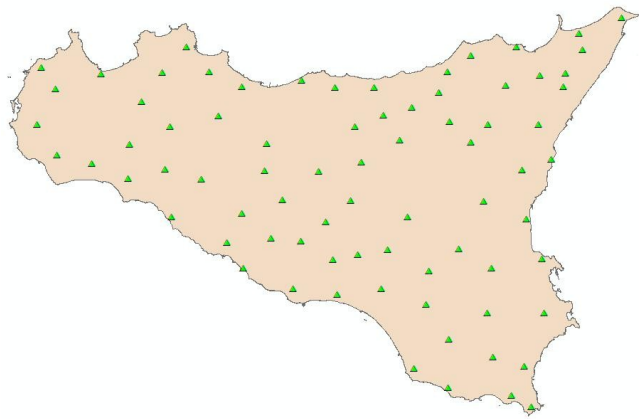


Figure 2. Locations of 79 meteorological stations in Sicily.

Only 24 of the meteorological stations had irradiation measures. Therefore H_s was estimated using the methods developed by Rich et al. [43] and further modified by Fu and Rich [44,45]. This approach used the geographic and topographic properties of a digital elevation model to estimate total annual irradiance (H_s). In the current study the 30m resolution DEM was used for this modelling step. The results were compared with irradiance values obtained at the 24 weather stations and the error was < 5 %. The resulting map is shown in Fig. 3.

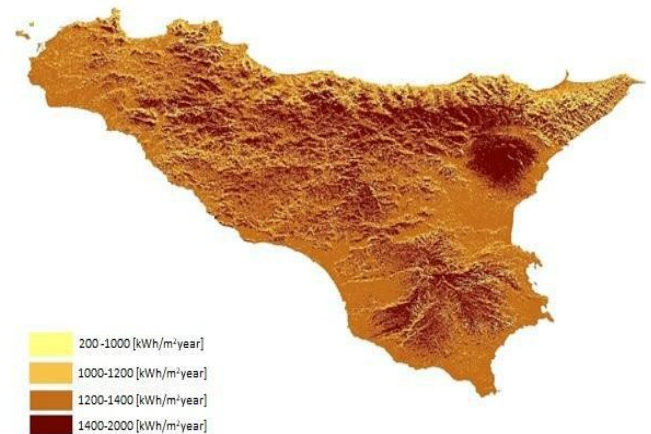


Figure 3. Map of the yearly Irradiation calculated.

METHODS AND APPLICATION

First of territory was analyzed in order to verify the possible suitable lands for open ponds microalgae cultivations. The geographical, climatic, and other constraints that were considered are summarized in Table 1..

Table 1. Criteria for suitable lands.

Constraints	Criterion	Notes	References
Land use	exclusion	There were excluded all private, agricultural and urban lands.	-
S	$S < 5\%$	Suitable pedoclimatic conditions for lands with a $S < 5\%$.	[39]
A	$A < 500$ [m] a.s.l	Suitable pedoclimatic conditions for lands at less than 500 m altitude.	[39]
Environmental constraints	exclusion	All natural reserves excluded.	-
T	$T > 15$ [°C]	Suitable pedoclimatic conditions for lands with a $T > 15$ [°C]	[39]

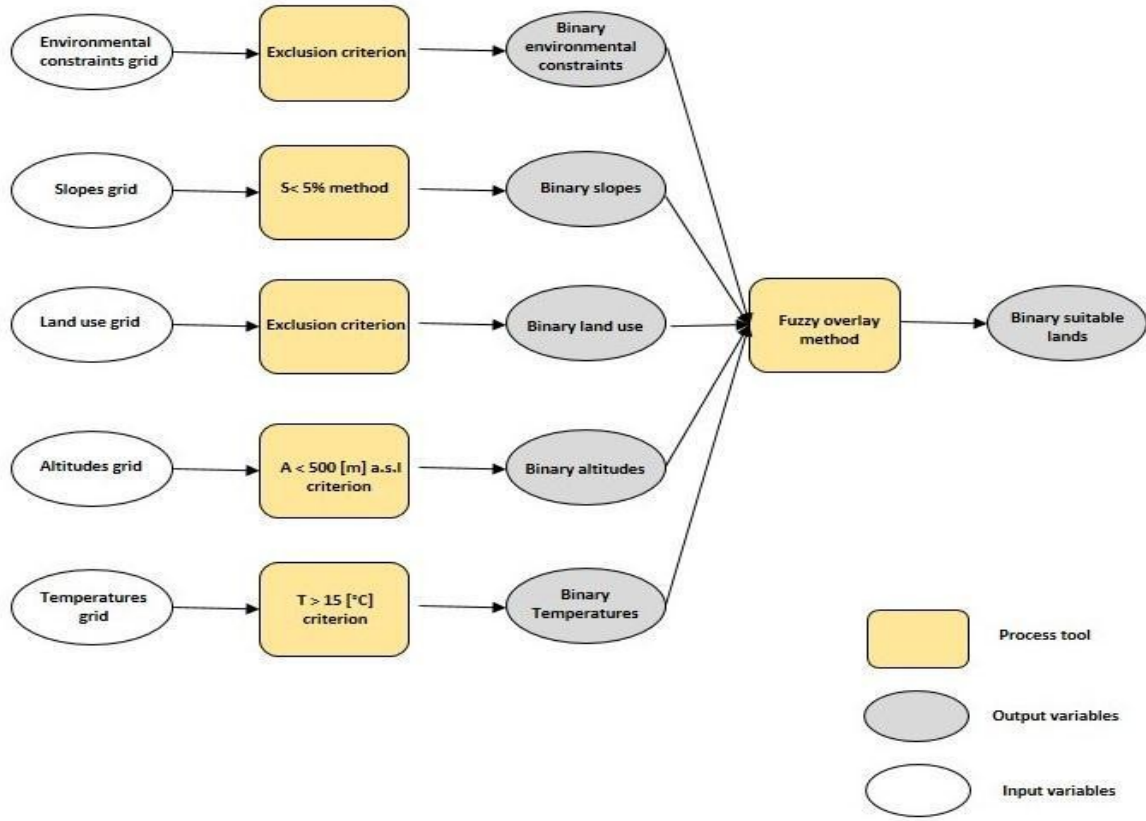


Figure 4. Schematic flow diagram model implementation for suitable lands.

Different raster layers including land use, altitude, slope, and temperature were combined using a fuzzy operation (combination of AND Boolean operators) in order to exclude those areas not suitable for the possible locations. The result was a binary grid of suitable/not suitable land areas. A schematic model flow is represented in Fig. 4.

In order to calculate the theoretical production of biomass from microalgae ($BM_{production}$) for the territory of reference and the corresponding microalgae lipid production ($MO_{production}$) a model implemented in [46] was adapted for this case study.. The main equations of the model are the following:

$$BM_{production} = \frac{\eta_{transmission} \times \eta_{capture} \times H_s}{E_{micro\ algae}} \quad (1)$$

$$MO_{production} = \frac{f_L \times BM_{production}}{\rho_L} \quad (2)$$

$$E_{micro\ algae} = f_L \times E_L + f_P \times E_P + f_C \times E_C \quad (3)$$

$$\frac{\eta_{transmission}}{PAR_{component}} = \eta_{light\ distribution} \times \eta_{land\ use} \times \alpha \times \quad (4)$$

All of the variables are briefly explained in Nomenclature.

$$\eta_{capture} = \eta_{photo\ synthetic} \times \eta_{photo\ utilisation} \times \alpha \times (1 - r) \quad (5)$$

$$\eta_{photo\ utilisation} = \frac{I_s}{I_1} \left[\ln \left(\frac{I_s}{I_1} \right) + 1 \right] \quad (6)$$

The model was applied for a specific microalgae species, *Chlorella vulgaris*, well documented in literature [47-48]. It

belongs to microalgae group called *diatomee*. These microalgae are typically brown and unicellular. They may inhabit different environments with salt or fresh water and present usually a percentage of lipids between 14% and 22%. In order to calculate $BM_{production}$ and $MO_{production}$ several assumptions were made during the construction of the model, especially with regard to loss factors, such as respiration, release of exuded organic carbon,

and photo-inhibition, which are listed in Table 2. These assumptions are considered to be realistically achievable and they refer to optimal values calculated for *Chlorella vulgaris*.

Constraints	Optimum value	Reference
$\eta_{\text{Light distribution}}$	0.96	[49]
$\eta_{\text{Land use}}$	0.98	[49]
$\eta_{\text{Photo synthetic}}$	0.27	[51]
$\eta_{\text{Photo utilisation}}$	1	Calculated from Eq. (6)
E_L	38.3 [MJ/kg]	[50]
E_P	15.5 [KJ/kg]	[50]
E_C	13 [MJ/kg]	[50]
ρ_L	0.864 [kg/l]	[53]
$PAR_{\text{Component}}$	0.458	[31,32,37]
α	1	[49]
r	0.2	[49]
I_s	200 [$\mu\text{mole/m}^2/\text{s}$]	[52]
I_l	200 [$\mu\text{mole/m}^2/\text{s}$]	[49]

Table 2: Assumptions for $BM_{\text{production}}$ and $MO_{\text{production}}$ calculations.

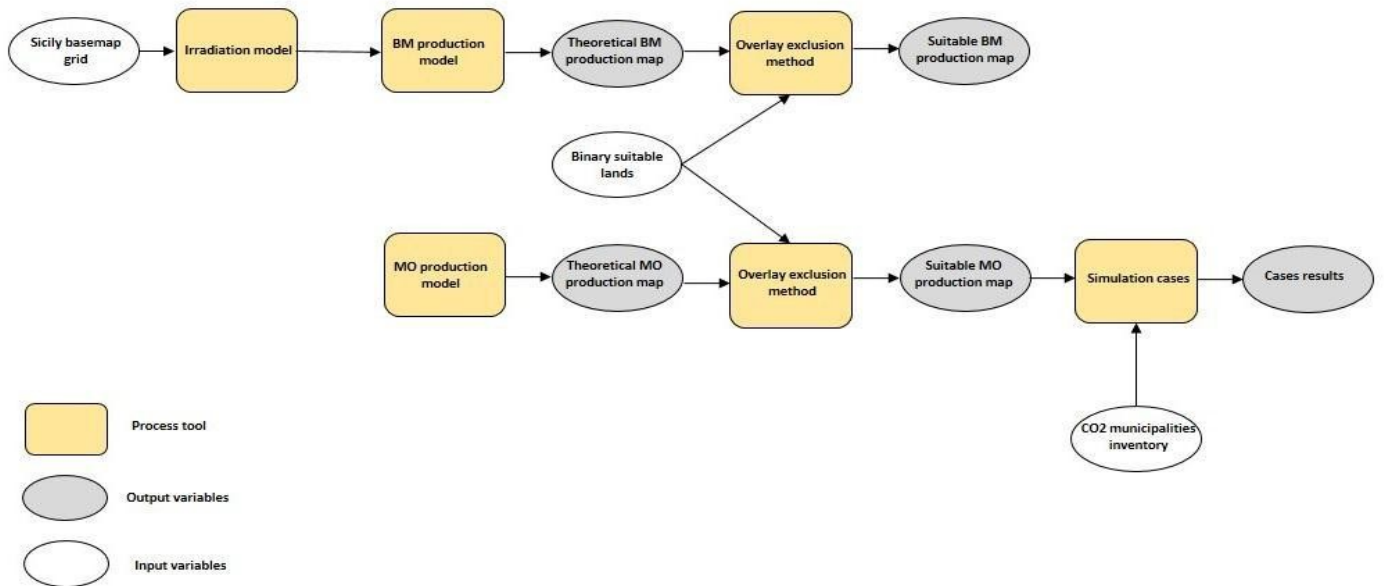


Figure 5. Schematic flow diagram model implementation for $BM_{\text{production}}$ and $MO_{\text{production}}$.

Considering all these assumptions it is possible to solve Eq. (4) and Eq. (5) and later (6) and (2) by calculating Irradiation as previously explained in paragraph 3.4. The results of these equations are two continuous grid maps of “theoretical” $BM_{\text{production}}$ and $MO_{\text{production}}$. That were combined with suitable lands to identify optimal locations. Several sample locations were selected in order to evaluate the results. Thanks to data from “Covenant of Mayors” [40] database it was possible to simulate the eventual CO_2 saved by using the theoretical biodiesel produced in place of traditional diesel for transports and heating systems. Fig. 5 shows the second part of the model.

RESULTS AND DISCUSSION

According to the model implemented for $BM_{\text{production}}$ and $MO_{\text{production}}$ it was generated a continuous map of maximum theoretical productions was generated with a resolution of 30m, as shown in fig. 6 and 7. Obviously, as the model itself basically considers only the relation with irradiation according those optimum parameters previously discussed (see table 2), some illogical locations, such as the peak of Mt. Etna, were identified in the output. What is interesting, as shown in figures 6 and 7, is that the average value of $BM_{\text{production}}$ is 20.86 [$\text{kg/m}^2/\text{year}$] while for $MO_{\text{production}}$ the average value is 4.30 [$\text{l/m}^2/\text{year}$]. Moreover, the 73% of the territory presents a 21 [$\text{kg/m}^2/\text{year}$] < $BM_{\text{production}}$ < 24 [$\text{kg/m}^2/\text{year}$] while the 70% of

the territory presents a $4.0 \text{ [l/m}^2\text{/year]} < \text{MO}_{\text{production}} < 4.5 \text{ [l/m}^2\text{/year]}$. The results in comparison with other research such as [27-29] suggest that Sicily offers a good prospective for the use of these biomasses.

The model implemented was then integrated with a “suitable lands” sub-model. The results define those territorial units that are available according to the constraints mentioned before. The model was tested for three different scenarios: case 1, case 2 and case 3. It was simulated the location of the theoretical plant with *raceway open ponds* of about $1.4 \cdot 10^6 \text{ [m}^2\text{]}$ and the

final use of biodiesel produced from all municipalities inside in a buffer with a fixed radius (20 km) (see Fig. 8). The case 2 and case 3 were chosen because of their proximity with the most populated cities of Sicily, Palermo and Catania. Case 1 was chosen in the Province of Ragusa, with a good compromise between the $\text{BM}_{\text{production}}$ and $\text{MO}_{\text{production}}$ and its short distance to the sea, first nutrient for microalgae. As reported in Table 3, the case three presents the best results as the theoretical biodiesel production would take the place of 12 % of the diesel in the territory of reference.

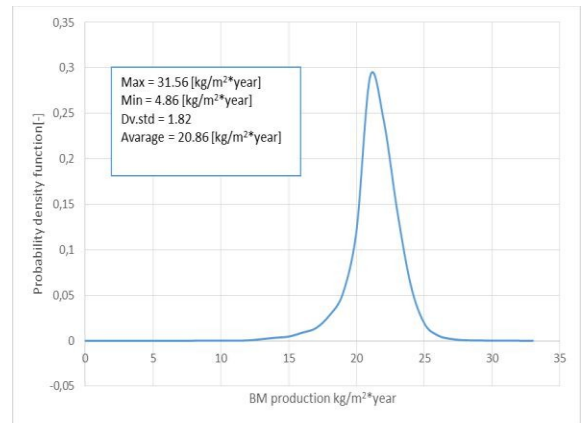
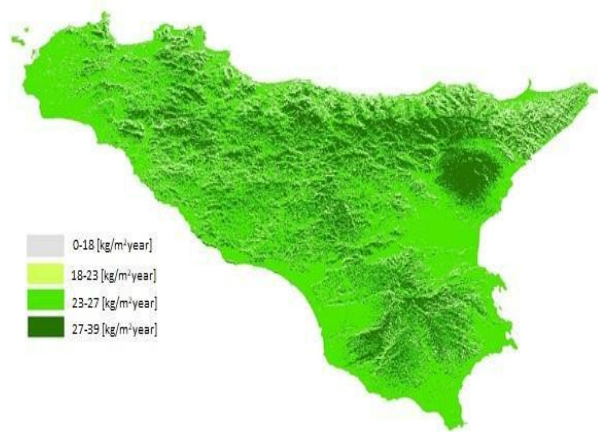


Figure 6. Theoretical $\text{BM}_{\text{production}}$ map and its PDF.

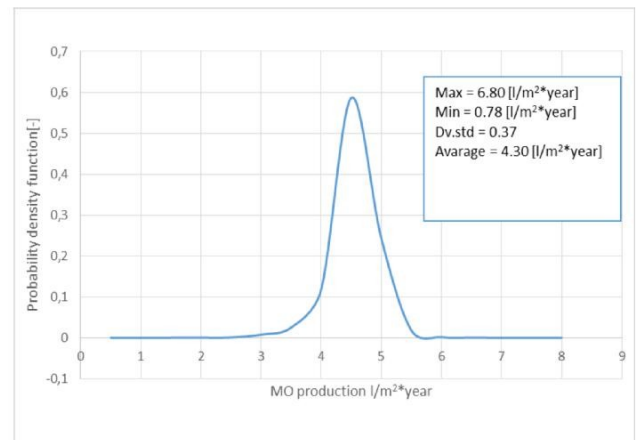
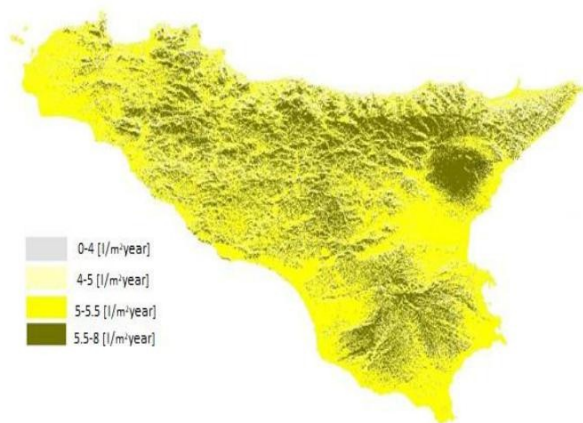


Figure 7. Theoretical $\text{MO}_{\text{production}}$ map and its PDF.

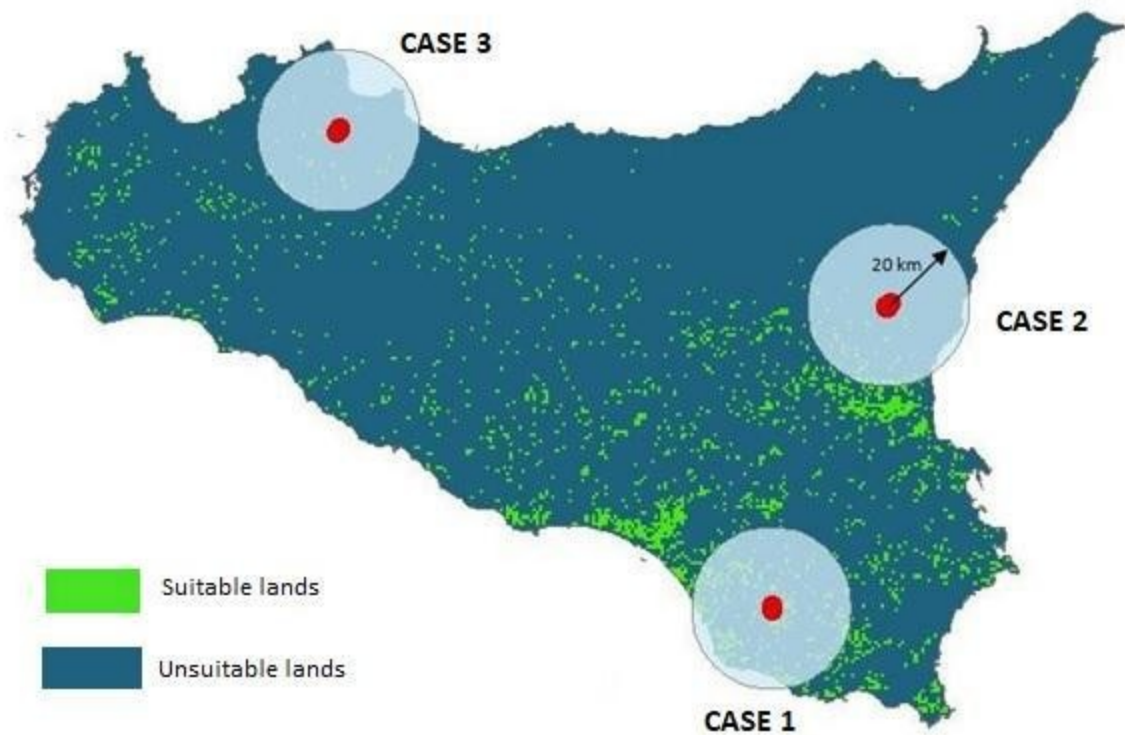


Figure 8: Test cases according suitable lands.

Table 3: Simulation results for all cases.

	Theoretical BM _{production}	Theoretical MO _{production}	Total MO _{production}	Theoretical Biodiesel production	CO ₂	Percentage of biodiesel consumption
	[kg/(m ² *year)]	[l/(m ² *year)]	[l/year]	[l/year]	[t]	%
Case 1	27.1	5.58	8.06 *10 ⁶	7.9*10 ⁶	21.09*10 ⁴	12
Case 2	27.35	5.63	8.13*10 ⁶	7.9*10 ⁶	21.28*10 ⁴	8
Case 3	26.88	5.53	7.99*10 ⁶	7.8*10 ⁶	20.9*10 ⁴	9

CONCLUSIONS

The present paper is based on the implementation of a model that simulates optimal locations for siting microalgae cultivation plants for biofuel production. The considered territory offers good prospects given that its high production of biomasses such as *Chlorella vulgaris* family microalgae. The results of potential biomasses production as well as mass of oil productions confirm that Sicily is potentially a good place to locate these facilities. The model was based on a mathematical process previously studied [46] in combination with the use of GIS that takes into consideration some important geographical constraints. The combination with geographical patterns such as land use, slopes, altitudes, air temperatures, and, above all, irradiation maps were used to identify optimal locations. This model gave a good result in terms of implementation time and precision and it could be adapted by governing institutions in the decision-making processes in planning applications. Future research will focus on making the model more precise by

considering more sophisticated transport systems and other geographical constraints.

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